MASTER ASTRONOMER PROGRAM

2019 Program Handbook

by Zach Schierl and Leesa Ricci
Cedar Breaks National Monument
National Park Service

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Section 1:
About the Master Astronomer Program

Welcome to the Master Astronomer Program

All of us at Cedar Breaks National Monument are glad that you are excited to learn more about astronomy, the night sky, and dark sky stewardship. In addition to learning about these topics, we also hope to empower you to share your newfound knowledge with your friends, family, and neighbors, so that all residents of Southern Utah can enjoy our beautiful dark night skies.

The Master Astronomer Program is an interactive, hands-on, 40-hour workshop developed by Cedar Breaks National Monument that weaves together themes of astronomy, telescopes, dark sky stewardship, and science communication. The Program is aimed at individuals with little or no prior astronomy experience, but who are excited to learn more.

The objectives of the Master Astronomer Program are to:

- Foster participants' appreciation of dark night skies by increasing their knowledge of astronomy, celestial objects, and telescope use.
- Educate and inform citizens and civic leaders about the aesthetic, cultural, ecological, and economic benefits of dark night skies, how they are currently being threatened, and potential solutions.
- Enable and empower participants to educate others about astronomy, dark sky stewardship, and dark sky friendly lighting by giving them a robust, science-based understanding of these topics combined with instruction in effective communication and teaching techniques.
- Cultivate a passionate and knowledgeable group of volunteers dedicated to astronomy education and promoting stewardship of dark night skies in their community.

By the end of the 40-hour Master Astronomer Workshop, participants will be able to:

- Use their expanded knowledge of astronomy to promote dark sky stewardship by facilitating meaningful connections between individuals and the night sky.
- Independently set up and operate a backyard telescope and be able to locate and explain the significance of several prominent celestial objects.
- Articulate the significance of dark night skies by explaining the impact of light pollution on many different aspects of society.
- Evaluate outdoor lighting fixtures to determine if they are "dark sky friendly", and suggest concrete actions that interested citizens can take to help preserve dark skies in their community.

About this Handbook

The Master Astronomer Handbook is a reference for you throughout the Program and beyond. To get the most out of workshop, we highly recommend that you read the relevant handbook chapters prior to each workshop session. Due to time limitations, we will not cover 100% of the material presented in these pages, nor are you responsible for knowing all of it. Workshops will revolve around hands-on activities that reinforce the concepts that we feel are most important for beginning astronomers and dark sky enthusiasts to learn.

Each chapter begins with a series of goals that we have identified as key to being able to communicate the topic to others. Words in **bold** throughout the text have a corresponding glossary entry in Appendix A. At the end of each chapter are review questions and a list of common misconceptions about the chapter topic. For those interested in diving deeper into a particular subject, the “For More Information” section at the end of each chapter contains links to resources that will allow you to expand your knowledge of the topics presented in the chapter.

Please note that this handbook is a living document. While every effort has been made to ensure that the information within is up-to-date and accurate, astronomy is a rapidly evolving field and new discoveries seem to occur daily. If you find errors or have suggestions on how to improve the handbook, we would love to hear from you.

Instructional Philosophy

One of the unique aspects of the Master Astronomer Program is that it is not simply an astronomy course or a series of lectures by astronomy experts. While we use slide presentations from time to time, most workshops will revolve around hands-on, multimodal learning activities which not only promote, but require, active participation by attendees. We ask for your full participation in these activities. Pedagogical research has shown that active learning promotes retention, understanding, and appreciation of the topic being taught. Whenever practical, workshops will be held outside under the actual night sky.

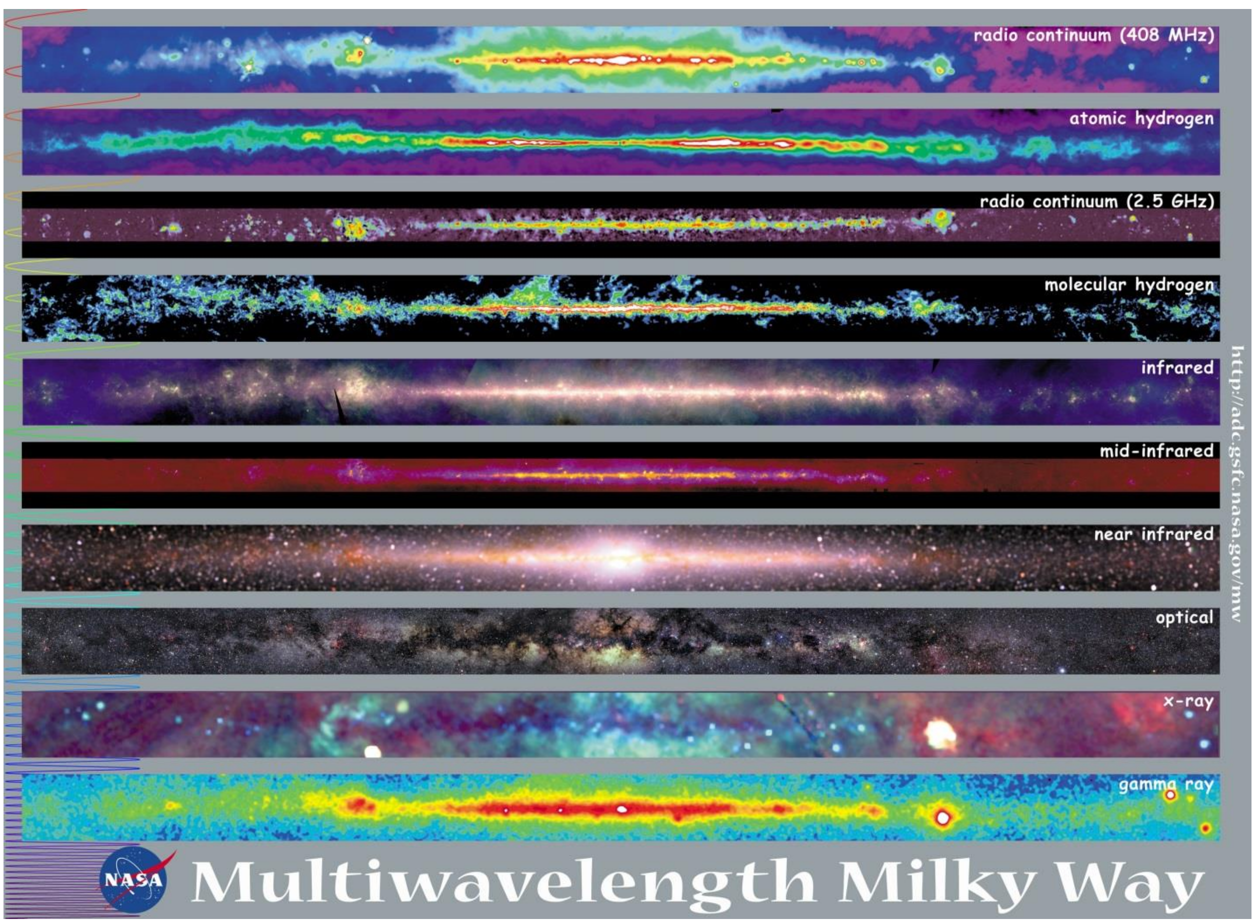
Volunteer Service

The Master Astronomer Program was modeled after the *Master Gardener* and *Master Naturalist* programs taught across the country. A core element of these programs is volunteer service that gives participants practice sharing their knowledge with others and a way to remain engaged with the program content.

In line with this model, in order to become an official Master Astronomer, program participants must contribute at least 10 hours of volunteer service in astronomy and dark skies education and outreach within one year of workshop completion.

SECTION 2: **ASTRONOMY & THE NIGHT SKY**

CHAPTER 2.1 - LIGHT



Ten images of our Milky Way Galaxy taken in ten different wavelengths of light, from radio waves on top, to gamma rays on the bottom. (NASA/Goddard Space Flight Center)

Chapter 2.1 Goals

After reading this chapter and participating in the corresponding workshop activities, you should be able to:

- Compare and contrast the many types of electromagnetic radiation (light) and explain why different types of astronomical objects emit different wavelengths of light.
- Use the magnitude system to estimate the brightness of stars and other objects, and explain the difference between magnitude and luminosity.
- Describe the practice of spectroscopy and at least one way it is used by astronomers to learn more about the universe.
- Explain the basic physiology of human vision at night and how dark adaptation affects our ability to observe the night sky.

What is Light?

Light brings us the news of the universe

—Sir William Bragg, 1933

Unlike geologists, ecologists, and chemists, astronomers rarely get to examine the objects they study in person. In most cases, analyzing **light** from astronomical objects is the only way to learn about our universe. Everything in this handbook, from stars and galaxies to telescopes and **light pollution**, involves light. Without light, astronomy would not exist. At the same time, light is the greatest threat to astronomy, as we'll see in *Chapter 3.1.*

Light**,** or **electromagnetic radiation,** is a form of energy. When we use the word "light" in everyday conversation, we are typically referring to **visible light**, which is just one type of radiation on the **electromagnetic spectrum** (Fig 1). We can't see the other varieties with our eyes, but astronomers can detect them using special cameras and telescopes. We use these other forms of light to, among other things, communicate with people around the globe (**radio waves**), keep hamburgers hot (**infrared radiation**), and to take pictures of our innards (**x-rays**).

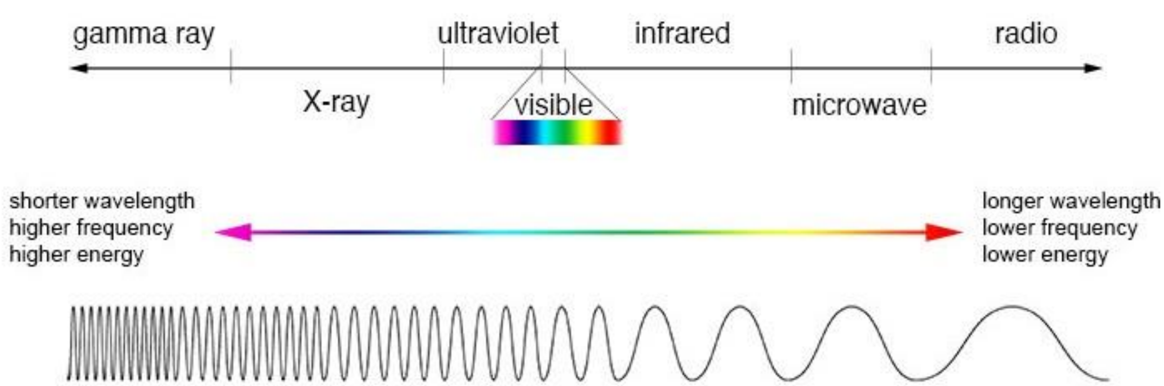


Figure 1-The different types of electromagnetic radiation. (NASA's Imagine the Universe)

Wavelength and energy

The many varieties of light on the electromagnetic spectrum differ based on their energy. Light behaves both as a wave and a particle. If we think of light as a wave, we can refer to its **wavelength**, the distance between two successive wave crests or troughs. Wavelength is important because it tells us how energetic the light is.

At one end of the electromagnetic spectrum (Fig 1) we find light with a long wavelength (measured in meters) and low energy: radio waves. Radio waves can be sent around the globe, and even to other planets, using relatively little energy, making them excellent for long-distance communication. Because they carry so little energy, we don't notice them as they pass through the air around us.

As wavelength *decreases* however, energy *increases*. We are all familiar with the damaging effects of **ultraviolet** radiation, an energetic, short wavelength form of light that causes skin cancer and sunburns. And at the high energy end of the electromagnetic spectrum, we find x-rays and **gamma-rays**, extremely energetic types of light that can cause serious damage to human cells.

Everything in the universe, with the possible exception of **black holes** and whatever **dark matter** is, emits electromagnetic radiation. Which type(s) they emit depends largely on their temperature. Hotter objects generally emit more energetic forms of light than cooler objects. For example, a hot star might emit mostly ultraviolet light, while a cool planet (like Earth) emits mostly infrared radiation. Consequently, astronomers studying hot, energetic objects need telescopes capable of detecting gamma rays and x-rays, while those studying cool interstellar clouds of hydrogen require radio telescopes. Table 1 shows examples of astronomical objects that emit different wavelengths of light. The collage on the cover of this chapter shows ten images of our **Milky Way Galaxy,** each captured in a different wavelength.

Trying to understand the universe through visible light alone is like listening to a Beethoven symphony and hearing only the cellos.

—astronomer James B. Kaler

Table 1: The Electromagnetic Spectrum in Astronomy

Wavelength:	Emitted by:
Gamma ray	Supernovae Active galactic nuclei Colliding neutron stars
X-ray	Solar corona Pulsars Accretion disks around black holes Supernovae remnants
Ultraviolet (UV)	Stars (esp. young, massive stars)
Visible	Stars of all kinds Emission nebulae
Infrared (IR)	Planets Cool stars Nebulae Humans
Microwave	Cosmic Microwave Background
Radio	Interstellar gas and dust clouds

We humans have evolved to see only visible light, so our naked eye view of the universe is, in a way, biased. Visible light is only a tiny sliver of the light around us. As we speak, our Sun is emitting radio, infrared, visible, ultraviolet, and x-rays. Yet we don't "see" most of the light that the Sun and other stars emit. For example, the brightest star in the night sky to our eyes is Sirius, in the **constellation** Canis Major. But if our eyes could see in the ultraviolet, Sirius' neighbor Adhara would shine the brightest instead. So our eyes lie to us – or, at least, are not telling us the whole story.

Figure 2-Infrared image of a lizard in a human hand. This is a false color image, meaning that the colors are not true, but used to represent varying intensities of infrared radiation, which would otherwise be invisible to the human eye. (NASA/IPAC/Caltech)

False color

How can we "see" wavelengths that are invisible to our eyes? Many telescopes and cameras are sensitive to other regions of the electromagnetic spectrum. After the light is collected, astronomers can use **false color** images to display the data. A false color (or representational color) image uses colors of visible light to represent different intensities of wavelengths that we can't see.

For example, Figure 2 is an image from an infrared camera. Yellow and white represent higher intensities of infrared radiation (the hand) while blue and purple represent lower intensities (the cold-blooded lizard). False color is used extensively in astronomy, so keep this in mind as you enjoy astronomical images. While false color images are incredibly useful, they are not a realistic representation of what the human eye would see looking at the same object.

Reflections, Scattering, and Absorption

So far, we've been talking about what kinds of light astronomical objects emit, or generate themselves. Yet some objects don't emit any visible light, but are still visible to the naked eye. Others shine brightly in visible light, yet are invisible to regular telescopes. How can this be?

If you've ever seen a **planet** like Jupiter or Mars in the night sky, you're seeing not *emitted* light, but *reflected* light. **Reflection** occurs when light bounces off of a surface rather than being absorbed. Like humans, planets are too cold to emit their own visible light. Instead, the planets reflect visible light from the Sun like a mirror. If the Sun stopped shining, all the planets would wink out in visible light shortly thereafter, but would continue glowing at infrared and radio wavelengths (Fig 3). Without reflection, the world would be a dark place. Most objects on planet Earth do not emit their own visible light. Except for things like monitors and screens, light bulbs, and perhaps fireflies, everything around you is visible due to reflected light.

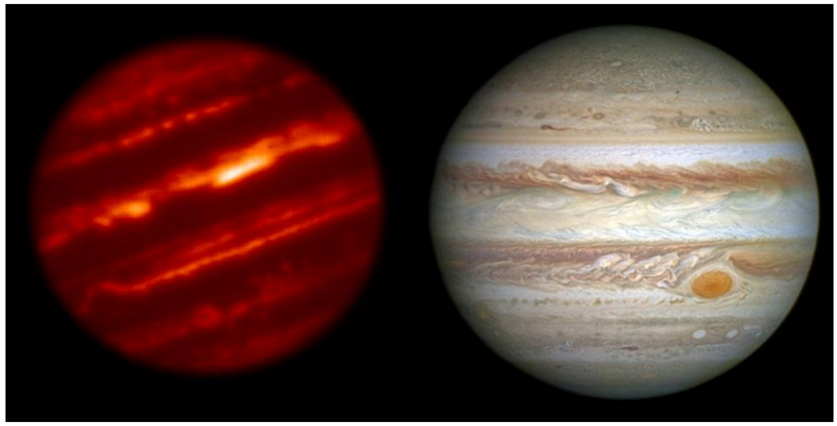


Figure 3-Jupiter seen in emitted infrared light (left) and reflected visible light (right). (Left: NASA/JPL-Caltech, Right: NASA/ESA/A. Simon)

Light can also interact with matter by **scattering**. Scattering occurs when light runs into particles that are smaller than the wavelength of the light itself. Our atmosphere is especially skilled at scattering light. Of all the colors of sunlight that enter our atmosphere, blue light has the shortest wavelength, so it gets scattered the most. This is why the sky is blue during the daytime. In the evening, as the sun sets, sunlight must pass through a thicker layer of our atmosphere, resulting in even more scattering of blue light. The more blue light you scatter, the redder the remaining sunlight appears, which is why sunsets and sunrises often have brilliantly ruddy hues. This phenomenon also has important consequences for light pollution, as we will see in *Chapter 3.1: Introduction to Light Pollution.*

Finally, some objects *absorb* certain wavelengths of light entirely. For example, dusty **molecular clouds** are often opaque to visible light, shrouding our view of stars and solar systems being born inside, as well as anything beyond them. Fortunately, the long wavelengths of infrared radiation are relatively unaffected by the dust, making infrared telescopes useful for studying things that lurk in dusty corners of the universe.

The Cosmic Speed Limit

All forms of electromagnetic radiation travel at the **speed of light** in a vacuum (the vast majority of outer space is essentially a vacuum). The speed of light, often denoted by the letter *c*, is approximately 300,000 km/sec (186,000 mi/sec, or about 671 million mi/hr), and is the fastest allowable speed in the universe. To put this number into perspective, if Utah were a vacuum, light could make the trip from Cedar City to Salt Lake City in one millisecond. By the end of an entire second, the light could have circled the Earth’s equator more than seven times.

Light travels so fast that how long it takes light to get somewhere turns out to be a useful way to measure the universe. Somewhat confusingly, a **light-year (ly)** is not a period of *time*, but rather the *distance* that light travels in one year. One light-year is equal to about 9.46 trillion kilometers (9,460,000,000,000 km) or six trillion miles.

Light from the surface of the Sun reaches Earth in about eight minutes, so we say that the Sun is "eight light-minutes" away. Beyond our Solar System, distances are almost always expressed in light-years, because using miles or kilometers quickly becomes cumbersome. As a result, looking at the night sky is, in a way, like travelling back in time. Even the light from the nearest stars, travelling at the cosmic speed limit, takes years to reach us. When we look at a celestial object, we are not seeing it as it is now, but as it was in the past. For example, when we look at the star Vega, located about 25 light-years from Earth, we are seeing the light that was leaving it 25 years ago. And Vega is our next door neighbor…cosmically speaking that is. The Hubble Space Telescope can see galaxies that are *billions* of light-years away, giving astronomers a peek into what our universe looked like in its infancy.

Measuring Light with the Magnitude System

Astronomers spend a lot of time looking at light and have long needed a way to measure it. For more than 2,000 years, astronomers have used **apparent magnitude** to express the brightness of objects in the sky. When you hear a stargazer refer to a "2nd magnitude star," they are making a statement about its apparent brightness.

The Greek astronomer Hipparchus developed the magnitude system starting around 129 B.C.[1] He referred to the brightest stars in the sky as "first magnitude," slightly dimmer stars as "second magnitude," and the faintest stars that he could see as "sixth magnitude." Hipparchus' system is why star magnitudes often seem "backwards" to many people: the higher the magnitude, the fainter the star.

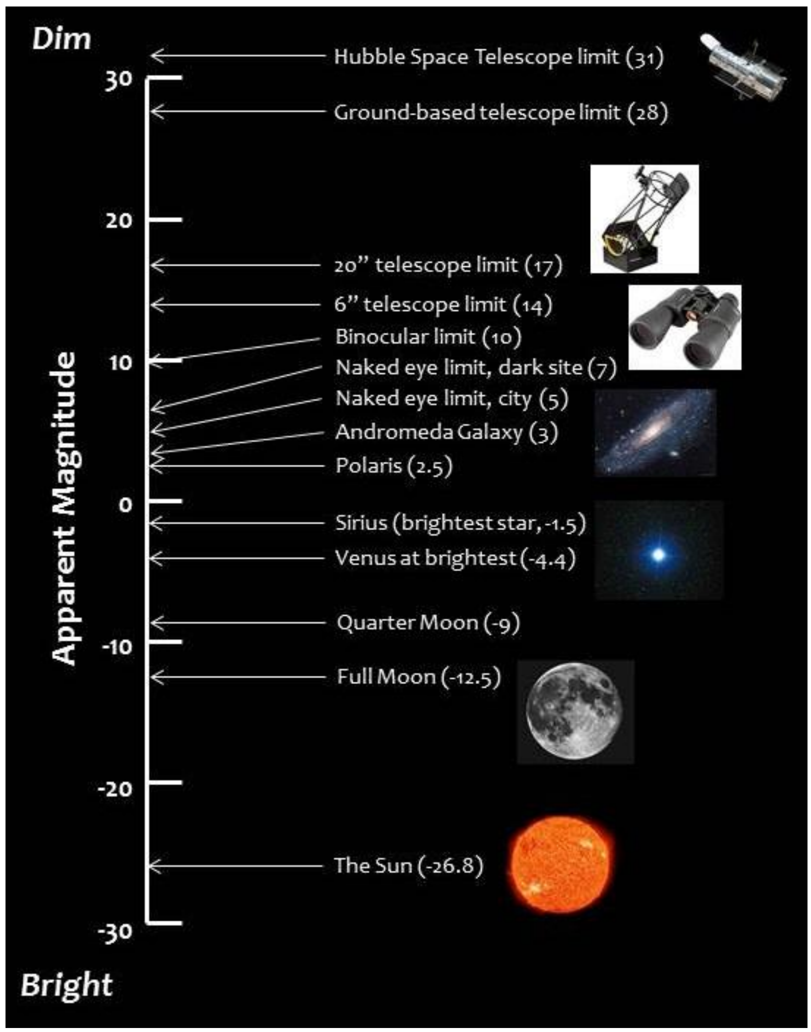


Figure 4-The apparent magnitude scale used to express the brightness of objects in the sky. Also shown is the magnitude of the faintest object detectable by various telescopes. (NPS/Zach Schierl)

While the magnitude system has been tweaked over time, it still closely resembles the system devised by Hipparchus so long ago. Figure 4 shows the magnitude scale used by astronomers today and the magnitudes of several well-known celestial objects. The biggest change is that the brightest objects in the sky, such as the Sun, Moon, planets, and brightest stars, are now assigned negative magnitudes.

It is important to note that the magnitude scale is logarithmic. Moving one magnitude up or down the scale corresponds to a 2.5x change in brightness. Moving up or down five magnitudes corresponds to a 100 fold change in brightness. For example, a sixth magnitude star is 100 times fainter than a first magnitude star.

Magnitude vs. Luminosity

While the apparent magnitude system is useful, it only tells us how bright a star appears from Earth, not how bright it actually is. If we want to know the intrinsic brightness of a star, that is, how much light it actually emits, we must look at its **luminosity**. Luminosity is defined as the total amount of electromagnetic radiation emitted by an object per second.

Apparent magnitude depends on two factors: the luminosity of the star, and how far away it is. Because objects appear dimmer with increasing distance, apparent magnitude and luminosity don't always correlate. Many of the closest stars to our Solar System are not even visible to the naked eye because their luminosities are so low. In contrast, one of the most luminous stars in the night sky, Rho Cassiopeiae, is barely visible to the naked eye because it is more than 8,000 light-years away. Be careful not to confuse luminosity with magnitude, and watch your step around generic terms like "brightness" that could refer to either. Table 2 compares the luminosity, apparent magnitude, and distance of several celestial objects to further illustrate this concept.

Table 2: Luminosity, apparent magnitude, and distance of selected objects[2]

Object	Luminosity (relative to Sun)	Apparent magnitude	Distance
Sun	1	-26.8	8 light minutes
Proxima Centauri (closest star to Sun)	0.0017	11.01	4.2 light-years
Altair (star)	10.6	0.76	16.8 light-years
Deneb (star)	196,000	1.25	3227 light-years
Mu Cephei (star)	283,000	4.23	5258 light-years
Andromeda Galaxy	2.6×10^{10}	3.44	2.5 million light-years
Quasar 3C 273	$\sim 4.0 \times 10^{12}$	12.9	2.4 billion light-years

Spectroscopy

Spectroscopy is the study of the ways in which atoms absorb or emit electromagnetic radiation. Spectroscopy involves using a **spectrograph** to split light into its component wavelengths, creating a **spectrum** (plural=**spectra**). You've engaged in basic spectroscopy yourself if you've ever used a prism to display the rainbow of colors contained within sunlight or a light bulb.

If a photo of an astronomical object is worth a thousand words, then a spectrum is worth a thousand photos. Analyzing the spectrum of a planet, star, or galaxy is almost always more illuminating than looking at a photo. Most modern research telescopes use spectrographs to record detailed spectra of the objects they observe. Studying these spectra can reveal volumes about the composition and nature of these objects.

Some objects, such as **incandescent** light bulbs, emit a **continuous spectrum** (Fig 5). That is, they emit light across a continuous range of wavelengths determined by the object's temperature. At first glance, our Sun appears to emit a continuous spectrum, but in 1802 the English chemist and physicist William Wollaston discovered something strange. Wollaston noticed that the Sun's spectrum actually contained gaps: narrow sections of the spectrum where no light was present. These gaps, now known as **absorption lines** (Fig 5) were soon found in the spectra of other stars as well.

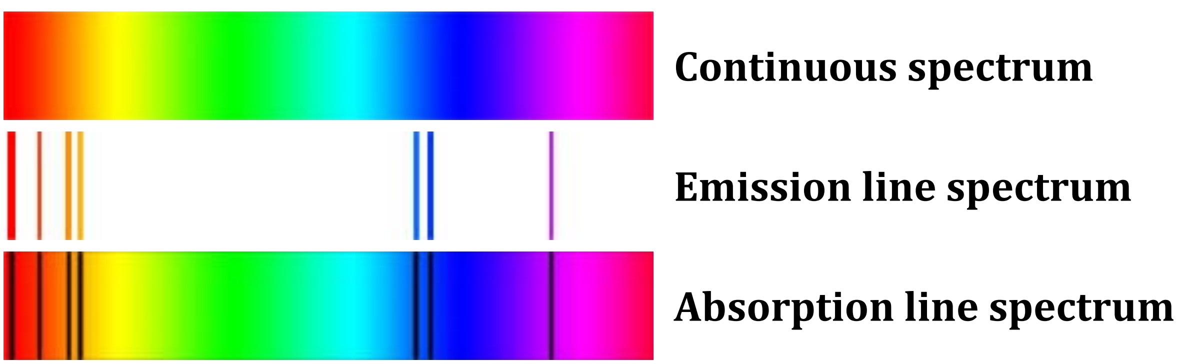


Figure 5-Different types of spectra are emitted by different types of objects. Incandescent light bulbs emit a continous spectrum (top). Hot gas emits light only at very discrete wavelengths, producting an emission line spectrum (middle). Light passing through a cooler gas produces an absorption spectrum when certain wavelengths of light are absorbed by the gas (bottom). (NASA's Imagine the Universe)

We now know that absorption lines are the result of atoms and molecules in a star's atmosphere absorbing certain wavelengths of light. Each atom or molecule produces a characteristic set of absorption lines, determined via laboratory tests. This means that astronomers can use absorption lines as a sort of chemical fingerprint to determine what elements exist inside a star or other object. Today, astronomers classify stars based on the pattern of absorption lines present in their spectra, a concept discussed in greater detail in *Chapter 2.7: Stars.*

Low density objects, such as tenuous clouds of hot gas, emit very specific wavelengths of light rather than a continuous spectrum. When this happens, we say that the spectrum contains **emission lines** (Fig 5). Somewhat like burning different substances in a Bunsen burner, the color of the emission lines also tells us something about the composition of the object in question.

Spectroscopy is a relatively new tool in the astronomer's toolbox, and an incredibly important one. The connection between spectral lines and chemical elements wasn't unraveled until 1860, but since then spectroscopy has been used to discover the expansion of the universe, measure the distance to stars and galaxies, and reveal many other insights into our universe.

Seeing in the Dark: Human Vision at Night

Stepping out of a brightly lit cabin or tent and looking up at a dark night sky can be…underwhelming. Even when the night sky is free from light pollution, we have to consider another factor that determines how many stars we can see: our own eyeballs.

A sunny day is roughly one billion times brighter than the darkest night, yet our eyes are able to function in both environments. How do our eyes manage to see well during the daytime, yet also glimpse faint galaxies millions of light-years away at night?

The answer lies in the anatomy and physiology of our eyes. Our retinas contain two different types of image-forming cells: **rods** and **cones**. Cones function best when there is a lot of light entering our eye. They are responsible for our daytime or **photopic vision**, but are almost useless at night. Cones are unique in their ability to detect color. This is why at night, when our cones lie dormant due to low light, most objects appear gray and monochromatic (Fig 6). Only the brightest celestial objects, such as planets and some bright stars, are bright enough to activate our cones and allow us to see their color.

Figure 6-On the left is an image of the Lagoon Nebula taken with a backyard telescope. The true color of the nebula, reddish-pink, is apparent in the long-exposure photograph. On the right, the photo has been altered to approximate what the human eye would see when looking at the nebula through the same telescope. Because the nebula is not bright enough to trigger the color-seeing cones in our eyes, the nebula appears gray and monochromatic. (Zach Schierl)

In contrast, our rods function admirably in low light. Rods are responsible for **scotopic vision**, or night vision, which we use anytime we are in a dark environment. Somewhat like transition lenses for eyeglasses, our rods need a period of adaptation when going from a bright environment to a dark one. Rods need at least 20-30 minutes of darkness before they reach their greatest sensitivity, leading to the temporary blindness we experience when going from a bright room to a dark room.[3]

The process of allowing our rods to achieve maximum sensitivity is called **dark adaptation.** During dark adaptation, our eyes become roughly 100,000 times more sensitive to faint light.[4] Unfortunately, even very brief exposure to a bright source of light, such as a flashlight, cell phone screen, or a bright moon, can completely reset the dark adaptation process, preventing your eyes from reaching their full potential for another 30 minutes. In many urban and suburban areas, light pollution itself is bright enough to prevent our eyes from ever achieving full dark adaptation.[5]

During the day, our eyes are most sensitive to green and yellow light, but at night our eyes become more sensitive to blue wavelengths. For this reason, astronomers often use red lights at night to help preserve dark adaptation.

High elevation also limits our ability to see well at night. The decreased oxygen supply at high altitudes actually limits the effectiveness of our rods. Rod sensitivity has been found to decrease by 5% at 1100 meters (3600 feet), 18% at 2800 meters (9186 feet), and 35% at 4000 meters (13,123 feet) without the use of supplemental oxygen.[6] While a 14,000 foot peak might be a great place to put a telescope (because the thinner air minimizes atmospheric distortions), it’s not be the best place to look at the night sky with the naked eye.

Review

Common misconceptions

Below is a list of commonly encountered misconceptions about light. As a way to review content from this chapter, see if you can explain why each misconception is inaccurate:

- All light is the same; there is only one kind of light.
- Radio waves, x-rays, ultraviolet rays, etc.…are not types of “light.”
- Planets “shine” the same way that the Sun does.
- Planets emit their own visible light.
- A light-year is a measurement of time.
- It takes only a few minutes for your eyes to adapt to the dark

Questions for thought

- Light travels at a finite speed. What are some consequences of this? *(Hint: think about how we communicate with distant spacecraft.)*

- Many images from large telescopes such as Hubble are false-color images. What does this mean? Are these images real? Fake? How would you describe this concept to someone?

- The human eye can see objects down to magnitude 6 or 7 from a dark site. The Hubble Space Telescope can see objects down to magnitude 30. Approximately how many times more sensitive is Hubble to faint light compared to the human eye?

- Given that the human eye requires ~30 minutes to dark adapt, how many people ever get to see a fully dark-adapted view of the night sky? Can you think of any situations in which dark adaptation might be impossible?

- Many wavelengths of light (such as infrared and x-rays) are blocked partially or completely by Earth's atmosphere. How are astronomers able to study objects that emit these wavelengths?

- How does spectroscopy help astronomers better understand the universe? What information do we get from spectroscopy that we can't get simply by looking at an object through a telescope?

For More Information

- *Astronomy Cast* Episode 16: "Across the Electromagnetic Spectrum": http://www.astronomycast.com/2006/12/episode-16-across-the-electromagnetic-spectrum/
- "The Multiwavelength Milky Way" (NASA): https://mwmw.gsfc.nasa.gov/
- "Tour of the Electromagnetic Spectrum" (NASA): https://science.nasa.gov/ems
- "The Stellar Magnitude System" (Sky & Telescope): http://www.skyandtelescope.com/astronomy-resources/the-stellar-magnitude-system/

Chapter 2.2: Celestial Motions

Star trails over La Verkin Creek, Zion National Park, Utah. This long-exposure photograph looks east, and captures the motion of stars rising above the canyon rim. Hidden just behind the tree branches at upper left is Polaris, the North Star. All other stars appear to revolve counterclockwise around this point as the Earth rotates on its axis. (Zach Schierl)

Chapter 2.2 Goals

After reading this chapter and participating in the corresponding workshop activities, you should be able to:

- Use Earth's rotation, orbit, and other movements through space to explain the apparent motion of objects in the sky and the natural cycles of light and dark on our planet.
- Describe how and why the apparent motion of the Moon and planets differs from the apparent motion of the stars and constellations.

Introduction

Humans have been watching the sky since antiquity. Today, stargazing is usually a leisure activity, but this hasn't always been the case. Our ancestors had a much stronger connection with the sky than we do today, not necessarily because they wanted to, but because they had to. The predictable motions of objects in the sky were the means by which humans have historically kept time and navigated around the globe.

While most of us have traded stars for smartphones, there is still value in learning why the sky looks and changes the way it does. Understanding celestial motions can help you better understand our place in the universe, and is of great practical use when operating a telescope. For the most part, the changing appearance of the sky is due not to the movement of the stars or planets themselves, but rather to our own planet's motion through space.

Diurnal motion

From an early age, most of us become familiar with how the Sun rises in the east and sets in the west. This is an apparent movement caused by the Earth's counterclockwise (as seen from above the North Pole) **rotation** around its axis. To experience this for yourself, stand up straight and slowly rotate counterclockwise. Notice how stationary objects appear (or rise) and disappear (set) from your field of vision as you rotate, just like the Sun appears to rise and set due to the Earth's rotation.

Because our lives increasingly take place indoors at night, or under the fog of **light pollution**, we often overlook the fact that this same motion occurs at night. The rotation of the Earth causes nearly everything in the sky, including the Moon, planets, and distant galaxies, to rise and set on a daily basis. The daily rising and setting of objects due to Earth's rotation is known as **diurnal motion**. Due to diurnal motion, nearly all species on Earth have evolved under natural cycles of light and dark stemming from the rising and setting of the Moon and Sun.

The easiest way to see this motion for yourself is through a telescope. While some telescopes have motors that follow, or track, objects as they move across the sky, many others do not. Observe a star through a non-motorized telescope and you will witness it drift from the **field of**

view in a matter of seconds or minutes as the Earth's rotation carries it across the sky. It can be tempting to attribute this motion to the movement of the stars themselves, but in reality it is simply a manifestation of our own planet's rotation.

Figure 1-Stars "trail" in long-exposure photographs because Earth's rotates on its axis. The North Star, Polaris, is the star that appears stationary in the center. (Zach Schierl)

Circumpolar stars and constellations

One special case is the stars and constellations located near the **north celestial pole,** the point in the sky located directly above Earth's north geographic pole. This point is, at the moment, near the 48th brightest star in the night sky, a star we call **Polaris,** or the **North Star**. Because Polaris is closely aligned with the Earth's rotational axis, it appears more or less stationary in our night sky (Fig 1). Stand and rotate again, only this time fix your gaze on an object directly above your head, that is, above *your* rotational axis. As you spin, notice how this object remains stationary, while objects in your peripheral vision appear to rise and set.

Here in the Northern Hemisphere, stars appear to revolve counterclockwise around the north celestial pole (Fig 1). The further a star is from the pole, the larger circle it will trace out. Consequently, stars and constellations that lie very close to the north celestial pole trace out such small circles that they might never set from your location. These are known as **circumpolar stars** and **constellations**. The closer you are to the North Pole, the more of them there will be. Note that this idea holds in the Southern Hemisphere, where all stars appear to rotate around the *south celestial pole*. Unlike the relatively bright Polaris however, the South Star (Sigma Octantis) is a dim bulb, ranking as the 2,707th brightest star in the night sky.

What is a day?

Earth takes 23 hours and 56 minutes to complete one full rotation on its axis. This period is known as a **sidereal day**, and is also the time it takes for a given star to return to the exact same spot in the sky. A **solar day**, the time it takes for the Sun to return to the same spot in the sky (i.e., noon to noon) is four minutes longer: 24 hours. This slight difference is due to Earth's **orbit** around the Sun. In the time it takes Earth to rotate once, we have moved about 1° in our orbit. Therefore, the Earth needs to rotate for an extra four minutes before the Sun returns to the same spot on the sky (Fig 2).

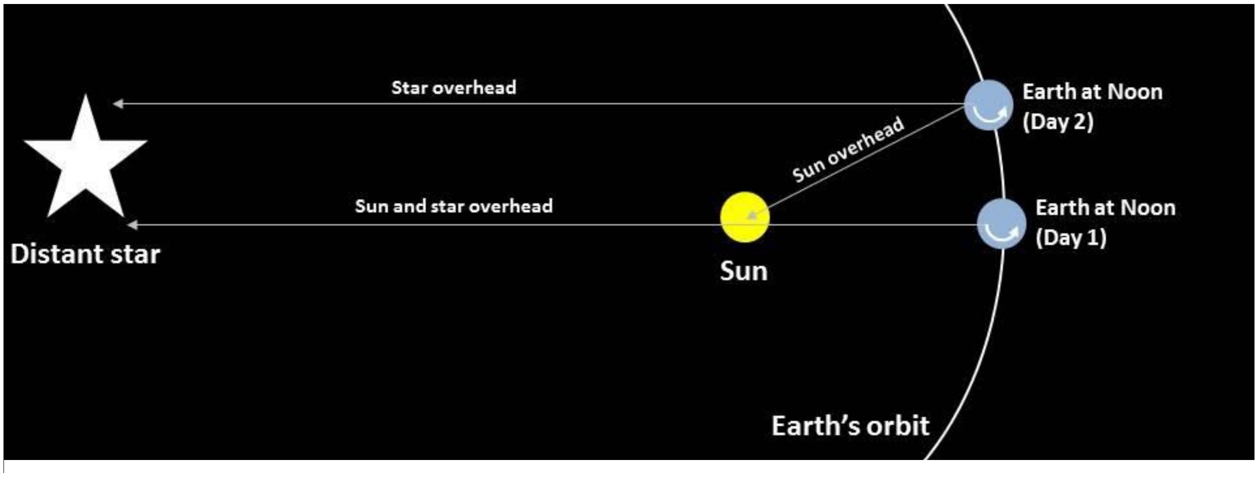


Figure 2-The four minute difference between the sidereal and solar day is due to the fact that Earth is also moving in its orbit around the Sun. (NPS/Zach Schierl)

Annual motions

Earth **orbits** the Sun at an average velocity of 108,000 km/hr (67,000 mi/hr). Celestial motions that result from our orbit are known as **annual motions**. It takes one year (or "annum"), or 365.25 days to be precise, for the Earth to complete one full orbit around the Sun. Because of that extra quarter of a day, we add a leap day to our calendar every four years. Just as Earth rotates counterclockwise, it (and all the other planets) also orbits the Sun in a counterclockwise direction as seen from above the North Pole.

As we orbit the Sun, the night side of Earth faces out into different directions of space, giving us the pleasure of seeing different stars and constellations at different times of year (Fig 3). Because of Earth's orbit, we have summer constellations and winter constellations. If not for annual motion, we'd see the same stars every night of the year.

Due to our orbital motion, a given star will rise about four minutes earlier each night. This may seem trivial, but it adds up to about 30 minutes per week and 2 hours per month. A star rising in the east at midnight on New Year's Eve will rise at 8 pm by the end of February.

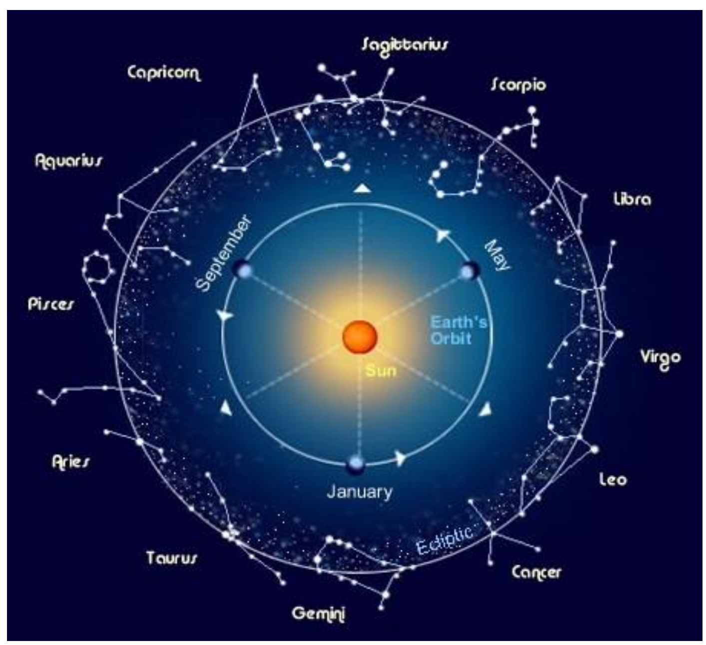


Figure 3-The stars and constellations that we see at night change throughout the year as Earth orbits the Sun and the night side of Earth faces out into different directions of space. (Lunar and Planetary Institute, Houston)

The Reason for the Seasons

One of the most prevalent misconceptions in astronomy is that the **seasons** are caused by changes in the Earth's distance from the Sun. Because our orbit is an ellipse, not a circle, our distance from the Sun *does* vary, although this is not the cause of the seasons. Earth is closest to the Sun (147 million km, or 91.4 million mi) in early January, at a point in our orbit known as **perihelion**. By the Fourth of July, we've reached our greatest distance from the Sun (152 million km, or 95 million mi) at a point known as **aphelion**. The fact that we are closest to the Sun in January when most of the U.S. is experiencing the bitter cold of winter is often sufficient to debunk the idea that seasons are related to our distance from the Sun.

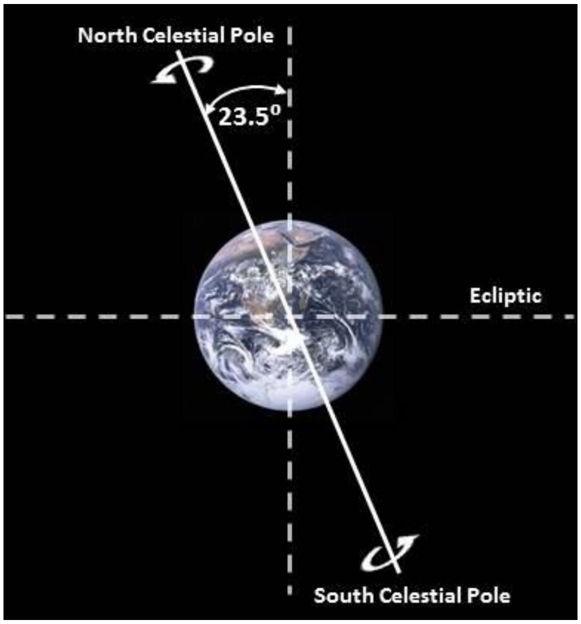


Figure 4-The Earth's rotational axis is tilted 23.5° relative to the ecliptic (the plane of our orbit around the Sun). (NPS/Zach Schierl)

Seasons are actually the result of the Earth's **axial tilt** combined with our orbital motion. Our rotational axis is tilted by 23.5° relative to the plane in which we orbit the Sun, known as the **ecliptic** (Fig 4). While our rotational axis always tilts towards Polaris (at least on human timescales), the orientation of the tilt relative to the Sun changes as we orbit (Fig 5). On one side of our orbit, the Northern Hemisphere leans towards the Sun, while six months later the

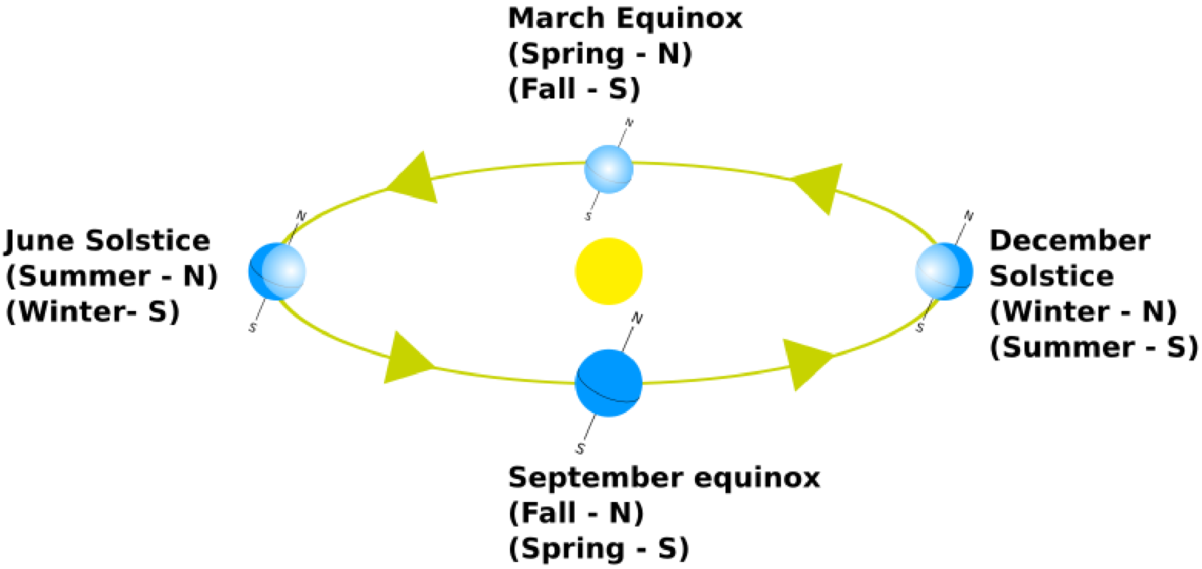


Figure 5-The Earth's axis maintains a constant tilt toward Polaris, resulting in different hemispheres being tilted toward the Sun at different points in our orbit, causing the changing seasons. (Wikimedia User: Colavine, public domain)

Southern Hemisphere leans towards the Sun while the Northern Hemisphere leans away (Fig 5).

When a given hemisphere is leaning away from the Sun, it follows a lower path across the sky each day (Fig 6), resulting in fewer hours of daylight and less solar heating. Solar radiation also strikes us less directly when the Sun is lower in the sky. These two factors combine to produce the colder temperatures we experience during local winter.

The point in our orbit when the Northern Hemisphere leans most directly towards the Sun is known as the **summer or June solstice** (Fig 5). On the other side of our orbit is the **winter or December solstice**, when the Sun is up for the shortest amount of time in the Northern Hemisphere. In between are the **spring (or vernal)** and **autumnal equinoxes**, the days when neither hemisphere is leaning toward the Sun and day and night are roughly equal for all locations on Earth.

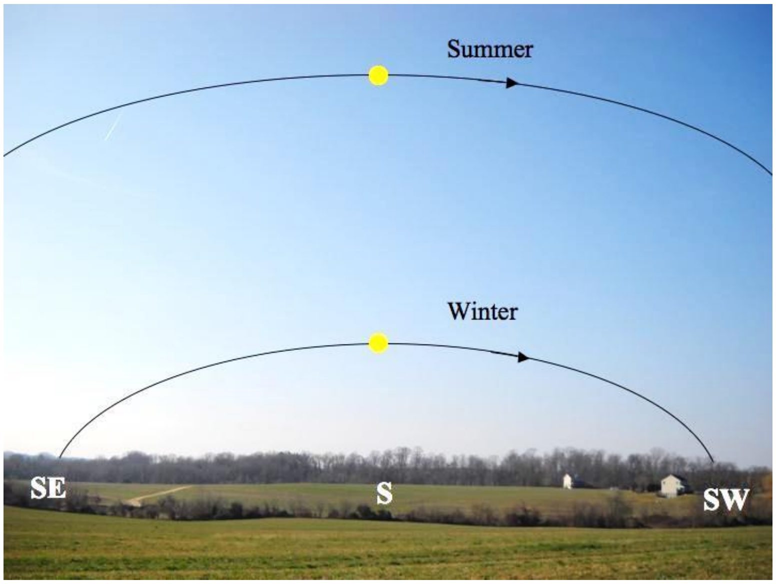


Figure 6-From mid-northern latitudes, the Sun's path across the sky is much shorter and lower during winter than it is in summer, leading to fewer hours of daylight and colder temperatures. (U.S. Naval Observatory Astronomical Applications Department)

The Zodiac and Ecliptic

It's odd to think about, but the stars we see at night are still there during the day, we just can't see them because the sky is so bright. Imagine for a moment that we could magically darken the daytime sky behind the Sun, perhaps by conjuring a total solar **eclipse**. We would see the Sun superimposed on a canvas of background stars and constellations. As we orbit the Sun, it appears to "wander" through the stars and constellations, eventually returning to the same position relative to the stars one year later. The apparent path of the Sun across the sky is called the **ecliptic,** which also represents the plane of our orbit around the Sun. The movement of the Sun along the ecliptic over the course of a year is another important annual motion.

During its annual journey around the ecliptic, the Sun passes through a set of constellations collectively known as the **zodiac** (Fig 7). "Ecliptic" and "zodiac" may be familiar terms to you, perhaps due to their prominence in western astrology. While astronomy and astrology were intertwined centuries ago (Johannes Kepler, who established the laws of planetary motion in the 17th century, often paid his bills by making astrological predictions for kings and other nobles), today they are two unrelated disciplines, with drastically different goals and motives.

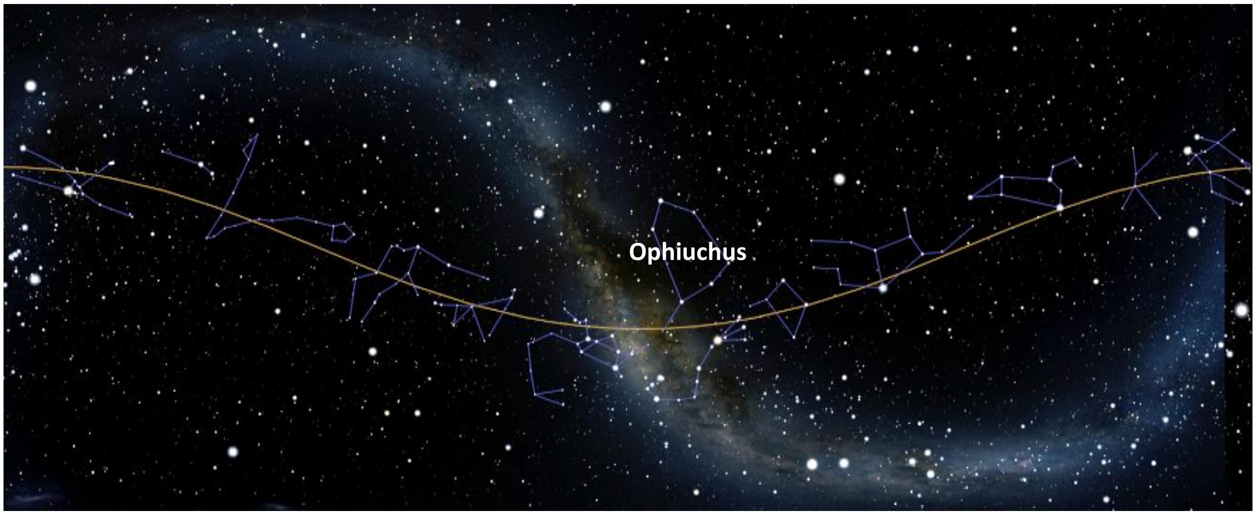


Figure 7-The Sun's annual path along the ecliptic (orange line) passes through thirteen constellations, including Ophiuchus, that are collectively known as the zodiac. (NPS/Stellarium)

As Master Astronomers, the zodiac and ecliptic are important. All the planets orbit in more or less the same plane as the Earth and Sun, so they too appear to follow the ecliptic, as does our Moon. Thus, if we want to observe planets or the Moon, the zodiac constellations are where we will find them.

> **Fun Fact**
>
> The words "zoo" and "zodiac" are derived from the same root: most of the zodiac constellations represent animals.

Astronomers are often asked about astrological signs or "sun signs." These astrological concepts are rooted in the fact that the Sun is always "in" one of the zodiac constellations (that is, in front of its stars during the daytime). Your sun sign is supposedly the constellation that the Sun was "in" on your birth date.

This topic reveals an important distinction between astronomy and astrology. Due to the wobble of the Earth's axis over time, the Sun no longer lives in each zodiac constellation for the same period of time it did millennia ago when the astrological signs were first established. Table 1 shows the dates that the Sun resides in each astronomical zodiac constellation in the present day. Furthermore, while the astrological zodiac famously contains twelve constellations, the Sun actually passes through a thirteenth: Ophiuchus, the Serpent Bearer. If you were born between Nov 30th and Dec 17th, consider yourself lucky to be an Ophiuchan!

Our Changing Moon

So far, all the celestial motions we have discussed have been the result of Earth's movement, either rotational or orbital, through space. Next we'll explore how the movement of other objects, such as the Moon and planets, affects our sky.

While we now know that not everything revolves around us, at least one thing still does: the Moon. The Moon rises and sets each day, just like the Sun and stars, due to the rotation of the

Table 1: The Astronomical Zodiac Constellations		
Zodiac constellation:	**Sun in residence from:**	**Length of stay:**
Aries *(Ram)*	April 19 – May 13	25 days
Taurus *(Bull)*	May 14 – June 19	37 days
Gemini *(Twins)*	June 20 – July 20	31 days
Cancer *(Crab)*	July 21 – August 9	20 days
Leo *(Lion)*	August 10 – September 15	37 days
Virgo *(Maiden)*	September 16 – October 30	45 days
Libra *(Scales/Balance)*	October 31 – November 22	23 days
Scorpius *(Scorpion)*	November 23 - November 29	7 days
Ophiuchus *(Serpent Bearer)*	November 30 - December 17	18 days
Sagittarius *(Centaur Archer)*	December 18 – January 18	32 days
Capricornus *(Sea-goat)*	January 19 – February 15	28 days
Aquarius *(Water bearer)*	February 16 – March 11	24 days
Pisces *(Fishes)*	March 12 – April 18	38 days

Earth. However, because the Moon also orbits Earth once every 27.3 days, its movement and appearance in the sky is more complicated.

The Moon's orbit around Earth is inclined by about 5° relative to our orbit around the Sun (Fig 8). As a result, the Moon generally follows the ecliptic like the Sun, but deviates from it slightly. Because the Moon orbits us once every 27.3 days (also in a counterclockwise direction as seen from above the north pole), it makes a complete circuit through the zodiac about once per month instead of once per year like the Sun. While the stars rise four minutes earlier each night, because of the Moon's rapid eastward motion through the zodiac, moonrise gets about 50 minutes *later* each night.

Lunar Phases

Unlike many other objects, the Moon's appearance changes as it moves across the sky. The Moon goes through a complete set of **phases** every 29.5 days (Fig 9). (Can you guess where the word "month" comes from?) What causes the Moon to behave in this way?

The first thing we need to understand is that the Moon does not emit its own **visible light**. We see the Moon only via reflected sunlight. Because the Moon is (roughly) spherical, half of it lit by the Sun at any given moment. Which phase we observe from Earth simply depends on how much of the lit half we can see. When we can see the entire lit half, we call it full moon. When the lit half faces away from us, we call it new moon.

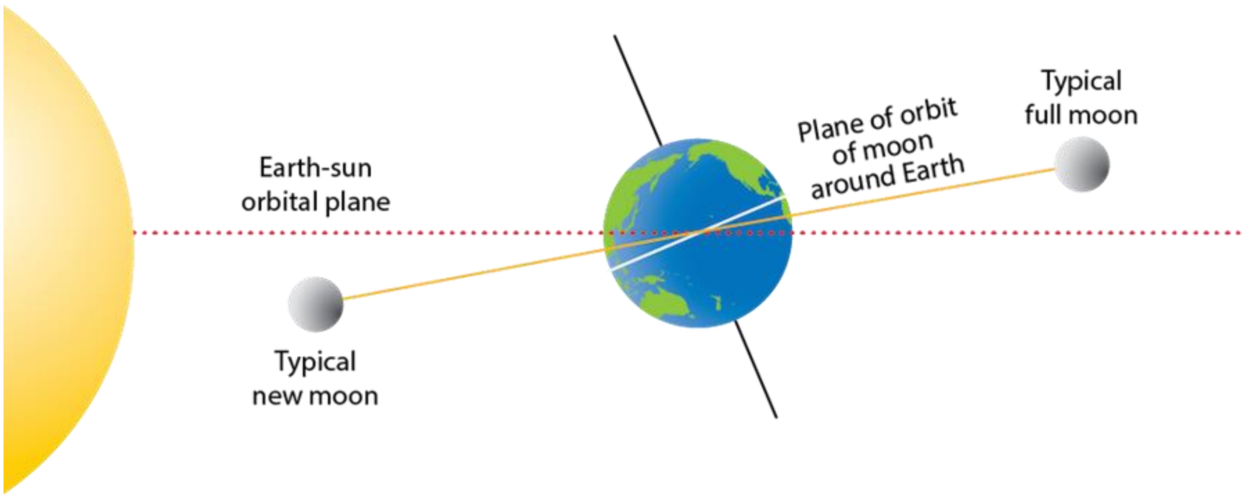


Figure 8-The Moon's orbit around Earth is inclined by 5° to the Earth-Sun orbital plane. Note that this figure is not drawn to scale. (Byron Inouye, University of Hawai'i)

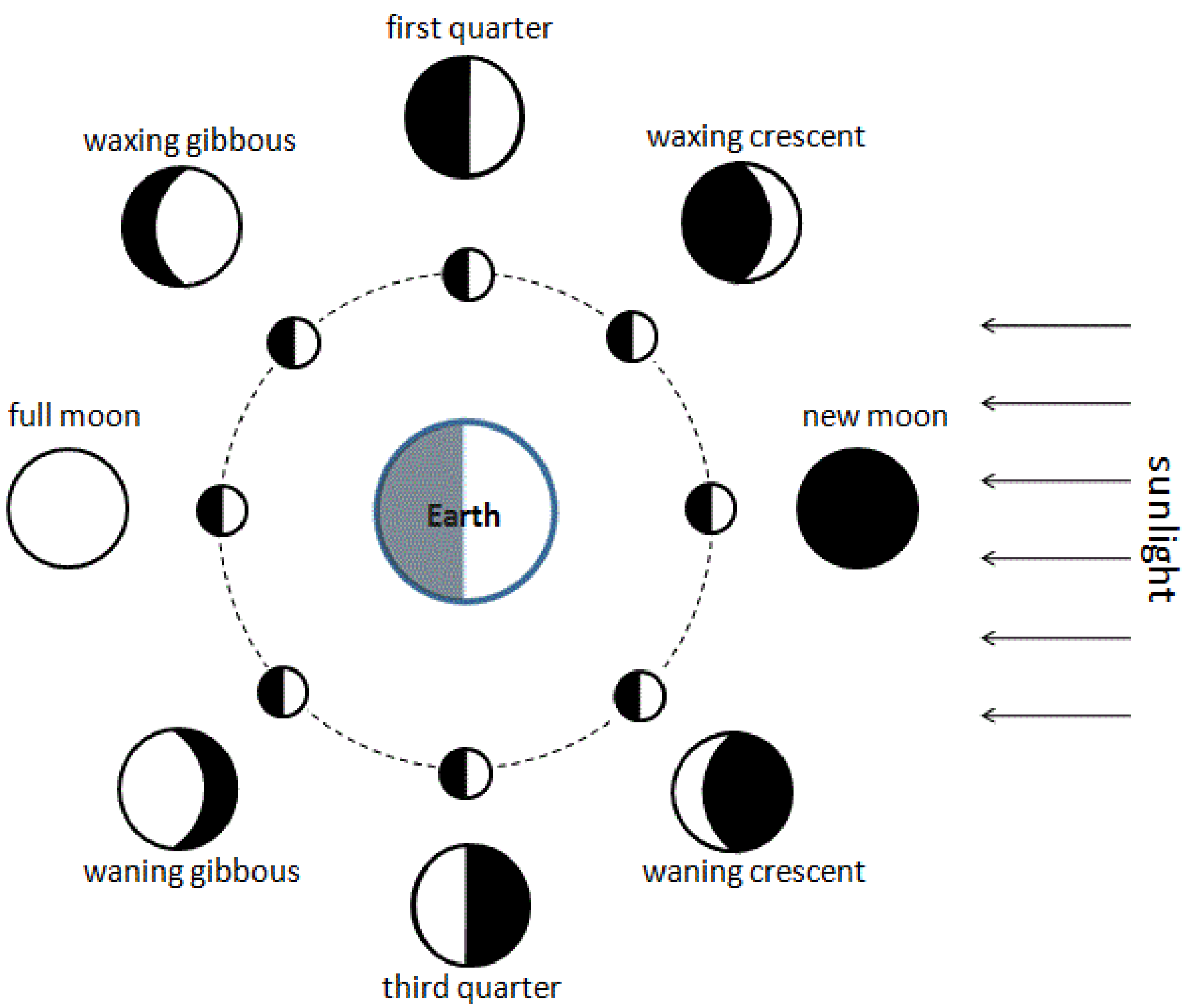


Figure 9-The phases of the Moon (Wikimedia user: Andonee, [CC BY-SA 4.0](CC BY-SA 4.0))

To simulate lunar phases for yourself, stand about six feet away from a bright lamp (the Sun) located near head level. Find a golf ball (or any reflective spheroid) to represent the Moon. You get to be the Earth. Begin by facing the lamp and holding the ball out at arm's length. Hold the Moon slightly above or below the lamp so it does not block your view of the light. (Remember that the Moon orbits on a plane inclined 5° to the Earth-Sun system, so this is realistic.) In this orientation, note how the entire lit half of the Moon is facing away from Earth, meaning that we cannot see it at all. This is a new moon.

Now rotate 180° and face away from the lamp. Again, hold the ball at arm's length and slightly above your head so that light from the lamp hits it. Notice how this time the entire lit half of the Moon is facing you (the Earth) so we see a full moon. By rotating and holding the golf ball in different positions, you can simulate the entire set of lunar phases shown in Figure 9.

The Moon always keeps the same hemisphere facing Earth. This is not because the Moon doesn't rotate (it does) but because the Moon takes the same amount of time to rotate on its axis as it does to orbit us (about 27 days), a phenomenon known as **synchronous rotation.** The side we never see from Earth is known as the *far side*. However, you may have noticed during the golf ball activity that the far side of the Moon is lit by the Sun during new moon. While there is a *far* side of the Moon, there is no perpetually *dark* side. Pink Floyd was wrong.

Eclipses

Because the Moon's orbit is inclined by 5° to our orbit around the Sun, the Moon usually passes slightly above or below the Sun at new moon. About twice per year though, the Earth, Moon, and Sun line up and the new moon completely or partially blocks the Sun's light. This is a **solar eclipse.** When the new moon completely blocks the Sun's disk, we get a **total solar eclipse**, allowing us to see the Sun's outer atmosphere: the corona (Fig 10). Total solar eclipses are possible because the Moon and Sun have roughly the same apparent size. While the Moon has only 1/400th the diameter of the Sun, it just happens to be about 400 times closer.

Figure 10-The three types of solar eclipses: total (left, with the Sun's corona visible), partial (center), and annular (right). (Total/partial: NASA/MSFC/Joseph Matus. Annular: Wikimedia user Smrgeog, CC BY-SA 3.0)

Total solar eclipses are rare, and more often the new moon blocks only part of the Sun, causing a **partial solar eclipse** (Fig 10). A third variety, an **annular solar eclipse**, occurs when the Moon is too small (the Moon's apparent size varies because its orbit around us is slightly elliptical) to block the entire sun, resulting in a narrow ring of sunlight around the dark Moon (Fig 10). When you witness a solar eclipse, you are essentially standing in the Moon's shadow. However, because the Moon is small compared to Earth, the shadow only covers a small portion of our planet, meaning that any given eclipse is only visible from certain areas of Earth's surface.

Lunar eclipses can occur during full moon, when the Earth passes between the Sun and Moon. In this case, the normally bright full moon darkens as it enters Earth's shadow. The Moon never goes completely dark because of sunlight refracted through our atmosphere to the surface of the Moon. This causes the characteristic dark red or orange color of the Moon during a lunar eclipse (Fig 11). Because the Earth's shadow is much larger than the Moon itself, lunar eclipses last longer and are visible across a much larger portion of Earth as compared to solar eclipses.

Figure 11-A series of images showing the progression of a total lunar eclipse. At left, the Moon is just beginning to enter the Earth's shadow. Eventually, the Moon is entirely immersed in Earth's shadow, but sunlight refracted through Earth's atmosphere still reaches the Moon, giving it a deep red color. (Steve Schultz)

Lunar Influence

Because of its proximity to us, the Moon influences life on Earth more than any other celestial object besides the Sun. For example, the Moon is by far the brightest source of natural light at night. On the handful of nights around full moon, its illumination dramatically alters the nighttime environment. Moonlight is known to influence animal behavior and physiology[1], and likely influenced human behavior as well prior to the advent of electric lighting.[2] Unlike **light pollution**, moonlight is a natural source of light that has existed throughout Earth's history.

The Moon is also the primary cause of our tides (the Sun also plays a small role). It is large enough and close enough that the side of the Earth facing the Moon experiences a stronger gravitational attraction than the side facing away. This causes the Earth to physically flex in response to the uneven gravitational pull. The most obvious consequence of this is the cyclic rising and falling of water levels in large bodies of water such as oceans and the largest lakes.

Wandering Stars

Ancient Greek sky watchers noticed that out of all the stars in the sky, there were five that, in addition to rising and setting each day, wandered among the stars. They called them *planētes asteres*, meaning "wandering stars." Today, we call them **planets**. While the Greeks were certainly not the first to notice the peculiar motions of these objects, astronomers nevertheless use their name to this day. The planets appear to move relative to the fixed stars because they, like the Earth, are in orbit around the Sun. All eight major planets orbit in nearly the same plane as the Earth and Sun so they closely follow the ecliptic and can always be found in one of the zodiac constellations (Figs 7, 12).

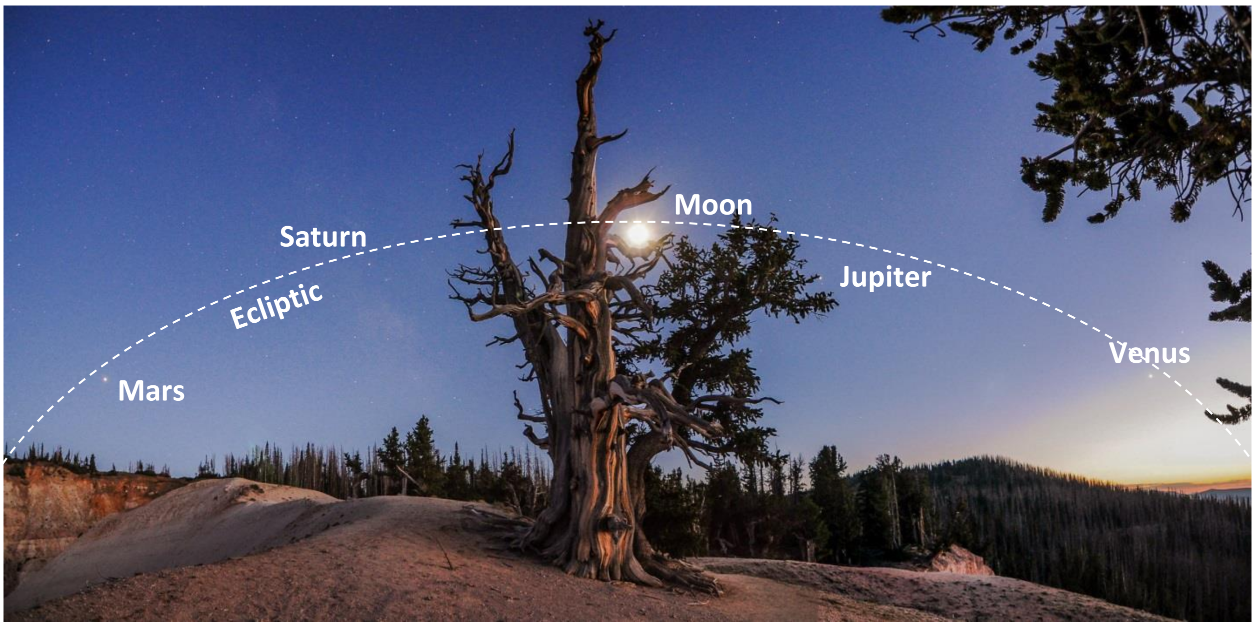


Figure 12-Four planets and the Moon as seen from Cedar Breaks NM in August 2018. Note how all five objects lie close to the ecliptic. (Zach Schierl)

Inferior planets, those closer to the Sun than us, and **superior planets,** those further from the Sun than us, behave differently. The inferior planets, Mercury and Venus, never stray far from the Sun as seen from Earth. Because Mercury's orbit lies so close to the Sun, it never appears more than 28 degrees away from the Sun in our sky. (A **degree** is an angular measurement on the sky, equal to 1/360th of a circle. The sky from horizon to horizon spans 180°.) Because we have to look *toward* the Sun to see Mercury, it is only visible in twilight either just after sunset or just before sunrise. Most of the time it is so close to the Sun that it is lost in our star's glare entirely. Venus is slightly easier to spot, but still never gets more than 48° away from the Sun. Neither Mercury nor Venus will ever be visible in the middle of the night.

In contrast, the superior planets can be seen at any time of night, depending on where they are in their orbit relative to Earth. Superior planets are best observed when they reach **opposition**, the time when they are directly opposite the Sun in the sky and at their highest point in the sky at midnight. The superior planets appear brightest and largest during opposition because we are closest to them. By definition, the inferior planets can never appear opposite the Sun in the sky because they are closer to the Sun than we are.

Because each planet orbits the Sun at a different speed, each planet also traverses the zodiac at a different rate. Planets closer to the Sun complete an orbit faster than those further out. Venus, for example, appears to race around the sky quickly, while Saturn takes decades to complete a circuit of the zodiac and remains visible in the same general part of the sky for years at a time. Information on the current visibility and positions of the planets can be found in astronomy periodicals or online, such as at http://www.nakedeyeplanets.com/visibility.htm

Slow Motions

Earth's orbit and rotation combined with the movements of the Moon and planets results in an ever changing view of the sky. While we've now covered the motions that control what our sky looks like on a day to day basis, many others affect the appearance of the sky on larger timescales. We'll briefly look at some of these in this final section.

Precession

Earth's rotational axis "wobbles" over time in a process called **axial precession** (or simply **precession**). While the *amount* of tilt changes slightly (between 22°-24.5° over 41,000 years), it is the *direction* of the tilt that changes more dramatically. Over a 25,772 year period, the axis traces out a circle in the night sky. In other words, the celestial poles are not fixed relative to the stars, but instead wander around the northern and southern skies. This means that we have

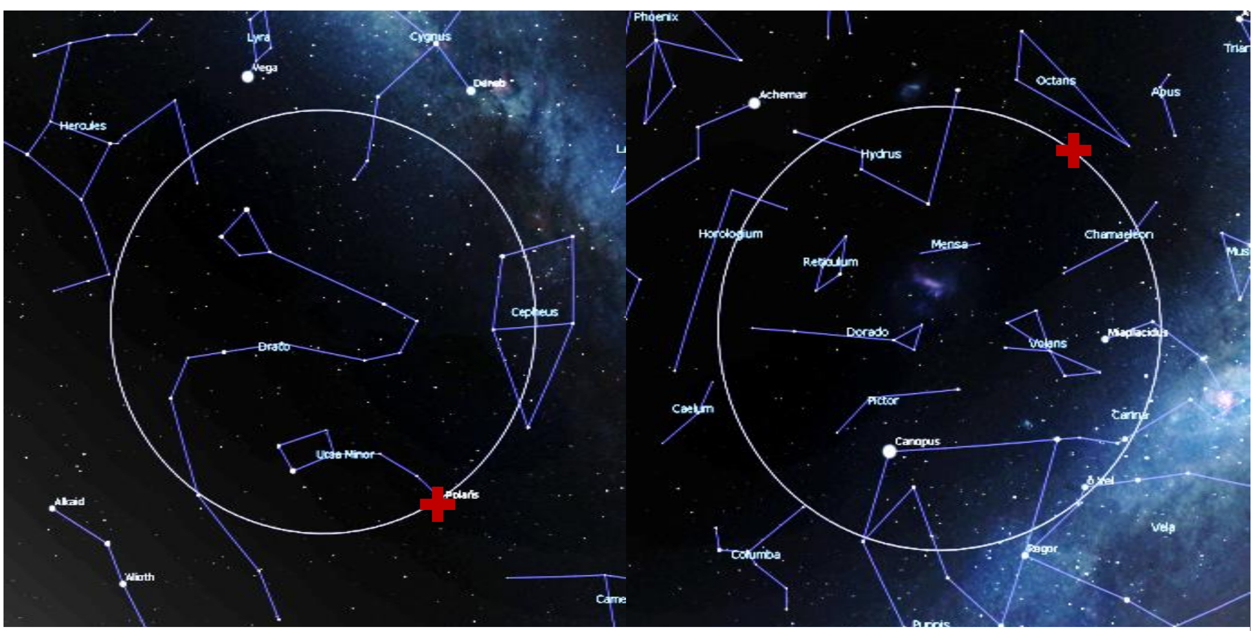


Figure 13-Circles representing the precession paths of the north (left) and south (right) celestial poles. Cross indicates the current position of the poles. (NPS/Stellarium)

different north stars thru time (Table 2). As of 2017, Polaris lies within one degree of the north celestial pole, making it a decent north star. As we speak, the north celestial pole is drifting even closer to Polaris, and by 2100 will be within one half degree (the diameter of the full moon) of the star.[3] From that point onward, the north celestial pole will begin leaving Polaris behind. In less than a thousand years, Polaris will no longer be an accurate north star.

Figure 13 shows the precession of the north and south celestial poles. Notice that most of the time there is no bright star near either pole. We're fortunate right now in the Northern Hemisphere. Polaris is the 48th brightest star in the sky, making it bright enough to be seen from all but the most light-polluted locations. It is one of the brightest stars to come near either celestial pole during the entire 25,772 year precession cycle.[4] In contrast, the closest naked eye star to the south celestial pole is, as of 2017, Sigma Octantis, which ranks 2,707th in brightness.[5]

Table 2: Past and Future Pole Stars

Years from Now	Closest Pole Star
-9400 (7400 BCE)	Rukbalgethi Shemali (Tau Herculis)
-4800 (2800 BCE)	Thuban (Alpha Draconis)
-3000 (1000 BCE)	Kochab & Pherkad (Beta & Gamma Ursa Minoris)
Present	**Polaris** (Alpha Ursa Minoris)
+5500 (7500 CE)	Alderamin (Alpha Cephei)
+8000 (10,000 CE)	Deneb (Alpha Cygni)
+12,000 (14,000 CE)	Vega (Alpha Lyrae)

Proper Motion

When we talk about the movement of the Sun or planets, we do so in reference to the "fixed" stars. But are the stars really fixed? Over the course of a single human lifetime they certainly seem to be; constellation patterns don't change appreciably on human timescales. But the stars *are* moving, as is our Sun and entire Solar System. We don't easily notice for the same reason that a fast-moving, high-altitude jetliner appears to creep slowly across the sky. The stars are so far away that, even though they are all moving rapidly in different directions, it takes many years for us to detect that movement.

The slow and gradual shift in the relative position of the stars over time is known as **proper motion**. Only a few stars are close enough for this effect to be detectable by backyard astronomers. Barnard's Star, in the constellation Ophiuchus, has the largest proper motion of any star, and it only moves the equivalent of half the diameter of the full moon in a typical human lifetime.[6] On large timescales, these small changes add up though. Star patterns such as the Big Dipper and Orion that are familiar today will look very different millennia from now (see *Chapter 3.2, Figure 2*).

Galactic Motion

On an even larger scale, the Sun and all the other stars, gas, and dust in our **Milky Way Galaxy** are orbiting the center of the galaxy at roughly 725,000 km/hr (450,000 mi/hr). While this is an incredible speed, the Milky Way is so large that it still takes the Sun about 230 million years to complete one orbit of the galactic center. Consequently, this movement does not change our view of the sky in any significant way.

Furthermore, the Milky Way is itself moving with respect to other nearby galaxies. For example, we are hurtling toward our nearest large galactic neighbor, the Andromeda Galaxy, at about 320,000 km/hr (200,000 mi/hr). Astronomers forecast a collision of titanic proportions in several billion years, although the likelihood of any two stars or planets colliding is essentially zero, due to the fact that galaxies are mostly empty space.

Universal Expansion

Finally, we now know that the universe as a whole is expanding, and that almost all galaxies (except those close enough to be gravitationally bound to each other, like the Milky Way and Andromeda) are moving further and further apart from each other. The Milky Way is moving away from every galaxy in the universe that isn't a part of our **Local Group** of galaxies. While such motions are important for understanding the origin and evolution of the universe, they simply don't affect how the night sky appears from Earth on a night to night basis.

Table 3: Celestial Motion Cheat Sheet

Motion:	Why it Happens:
Rise and set of the Sun, Moon, planets, and stars	Daily rotation of Earth
Different stars/constellations visible at different times of year	Orbit of Earth around the Sun
Sun travels through the zodiac constellations	Orbit of Earth around the Sun
Sun appears higher in the sky in summer than in winter	Tilt of Earth's axis combined with orbital motion around Sun
Planets appear to "wander" relative to the fixed stars	Orbit of planets around the Sun combined with Earth's orbital motion
Constellation patterns change slowly over thousands of years	Motion of Sun relative to other stars within the Milky Way Galaxy
North star changes over time	Wobble of Earth's rotational axis

Review

Common misconceptions

Below is a list of commonly encountered misconceptions about celestial motions. As a way to review content from this chapter, see if you can explain why each misconception is inaccurate:

- Orbit and rotation are the same thing.
- It is hotter in the summer because Earth is closer to the Sun.
- Day and night are exactly equal on the equinoxes.
- The Moon has a perpetually dark side.
- The Moon does not rotate on its axis.
- The phases of the Moon are caused by the Earth casting its shadow on the Moon.
- The Full Moon controls human behavior.
- The North Star is constant and doesn't change/move.
- There are 12 zodiac constellations.

Questions for thought

- Think about the constancy of celestial motions over time and the patterns of light and dark created by the rising and setting of the Sun and Moon. How have these patterns influenced organisms on Earth? Do humans have any influence over these patterns?

- Imagine you were an astronomer several thousand years ago observing the night sky. What might you have made of the complex motions of the Sun, Moon, and planets?

- In an age when few of us still navigate or tell time using the stars, why might it be important for people to understand celestial motions and how the night sky works?

- How do celestial motions affect you as a stargazer? As a telescope operator?

- Mars rotates on its axis every 24 hours and 37 minutes, and orbits the Sun every 780 Earth days. How would celestial motions be different (or the same) on Mars? Would the Sun and stars still rise and set? Does Mars have seasons? Do you need other information to determine the answer?

- Do other planets in the Solar System experience eclipses like we do? What is needed for an eclipse to occur?

For More Information

- Kinesthetic Astronomy activity on celestial motions, developed by Cherilynn Morrow and Mike Zawaski: http://www.spacescience.org/eduresources/kinesthetic.php
- *Stellarium (*free open source planetarium software for your computer): http://www.stellarium.org/
- "Visibility of the planets": http://www.nakedeyeplanets.com/visibility.htm

CHAPTER 2.3: HISTORY OF ASTRONOMY

Chaco Culture National Historical Park, a unit of the National Park Service that protects the remains of numerous archaeoastronomy sites. (National Park Service)

Chapter 2.3 Goals

After reading this chapter and participating in the corresponding workshop activities, you should be able to:

- Provide examples of the roles the sky played in the lives of ancient societies and develop an appreciation for the sky as an important cultural heritage resource.
- Explain the significance of several archaeoastronomical sites, and summarize the challenges of ascribing astronomical significance to archaeological sites.
- Describe the rise of astronomy as a scientific discipline and human understanding of the universe at the dawn of the telescopic age.

Introduction to Archaeoastronomy

Before the telescope was invented, astronomy was limited to what we could see with our naked eyes. It may seem strange that observatories were built many years prior to the advent of the telescope, but there was plenty to do. The Earth needed measuring. The distances to the Sun, Moon, and planets needed to be determined. Navigators needed a way to accurately measure longitude and latitude. And calendar makers needed to figure out how to make the days, weeks, and **seasons** fit comfortably into a year. These are all things that we take for granted today, but that posed great challenges to skywatchers of the past.

Archaeoastronomy is a combination of archeology and astronomy. It is the study of the astronomical knowledge of ancient or prehistoric cultures. There is a lot of guesswork and professional disagreement in archaeoastronomy because history is not an open book. Architecture, paintings, statues, and other physical remains that *could* be astronomical in nature are often placed into the archaeoastronomy category but consensus is often a hard-fought battle.

Many possible archaeoastronomy sites exist around the world, but few that are obvious observatories. Stonehenge is one oft-cited example, and serves as a good example for the possibilities and problems of archaeoastronomy in general. In 1720, William Stukeley worked with astronomer Edmund Halley (of Halley's Comet fame) to show that Stonehenge was purposely laid out to align with the north magnetic pole. He believed that its builders knew about magnetism and even tried to date the site using this assumption. Stukeley estimated that Stonehenge was completed in 460 BCE[1], however modern archeologists place the beginning of construction around 3000 BCE and the end of construction around 1600 BCE, so it seems that Stukeley was over a thousand years off.

Stukeley wasn't unique in his grandiose statements about the purpose of Stonehenge. So many non-predictive theories have arisen over the years that Stonehenge begins to feel like a giant catalyst for wishful thinking. But what do we actually *know* about it? We know Stonehenge was built by humans. We know that it took over a thousand years to construct. Those are facts. It makes sense that the people who constructed it built it for a reason. But what that reason was is much less clear.

One of the inherent problems of archaeoastronomy is that many possible sites come from times and places where people were not using written language. Although we lose languages every day, there are still around 7,000 distinct languages in the world and only about 200 are written languages.[2] Many languages were simply never written. For a large portion of human history writing was often difficult (carving) or expensive (printing) or easily worn away by time (paper/papyrus).

Stonehenge is one of the best known mystery **megaliths** in the western world, but is not unique; a large number of megalithic sites exist all over the planet. Megalithic structures go way back and are found all over the world. Wurdi Youang in Australia may have stones to mark the **solstice** and **equinoxes**[3] while El Infiernito in Colombia may have been used to track the equinox.[4] Stones may have been erected to track the Sun, Moon, or stars, or they may have been used as large sundials. In any case, humanity's obsession with astronomy may have been slightly outdone by its seemingly universal obsession with really big rocks.

The point is that Stonehenge is in no way unique. People have gone back and forth about the observatory hypothesis for Stonehenge for centuries now, but was El Infiernito an actual observatory? How could it have been used? Many archaeoastronomy sites may simply have been used to tell time, or mark the solstice and equinox, or may have been used for religious purposes. Let's examine some of these possible uses.

How to Tell Time (in 4000 Easy Steps)

Say you meet the love of your life in 1595, but you're getting ready to go on a long journey with your family, and you want to come back to the same spot you met them in a few months. Let's say you want to see them on August 19th at midnight. Unfortunately your beloved is on the Julian calendar and you're using the Gregorian calendar. You know that August 19th is the night of a full moon, but in the Julian calendar, that happens on August 9th meaning your beloved is not synced to your time schedule. You never meet again and you end up permanently alone.

This tragedy could have been prevented if someone had just standardized the calendar.

Besides the negative impact non-standardized calendars would have on one's dating life, it's important to know things like when to plant the crops, around what time the last frost is most likely to occur, and when you simply can't invade Russia because winter is coming.

We know that one year is the time it takes for the Earth to go around the Sun, but even before people understood that the Earth orbited the Sun, people knew that one year was the time it takes for the Sun to travel back to the same position in the sky at the same time. For example, from June solstice to June solstice, the Sun will return to the same place. If you notice the Sun sets at a specific point on a specific day, in just over 365.242 days, it will set in the same location again.

Now of course, there are problems. How does one calculate 0.242 days without a clock? Let's say we round up and just go with the Julian year (365.25 days) adding a leap year every four years. Your calendar is getting off track by eleven minutes every year. That doesn't seem like a lot. It would take 130 years before the calendar was off by even one day. So in one human lifespan, it's nothing. But after a few millennia, it would wreak havoc on the calendar, and no one wants to celebrate Halloween in August.

When the Julian year was instituted by Julius Caesar, replacing the Roman Calendar in 46 BCE, the calendar was already off by about 80 days. In order to start off correctly, the year 46 BCE was decreed in Rome to have 445 days (in order to offset the 80 day drift) and it was a nightmare. It was extremely confusing to have an extra three months added to the year, but in order to get the year back on track, it was necessary.[5]

An entire book could be written on the standardizing of the year, month, days, and hours. Indeed, many such books have already been written because standardizing time was so laborious and so controversial that it makes for some entertaining history. Not every unit of time can become so controversial; days are universal because night and day are obvious enough that it would take some pretty arbitrary thinking to not recognize the time slice of "one day." Similarly, a "year" is pretty universal (how long it takes the Sun to return to the same place in the sky/how long it takes to get to the longest day or longest night/how long it takes to go from winter to winter or summer to summer). However seasons, months, weeks, and how to reset the calendar to combat drift, varied across the world.

Many calendars try to find a way to make a year mesh well with the **phases** of the Moon (the time it takes from one phase to the same phase). Making a solar calendar work with a lunar calendar was maddening because it takes *almost* 360 days from year to year, and there are roughly 12 full moons of roughly 30 days each in that time period. 12 times 30 is 360, so it's tempting to create a calendar with only 360 days. The problem is of course, the Moon doesn't have an even 30 day cycle, it has a 29.53 day cycle, and the Sun has a 365.24219 day cycle.

360 is an almost magical number that divides into oh so many other numbers like 10, 12, 20, 24, 30, 60, 72, and 16 others. Unfortunately the number 365 is an ugly train wreck in comparison, divisible only by 1, 5, 73, and itself. You could theoretically make a 365-day year made up of five months of 73 days, but that corresponds astronomically to almost nothing. It's basically useless.

However this didn't stop two guys in the 1960s from creating such a calendar, calling it the Discordian Calendar and creating a parody religion to go along with it.

Two major problems arose that clever people circumvented in most calendars: First, it was common to add in five "extra" days to the calendar. These were days that didn't count as days, and often they were special. For the Maya, the five nameless days (or Wayeb) were days added to the year, not as part of a 365-day year, but as non-days to a 360-day year.[6]

While calendar keeping is no longer the job of astronomers, for many centuries it was an integral part of the study of the heavens, so it makes sense that ancient astronomy was often tied to timekeeping.

Ancient Calendars

Many archaeoastronomy sites deal with just keeping track of the Sun. These "observatories" can be very old. For example, the Kokino Observatory in The Republic of Macedonia is from the Bronze Age and may have been used to track the Sun (Fig 1).[7]

Figure 1-The Kokino Observatory in Macedonia. (U.S Embassy in Macedonia)

The "Brazilian Stonehenge" of Calçoene was erected about 1,000 years ago and is aligned with the winter solstice. This alignment leads some archaeologists to conclude that it was an observatory.[8]

Another such observatory, Chanquillo, is a megalithic site built around 300 BCE in Peru. It has 13 "teeth" or towers that mark the annual rising and setting of the Sun. From the observational platform, the Chanquillo inhabitants would have been able to determine the day of the year within an accuracy of two to three days just by observing the Sun.[9]

In addition to tracking the Sun, Venus was a particularly interesting object to Mesoamerican and South American cultures. Venus is the brightest recurring object in the night sky after the Moon, and also has an interesting synodic period. A **synodic period** is the time it takes for an object to appear at the same point in relation to other objects and it turns out that Venus' synodic period, the time it takes for Venus to return to the same place in the sky in relation to the Sun-Earth system, is 584 days. Earth's year is 365 days, and long before people debated whether or not the Earth travelled around the Sun, they knew that it took 365 days for the Sun to return to the same place in the sky in relation to the Earth and background stars.

Mesoamerican cultures, such as the Mayans, figured out that eight Earth years equaled five Venus synodic periods, and worked this period into their calendars. Compared to other well-known cultures and calendars, the Mayans and Aztecs were preoccupied with the planet Venus, and recorded and predicted its movements.[10]

A number of archaeoastronomy sites exist in North America as well. For example, the Medicine Mountain National Historic Landmark has been suggested by astronomer John Eddy to align with the summer solstice, and the stars Sirius, Aldebaran, and Rigel (Fig 2).[11]

Figure 2-Bighorn Medicine Wheel, Wyoming. (National Park Service)

Another archaeoastronomy site that had a suggested calendrical use is at Namoratunga. Built around 300 BCE, on the western side of Lake Turkana (a large lake that runs from Northern Kenya to Southern Ethiopia), the Namoratunga site stands with stones encircling what appears to have been a burial site. These stone slabs were erected in the desert but it’s difficult to know if they were aligned to some astronomical objects.[12] Like Stonehenge, Namoratunga offers us a glimpse into the many “maybes” that are ubiquitous in archaeoastronomy.

One last extremely ancient calendar on our list is from the Nabta Playa in Egypt. Before the early dynasties of ancient Egypt, people settled in the Nubian Desert between 9000 and 3000 BCE. Although this area is now part of the Sahara, one of the largest deserts on Earth, the climate was not always so harsh. Monsoons in the summer reached the playa, and by 5000 BCE stone megaliths had been erected. These have been suggested to align to the solstice, but like other megalithic structures, there is no general consensus.[13]

Separating megalithic structures used for astronomical markers and megalithic structures used for other purposes is not always possible. We have to be careful when looking at structures that have a great many stones and therefore a great many possible alignments, because we may over-interpret data towards an astronomical bias. Regardless of archaeoastronomical purposes, megalithic structures occur all over the world, and are impressive feats of human ingenuity.

The Heavens vs. Heaven

Anyone who’s ever worked outside knows that the daily position of the Sun affects the Earth. Indeed, we now know that the Earth formed with the Sun and other planets around 4.6 billion years ago. The Sun is what makes liquid water and therefore all life on Earth possible, it causes wind, it correlates to the seasons (although in reality our own 23.5^{o} **axial tilt** is responsible for seasons), and without it plants would not be a viable form of life. We are totally dependent on the Sun. Life as we know it is not possible without a host star. Anatomically modern humans have been around for about 195,000 years and recorded history simply does not go back as far humankind.[14] Did people 200,000 years ago know the Sun was an integral part of their existence? 100,000 years ago? 50,000? We don't know. Even when we find clues, like the direction some early humans were buried, or cave art, or "observatories" that align to the Sun, we have to be careful not to over-interpret data.

Another question we have to ask ourselves is whether or not a particular site or object correlated to astronomy was for religious, scientific, or artistic purposes.

We have to recognize that science, as we know, it hasn't been around for very long. When we say "science" we are talking about areas of study that can be physically and objectively tested, can be known, and can be quantified. Art is subjective and therefore not a science. The vast majority of history will never be known, is subject to many interpretations, and is therefore not a science. This doesn't mean that there is no place for empiricism in fields that are not "hard" science. Indeed we have a whole category of fields under the umbrella of social sciences precisely because they use both qualitative and quantitative methods in their research.

Before the rigorous debate over what is and isn't a science took hold in the 20th century, the boundaries between astronomy, astrology, philosophy, and religion were quite blurry. For example, Anaximenes of Miletus, born 585 BCE, wrote that Thales of Miletus forewarned the Ionians of an **eclipse,** and told them the year in which it would take place. Herodotus recorded that the Medes and Lydians, when they observed this predicted eclipse, stopped fighting, and were both anxious to have terms of peace agreed on.[15] Why did they stop fighting? To observe and record the eclipse for future generations? Or did they believe the eclipse was an omen? They could have stopped fighting and watched and recorded the eclipse out of sheer scientific curiosity, but it's just as plausible that Anaximenes was recounting a superstitious episode in human history.

Another example is the "Demon Star," Algol in the **constellation** Perseus. Algol dips in brightness roughly every 69 hours. If you watch Algol for a week, you'll notice it gets more than three times dimmer in just under three days. Ancient people may have known about Algol's variability, as the very name Algol (Demon Star) could be a reference to its odd behavior. We have to ask ourselves: were people paying attention to the behavior of the star for pragmatic reasons, or superstitious ones? We must also ask ourselves when looking at the Mayan Calendar: did the Mayans track Venus because they believed this would help smooth out any bumps in the calendar, or for religious purposes?

Perhaps it was both.

Even our own "founding fathers" of astronomy were full of superstition. We like to think of the founders of western astronomy as being interested exclusively in facts and having a pure scientific mind, clear of mysticism. However, even a very cursory reading of Kepler or Newton will reveal that this is pure fiction. Standing on the shoulders of Copernicus, Kepler did shatter the geocentric model using empiricism, it's true, but he also believed in astrology and was very invested in mysticism.[16] Yet we talk about him as though he existed in a lab 24/7.

Another notable, though less famous example is Johann Elert Bode, who determined the orbit of Uranus and got it renamed – you think Uranus is bad? William Herschel had named it after King George III. But Bode was also instrumental in getting the **main asteroid belt** discovered. He did it by suggesting (or expounding on Johann Titius's idea) that the planets should be lined up in the Solar System evenly, but there's a gap between Mars and Jupiter. He said: "Can we believe that the creator of the universe left this space empty? Certainly not." His popularization of this idea, later called the Titius-Bode Law, led to the discovery of the first asteroids, Ceres, Pallas, and Vesta. But his reasoning was wrong. The Titius-Bode Law does not work. It doesn't work for our Solar System, and it doesn't work with other solar systems, however it drove astronomers all around the western world to look for *something* in between Mars and Jupiter. His idea was predicated upon nothing more than celestial numerology and a religious feeling. But we still got the main asteroid belt out of it.

All this is to say it took millennia for astronomy to become disentangled from religion and astrology. We have to view the history of astronomy through the correct lens, and trying to make early astronomers fit into modern scientific frames is futile.

Archaeological Sites

Perhaps the most famous archeological site that may have some astronomical significance in North America is Chaco Canyon in northern New Mexico. The largest house, Pueblo Bonito, has 700 rooms arranged around a semicircle, covers 4.5 acres, contains rooms five stories high, and includes many underground chambers called kivas. It was built sometime between 950 CE and 1125 CE by the ancestral Puebloans.

Of the many archaeoastronomical theories associated with this area, perhaps the most interesting is the depiction of what *could* have been the 1054 **supernova** (now known as the Crab Nebula) on one of the canyon walls, and the Sun dagger on Fajada Butte, a spiral that curls around like a snake and has a sliver of light that strikes it in the middle on the summer solstice. In general, structures at Chaco Canyon displays a strong degree of symmetry along the **cardinal points**.[17] Cardinal directions, that is, **east** (where the Sun rises), **west** (where the Sun sets),

north, and **south**, are almost universal. If a society has cardinal directions, it's a good indicator they've been studying the Sun's movement.

What is interesting about the cardinal points is that many separate cultures came to use them independently. Contrast that with the plethora of different calendars that exist. Some have an added 13th month (Hebrew Calendar), or 19 months each with 19 days and an added 4 extra days (Baha'I Calendar), or 18 months each with 20 days and 5 extra days (Mayan Calendar). Some calendars predominantly follow the Sun (Gregorian Calendar), others the Moon (Islamic Calendar), others follow the rising of constellations (Borana Calendar) or setting of specific stars (Mursi Calendar). But can we consider calendars "astronomy"?

Likewise, can we consider depictions of events in the sky to be "astronomy"? The Chaco Canyon "Supernova" may be an artistic depiction of a regular star, a supernova, a variable star, or some other phenomena. In 1843, for example, the hypergiant star Eta Carinae erupted (but did not go supernova), causing it to become the second brightest star in the sky for a short while. Later the Boorong people of Australia were recorded discussing the star's brightness, color, and location and this remains in their oral history.[18] While Eta Carinae can only be seen in the Southern Hemisphere, a phenomenon like it is possible in the Northern Hemisphere sky. The Chaco Canyon "Supernova" could be a depiction of a great myriad of celestial phenomena.

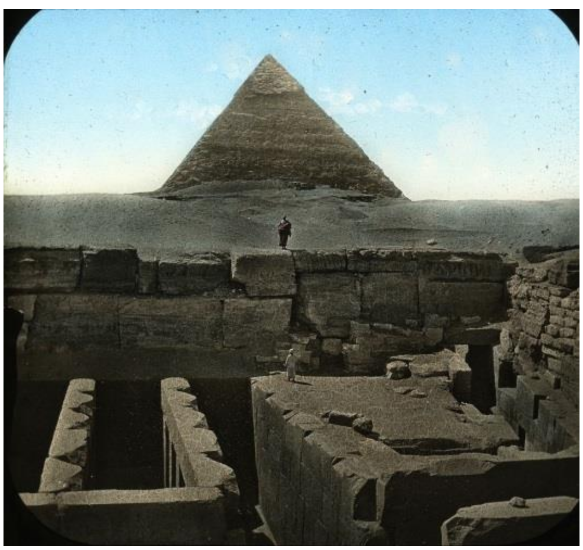


Figure 3-Giza Pyramid Complex. (Brooklyn Museum)

What about alignments to the stars? Is that astronomy? The Great Pyramid, or the Pyramid of Khufu, is the tallest pyramid in the world, the largest in the Great Pyramid Complex, and the only member of the Seven Wonders of the Ancient World still standing today (Fig 3). Originally 146.5 meters (481 feet), it was the tallest man-made object for almost 4000 years, until it eroded to the point that the Strasbourg Cathedral in France (142 meters/466 feet) overtook it in 1647.

Khufu's Pyramid is one of the most accurately built structures in the world. It is incredibly flat, even, and well-oriented. It includes inner shafts that run in straight lines through the structure.

The northern shaft would have been aligned to the star Thuban at the time of its structure. Although Thuban was no longer the **north star** when the pyramid was constructed in 2550 BCE, there was no true north star at the time, and Thuban was as close to a north star as any visible star in the night sky would have been. Thuban was off by about 1.7 **degrees** from true north. Nevertheless, the north shaft was aligned to this “north” star.[19]

There is no clear astronomical purpose for the alignment, but there may be a connection between Egyptian religion and the North Star. This provides an insight into some archaeoastronomical sites; that some well-documented alignments were not made for observation, but rather for religious purposes. This does not lessen the impressiveness of the archaeologic feat or the ancient Egyptian’s obvious knowledge of the stars, but it can be difficult to disentangle cultures’ interest in the heavens and their interest in heaven.

Another great example is the **zenith** tubes in Central America. South of Mexico City lies the Oaxaca Valley and the capital city of the Zapotec civilization, Monte Alban. The Zapotec go back at least 2500 years in civilization, reaching their apex of power and influence around 500 CE. One of the buildings at this ancient site contains a room with a 1.5 meter (5 foot) tube straight overhead. It is possible that this was a “zenith tube,” that is, that the room inside this building was built to catch the light of the Sun only when it was directly overhead. This building, Building J, may has have been used as a calendar temple, but it also may have been used to study the Sun, or for religious purposes.[20]

In all these cases, and many others, we need to ask ourselves: if there is a clear astronomical aspect to a site or object, what was its purpose? Was its purpose religious, artistic, scientific, pragmatic, political, or even accidental?

The Specific Case of Polynesia

It’s easy to see how we could attribute astronomical significance to a site that may not have anything to do with astronomy, or how we could attribute astronomical significance to a site that is aligned to celestial phenomena for religious or other non-scientific purposes. These are **Type I Errors**, or false positives. You can think of false positives as “crying wolf” or seeing something there when in reality, it isn’t.

But what about missing something when it *is* there? Archaeoastronomy is subject to this type of error as well, known as **Type II Errors**.

In the 1700s, Europeans began to explore the islands of the Pacific Ocean and were surprised to find common languages throughout Polynesia. This in itself is astounding, considering how widespread Polynesia is geographically. To put it into perspective, this would be as surprising as finding a similar language between China, Saudi Arabia, and Germany. The geographic distance is so large that a similar language is not only impressive, but immediately tells us something about Polynesia; people from islands far away from each other had regular contact with one another. Without the aid of a compass, how does one navigate the vast Pacific Ocean? There is a lot of evidence that Polynesian navigators were exceptionally familiar with the stars, their directions, and their motions.

We know that Polynesian astronomy was robust before Western presence. The people of Mangareva marked the solstices accurately by placing stones on either side of the solstice Sun during the rising and setting.[21] Rapa Nui's (Easter Island) has megaliths (Ahu Huri a Urenga) that are oriented toward the rising Sun on the June solstice, and because of their odd location inland on the island (as opposed to the more well-known megaliths close to the shore), it is likely this was a very purposeful placement.[22]

Another example is Mokumanamana, an uninhabitable rock hundreds of miles from Kauai and less than one square mile in area, just above the Tropic of Cancer. This is the closest Hawaiian Island to where the Sun could reach its zenith at the most northern latitude, and though uninhabited, Mokumanamana is covered in dozens of alters. Why? It's a mystery, but the most intriguing explanation is that its location, just above the Tropic of Cancer at the limits of the Sun's overhead passage, made it a special destination.[23]

Perhaps the most compelling living evidence of Polynesian astronomy is the language itself. For every star or constellation you can name, there is a Hawaiian, Maori, Tongan, and Samoan name for it. For example, the name for the stars of the Pleiades cluster is similar across Polynesia.

Table 1: Polynesian names for the Pleiades star cluster	
Mataliki	Tonga
Matalike	Vanuatu
Matari'i	Tahiti
Matariki	Maori
Makeriker	Pohnpei
Makali'i	Hawai'i
Li'i	Samoa

Language in this case is very telling. Of course, constellations are different in other cultures, but the fact that a language has names for its own constellations means that people were paying attention to the night sky. It's certainly possible that a society that gives just a few names to astronomical objects (Sun, Moon, stars) may have been interested in astronomy, but we can't tell for sure without documentation.

However, a society that gives every star a name, categorizes astronomical objects into groups (planets vs. stars vs. meteorites), and ascribes directional or usable information to objects in the sky, is *undeniably interested* in astronomy. This is what we find in Polynesian languages.

Astronomical concepts and terms are also pervasive in many Polynesian languages. Concepts like the zenith, the horizon, the meridian, the cardinal points, the **ecliptic**, and even areas of the sky that we simply don't use in English, have Hawaiian names.[24] There are also many divisions of the sky in the Hawaiian language. David Malo, a Hawaiian historian, laid out nine separate levels of the sky in the Hawaiian language in 1903 from the lowest being a place just above one's head, to the highest place in the fixed heavens.[25]

Language tells us how people see the sky. For example, in the Hawaiian language, Venus has several names including: *Hokuloa* (great star), *Ka hoku komohana* (star of the west), and *Ka'awela* (the star close to the Sun).[26] *Ka'awela* in particular tells us something; we don't need to find a book where ancient Hawaiians wrote down "we have found a star that follows the Sun all the time." We know they knew that Venus followed the Sun because they named it after its behavior. In this way, language can tell us something about archaeoastronomy just as much as finding ancient observatories and physical objects.

Polynesian culture offers us very few glimpses from the past for a variety of reasons, including a long history of oral tradition, cultural decimation through colonialism, and living in a tropical environment where even if things like wood henge or papyrus had been created they would simply never have survived the weather (humidity is hard on history). But we do know that an enormous number of astronomical terms exist across these nations in the original languages, and that means that the languages themselves have already told us something: that astronomy was important.

Ancient Astronomy

Once a writing system emerges, if the language is translatable, and if the documents are well-preserved, understanding an ancient culture's connection to the stars becomes much easier to disentangle. Many cultures with a written language simply wrote down what they saw in the heavens, and if those records survived time and chaos, then we have a wonderful sliver of insight into the past.

We can study these ancient cultures regionally, chronologically, or a myriad of other ways, but let's go by subject. Whether watching the Sun, the Moon, the stars, meteorites, or **comets,** a pattern emerges: people recorded objects and their behavior long before they understood them. In many cases, these objects took on a spiritual or mystical role within the culture, and in some cases became extremely important not just because of their celestial status, but because of their usefulness. Think of the Greek and Roman fascination with the planets, but also the mysticism applied to them. Jupiter wasn't just a planet, he was a god.

Table 2: Partial Timeline of Known Solar Observations

Year	
2137 BCE	A total eclipse of the Sun is mentioned in *Historical Documents of Ancient China*.
800 BCE	Sunspots are recorded in China's *Book of Changes*.
499 BCE	Anaxagoras taught that the Sun is self-luminous.
830 CE	Habash al-Hasib determines time using the altitude of the Sun.
1050 CE	During a total eclipse of the Sun on August 30th, it was surrounded by a "red ring" (the chromosphere?)
1613 CE	Christopher Scheiner records faculae on the solar surface.

What becomes difficult to disentangle is who did what first. What was the first observatory? Was it the megalithic structures of Nabta Playa (5000 BCE)? Or was there an observatory built for astronomical research at Taosi in Shanxi Province, China (2300 BCE)? Or perhaps it was Chanquillo's 13 Towers in Peru (300 BCE).

We don't know when or where the first observatories were built, because time steadily erases history. We do know that observations of the heavens have been made by every known society on every habitable continent, but we simply don't know when the first sundial or gnomon or observatory was built. We can only know which ones have survived the creeping invalidation of time.

Table 3: Partial Timeline of Known Stellar Observations

Year	
400 BCE	Alcor "has become a little star, sometimes visible and sometimes invisible, like an omen portending no good…" quoted from the Mahabharata.
310 BCE	Aristarchus of Samos was born. Wrote that the Sun and the stars have the same nature.
140 CE	Claudius Ptolemy enumerates 6 stars as being "fiery red": Arcturus, Aldebaran, Pollux, Antares, Betelgeuse, and Sirius (which is not red and does not belong in his list of red stars…)
300 CE	Cleomedes states that the fixed stars are larger than the Sun.
724 CE	A Chinese expedition was sent to the South Seas to observe Canopus and stars further south that had not yet been named.
~500 CE	Aryabhata gives the stars' distances as 4,400,000 distances of the Sun (what we now call **AU**). 4.4 million **astronomical units** is roughly 70 light-years away.
1029 CE	Azarquiel, an Arabian astronomer, proved the Sun had an **apogee** with the use of background stars.
1230 CE	Erazmus Witelo wrote that stars twinkle because of moving air currents.

Problems in Archaeoastronomy

Too Many Possibilities

Imagine the place where you live. Perhaps a house or an apartment. Is it facing some cardinal direction? Probably. But why? Many cities lie on a grid system. Here in Utah, we have 100 North, 300 East, etc. Your home has a high chance of facing the street, just because it's easier to build a path to a front door than an oddly placed door. You also probably live in a square-ish building, which, since one side is facing the street and the street is a cardinal direction, means that all four sides are aligned to the four cardinal directions. Additionally, if you have windows, they'll be on these cardinal-facing sides of the house, and the Sun will probably stream into at least one of them on at least one of the solstices or the equinoxes. Now imagine 5,000 years into the future. Archeologists find huge cities all lined up to the cardinal directions with millions of houses oriented to the solstice Sun. Can they conclude that we were obsessed with the alignment of the Sun or the cardinal directions? That we had a special affinity for four-sided living quarters because they made astronomical sense to us? Of course not.

Figure 4-And here we see the astronomical significance of these gigantic lines. Notice their cardinal directions… (Walter Mittelholzer, public domain)

We build four-sided houses because they're easy to make. We have streets that run to the cardinal directions because it makes city planning, layout, and navigation easier to deal with. We're barely even aware of when the solstice is going on, much less if it's aligned properly to the kitchen or bathroom or bedroom or living room window. But what if archeologists find a cookie-cutter housing project still standing in 7021 CE, and it turns out that it's the bathroom window that was aligned closest to the solstice rising or setting? Will they then think our bathrooms held some astronomical significance to us? What if it's the kitchen window? Of course, we know why that happens; there are a lot of windows on any given house, and neighborhoods are often constructed by the same company. That's it. End of significance.

Yet it's easy to fall into this trap with archaeoastronomy. Sometimes there are just too many possibilities. This is the problem with something like Stonehenge. Its complexity makes it impossible to say without a doubt that it's aligned to anything. It's too big. It's too round. There are an enormous number of things it could align to, and an enormous number of things that could just be coincidence. This is why archeologists and astronomers can't call it an observatory, but can only say it *might* have been built to correlate with some astronomical phenomena.

Lack of Communication or Shared Cultural Understanding

As we've seen with the Mayan calendar, we may go into a culture with expectations only to find out that we don't understand their reasoning at all. Why have a Venus Cycle at all? Not understanding the purpose or significance of an archaeoastronomy site doesn't negate its astronomical importance. Archaeoastronomers are constantly trying to avoid seeing things that aren't there while not missing things that are simply because they don't appear "right" to modern eyes.

Cultural Eradication

Many societies could have told us themselves about their astronomy, if conquerors and explorers hadn't wiped them out or decimated them to the point that a cultural heritage became almost impossible to maintain. There is no way around this reality. Much of history has been purposely destroyed, and some of it will never be recovered.

Now You See it, Now it's… Kinda Moved

Another challenge is that the sky today doesn't look *exactly* the same as it did 1,000, 4,000, or 10,000 years ago. Earth experiences a variety of movements we are relatively unaware of, but that affect how the sky looks over time. **Axial precession**, described in *Chapter 2.2,* takes about 26,000 years to complete one cycle and causes the pole star (for us the north star) to shift. We saw how the Great Pyramid of Giza would have been aligned closely to Thuban when it was built in 2560 BCE. Many other stars have been, and will be again, the pole star.

In addition to the movements discussed in *Chapter 2.2*:

- Earth's orbit shifts from almost completely circular to mildly elliptical. How long does it take to go from circular to elliptical and back? About 400,000 years.
- Earth's axial tilt changes over time. It takes 41,000 years to shift from 22 degrees to 24.5 degrees and back again. The last maximum was reached in 8700 BCE. We are currently at a 23.44 degree tilt.

We don't notice most of the Sun-Moon-Earth motions within one human lifetime, but over thousands or tens of thousands of years, these motions change the way the sky appears to the inhabitants of Earth. If we are considering a site like the Great Pyramid at Giza (built around 4560 years ago), or Nabta Playa (which was built around 7000 years ago), we cannot rely on the modern sky to tell us about the way buildings were aligned in the past.

Early Astronomy

Where is the cutoff between archaeoastronomy and early astronomy?

As we discussed, the vast majority of the world's languages are unwritten languages, even today. The first requirement of empirical astronomy (that is, astronomy that's done using the scientific method) is *the ability to stand on the shoulders of the people that came before*, and this is much easier to do when a society is reliant upon writing for glimpses into the past, instead of oral tradition. This is especially true when dealing with large numbers or large datasets because humans are notoriously bad at remembering long lists of numbers – for example, how many phone numbers do you really know off the top of your head?

This isn't to say that societies without a written language never practiced empiricism, data collection, tabulation, etc. There is likely no culture that has ever existed that neglected to study the night sky. But we are biased against cultures that did not have a writing system because history is only a study of what remains today, and we are biased towards cultures that have longstanding documentation of their scientific achievements. This brings us to the second requirement: In order for a society to practice empirical astronomy, they must have *preserved their data*. What can destroy data?

- Purposeful destruction, such as the burning down of the Library of Alexandria, or the systematic burning of books by Qin Shi Huang, or in more recent history, the Khmer Rouge which destroyed almost all of the books in the National Library of Cambodia. A great many libraries have been purposely destroyed throughout civilization often as a byproduct of political violence. Coups, wars, revolutions, and rebellions are usually hard on scientific advancement.
- Data can also be lost simply through natural degradation over time. It's not surprising that most of the preserved papyrus, scrolls, books, cloth, and even buildings, come from fairly dry environments. This is not because people didn't live in humid areas thousands of years ago, but water destroys relics of the past at an incredible rate.

And finally, a third requirement is that the society in question must *have been around long enough* to have made noticeable observations in the field of astronomy. That can be difficult, given that in order to collect data on things like the behavior of the stars, you need a multi-generation study of the sky. While the heavens do move and change, those changes typically occur on time scales much longer than the human lifespan.

All of this means that when we talk about early astronomy, we are talking about a tiny fraction of the actual astronomy that's taken place on our planet. But the data is a little easier to sort through with early astronomy as opposed to archaeoastronomy.

Astronomy is a vast and wide and deep field. What can be considered astronomy? The study of stars, planets, comets, meteorites, the Sun, changes in the motions or behavior of these objects over time, and what the universe is made out of, where it came from, where it's going, etc. all fall into the field of astronomy. Finding ways to measure the universe, understanding time, position, and changes in the heavens, all contributes to our knowledge of the cosmos. Once we understand those changes, predicting them becomes astronomy as well.

Pre-Telescopic Instruments

An enormous number of instruments besides the telescope have been used to ascertain information about the heavens. The first one must be considered an invention in its own right: written records. Tables of astronomical data come from all over the world. For example, around 555 CE in the Sasanian Empire, the Zik i Sahriyaran (*The Royal Astronomical Tables*) were revised for the king, Anushiruwan (Khosrow I). In 595, Ananias of Sirak was born and went on to compile data on the orbit of the Moon based off of the changes on its face. These tables are not unique and tables just like them compiling astronomical data appeared all over the world, and include civilizations from every continent, except Antarctica.

Some, like the Mayan Venus Tables (also known as The Dresden Codex), followed a planet and recorded its behavior (Fig 5). In these tables, Venus is specifically recorded and its appearances and disappearances in the morning and evening sky are foretold for the reader. This makes the codex predictive: That is, the Mayans found a pattern in the planet's movements, and created tables to predict that behavior.

Figure 5-Six pages of the Mayan Venus Table, circa 1300 CE. (Public domain)

Other tables, like the Venus Tablet of *Ammiṣaduqa* from the 1600s BCE, not only record the behavior of the planet Venus, but also carry a lot of omens and prophecies around that behavior.[27] These astrological prophecies are fanciful, but nevertheless we know that Venus was being watched and recorded. Without access to older tablets rich with astronomical data, someone like Aristarchus never could have made discoveries about long-term changes, such as the precession of the equinoxes.

Astronomical tables can be thought of as a pre-telescopic instrument; without them, long-term changes in the heavens would not have been observable. These tables, which by and large simply recorded observations, make up the very earliest beginnings to a true understanding of the behaviors of the Sun, the Moon, the planets, and the stars.

The Armillary Sphere, the Quadrant, and Trigonometry

If we divide the sky up into a full circle, and we say that circle is made up of 360 arbitrary smaller but equal bits called degrees, we can begin to say "the Moon takes up this much of the circle" and "Capella is this many degrees away from Pollux" etc. These degrees are arbitrary – that is, they don't have an actual unit of measurement. They're relational. They simply take up a certain percentage of the circle – in this case, a giant sphere laid over the sky.

Using an armillary sphere (Fig 6), or a much smaller circle, we can tell how far away things are from each other in degrees. These trigonometric, angle-based instruments were the first truly precise method of taking measurements in astronomy. An armillary sphere simply showed a representation of the sky. Sometimes they included tick marks for degrees, but older ones just showed the circles of the sky, and how they behave from the vantage point of Earth.

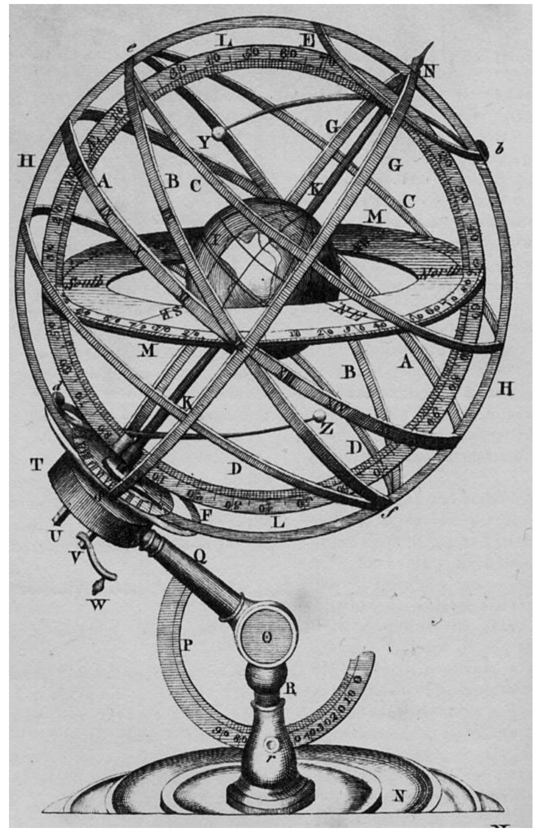


Figure 6-Diagram of an armillary sphere. (Public domain)

Some of the oldest armillary spheres come from China. Around 104 BCE, Lo Hsia Hung flourished and designed one of the first armillary spheres (if not the first). He also wrote that the Earth moves “constantly but people do not know it.” In 52 BCE Keng Shou-Chhang introduced the first permanently fixed equatorial ring (the outside ring of an armillary sphere). In the year 84 CE Fu An and Chia K’uei added an ecliptic ring to Keng Shou-Chhang’s equatorial ring, and about 100 years after that, Tshai Yung wrote of an 8 foot circumference armillary sphere. By 260 Wang Fan created a complete celestial sphere.[28]

Ptolemy also had an armillary sphere, and made calculations using another instrument: the **quadrant** (Fig 7). A quadrant is one quarter (quad) of a circle, marked with degrees. If the quadrant is correctly pointed at the horizon, then the other side will be pointed straight up (to the zenith) because it's a 90 degree angle. A sliding bar in the middle then allows an astronomer to sight a star and determine how many degrees above the horizon it lies (its **altitude**). Quadrants were in use at least by the 2nd Century, by Ptolemy, who was famous for taking fairly accurate measurements.[29]

Figure 7-Ptolemy’s Quadrant. (Public domain)

By the 1200s, the Persian scientist Nasir al-Din el Tusi was using the **torquetum**, a complex machine following the rules of the quadrant, but made additionally complicated by having degrees for the equator, as well as the altitude, and being portable (Fig 8). Though el-Tusi is more famous, he did not invent the torquetum. He took the design from a 12th century Andalusian mathematician and inventor: Jabir ibn-Aflah (also known as "Geber"). The torquetum allowed even more complex measurements to be taken of the night sky and became popular with astronomers from the 1100s well into the 1500s.

One consideration we have to make is this: If the sky can be divided into 360 degrees, it must become apparent at some point that those degrees can further be divided. Just like on a clock, where 60 minutes equals an hour, and 60 seconds equals a minute, there are 60 **arcminutes** in every degree, and 60 **arcseconds** in every arcminute. This means that there are 1,296,000 arcseconds in a spherical sky. While a 1-foot by 1-foot quadrant *might* be large enough to put a quarter of the degrees of the sky onto (90 degree tick marks), it's certainly not large enough to put a quarter of the sky in arcseconds onto because you simply can't fit 324,000 tick marks on a 1-foot by 1-foot instrument.

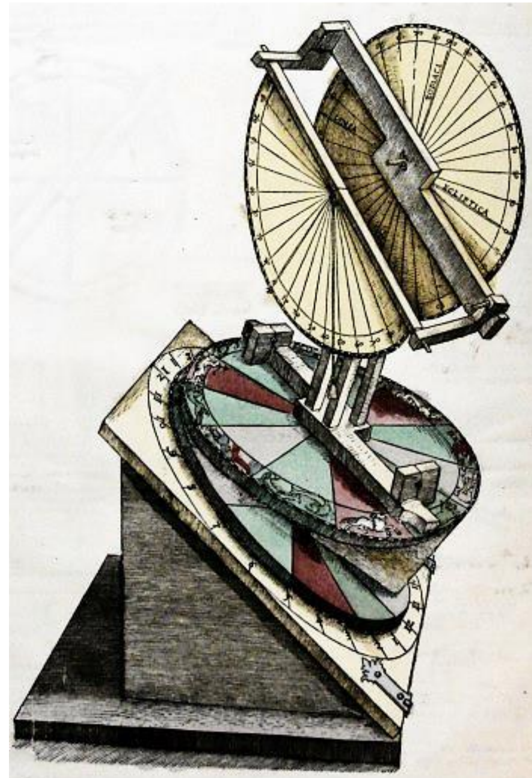


Figure 8-Drawing of a torquetum. (Public domain)

Figure 9-Tycho Brahe sitting in his mural quadrant. (Public domain)

In order to get more accurate measurements of the sky, astronomers had to build bigger instruments. The best example of this is Ulugh Beg, a Timurid (Persian-Turkic-Mongol empire) astronomer/king. In the 1400s he built an enormous observatory at Samarkand, one with a quadrant 55 meters (180 feet) high.[30] This allowed him to make much more accurate observations of almost 1,000 stars and their positions. It wasn't until Tycho Brahe that Ulugh Beg was one-upped, though Tycho did it 150 years later.

Tycho Brahe had what every astronomer wishes they could find: a wealthy patron. He was basically given the island of Hveen to build a castle observatory, paid for by Frederick the II, King of Denmark at the time. The king financed Brahe's career, buildings, and equipment, virtually ensuring that the next generation of accurate astronomical measurements would belong to Denmark. This castle observatory was called “Uraniborg” and it was full of pre-telescopic instruments, including armillary spheres and a large mural quadrant (Fig 9).

Tycho Brahe had an interesting life. He was the oldest son in a family of ten children. His uncle was wealthy and a friend to the King of Denmark. In his 20s he got into a duel and lost his nose. We don’t know for sure what the duel was about, but the legend is that it was over a mathematical disagreement. Although the telescope was not invented within in his lifetime (he lived from 1546-1601), he made enough observations that Johannes Kepler was able to form his famous laws of planetary motion using his data.[31] Brahe’s quadrant was not as large as Ulugh Beg’s, but it had the advantage of transversal lines that made marking smaller spaces easier. These early observations, using non-telescopic equipment, were fundamental in laying the groundwork for later astronomers.

Many treatises with tables of data abound from this time period, discussing how light and lenses work, how the stars move, how the Sun-Earth-Moon connection works, and where the Earth exists in the universe. Without this pre-telescopic time period, the “big guns” of early astronomy, such as Galileo, Newton, and the Herschels, would have been hampered. Whether blocking unwanted light, measuring the degrees between stars, or making careful observations on the movement of celestial bodies, astronomers have been making progress in our understanding of the universe long before the advent of the telescope.

Conclusion

Trying to keep in mind all of these facts, the different sky, religious and cultural significance, whether or not a site was built purposely for astronomy or if its astronomical alignments are mere coincidence, etc. is difficult when studying ancient cultures and their relationship to astronomy.

It is likely that many ancient societies were aware of the changing heavens in a way we barely notice today. Because of modern inventions like clocks, we don’t have to rely on the stars for information about time. We don’t rely on the night sky or the position of the Sun to tell us about the seasons, or when it’s time to harvest crops, or how far we’ve traveled. We’ve given up virtually all mysticism surrounding celestial objects, but we’ve also given up a shared cultural understanding of how the heavens behave.

Modernity also separates us from our ancestors; most people on the planet live in cities that are so bright they block out much of the night sky. Most of us will never look up and see Algol and wonder “why does this star grow dim?” Most of us will never see Thuban and compare it to Polaris. When we wander down a lighted street at night and can only see the very brightest stars and nothing else, we aren’t seeing the heavens as our ancestors saw them. We are surrounded by our own creations and have created the modern sky in the same way we've created modern cities.

For humans alive today, the past is a foreign country, separated by a vast chasm of time and technology.

Review

Common misconceptions

Below is a list of commonly encountered misconceptions about the history of astronomy. As a way to review content from this chapter, see if you can explain why each misconception is inaccurate:

- Astronomy didn't start until the telescope was invented.
- Astronomy was practiced only in a few places (e.g. only in Greece).
- Astronomy has always been different from astrology or mythology.

Questions for thought

- How would you define "astronomy"? Were the people and cultures described in this chapter practicing astronomy? Why or why not? What conditions need to be met before we can call observing the sky "astronomy"?

- Why was the sky important to ancient cultures? Is the sky still important for any of the same reasons or have our values changed? Why or why not?

- How has the sky changed over the past several thousand years? Is it easier or harder to watch the sky today? Are there things that the ancients would have been able to see that we can't today?

- How would you respond if someone suggested that only a few civilizations seem to have practiced astronomy in the past?

For More Information

- *Ancient Astronomy: An Encyclopedia of Cosmologies and Myth,* by Clive Ruggles, 2005
- *Empires of Time*, by Anthony Aveni, 2002
- *Journal of Astronomy in Culture:* http://escholarship.org/uc/jac
- *Skywatchers, Shamans, and Kings,* by E.C. Krupp, 2004

CHAPTER 2.4 - TELESCOPES & OBSERVATORIES

The gold-plated primary mirror of NASA's James Webb Space Telescope (JWST), currently scheduled for launch in 2021. (NASA/Chris Gunn)

Chapter 2.4 Goals

After reading this chapter and participating in the corresponding workshop activities, you should be able to:

- Describe the purpose of a telescope in astronomy and how they are measured and compared.
- Compare and contrast several different types of telescopes and mounts, and list some advantages and disadvantages of each.
- Evaluate the suitability of a location for observing the night sky by considering multiple factors, such as climate, light pollution, and elevation.

Telescopes and Astronomy

O telescope, instrument of knowledge, more precious than any scepter.

—Johannes Kepler, in a letter to Galileo (1610)

Restricted by our poor night vision and shrouded by Earth's atmosphere, we are unable to see very far into the universe with the naked eye. A **telescope** collects light from the sky, augmenting our vision and allowing us to see and study fainter and more distant objects. While backyard telescopes collect visible light, research-grade telescopes can be designed to gather any wavelength of light on the **electromagnetic spectrum**. Radio telescopes, x-ray telescopes, and infrared telescopes are all indispensable tools for modern astronomers.

Contrary to popular belief, **magnification** is not a useful metric for comparing telescopes. A telescope is best thought of as a "light bucket." The most important attribute of any telescope is the diameter, or **aperture**, of its main light gathering lens or mirror, known as the **objective**. If you hear someone refer to an "eight inch telescope," this simply means that the primary lens or mirror is eight inches in diameter. Just like a wider bucket collects more rain, wider telescopes collect more light, leading to brighter and better views. Figure 1 compares the aperture of major telescopes around the world.

Mathematical Morsels

Most telescope mirrors and lenses are circular, so the total light collecting area of a telescope can be calculated using the formula for the area of a circle: $A = \pi r^2$, where r is the radius of the objective. Because the radius is squared, *doubling* the aperture of a telescope results in a *four-fold* increase in the amount of light collected. In other words, an 8" telescope gathers four times as much light as a 4" telescope, not twice as much as you might expect.

Larger aperture telescopes also have better **resolving power**, or resolution. This refers to a telescope's ability to distinguish very small or closely spaced objects. For example, even though the Moon is very bright and can be seen well with a small telescope, we would need a large telescope with excellent resolving power to distinguish small craters on the Moon, or to see the lunar landers from the Apollo missions (the latter is impossible with Earth-based telescopes.)

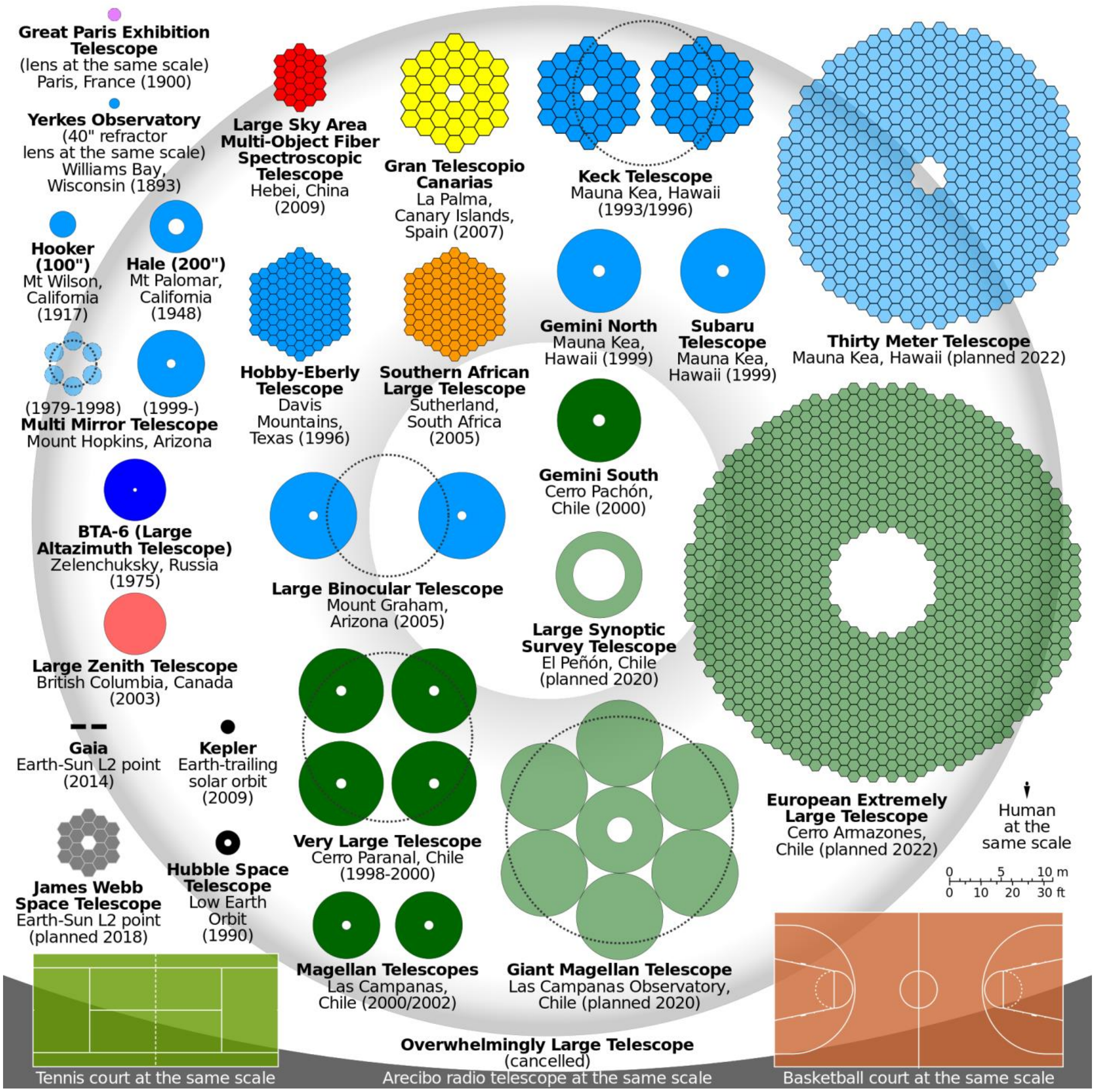


Figure 1-Aperture comparison of some of the world's largest and most famous telescopes, including several still in the planning and development stage. (Wikimedia user: Cmglee, CC BY-SA 3.0)

Who invented the telescope?

Spoiler alert: it wasn't Galileo! Until the 17th century, the only tools astronomers had for studying the heavens were the human eye and measuring instruments such those described in *Chapter 2.3*. Even so, some of the most significant discoveries in the history of astronomy came from the pre-telescopic era, such as the realization that the Sun, not the Earth, is the center of our Solar System.

The question of who invented the telescope is convoluted and controversial, to put it mildly. The invention of such a significant instrument has been ascribed to many over the years and many nations claim it for themselves. It is likely that we will never know for sure. The knowledge that a series of lenses held in sequence can magnify distant objects has existed since at least the mid-1500s[1], and possibly as far back as Alhazen's work in the late 900s.[2] The year 1608 is often cited as the year that the telescope was "invented," but in practice this was merely the year in which the device began to be seen as potentially useful, as opposed to being viewed as a novelty item.

The first applications of the telescope were militaristic, not scientific. In 1608, a Dutch spectacle maker named Hans Lipperhey presented the rudimentary telescope he had constructed to a Dutch army commander. The army quickly realized its utility: "The said glasses are very useful in sieges and similar occasions, for from a mile or more away one can detect all things as distinctly as if they were very close to us. And even the stars which ordinarily are invisible to our sight and our eyes, because of their smallness and the weakness of our sight, can be seen by means of this instrument."[3]

The army paid Lipperhey 300 guilders on the spot, very roughly equal to $25,000 today. In exchange, he agreed to produce more telescopes for the army and not to reveal the secrets of his device.[4] Despite Lipperhey's promise, knowledge of the telescope quickly spread throughout Europe. Glassmakers in many countries soon produced their own versions, and scientists discovered that the new instrument had applications beyond war.

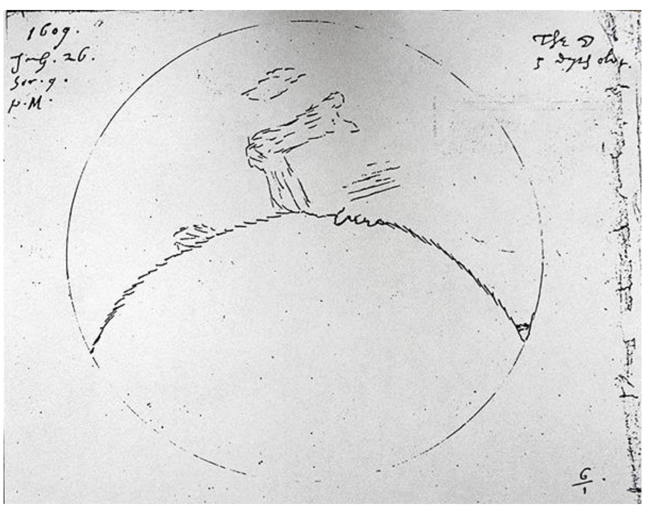


Figure 2-A sketch of the Moon made by English astronomer Thomas Harriot in 1609 using a telescope, the earliest such observation on record. (Public domain)

The first documented astronomical use of the telescope was British astronomer Thomas Harriot's observation of the Moon in August 1609 (Fig 2).[5] Galileo would make his first telescopic observations of the Moon later that same year. By early 1610, Galileo had constructed telescopes good enough to discover the four largest moons of Jupiter, and had also observed Venus and Saturn (Fig 3 left).

Many others made improvements to the telescope in the following decades. One of the biggest leaps came in 1668 when Isaac Newton built his first **reflecting telescope** using polished mirrors instead of lenses to collect light. This made telescopes cheaper and allowed them to be built much larger, although the design did not become common until the mid-1700s.[6] Modern

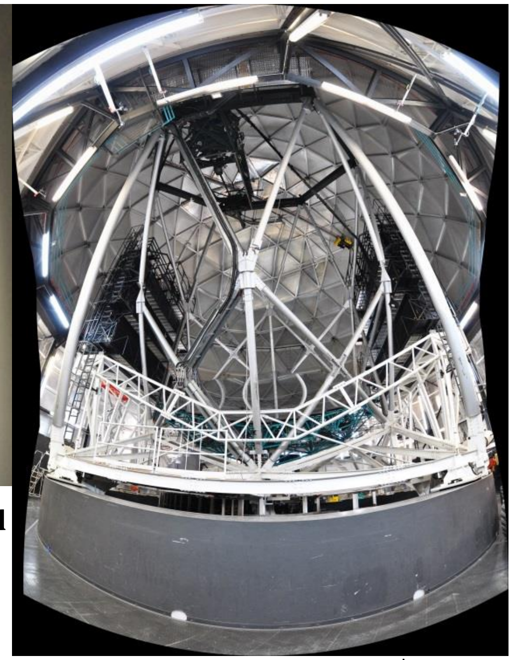


Figure 3-Two of Galileo's surviving telescopes (left) and McDonald Observatory's 11 meter (433 inch) Hobby-Eberly Telescope in Texas (right), one of the largest telescopes in the world . (Zach Schierl)

advancements in optics, materials, and electronics have brought telescopes into the 21st century. Many large telescopes are now barely recognizable as such (Fig 3, right) and for just a few hundred dollars, amateur astronomers can now purchase backyard telescopes that rival those used by professionals just a century ago.

Lenses or Mirrors?

Modern telescopes generally fall into one of three categories, based on the optical design used to collect light (Fig 4).

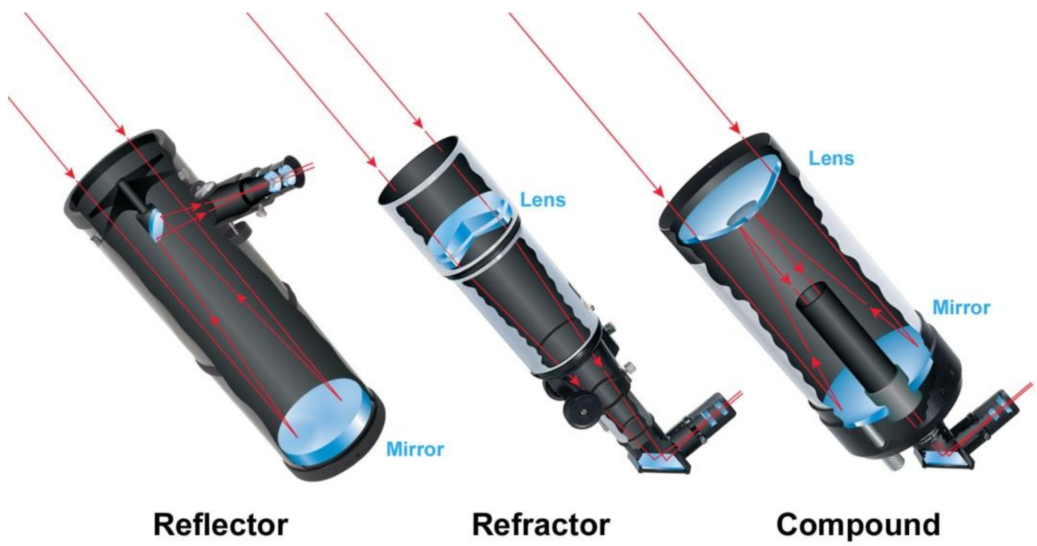


Figure 4-Diagram showing how light is gathered and focused by the three most common telescope optical designs. (Sky & Telescope/Gregg Dinderman & Brett Pawson)

Refracting telescopes

Figure 5-A 120mm backyard refracting telescope. The eyepiece is located at bottom right. (Wikimedia user: fractal.scatter, public domain)

Refracting telescopes, commonly known as **refractors**, use a series of glass lenses to gather light. The early telescopes of Galileo and others in the 1600s were refractors. Light enters the telescope via a lens (in practice, usually a pair or triplet of lenses) near the opening of the **optical tube** (Fig 4). Light rays are refracted (bent) by the lens, causing them to converge near the other end of the tube and form an image. The image is viewed via an **eyepiece** located at the opposite end of the optical tube from the primary lens (Fig 5).

Refractors require high quality, transparent glass, because light must be transmitted *through* the lens. This makes refractors more expensive than other types of telescopes. The weight of the lenses must be supported from the side so that the light path is not obstructed, which significantly limits the maximum aperture of a refractor. The largest refracting telescope in the world, located at the Yerkes Observatory in Williams Bay, Wisconsin, is just 40" in diameter. Due to their high cost and size limitations, refracting telescopes have been largely abandoned by professional astronomers in favor of reflectors. Smaller refractors remain popular with amateurs and astrophotographers because of the sharp, high quality images they produce.

Refractors are subject to a phenomenon known as **chromatic aberration**, in which colored fringes of light appear around bright celestial objects such as the Moon and planets. This happens because lenses bend different colors of light at different angles. Adding additional lenses can reduce this effect, but at the expense of increased cost. Refractors with a three-element primary lens that minimizes chromatic aberration are known as *apochromatic* refractors. Instruments that only contain two lenses, and thus suffer from more chromatic aberration, are known as *achromatic* refractors.

Table 1: Refracting Telescopes	
Advantages	**Disadvantages**
• Crisp, sharp images of bright objects • Tube is sealed from dust and dirt • Optics do not need regular alignment • Good for astrophotography • Image can be right side up in order to facilitate terrestrial viewing	• Expensive. Highest cost per inch of aperture • Limit to how big lenses can be made • Long, bulky optical tubes • Chromatic aberration a problem in cheaper models

Reflecting telescopes

Reflecting telescopes, commonly known as **reflectors**, forgo lenses and instead use highly-polished reflective mirrors to gather and focus light (Fig 4). The concept of using mirrors in a telescope was explored by Niccolo Zucchi in the early 1600s, and the first functioning reflecting telescope was built by Isaac Newton in 1668.[7] The most common variant is still known as a "Newtonian reflector" or simply a "Newtonian."

Figure 6-A 4.5" reflecting telescope. Note the eyepiece at upper right, on the side of the optical tube. (NPS/ Zach Schierl)

In a Newtonian reflecting telescope, light enters the optical tube and travels the length of the tube before striking a concave primary mirror at the bottom of the tube (Fig 4). The primary mirror is coated by a very thin layer of reflective material, such as aluminum, and reflects light back towards a small angled mirror (the secondary mirror) set near the opening of the tube. This mirror redirects the light through the side of the tube to an eyepiece. As a result, the observer typically looks through an eyepiece located on the side of the optical tube, rather than at the end as with a refractor (Fig 6).

In a reflector, light does not pass through the mirrors but rather bounces off of them. Consequently, mirrors are much cheaper to manufacture than lenses because only one face needs to be polished and figured. Furthermore, mirrors can be supported from below, permitting the massive apertures of many modern telescopes. Nearly all research-grade telescopes built since the dawn of the 20th century are reflectors, including the famous Hubble Space Telescope. The largest reflectors have diameters exceeding 10 meters, ~10 times the diameter of the largest refracting telescope. Reflectors are also extremely popular among amateur astronomers because of their low cost per inch of aperture.

The primary downside of reflectors is that they require more maintenance than refractors. The open tube design of a reflector allows dust and dirt to accumulate on the mirrors over time. Occasional cleaning must be done very carefully to avoid scratching the delicate reflective coatings on the primary mirror. To obtain sharp images, the primary and secondary mirrors must also be carefully aligned with each other, a process known as **collimation**. Even routine handling or transporting a reflector in the back of a vehicle can be enough to knock the mirrors out of alignment, so frequent checks are a must. Finally, reflecting telescopes typically have long optical tubes, making larger aperture models bulky and difficult to transport in smaller vehicles. Larger models sometime have collapsible tubes to improve portability, but these can make the telescope more time-consuming to set-up.

Table 2: Reflecting Telescopes	
Advantages	**Disadvantages**
• Cheap. Lowest cost per inch of aperture • Very large apertures are possible, good for seeing faint objects • Free from chromatic aberration	• Open tube design allows dust and dirt to enter telescope • Requires frequent alignment of mirrors (collimation) • Often large and bulky • Not appropriate for • terrestrial viewing

Catadioptric telescopes

Catadioptric (or **compound**) telescopes use a combination of lenses and mirrors to gather and focus light (Fig 4). Over the past several decades, catadioptric telescopes have become one of the most common backyard telescope designs. Most models come equipped with a **tracking drive** and a **GoTo** computer controller that can assist the user in locating objects.

Figure 7-An 8" Schmidt-Cassegrain telescope. (NPS/Zach Schierl)

One of the most ubiquitous catadioptric telescopes is the **Schmidt-Cassegrain**. These telescopes have a very distinctive short & stubby appearance (Fig 7). Using both lenses and mirrors effectively folds the light path and allows the optical tube to be very short and compact, making for a very portable telescope compared to other designs. Disadvantages of Schmidt-Cassegrains are a small **field of view**, and high cost per inch of aperture. Like a refractor, the eyepiece is typically located on the bottom end of the optical tube.

Table 3: Catadioptric Telescopes	
Advantages	**Disadvantages**
• Compact size, portable • Closed tube, no dust/dirt on optics • Free of chromatic aberration • Excellent for astrophotography • Optics do not need regular alignment or maintenance	• Higher cost per inch of aperture than reflectors • Heavy • Hard to obtain wide-field views

Mount designs

A good telescope is nothing without a solid mount. Many cheap telescopes sold at department stores or big box retailers have decent optics, but a mount so flimsy that they are essentially useless.

Figure 8-A Schmidt-Cassegrain telescope on an altazimuth mount. Red arrows indicate the axes of rotation. (NPS/Zach Schierl)

Alt/az (altitude/azimuth) & Dobsonian mounts

The simplest type of mount allows the telescope to be moved on two axes: **azimuth** (side to side) and **altitude** (up/down). These are known as **altazimuth** mounts, often abbreviated simply as **alt/az** (Fig 8).

A common altazimuth variant is the **Dobsonian** mount (Fig 9). Developed by amateur astronomer John Dobson in the 1950s, Dobsonian-mounted telescopes (which are almost always reflectors) rest on a box-like lazy susan structure, usually constructed of low-cost materials such as plastic or particleboard. The telescope can be easily moved up/down and side to side by hand, making Dobsonians by far the easiest type of telescope to set-up and operate. The simplicity of the mount also means they are extremely cheap. For example, a 10” reflecting telescope (Fig 9) on a Dobsonian mount can be purchased for ~$600, thousands less than a 10" computerized Schmidt-Cassegrain (Fig 8).

Figure 9-A 10” reflecting telescope on a Dobsonian mount. (NPS/Zach Schierl)

Dobsonians are great for beginning telescope users. However, most Dobsonian mounts do not have tracking drives and must be manually adjusted to track objects as they move across the sky. As a result, Dobsonian telescopes are not suitable for long-exposure astrophotography. Some knowledge of the night sky is also required to find objects, as most Dobsonians do not have GoTo computer controllers. Some are now offered with “PushTo” technology, which tells the user how to move the telescope in order to locate the desired object, but does not locate the object automatically or track the object after it is found.

Table 4: Dobsonian Mounts	
Advantages	**Disadvantages**
• Simple & easy to use • Cheap • Facilitates learning the night sky	• Expensive add-ons needed to automatically track objects • Knowledge of sky needed to find objects • Not suitable for astrophotography

Equatorial mounts

Equatorial mounts are the most common alternative to altazimuth mounts and are usually attached to the top of a tripod. Like alt/az mounts, equatorial mounts allow a telescope to be moved on two axes, but also add a third axis that is aligned with **the north celestial pole** (Fig 10). This allows movement of the telescope on the other two axes to essentially mimic the rotation of the Earth, making it easy to track objects as they move across the sky. Most equatorial mounts are equipped with a **tracking drive**, small motors attached to each axis that continuously move the telescope to compensate for Earth's rotation. Without these motors, sky objects will quickly drift out of the field of view.

Equatorial mounts are a must for long exposure astrophotography. However, for basic observing they can be overkill as they are typically heavier, more complex to set-up, and much more expensive than alt/az mounts.

Figure 10-A reflecting telescope on an equatorial mount. The axis shown by the red line must be precisely aligned with the north celestial pole. (NPS/Zach Schierl)

Telescope Nuts & Bolts

Focal length

The **focal length** of a telescope is the distance that light travels from the objective to the focal point or eyepiece. For reflectors and refractors, the focal length is approximately the same as

Table 5: Equatorial mounts	
Advantages	**Disadvantages**
• Allows for easy tracking of celestial objects • Permits astrophotography • Often more robust & sturdy than alt/az mounts	• Expensive • Heavy & bulky • Increased set-up time and more difficult for beginners to use

the length of the optical tube. In Schmidt-Cassegrain telescopes, the folded light path makes the focal length much longer than the tube itself.

Focal length is important because, among other things, it helps determine the **magnification** of the telescope when used in combination with different eyepieces (see below). Telescopes with longer focal lengths generally provide better views at higher magnification than telescopes with shorter focal lengths.

Eyepieces and magnification

Regardless of telescope type, the final step in starlight's journey to your eye is the **eyepiece.** An eyepiece is a small metal cylinder containing a series of small lenses inserted into a telescope's focuser (Fig 11). Unlike the telescope itself, the function of an eyepiece is to magnify the image before the light reaches your eye. Which eyepiece is used determines both the **magnification** and **field of view** of the telescope**.** Because eyepieces are interchangeable, these parameters will vary depending on the chosen eyepiece. Eyepieces are measured by their focal length (in millimeters), which is stamped on the eyepiece itself (Fig 11). Eyepieces with *shorter* focal lengths yield *higher* magnification views. Information on how to calculate magnification can be found in *Chapter 4.1: Using a Telescope.* Eyepiece quality is important and it is not uncommon for a single eyepiece to cost more than a small telescope.

Figure 11-A variety of different telescope eyepieces. (NPS/Zach Schierl)

Most research-grade telescopes forego eyepieces entirely and instead use **CCD cameras** or **spectrographs** to record light collected by the telescope. Digital cameras are far more sensitive to faint light than the human eye, allowing them "see" objects in much greater detail and in color (Fig 12). Today, almost no astronomical research is actually done by astronomers looking through the eyepiece of a telescope.

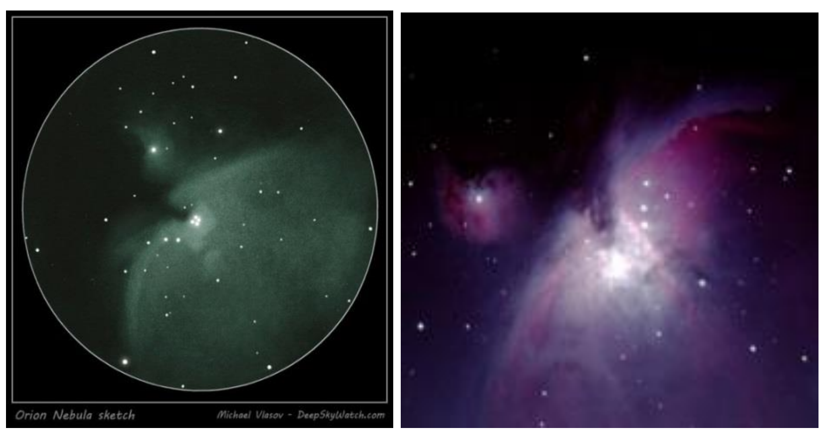


Figure 12-A visual sketch (left) and photograph (right) of the Orion Nebula as seen through telescopes of a similar aperture. (Sketch: Michael Vlasov, Photo: Zach Schierl)

The Magnification Myth

Figure 13-Simulation of how a view of Saturn through a backyard telescope deteriorates with increasing magnification. Note how Saturn becomes larger, but also increasingly dimmer and blurrier. (NPS/Zach Schierl)

One of the most prevalent myths in astronomy is that telescopes are measured by their magnification. As we've seen though, eyepieces are interchangeable and thus any telescope can be used across a wide range of magnifications. For example, a medium-sized backyard telescope may be capable of magnifications from 20x to over 500x. Furthermore, more magnification isn't always better. Most of the time, high magnification eyepieces actually produce blurrier views than low magnification eyepieces. Why is this?

Remember that aperture is the true measure of a telescope's capabilities. While both a 6" and a 12" telescope might be capable of magnifying an object 300x, the 12" telescope has gathered four times as much light as a result of its larger aperture. Magnification simply means spreading out the same light over a larger area so when an image is magnified, it gets bigger but it also becomes dimmer (Fig 13). For this reason, larger aperture telescopes that have more light to work with can better handle high magnifications. Deploying high magnification eyepieces on small aperture telescopes is generally a bad idea.

Figure 14-Advertisement for a cheap, but likely poor quality, telescope. (Joe Roberts, www.rocketroberts.com)

In addition, the more an astronomical object is magnified, the more any turbulence or instability in Earth's atmosphere is also magnified. Unless atmospheric conditions (known by astronomers as **seeing** conditions) are superb, extremely high magnifications will usually result in blurrier views. Consequently, many of the best views through backyard telescopes are had at low magnifications.

Caveat Emptor

Many telescopes sold in department stores, big-box stores, and catalogs advertise extremely high magnifications, or tout extravagant claims about how "far" the telescope can see (Fig 14). These telescopes are almost always cheaply made, poor-quality instruments that make such claims to take advantage of people with little or no knowledge of how telescopes actually work. Any reputable telescope manufacturer will advertise their telescopes based on aperture, NOT magnification. If you ever encounter a telescope advertised by magnification, run away...fast!

Finder telescopes

Nearly all telescopes are equipped with a **finder** (or **finder scope**), a smaller telescope used to help locate objects (Fig 15). Without a finder, locating an object through a telescope eyepiece can be extremely challenging because the field of view is so small. It's sort of like looking through a soda straw at the night sky and trying to find something.

Finder telescopes alleviate this problem because they have a much wider field of view, perhaps more akin to a toilet-paper tube instead of a soda straw. When looking for an object, begin by locating it in the finder, which will usually have cross-hairs. If the telescope and finder and well aligned with each other, centering the object in the cross-hairs will also place it right in the center of the main eyepiece. Most finders have apertures of 30-60mm and magnifications of 5-10x, similar to (half) a pair of basic binoculars.

Figure 15-A Schmidt-Cassegrain telescope equipped with a traditional finder telescope (left) and a Telrad zero-power finder (right). (NPS /Zach Schierl)

Some telescopes have a **zero-power finder** or **Telrad** (Fig 15) in addition to, or in lieu of, a traditional finder. A zero-power finder does not magnify the sky at all, but instead projects a bulls-eye, target, or red dot onto the sky to show where the telescope is pointed. When looking for bright, naked eye objects, a zero-power finder is often sufficient. A traditional finder is helpful when looking for fainter objects that are not visible to the naked eye.

Tracking drives

Many backyard telescopes are equipped with motors that slowly move the telescope in order to compensate for the Earth's rotation. Known as **tracking drives** or **clock drives**, these motors allow the telescope to keep up with an object as it moves across the sky due to Earth's rotation. Tracking drives are commonplace on equatorial and alt/az mounts, but are difficult and expensive to install on a Dobsonian mount. Tracking drives are very useful on telescopes used at busy education or outreach events, otherwise the operator will have to manually adjust the telescope for visitors every few minutes. Extremely accurate tracking drives combined with a high-quality equatorial mount are required for long-exposure astrophotography.

GoTo systems

In addition to a tracking drive, many modern backyard telescopes are equipped with a computerized **GoTo** system that can automatically locate objects in the night sky.

GoTo telescopes have both advantages and drawbacks. To initialize a GoTo system, the telescope must first be manually aligned on several known stars or planets. While computerized telescopes are often marketed toward beginners, this alignment process requires some prior knowledge of the sky, which can be frustrating for users who are not yet familiar with the stars and constellations. Newer (and more expensive) GPS-enabled models are starting to make this alignment process more beginner-friendly, although there can still be a steep learning curve.

Once initialized, GoTo telescopes can find objects quickly, and introduce users to a wider variety of objects than they might be able to find manually. They are also very useful for busy outreach events where it is important to be able to find and track objects quickly.

GoTo telescopes have an important place in amateur astronomy, but are inherently more complex than an alt/az or Dobsonian telescope. Pilots don't learn to fly on 747s, and likewise GoTo scopes aren't always the best choice for beginning astronomers. They take longer to set-up, need access to a power source, and cost more. Consistent use of a GoTo telescope can also hinder learning your way around the sky, because the computer is doing all the work for you.

Where to observe?

Bright objects like the Moon and planets can be observed from just about anywhere, even light-polluted cities. However, most astronomical objects are much fainter and require a unique set of conditions to be seen well. In this section, we'll briefly look at some of the factors that make for a good observing site. In short, telescopes, especially large ones, are best used from locations that are dark, high, calm, and dry.

Climate

Not surprisingly, good weather is one of the most important criteria for a good observing site. The best locations for astronomy receive minimal rainfall, have a high percentage of cloud-free nights each year, and have low average humidity. Portions of the Atacama Desert and the American Southwest can have 300+ clear nights per year, very dry air, and little rain.

Light Pollution

An observatory located under dry, cloud-free skies is of little use if swamped by the **light pollution** of a nearby city. In addition to good weather, a location relatively free of **skyglow** is crucial for modern observatories. Even a little bit of skyglow can interfere with or prevent observations of fainter objects such as galaxies and supernovae. An eye toward future light pollution conditions is important as well. For example, many observatories built in the early

20th century were located in remote areas far from city lights when first constructed, but are now dealing with the effects of expanding metropolitan areas and encroaching suburbs.

Light pollution is not a concern for *all* observatories. For example, an observatory built for the sole purpose of studying the Sun would not be concerned about light pollution, although air quality may still be an issue. Radio telescopes are also not affected by visible light pollution, but may be impacted by radio transmissions and often must be built in radio-quiet zones.

Elevation

We live at the bottom of a vast ocean of air. Much like a diver looking out of a swimming pool sees a distorted view of the Earth above, our atmosphere hinders our ability to observe the night sky. Starlight entering our atmosphere is absorbed, scattered, and distorted by gases and particulates. Views of the night sky from Earth's surface are therefore dimmer and fuzzier than they would be without our atmosphere.

Fortunately for astronomers, the Earth's atmosphere becomes thinner with altitude. As a general rule, the higher you go, the better the view will be. Elevations exceeding ~6,000 feet get you above most of the water vapor in Earth's atmosphere, a primary culprit of fuzzy views. Very few research-grade observatories are located below 6,000 feet, and many are located well above 10,000 feet.

Technology can also help solve the problem of our shaky atmosphere. Many large research telescopes are now equipped with a technology known as **adaptive optics** to help counteract the effects of that ocean of air above us. Think of adaptive optics like the image stabilization on your digital camera, only for gigantic telescopes. Amazingly, some large telescopes with adaptive optics situated at high altitudes can now achieve an image quality comparable to much more expensive space-based telescopes that don't have to look through any atmosphere at all. Note that while telescopic views of the sky improve with altitude, naked eye stargazing improves only up to a certain elevation because the decreased oxygen supply negatively impacts our night vision (*see Chapter 2.1*).

Geographic location

Astronomers prefer to build observatories near the equator, so that objects in both the Northern and Southern Hemisphere skies are visible. Unfortunately, weather patterns close the equator are often not conducive to astronomy, so most large telescopes end up being built at mid-latitudes. Polar areas are avoided due to the presence of 24 hour sunlight for half the year, as well as frequent **aurorae** that serve as a "natural" source of light pollution. Incidence of natural disasters, available infrastructure, and political stability are other factors astronomers take into account when building large, expensive observatories. A list of major ground-based observatories is in Table 6.

Table 6: Selected Major Ground-Based Observatories			
Name	**Location**	**Elevation (ft)**	**Largest telescope**
Mauna Kea Observatory	Mauna Kea, Hawaii	13,600	Twin 10 meter Keck Telescopes
Cerro Pachon	Andes Mountains, Northern Chile	8,907	8.1 meter Gemini South Telescope
Cerro Paranal Observatory	Atacama Desert, Northern Chile	8,645	4 x 8.2 meter Very Large Telescope
Roque de los Muchachos Observatory	La Palma, Canary Islands, Spain	7,438	10.4 meter Gran Telescopio Canarias
McDonald Observatory	Fort Davis, Texas	6,790	10.0 meter Hobby-Eberly Telescope
South African Astronomical Observatory	Sutherland, South Africa	5,899	9.2 meter South African Large Telescope (SALT)
Mt. Graham International Observatory	Mt. Graham, Graham County, Arizona	10,469	Twin 8.4 meter Large Binocular Telescope
Las Campanas Observatory	Atacama Desert, Northern Chile	7,810	Twin 6.5 m telescopes

Space Telescopes

Over the past several decades, astronomers have been increasingly turning to telescopes located in space to probe the universe. While **space telescopes** are extremely expensive compared to ground based telescopes, they offer some major advantages.

First and foremost, space telescopes observe the sky from above the Earth's atmosphere. Atmospheric turbulence is a major problem for Earth-bound telescopes, and a telescope in space will typically achieve much better resolution (resolving power) than a telescope with an identical aperture on Earth. Furthermore, in space, there is no weather or light pollution to contend with; it is dark and clear 24 hours a day, seven days a week, 365 days per year.

While space telescopes are amazing tools, they are also expensive…very expensive. Advances in adaptive optics now allow some ground based telescopes to equal or exceed the image quality of the Hubble Space Telescope in certain situations, and at a much lower cost.[8] At least for astronomers dealing with visible light, it is generally much more cost-effective to build Earth-based telescopes.

However, certain wavelengths of light (such as gamma rays, x-rays, ultraviolet, and infrared radiation) are almost completely absorbed by our atmosphere (Fig 16). In these cases, a space telescope the only option for observing objects that emit light in these wavelengths. The majority of the more than two dozen active space telescopes observe the sky in wavelengths other than visible light.

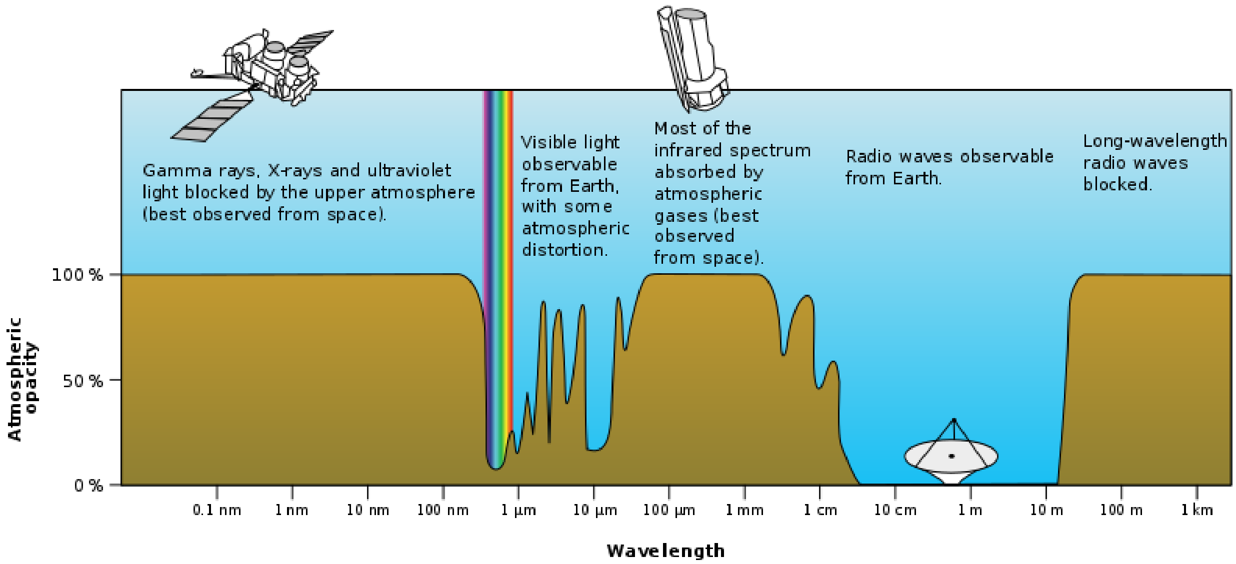


Figure 16-Earth's atmosphere blocks some wavelengths of the electromagnetic spectrum (such as gamma rays, x-rays, and ultraviolet) while transmitting others (such as visible light, and some radio and infrared radiation). (NASA)

Review

Common misconceptions

Below is a list of commonly encountered misconceptions about telescopes. As a way to review content from this chapter, see if you can explain why each misconception is inaccurate:

- The main purpose of a telescope is to magnify objects in space.
- Longer telescopes can see more than shorter ones.
- Most/all telescopes use lenses.
- The Hubble Space Telescope is the largest telescope.
- Galileo invented the telescope.
- Galileo was the first person to observe the night sky with a telescope.
- The Hubble Space Telescope travels across the universe to take pictures of celestial objects.
- Professional astronomers spend most of their time looking through telescopes.
- Large telescopes are needed to see interesting things.
- A telescope has a particular "power."
- All telescopes can see through clouds and/or rain.

Questions for thought

- How has the telescope changed astronomy and how we look at the night sky? What sorts of discoveries have been made using telescopes that would not have been possible with the naked eye?

- Several modern telescopes, such as those on Mauna Kea in Hawaii, have provoked controversy because they have been built on mountaintops considered sacred to native inhabitants. How would you approach this situation? How can astronomers balance scientific progress and traditional beliefs?

- If you were asked to recommend a telescope for someone just getting started in astronomy, what kind would you recommend and why? Are there any types that you would steer them away from?

- If you were going to build an observatory in your area, where would you put it? Be sure to consider all the factors discussed in the chapter. Are there any other factors not listed here that you would need to take into consideration? Would your house be a good location for an observatory?

- Is a larger aperture telescope always better? Can you think of any instances in which a smaller telescope might provide a better view of an astronomical object?

For More Information

History of the Telescope

- "The Telescope" (Galileo Project, Rice University): http://galileo.rice.edu/sci/instruments/telescope.html

Choosing a Telescope

- http://www.skyandtelescope.com/astronomy-equipment/how-to-choose-a-telescope/
- http://www.skyandtelescope.com/astronomy-equipment/telescope-buying-guide/
- http://www.adorama.com/alc/0014311/article/A-Beginners-Guide-to-Telescopes
- http://www.universetoday.com/83208/choosing-a-new-telescope-goto-or-not-goto/
- *Star Ware: The Amateur Astronomer's Guide to Choosing, Buying, and Using Telescopes and Accessories*, by Phillip S. Harrington, 4th Edition (2007)

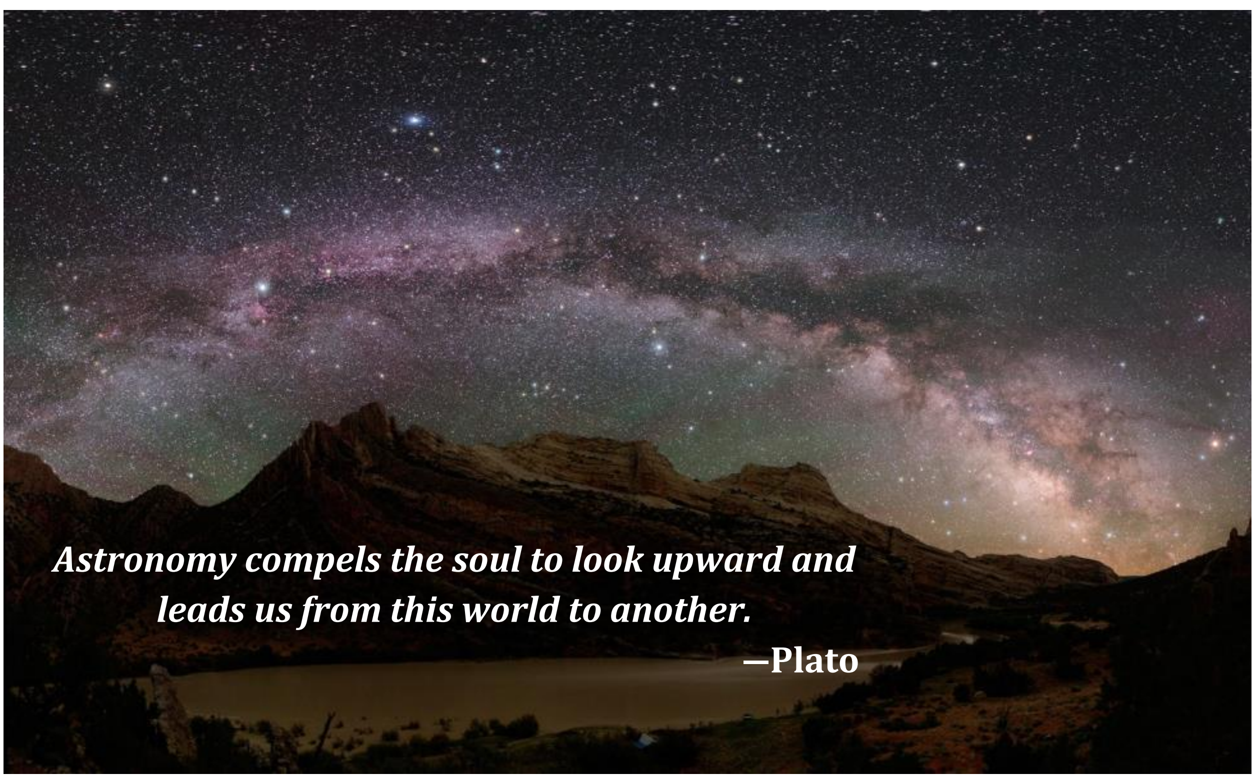
Astronomy Weather Forecasts

- Clear Sky Charts (astronomy focused weather forecasts): http://cleardarksky.com/csk/

Space Telescopes

- The Hubble Space Telescope: https://www.spacetelescope.org/
- "Observatories Across the Electromagnetic Spectrum" (NASA): https://imagine.gsfc.nasa.gov/science/toolbox/emspectrum_observatories1.html
- "Major Space Telescopes" (Space.com): https://www.space.com/6716-major-space-telescopes.html

CHAPTER 2.5: THE COSMIC CAST OF CHARACTERS



The summer night sky dazzles above the Green River in Dinosaur National Monument, Colorado. (NPS/Dan Duriscoe)

Chapter 2.5 Goals

After reading this chapter and participating in the corresponding workshop activities, you should be able to:

- Briefly explain the significance and science of each major category of object visible in the night sky to a general audience.
- Facilitate an understanding of the size and scale of the universe, and our place within it, by explaining the relative distances to objects in the night sky.

Introducing the Cast

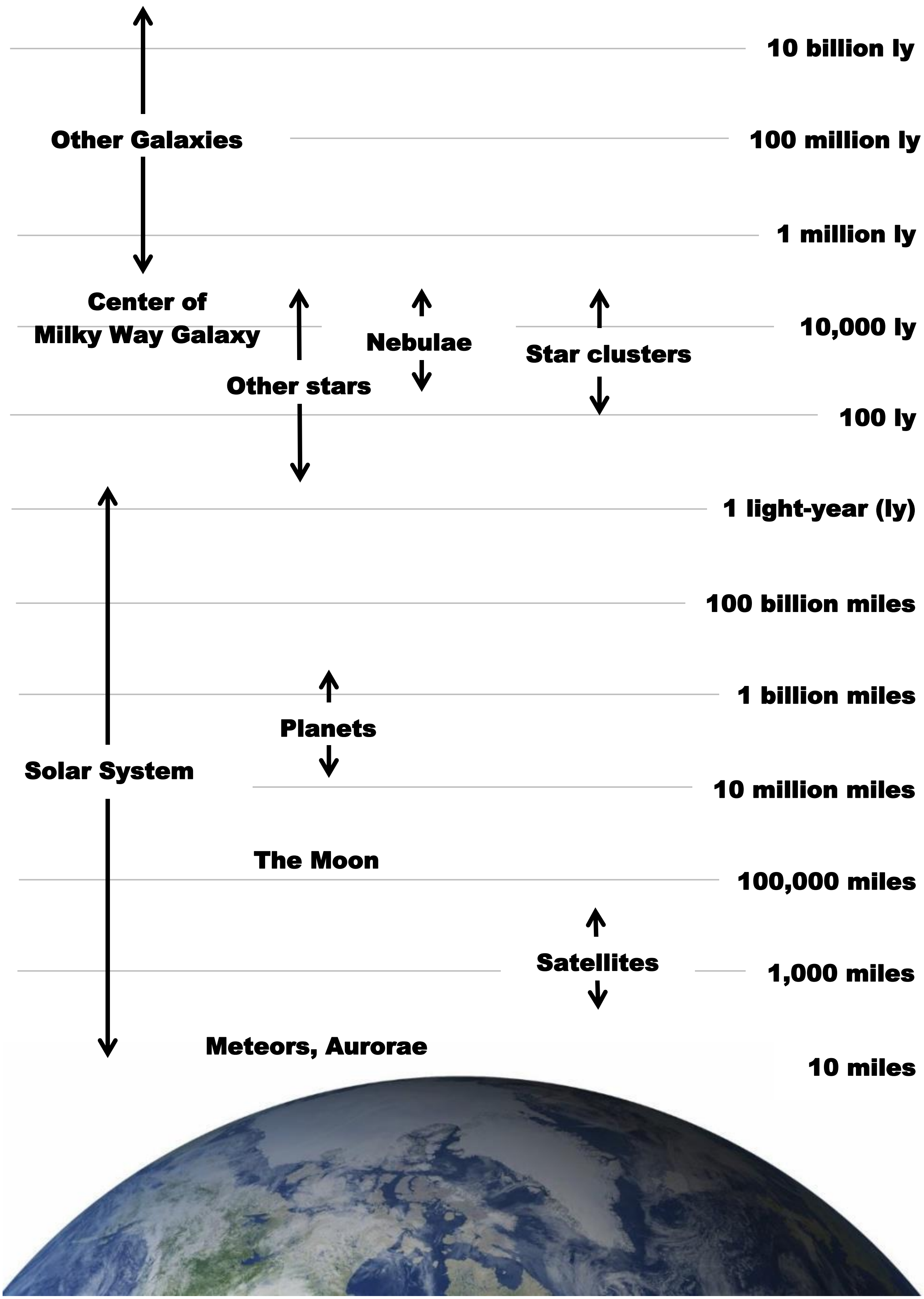
The night sky contains a diverse array of beautiful sights. From the ephemeral flash of a **meteor** to the fleeting glimpse of a faint **galaxy** billions of **light-years** away, there is always something exciting to see under a dark night sky. The cosmic menagerie can be confusing though. What's the difference between a galaxy and a **solar system** anyways? Why are there so many different kinds of **nebulae**? What exactly *are* all those colorful clouds in Hubble Space Telescope images? In this chapter, you'll meet the night sky's cast of characters and get a better sense of the universe's contents, as well as our place within it.

Our Cosmic Address

You are probably used to giving people directions to your home or apartment. As Master Astronomers, the ability to describe our cosmic "address" is an important skill:

- We live on the Earth, one of eight **planets** and numerous **asteroids**, **comets**, and **dwarf planets** orbiting a **star**: the **Sun**. Collectively, these objects comprise our **Solar System**.
- Our Sun is one of several hundred billion stars in the **Milky Way Galaxy**, a vast collection of stars, gas, and dust orbiting a central supermassive **black hole**. Many, if not most, of the stars in the Milky Way have their own solar systems (see *Chapter 2.9*).
- The Milky Way is the second largest galaxy in the **Local Group** of galaxies. Most of the galaxies in the Local Group are **dwarf galaxies**, but it also contains the behemoth Andromeda Galaxy, which will collide with the Milky Way in about 4.5 billion years.[1]
- The Local Group is a small part of the massive Virgo Supercluster of galaxies. Many other galaxies belonging to the supercluster are visible with a small telescope in the spring, in the direction of the constellation Virgo. Some astronomers suggest that the Local Group is part of an even larger supercluster known as Laniakea.[2]

The graphic on the next page gives a sense of the relative distance to different objects in the universe. Note that the graphic is logarithmic; that is, for each step on the ladder, the distance increases by a factor of 100. Even the nearest galaxies to us are nearly four billion times as far away as Pluto. The universe is a vast place, but telescopes and dark night skies bring it a little bit closer. Let's begin our tour!


10 billion ly
Other Galaxies
100 million ly
1 million ly
Center of
Milky Way Galaxy
Other stars
Nebulae
Star clusters
10,000 ly
100 ly
1 light-year (ly)
100 billion miles
Planets
1 billion miles
Solar System
10 million miles
The Moon
100,000 miles
Satellites
1,000 miles
Meteors, Aurorae
10 miles

Meteors & Meteor Showers

Most of us have seen a **meteor** (or shooting star) at some point in our lives, perhaps while watching a **meteor shower** or storm (Fig 1). Despite their common name, shooting stars have nothing to do with stars. Instead, the typical meteor is a small piece of space rock disintegrating in the Earth's upper atmosphere, just 80-120 km (50-75 mi) above you.[3] This makes meteors the closest astronomical objects visible to the naked eye.

Figure 1-Dozens of meteors flash across the sky in this composite image taken during August's Perseid Meteor Shower. (NASA/JPL)

Where do these rogue rocks come from? Our Solar System is full of debris left over from its birth: the "sawdust" of planetary formation. These leftovers range in size from microscopic dust grains, to pebble-sized rocks known as **meteoroids**, to **asteroids** hundreds of kilometers wide. While tons of this debris collides with Earth every day, most of the smaller particles disintegrate or vaporize in the atmosphere before reaching the surface.[4] Only larger meteoroids have enough mass to reach the ground as **meteorites**.

Meteoroids collide with Earth at a *minimum* speed of 40,000 km/hr (25,000 mi/hr)[5], fast enough to **ionize** gases in Earth's atmosphere around the meteoroid and producing the flash of light we see as a meteor. Larger meteoroids can produce meteors so bright that they cast shadows on the ground. In some cases, the meteoroid may visibly fragment into smaller pieces or emit audible sounds. These spectacular meteors are known as **fireballs** or **bolides**.

Observing Meteors

You can see meteors on any clear night. The darker your sky, the more you will see. Meteors can appear anywhere in the sky, so a site with few obstructions is ideal. The naked eye is best; telescopes and binoculars are not useful because their **field of view** is so small. You'll also see more meteors during the early morning hours, just before sunrise. During this time, you are standing on the "front windshield" of Earth as it travels on its orbit around the Sun. Just as splattered bugs tend to accumulate on the front windshield of your car, more meteoroids hit this side of Earth than the trailing side on which we stand in the evening hours. Given ideal viewing conditions, 4-16 meteors per hour can be seen in the early morning hours, varying slightly depending on the time of year.[6] This number is lower in the evening hours, and/or under even moderately light polluted skies.

During meteor *showers*, Earth passes through denser concentrations of debris (often left behind by **comets**) and the rate of meteors can increase dramatically for several hours or days. The path of all meteors associated with a particular shower can be traced back to a single point known as the **radiant**. Meteor showers are typically named for the **constellation** in which the radiant lies. Rates of 50 or more meteors per hour are not uncommon during major meteor showers (Table 1), while rarer and less predictable meteor *storms* can generate several hundred or thousand meteors per hour.

Table 1: Selected Annual Meteor Showers[7]

Shower name:	Peak Dates (varies by year):	Meteors per hour at peak:	Comments:
Quadrantids	Jan 3-4	120	Strong shower, but short duration peak (~6 hrs)
Eta Aquarids	May 6-7	40	Peak rates best seen from Southern Hemisphere
Perseids	Aug 11-12	100	Famous shower, occurs during warm Northern Hemisphere months
Orionids	Oct 21-22	20	Unpredictable storms can increase rate to 50-75 meteors per hour
Leonids	Nov 17-18	15	Famous for producing impressive meteor storms about every 33 years
Geminids	Dec 13-14	150	Typically the strongest and most reliable meteor shower of the year

Note that the peak rates listed for each shower assume the sky is dark (minimal light pollution & no moonlight) and that the radiant constellation is high overhead, which typically occurs in the pre-dawn hours. If these conditions are not met (e.g., you watch from your backyard or in the evening hours) you will not see the “advertised” number of meteors.

Aurorae

Anyone fortunate enough to have seen one can excitedly relate the story of their first **aurora**. Aurorae are natural light displays that occur in our upper atmosphere, 80-480 km (50-300 mi) above the Earth’s surface.[8] In the Northern Hemisphere they are known as the **Aurora Borealis** (northern lights), and as the **Aurora Australis** (southern lights) in the Southern Hemisphere.

Aurorae owe their existence to the Sun, which constantly emits a stream of high-energy electrons and protons into space, known as the **solar wind**. Upon arrival at Earth, these charged particles interact with our planet’s **magnetic field** and atmosphere in complex ways. Generally speaking, aurorae occur when particles from the solar wind excite atmospheric gasses such as

Figure 2-Auroral displays as seen from the International Space Station (left) and Yukon-Charley Rivers National Preserve, Alaska (right). (Left: NASA, Right: National Park Service)

oxygen and nitrogen, generating the red, pink, purple, and green colors that are most common during auroral displays (Fig 2).

Aurorae are most commonly observed in a zone around the north and south magnetic poles. Alaska, northern Canada, Scandinavia, and southern New Zealand are among the best places to see them. Aurorae are occasionally visible as far south as the southern United States, Mexico and the Caribbean, but only about once per decade (or once per solar cycle) on average.[9] For example, a naked-eye aurora was seen from Cedar Breaks NM on Memorial Day Weekend 2017. During periods of intense solar activity the Sun experiences **coronal mass ejections**, in which massive amounts of the Sun's atmosphere are ejected into space. A coronal mass ejection aimed directly at Earth is a common cause of visible aurorae at low latitudes. While the resulting aurorae can be spectacular, these solar storms can also damage satellites and electrical grids. A current aurora forecast can be found at http://www.spaceweather.com.

Artificial Satellites

Of all the celestial characters, one sight is unique to 20th and 21st century observers: **artificial satellites**. More than 1,000 operational satellites are currently in orbit around Earth, along with many other non-operational satellites and pieces of space junk.[10] A handful of these are occasionally visible from Earth in the hours following sunset and preceding sunrise.

Satellites move at a constant rate across the night sky, making them appear similar at first glance to aircraft. The key difference is that most satellites maintain a nearly constant brightness as they cross the sky. In other words, they don't blink. (One exception is the Iridium satellites, which are famous for producing bright, short-lived flares. However, these satellites are currently being deorbited and the flares are likely to cease in 2019.) Unlike aircraft, satellites don't emit their own light. We see them only when sunlight bounces off a reflective surface on the satellite and back to our eyes. Like a tall mountain peak, satellites high overhead bask in the Sun's glow even after the Sun has set from our vantage point on Earth, explaining

Figure 3-A 30-second exposure captures the motion of the International Space Station (center right) across the night sky. The light dome of Las Vegas is at left. (Zach Schierl)

why we can see them even after dark. Most satellites are faint, but larger ones such as the International Space Station have large reflective surfaces and rival the brightest stars and planets in the sky (Fig 3).

Satellites bright enough to see with the naked eye tend to be those in **low-Earth orbit**, the zone extending up to 2,000 km (1,200 mi) above Earth's surface. For example, the International Space Station orbits Earth about every 90 minutes, at a height of about 400 km (250 mi). Most satellites have predictable orbits and websites such as www.heavens-above.com can help you determine when a particular satellite will be visible from your location. Like meteors, satellites are best observed with the naked eye because they move too rapidly to track with a telescope, although you may occasionally catch a glimpse of one passing through a telescope eyepiece.

Solar System Objects

The Moon and planets are usually the first objects that new stargazers or telescope owners become acquainted with. In this chapter, we'll briefly discuss how to observe Solar System objects and then learn more about them in *Chapter 2.6: Our Solar System.*

The Moon

Derided by many astronomers, professional and amateur alike, as an annoying "natural" source of light pollution, the Moon is nevertheless a spectacular object in binoculars or a small telescope. It is best viewed during the crescent or quarter **phase** when sunlight hits the Moon at a shallow angle. This creates shadows that reveal fine detail among the deep craters, jagged mountain ranges, broad valleys, and smooth plains (**maria**) of the lunar surface (Fig 4). The greatest detail is typically seen along the **terminator**, the dividing line between the day and night side of the Moon (Fig 4).

As full moon nears, sunlight strikes the visible portion of the Moon more directly, washing out many of these features, much like direct sunlight at noon washes out the fine detail sought by landscape photographers on Earth. In addition, the Moon is so bright when full that it can be uncomfortable to look at through a telescope without a moon filter to decrease the brightness.

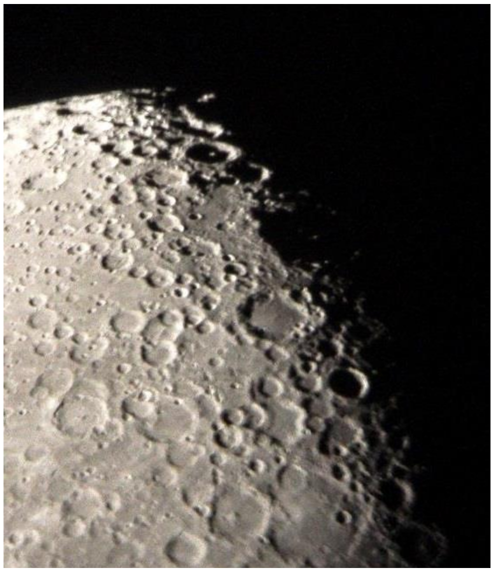


Figure 4-A view of the Moon's terminator through a backyard telescope. (NPS/Zach Schierl)

A frequently asked question about lunar observing is: "Can I see where the astronauts landed?" While the general area of the Apollo 11 landing site, Mare Tranquilitatis (the Sea of Tranquility), is more than 850 km (528 mi) wide, the lunar lander, flag, and footprints left behind are far too small to be seen with even the largest Earth-based telescopes. A typical backyard telescope can only resolve objects as small as about one mile across on the lunar surface.[11]

Another pernicious lunar myth is that the Moon is larger when on the horizon. In reality, this is nothing more than an optical illusion. Next time you see a bright orange full moon rising above the eastern horizon, hold up a dime at the end of your arm next to the Moon and note its apparent size relative to the dime. Repeat a few hours later when the Moon is higher in the sky and you'll see for yourself that it is the same size. In fact, the Moon is actually *farther* away when on the horizon and is thus ever so slightly smaller, however the difference is essentially imperceptible to the human eye.

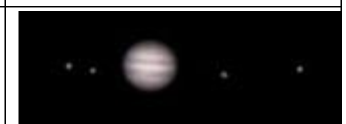
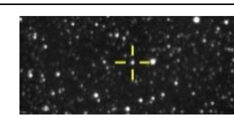
Planets, Dwarf Planets, and their Moons

Some of the best sights in the night sky are the planets of our own Solar System. Five of the seven planets (besides Earth) are visible to the naked eye, and mercifully are even bright enough to be seen from heavily light polluted areas. The outermost planets (Uranus and Neptune) and the **dwarf planets** (like Pluto) are fainter and require a telescope to see.

With the naked eye, planets can be difficult to tell apart from stars. However, because the planets "wander" relative to the background stars (*see Chapter 2.2*), we can detect them by watching for their movement from night to night. Like the Sun and Moon, the planets appear to follow the **ecliptic** and can always be found in one of the 13 **zodiac constellations**. If you are familiar with the zodiac constellations, you can identify planets by looking for bright stars that don't fit into the traditional constellation patterns.

While movement will betray planets to the naked eye, a telescope quickly reveals their true nature. All the major planets will appear as discs, as opposed to points of light like stars, through backyard telescopes. Several, such as Jupiter and Mars (when it is close to us), can exhibit great detail. Numerous moons of Jupiter and Saturn are also visible with small telescopes, and their orbital motion around their host planet can be observed in as little as a few hours. Table 2 summarizes the appearance of each planet to the naked eye and through a telescope.

Table 2: Appearance of the Planets with the Naked Eye and Telescopes

Planet	With naked eye, looks like:	With a telescope, looks like:	Telescope view:
Mercury	A moderately bright star near the horizon. Difficult to see because it never strays far from the Sun. Only visible a few weeks out of the year.	Small featureless disc. Exhibits **phases** like the Moon.	
Venus	The brightest object in sky after the Sun and Moon. Visible either just after sunset ("evening star") or just before sunrise ("morning star") depending on time of year.	Also exhibits phases like the Moon, but no surface features visible due to layer of clouds & haze that covers the planet.	
Mars	Bright, distinctly red/orange colored star. Can be nearly as bright as Venus when at closest to Earth (every 2.2 years).	Small pinkish orange disc. Surface details such as polar ice caps and dark markings are visible in larger telescopes when planet is close to us.	
Jupiter	Very bright yellowish star. Outshines nearly all true stars. Moves more slowly with respect to stars than the terrestrial planets.	Spectacular object. Several colorful cloud bands and four Galilean moons visible even through small telescopes.	
Saturn	Moderately bright star, much fainter than other naked eye planets due to distance. Not as distinctive as other naked eye planets.	A stunning sight. Ring system and several moons visible even through small telescopes. Subtle cloud bands and gaps in ring system are visible with larger telescopes.	
Uranus	Only visible to dark adapted naked eye at a very dark site, and even then, barely.	Small featureless pale-blue disc.	
Neptune	Not visible to naked eye	Smaller featureless green-blue disc. Largest moon (Triton) visible in larger telescopes.	
Pluto (dwarf planet)	Not visible to naked eye	No disc visible in backyard telescopes. Appears identical to a faint star. Detailed star charts are needed to identify with certainty.	

Asteroids

Asteroids, rocky pieces of rubble left over from the formation of the Solar System, appear merely as star-like points of light even through large telescopes. The term "asteroid" was coined by British astronomer William Herschel; it means "star-like" in Greek. Even with large telescopes, the only characteristic that distinguishes asteroids from stars is that, like planets, asteroids orbit the Sun and thus move or "wander" relative to the background stars over time (Fig 5). Only a few asteroids, such as Ceres and Vesta, are large and bright enough to be easily seen with backyard telescopes.

Figure 5-Asteroid 2005 YU55 (white streak) as seen on the evening of November 8, 2011. This near-Earth asteroid appears as a streak because it was passing inside the radius of the Moon's orbit, and thus moving across the sky very rapidly, when this long-exposure image was taken. (Whitman College/Zach Schierl)

Comets

Comets are a relatively rare sight in our night sky, but can be far more spectacular than asteroids. Often described as "dirty snowballs," comets are city-sized chunks of ice, rock, and dust that orbit the Sun on elliptical paths. Most comets spend the majority of their lives in the outer Solar System, where they are invisible even with large backyard telescopes.

When a comet approaches the Sun, it begins to lose mass and develop a coma (atmosphere) and possibly a tail (Fig 6). If a comet is large enough, or passes close enough to Earth, during this time they can brighten enough to be visible in small telescopes or, in rare cases, even to the naked eye.

Figure 6-Comet McNaught graced the Southern Hemisphere skies in 2007, becoming one of the brightest comets on record. (ESO/Sebastian Deiries, [CC BY 4.0](https://creativecommons.org/licenses/by/4.0/))

Naked eye comets are rare and their arrival is often unpredictable. While some comets have regular, predictable orbits and appear in our sky periodically, these are typically dimmer and only visible through telescopes (Fig 7). There are some exceptions however, such as Comet 1P Halley (Halley's Comet) which is usually bright enough to see with the naked eye when it rounds the Sun every 76 years.

Figure 7-Comet PanSTARRS, sketched through a 10" telescope. (Michael Vlasov)

Comets are unique among astronomical objects in that they are officially named for their discoverers (with a few historical exceptions such as Halley's Comet, which was named for, but not discovered by, Edmund Halley). Today, many new comets are found by automated survey telescopes, hence comet names such as Comet C/2013 US10 Catalina, Comet 2003 X1 PanSTARRS, and Comet 252P LINEAR.

Stars

Stars, large luminous spheres of **plasma** like our Sun, are by far the most abundant type of object visible in the night sky, both to the naked eye and with telescopes. Under reasonably dark and moonless skies, the naked eye can see upwards of 5,000 stars, a small telescope is capable of detecting several million, and a 15" telescope can see 380 million.[12]

Most stars don't look that different through a telescope than they do to the naked eye. Except for the Sun, all stars appear as points of light, even with large telescopes. Yet stars exhibit many other interesting properties that make them worth a closer look. Perhaps the most obvious stellar property that can be seen with a telescope (and in some cases, the naked eye) is color, which indicates the surface temperature of a star. Very hot stars are blue or white in color, whereas cooler stars are orange or even red. We'll explore the science of stars in more detail in *Chapter 2.7.*

Double, binary & multiple stars

A **double star** is any pair of stars that appear very close to each other in the night sky (Fig 8). In most cases, the two stars are close enough that they are only revealed as a pair by using binoculars or a telescope. **Multiple stars** are groupings that contain three or more individual stars.

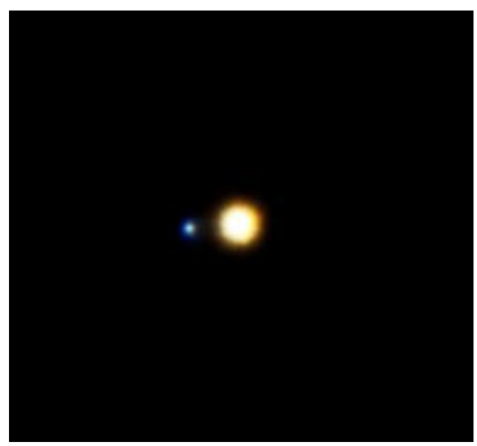


Figure 8-The double star Albireo (Beta Cygni), a brilliantly colored orange/blue pair easily visible in backyard telescopes. (Wikimedia user: Hewholooks, CC BY-SA 3.0)

Some double stars *are* true companions, while others only *appear* close together. If two stars lie along nearly the same line of sight, but actually lie at different distances from Earth, we call the coincidental pair an **optical double.** Usually though, double stars appear close to each other because they are close to each other. Many doubles are gravitationally bound to each other in a **binary star** system, where the two stars orbit a common center of mass. Don't expect to see a binary star system revolving through a telescope though; most binary stars take centuries or millennia to complete one revolution.

Because stars form in groups, binary stars are common. More than half of the Sun-like stars in the **Milky Way** are thought to be part of binary or multiple star systems, a percentage that only increases for more massive stars.[13] Among similar stars, our Sun is the oddball in that it is a single star without a companion (Fig 9). In contrast, stars smaller than the Sun, which make up the bulk of the stars in the Milky Way but are poorly represented in the night sky, are more likely to be single than binary, likely because they form in smaller groups to begin with.[14]

Figure 9-This illustration imagines a hypothetical Earth-like planet orbiting in a binary star system. How would life be different on a planet with multiple suns? (NASA/JPL-Caltech)

Double stars make excellent targets for backyard telescopes. They are typically classified based on the amount of separation between the stars. "Wide" double stars are easy targets for small telescopes, whereas "tight" doubles may require larger telescopes and/or exceptional **seeing** to split. Arguably the most beautiful double stars are those with a strong color contrast, such as the one shown in Figure 8.

Variable stars

Variable stars are stars whose **apparent magnitudes** are not constant, but vary over time. Some variable stars change so dramatically in brightness that they can be visible with the naked eye one month and then require a telescope to see the next. Some vary on a timescale of hours. Others oscillate slowly over many years. Some exhibit regular, periodic variations. Others are erratic and unpredictable. The cause of the variability depends on the star in question.

Perhaps the most well-known variable star is Algol in the constellation Perseus. Meaning "Demon's Head" in Arabic, Algol perplexed astronomers for centuries. Algol's apparent magnitude is normally 2.1, making it a moderately bright naked eye star similar to Polaris, our current North Star. Every 2 days, 20 hours, and 49 minutes however, its magnitude dims to 3.4 for about 10 hours, then returns to 2.1. We now know that Algol is part of a binary star system, and that its variability is caused by a smaller, dimmer star partially eclipsing the larger, brighter star every 2.86 days. Algol is thus an *eclipsing* variable star; that is, its variability is not due to any change in the star itself, but rather because some of its light is blocked from reaching us during these miniature eclipses.

In contrast, *pulsating* and *eruptive* variables vary in brightness due to actual changes in the amount of light emitted by the star. Such stars are usually either near birth or near death, and are unstable in some way. These stars often pulsate, expanding and contracting on regular timescales, or experience erratic bursts or eruptions that change the light output of the star. A classic example is the star Mira in the constellation Cetus. Mira is a **red giant** star that pulsates with a period of 330 days. Its magnitude over this 330 day period ranges from 3.5 (easily visible to the naked eye), to 10 (requiring binoculars or a small telescope to see).

Cepheid variables are a particularly useful type of pulsating variable star. The period of their variability is directly proportional to their **luminosity**. Astronomers can estimate the distance to these stars by comparing their luminosity (how bright the star actually is) to their apparent magnitude (how bright it appears). Individual Cepheids can be seen in distant galaxies, allowing astronomers to determine not only the distance of the star, but also the host galaxy.

Deep-Sky Objects

The term **deep-sky object** (or **deep-space object**) generally refers to any astronomical object that is not a star or part of our Solar System. Deep-sky objects include **nebulae**, **star clusters**, and **galaxies**, all of which are popular targets for backyard telescopes. While a few deep-sky objects are visible to the naked eye, most are faint and require binoculars or a telescope to see. Dark skies are also critical for optimal viewing of deep-sky objects.

In the following pages, you will see many colorful images of deep-sky objects. Remember that cameras capture far more color and detail than our eyes do. To give you a better sense of what these objects look like to the human eye, we've also included a number of sketches made at the eyepiece of a backyard telescope.

Nebulae

Nebula (plural=**nebulae**) means "vapor" or "mist" in Latin, and is derived from the Greek *nephelion*, meaning "little cloud."[15] This term has historically been applied to any celestial object with a hazy or cloudy appearance, which, given the size and quality of early telescopes, was just about everything other than stars and planets. Objects such as star clusters and galaxies were classified as nebulae as recently as 100 years ago. We now reserve the term "nebula" for interstellar clouds of gas and/or dust, of which there are several distinct types:

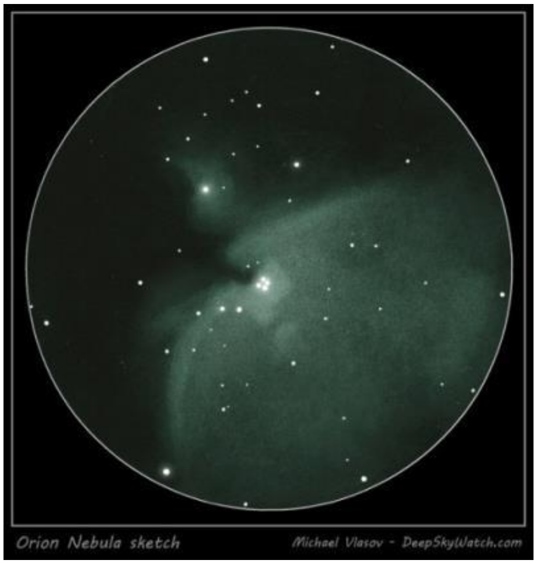


Figure 10-The Orion Nebula (M42), sketched through an 8" telescope. (Michael Vlasov)

Emission Nebulae

Emission nebulae are clouds of hydrogen gas and dust that *emit* their own visible light. Ultraviolet radiation from nearby hot, young stars ionizes the hydrogen, causing it to emit a specific wavelength of red light. While they appear colorless, grey, or green-ish in backyard telescopes (Fig 10), long-exposure photographs always reveal the characteristic red color of emission nebulae (Fig 11).

Emission nebulae are often nicknamed "stellar nurseries" because they are associated with the birth of new stars. Many emission nebulae are found alongside dark, cold **molecular clouds** that are collapsing to form new stars and solar systems. These newborn stars are the source of the energy that ionizes the hydrogen and causes it to glow. While these nebulae may appear dense in photographs, they are actually extremely tenuous. Even the densest emission nebula or molecular cloud contains less matter per cubic centimeter than the best vacuum chambers on Earth.[16]

Emission nebulae are among the largest deep-sky objects. Many appear several times larger than the full moon, and the clouds can physically span dozens to hundreds of light-years of space. However, because their light is spread out over such a large area, many are actually too faint to see with the human eye (even with a telescope) and are best captured on camera (Fig 11). A few of the closest and most compact emission nebulae, such as the Orion Nebula and the Lagoon Nebula, are among the most spectacular sights visible with a backyard telescope and are actually bright enough to appear as fuzzy patches to the naked eye.

Figure 11-The North American Nebula appears nearly four times larger than the full moon, yet because its light is spread out over such a large area, it is usually visible only in long-exposure photographs. (Oliver Stein, CC BY-SA 3.0)

Reflection Nebulae

In contrast to emission nebulae, **reflection nebulae** do not emit their own light, but instead contain tiny dust particles that *reflect* or *scatter* light from nearby stars. Like emission nebulae, they usually appear colorless to the human eye. In long-exposure photographs however, they are always a vibrant shade of blue. Just like particles in Earth's atmosphere, the dust grains preferentially scatter blue wavelengths of light, giving reflection nebulae their consistent color.

Figure 12-The Pleiades star cluster (M45) is surrounded by a blue reflection nebula. (NASA, ESA, AURA/Caltech, Palomar Observatory)

Reflection nebulae are often even fainter than emission nebulae; very few are bright enough to see in backyard telescopes. Perhaps the best example in the entire sky is M78 in the constellation Orion. The Pleiades star cluster (a.k.a. the Seven Sisters) is surrounded by reflective dust that shows up prominently in photographs but is difficult to see by eye (Fig 12).

Dark Nebulae

In contrast to all other types of nebulae, **dark nebulae** are defined by an absence of light. Once thought to be literal "holes in the heavens," these dark features are actually dense (~1,000 particles per cubic centimeter) clouds of dust and hydrogen molecules (molecular clouds) that are opaque to visible light.[17] As a result, they often appear as dark silhouettes against a backdrop of stars or a bright emission nebula (Fig 13). Many large dark nebulae are easily visible to the naked eye under dark skies as the black rifts and lanes in the Milky Way (Fig 14).

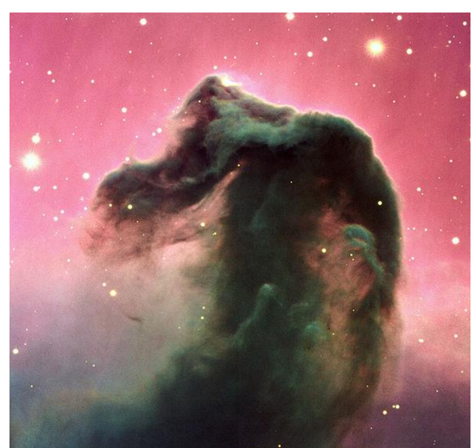


Figure 13-The Horsehead Nebula in Orion is perhaps the sky's most famous dark nebula, albeit one that is difficult to see through a backyard telescope. (ESO, [CC BY 4.0])

While these clouds block visible light, infrared radiation can pass through them with ease, allowing astronomers to see through the clouds and study the newborn stars that often lie inside.

Planetary Nebulae

The final two varieties of nebulae both involve star death. **Planetary nebulae** have nothing to do with planets whatsoever. Early telescopic astronomers observed their often spherical, planet-like shape and bestowed the confusing name that we sadly live with to this day.

Figure 14-The black patches snaking through the Milky Way are dark nebulae: clouds of interstellar dust that block our view of distant stars. (NPS/Zach Schierl)

Perhaps a more accurate moniker for these objects would be "ghost nebulae." These objects are expanding shells of gas representing the remains of small to medium-sized stars (Fig 15). While stars larger than about eight times the mass of our Sun end their lives in violent explosions known as **supernovae,** smaller stars like our Sun experience a less violent death and become planetary nebulae.

In this case, the outer layers of the dying star expand into space as a "bubble" consisting of various gasses: hydrogen, helium, nitrogen, oxygen, and neon to name a few. In some planetary nebulae, this bubble is symmetrical and neat, while others exhibit more complex patterns. Meanwhile, the star's core collapses to form a hot, dense **white dwarf**. Ultraviolet radiation from the white dwarf ionizes the medley of expanding gasses, making planetary nebulae some of the most colorful objects in the sky in photographs. Technically, planetary nebulae are also emission nebulae, but they are so different from the stellar nurseries discussed earlier that they are usually treated as an entirely different class of object.

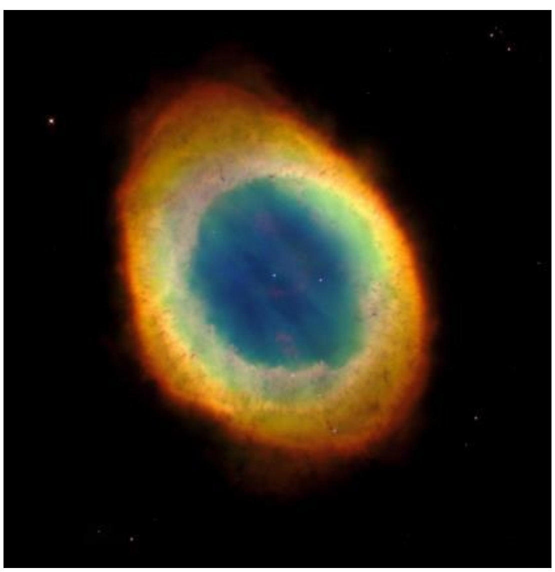


Figure 15-The Ring Nebula (M57), one of the brightest planetary nebulae in the night sky. Note the faint white dwarf in the center of the nebula. (The Hubble Heritage Team-AURA/STScI/NASA)

Only about 3,000 planetary nebulae are currently known in the Milky Way Galaxy.[18] This low number is due to their finite and relatively short lifetime. As the gases spread out, they eventually get too far from the white dwarf to be ionized. The gases in a planetary nebula typically glow for just 10,000-20,000 years before the continued expansion renders them invisible.

As a general rule, planetary nebulae are small, faint, and best observed with large telescopes under dark skies. Some are so small that they are hard to distinguish from stars. Still, a handful are bright enough to view through small telescopes, such as the Ring Nebula (M57) and the Dumbbell Nebula (M27) (Figs 15-16). However, like nearly all deep-sky objects, they are not bright enough for the human eye to see the color present in photographs.

Figure 16-The Dumbbell Nebula (M27), sketched through an 8" telescope. (Michael Vlasov)

Supernovae Remnants (SNRs)

In contrast to small stars, when a massive star dies its core collapses, rebounds upon itself, then blows the star to smithereens, all in a split second. This event is known as a **supernova**. The brightest supernovae can briefly outshine all the other stars in the host galaxy combined. Often, a **neutron star** or **black hole** is left behind in the aftermath. While the death of a massive star is the most common cause of supernovae, several other mechanisms can also produce similar stellar explosions. Supernovae are discussed more extensively in *Chapter 2.7.*

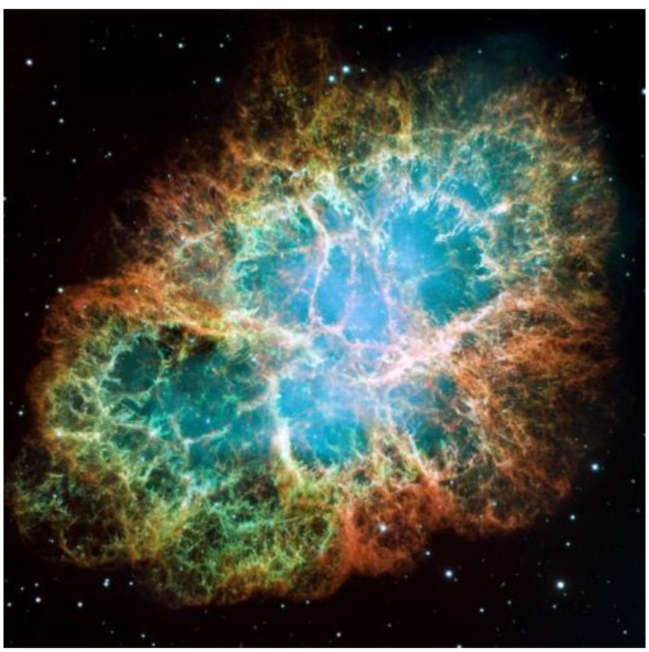


Figure 17-The Crab Nebula (M1) is the remnant of a supernova that appeared in the sky in 1054 AD. (NASA, ESA, J. Hester and A. Loll-Arizona State University)

Supernovae are so luminous that when one occurs within a few thousand light-years of Earth it can be seen in the daytime. Supernovae that close are rare however: on average only 4-5 occur in the entire Milky Way Galaxy each century.[19] Furthermore, the Milky Way is currently in a drought. The most recent supernova observed in the Milky Way occurred in 1604, prior to the development of the telescope.[20] We frequently see supernovae in other galaxies, but due to their great distance these appear only as faint points of light and require very large telescopes to study.

Somewhat easier to see are the handful of **supernovae remnants (SNRs)** scattered across the sky. While supernovae dim dramatically within a matter of weeks or months, the aftermath often glows for thousands of years (Fig 17). Only a few supernova remnants emit enough visible light to be seen using backyard telescopes; most emit predominantly radio waves and x-rays. Perhaps the most famous SNR is the Crab Nebula (M1) in the constellation Taurus, the remains of a supernova observed in 1054 AD by Chinese astronomers (Figs 17-18).

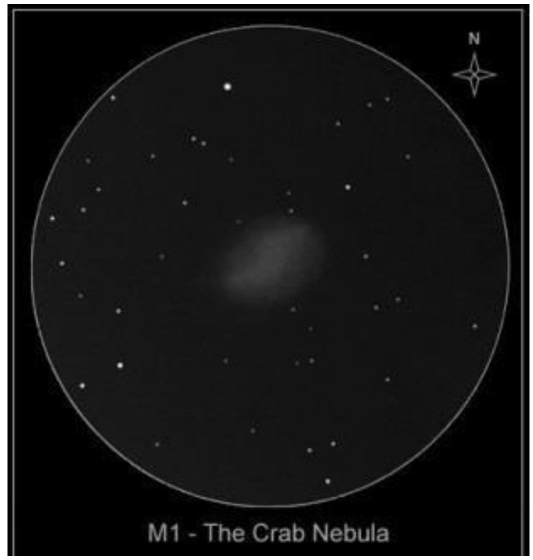


Figure 18-The Crab Nebula (M1), sketched through an 8" telescope. (Michael Vlasov)

Star Clusters

Open clusters

An **open cluster** is a group of up to several thousand newborn stars, all formed from the collapse of the same **molecular cloud**, and still bound together by their mutual gravity. Like a litter of puppies, the young stars in an open cluster are all approximately the same age and have the same composition. Most, but not all, stars form in open clusters.[21]

Younger open clusters are often associated with emission nebulae, whose glowing gas is usually the leftovers of star formation (Fig 19 left). Over time, intense stellar winds eject the residual gas and dust, leaving just the star cluster behind (Fig 19 right). As a cluster ages, its more massive stars evolve and die, while gravitational interactions and disturbances strip smaller stars from the cluster. Eventually, the cluster ceases to exist altogether. According to one source "half of them never get to celebrate their 200 millionth birthday."[22] The larger and more massive the cluster is to begin with, the longer it can survive. Astronomers theorize that our Sun was likely born in an open cluster containing 1,000-10,000 stars, but which has since dissipated.[23]

Figure 19-Examples of open clusters. At left is NGC 2244, an open cluster associated with a glowing emission nebula. In the center are the Pleiades, surrounded by residual dust that reflects blue light from the young stars (a reflection nebula). At right is NGC 265, an older star cluster with no visible gas or dust remaining. (Rosette: John Lanoue, public domain, Pleiades: NASA/ESA/AURA/Caltech-Palomar Observatory, NGC 265: European Space Agency & NASA)

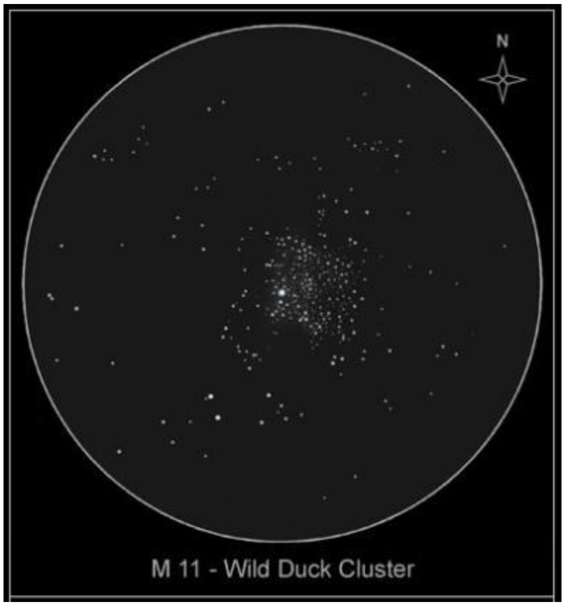


Figure 20-The Wild Duck Cluster (M11), sketched through an 8" telescope. (Michael Vlasov)

About 1,200 open clusters are known to exist in the Milky Way, with the vast majority concentrated along the **galactic disk**.[24] In Northern Hemisphere winter and summer, when the Milky Way is high overhead, open clusters are a dime a dozen. They are among the larger and brighter deep-sky objects, making them superb targets for small telescopes and binoculars (Fig 20). Several, like the Pleiades, are bright enough to see with the naked eye, and large enough that they are best observed with smaller telescopes that can fit the entire cluster into their field of view.

Globular clusters

In stark contrast to the newborn and adolescent stars of open clusters, **globular clusters** contain some of the universe's most ancient stars, in quantities that are difficult to fathom. Omega Centauri, a globular cluster visible from southern latitudes, contains an estimated 10 *million* stars, packed into a roughly spherical cluster less than 200 light-years in diameter (Fig 21). If you lived on a planet orbiting a star deep within such a globular cluster, "night" would not exist. Approximately 130,000 naked eye stars and more than 1,000 suns brighter than Sirius (the brightest star in our night sky) would illuminate the sky in a perpetual twilight 20 times brighter than the full moon.[25] Their enormous collective mass helps globular clusters remain intact far longer than smaller open clusters.

Figure 21-Omega Centauri, the Milky Way's largest globular cluster, contains an estimated 10 million stars. (ESO, CC BY 4.0)

Globular clusters are as ancient as they are massive. Many contain stars formed more than 10 *billion* years ago, early inhabitants of a fledgling universe. These stars formed before supernovae enriched interstellar space in elements heavier than helium, known by astronomers as **metals**. Thus, globular cluster stars are typically "metal-poor" and have very different compositions than younger stars like our Sun.

Because they are so old, globular clusters typically lack the luminous supergiant stars that are common in open clusters. Any massive stars that were once part of a globular cluster have long since gone supernova.

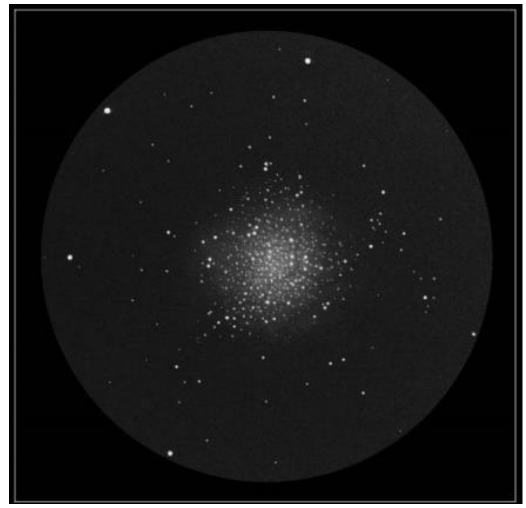


Figure 22-The Great Hercules Cluster (M13), sketched through an 8" telescope. (Michael Vlasov)

While most stars, open clusters, and nebulae are found in the **galactic disk**, the nearly 150 globular clusters in the Milky Way live in the **galactic halo**, orbiting the center of the galaxy like bees buzzing around a hive. Because of their location outside the plane of our galaxy, globular clusters are the most distant objects that are still a part of the Milky Way. Most globular clusters that we see are 10,000-40,000 light-years away, and a few are more than 100,000 light-years away. Nearly every other large galaxy has a collection of globular clusters in its halo as well. Some of the Milky Way's globulars are now thought to have been captured by interactions with other galaxies.[26]

Table 3: Star Clusters Compared

	Open Clusters	Globular Clusters
Age	*Millions* of years	*Billions* of years
Composition	"Metal" rich	"Metal" poor
# of stars	Hundreds *to* thousands	Hundreds *of* thousands
Concentration	Loose, "open"	Dense, "globular"
Location	Galactic disk	Galactic halo

Many globular clusters are bright enough to be observed with small telescopes, but it is through larger telescopes that globular clusters really shine. With a small telescope, it is difficult to resolve individual stars whereas with a larger instrument, individual stars can often be resolved all the way to the cluster core (Fig 22).

The Milky Way

Every single object we have discussed so far lies within the **Milky Way**. The Milky Way is a **galaxy**, a huge collection of stars, dust, and gas all bound together by gravity. Specifically, the Milky Way is a **spiral galaxy** shaped somewhat like a fried egg: mostly flat, yet with a noticeable bulge in the center when viewed edge on (Fig 23). The egg white, known as the **galactic disk,** is about 100,000 light-years wide, yet only about 1,000 light-years thick. Most of the stars, gas, and dust in the Milky Way are confined to this relatively thin disk. Our Solar System lies within the disk, about halfway between the center of the galaxy and the outer edge (Fig 23).[27]

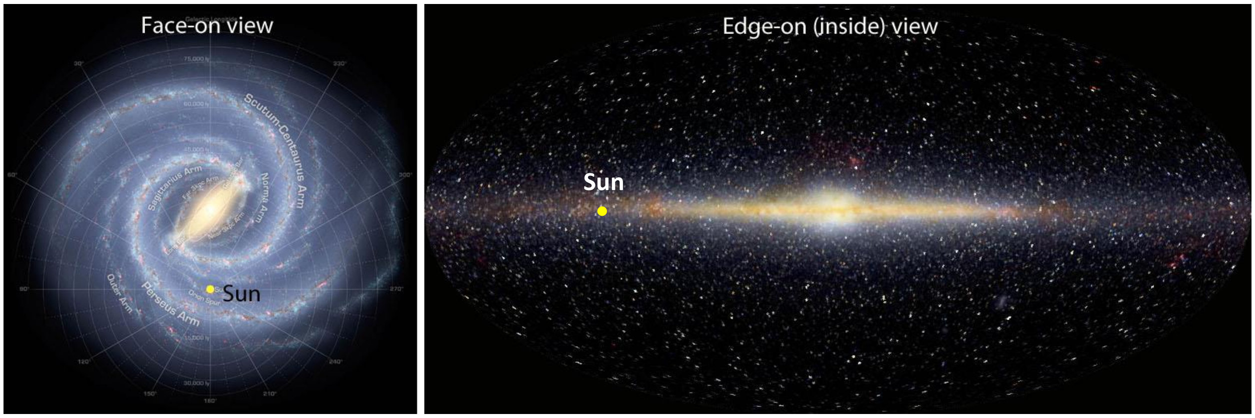


Figure 23-Simulated views of the Milky Way from above the plane of the galaxy (left) and looking along the plane (right). (NASA/JPL-Caltech/R. Hurt)

In total, the Milky Way contains between 100-400 billion stars, of which our Sun is just one. Most of these stars are not visible to us. Clouds of dust (dark nebulae) lurk throughout the galactic disk, making it difficult for us to see the distant reaches of the Milky Way. Objects in our own neighborhood of the Milky Way dominate our night sky. In fact, of all the stars visible to the naked eye, the vast majority (~68%) are located within just 500 light-years of Earth, impressive considering that the galaxy is 100,000 light-years wide.[28]

Many of the Milky Way's stars, those not obscured by dust but too distant or dim to see individually, appear collectively as a fuzzy band of light that stretches across the night sky (Fig 24). This is the galactic disk. The band appears thicker and brighter in Northern Hemisphere summer when we look toward the center of the galaxy and the **galactic bulge**, which is home to older stars and a supermassive black hole with approximately 4.5 million times the mass of the Sun. In the winter, the Milky Way appears fainter because we are looking towards the outskirts of the galaxy. Before we understood what galaxies were and that we lived inside one, the term "Milky Way" simply referred to this band of light. For some time, astronomers hypothesized that the Milky Way was made up of stars unresolvable to the naked eye, but it wasn't until Galileo aimed a telescope at the Milky Way in 1610 that this was demonstrated to be true.

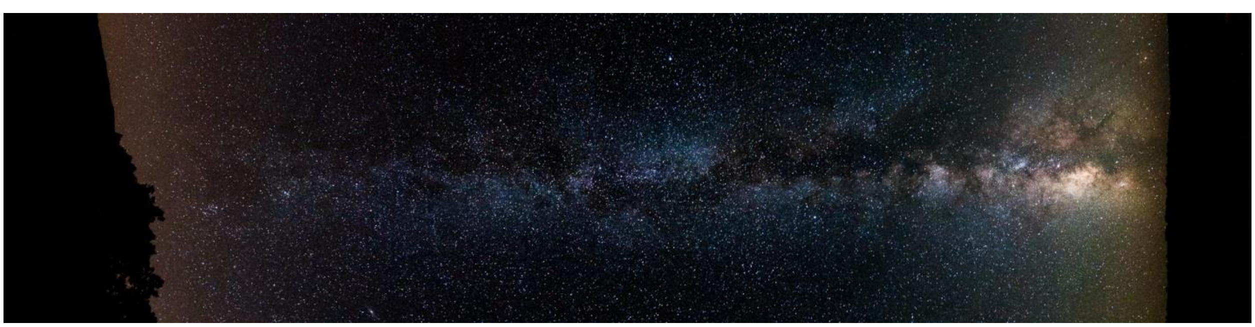


Figure 24-The Milky Way as seen on a summer evening from western Colorado. The fuzzy band of light is the disk of the Milky Way. Notice how the disk appears thicker and brighter to the right (south); this is the galactic bulge and galactic center. (Zach Schierl)

Other Galaxies

Our Milky Way is just one of an estimated two trillion (2,000,000,000,000) **galaxies** in the universe.[29] Galaxies are by far the most numerous type of deep-sky object, yet they were identified as their own class of objects as recently as the 1920s. Galaxies are islands of stars, gas, and dust in an otherwise empty and barren universe.

Galaxies are significant in part because they are the most distant objects visible in backyard telescopes. Even the closest major galaxy to us, the Andromeda Galaxy, is more than two *million* light-years away. Galaxies dozens or hundreds of millions of light-years away are visible even in small telescopes. Spring is the best time of year to observe other galaxies, when the night side of Earth is aimed away from the obscuring dust of our own Milky Way.

Just as not all stars resemble the Sun, not all galaxies resemble the Milky Way. Astronomers recognize several distinct types of galaxies based on their shape, contents, and morphology:

Spirals & barred spirals

Spiral galaxies are the celebrities of the galaxy world. When you picture a galaxy, you are probably imagining one like those in Figure 25. Spiral galaxies are natural works of art with their gently curved spiral arms wrapping around a bright nucleus. They are also the most numerous of the large, bright galaxies, and produce most of the visible light in the local universe.[30] While larger telescopes or cameras are needed to capture the incredible detail visible in Figures 25 and 27, several spirals are bright enough that the human eye can detect their spiral arms through the eyepiece of a backyard telescope under dark skies (Fig 26).

Figure 25-The Pinwheel Galaxy (M101), a typical spiral galaxy (left) and NGC 4394, a barred spiral galaxy (right). (Left: European Space Agency & NASA, Right: ESA/Hubble)

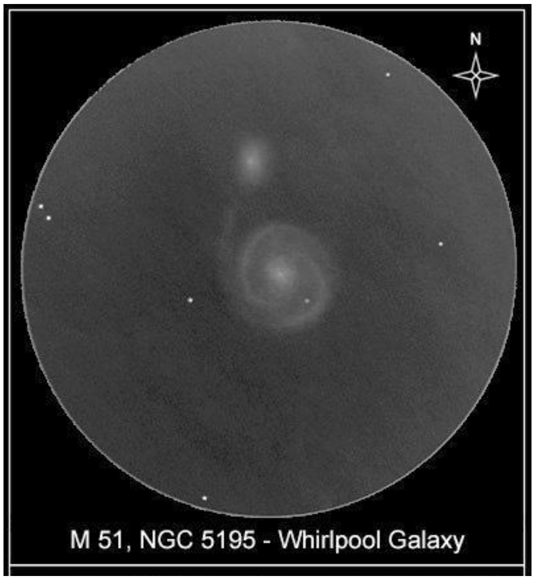


Figure 26-A face-on spiral galaxy (the Whirlpool Galaxy, M51), sketched through an 8" telescope. (Michael Vlasov)

We live in a spiral galaxy: our Milky Way is a **barred spiral galaxy,** a subtype in which the nucleus is elongated into a bar (Fig 25, right). Material within the spiral arms orbits the galactic nucleus, which is often home to a supermassive black hole. The closer a star is to the nucleus, the faster its orbital period. In other words, inner portions of the galaxy rotate more quickly than outer portions. Because of this, the arms in a spiral galaxy are not fixed structures; if they were, they would quickly become “wrapped” around the center the galaxy. Instead, spiral arms are continuously renewed, most likely due to density or shock waves that trigger bursts of star formation which cause the arms to appear brighter than the rest of the galaxy.[31] The arms of most spiral galaxies are dotted with the tell-tale signs of star formation, such as red and pink emission nebulae (Fig 27).

Just like a Frisbee looks different depending on whether you view it from above or the side, the appearance of a spiral galaxy depends largely on its orientation relative to our line of sight. Because spiral galaxies are more or less flattened discs, when we see them edge-on, they appear thin and slender, almost like a needle (Fig 28 left). Only when seen face-on, from above or below, does the spiral arm structure become apparent (Fig 28 right).

Figure 27-Abundant red and pink emission nebulae are seen in the arms of the Whirlpool Galaxy (M51) in this image from the Hubble Space Telescope. (NASA, ESA, S. Beckwith (STScI), and the Hubble Heritage Team (STScI/AURA)

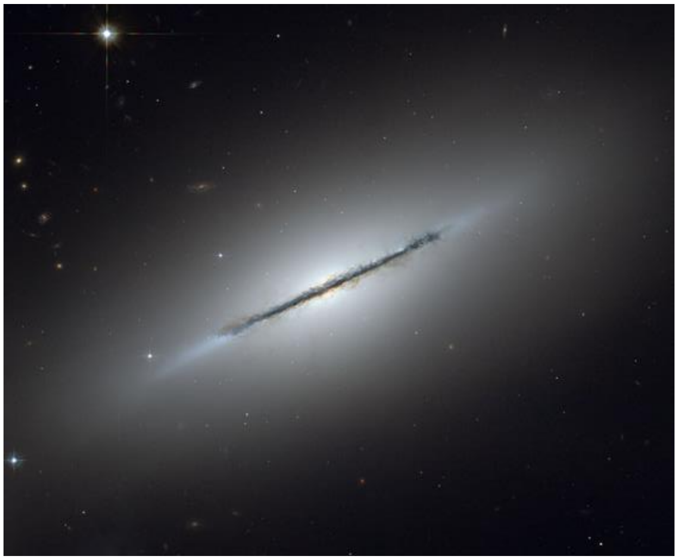


Figure 28-Two spiral galaxies, one seen edge-on (left) and the other face-on (right). (Left: NASA/ESA/The Hubble Heritage Team-STScI/AURA, Right: ESA/Hubble & NASA)

Elliptical galaxies

Elliptical galaxies differ from spiral galaxies in both shape and composition. They do not exhibit the flat disc of spirals, but rather are more spherical in shape. In contrast to spiral galaxies, ellipticals are typically made mostly of older, redder stars, contain little to no gas or dust, and lack regions of active star formation. Elliptical galaxies can be truly massive: M87, an elliptical galaxy in Virgo, is one of the most massive galaxies known, containing an estimated 800 billion stars (Fig 29).[32]

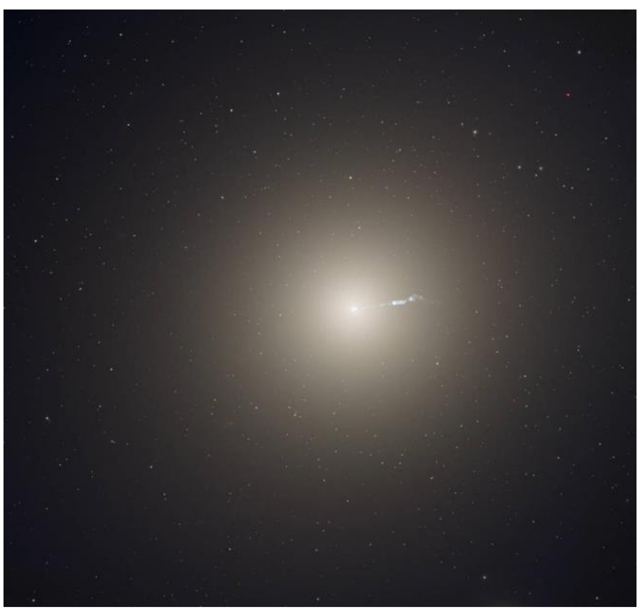


Figure 29-M87, a giant elliptical galaxy in the constellation Virgo. (NASA, ESA and the Hubble Heritage Team (STScI/AURA)

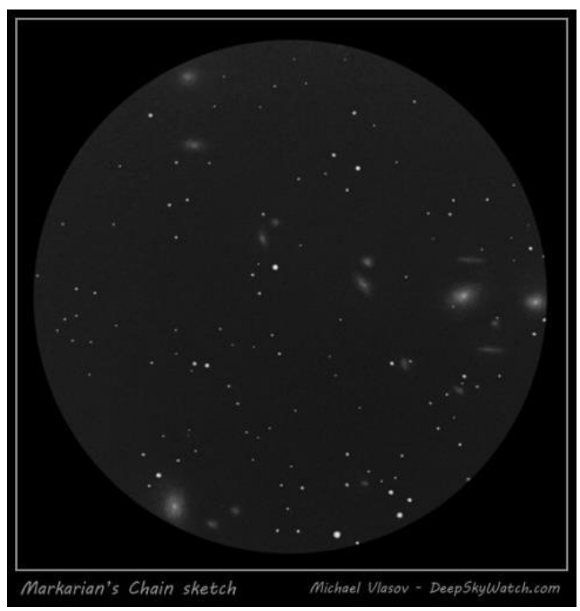


Figure 30-A group of elliptical galaxies (Markarian's Chain), sketched through a 10" telescope. (Michael Vlasov)

Elliptical galaxies are usually less interesting to observe in backyard telescopes because, with few exceptions, they display no internal structure and are nearly featureless. While ellipticals may not be as aesthetically pleasing as spirals, what they lack in detail they can make up for in quantity. For example, the Virgo Cluster of galaxies contains so many elliptical galaxies that in some areas dozens can be seen through a telescope eyepiece simultaneously (Fig 30).

Figure 31-NGC 4449, a dwarf irregular galaxy. (NASA, ESA, A. Aloisi (STScI/ESA), and The Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration)

Irregular & peculiar galaxies

Many galaxies do not fall neatly into the spiral or elliptical classification bins. The terms **irregular** and **peculiar** are reserved for these galaxies, which are often the byproduct of collisions between two or more pre-existing galaxies (Fig 31).

Dwarf galaxies

Dwarf galaxies are galaxies that contain less than a few billion stars (compared to the Milky Way's several hundred billion). Some contain only a few hundred thousand stars, making them similar in size to globular clusters. Dwarf galaxies are the most abundant type of galaxy in the universe yet cannot be easily observed through backyard telescopes because they are so small and diminutive. Many different types of dwarf galaxies exist, such as dwarf spirals, dwarf ellipticals, dwarf spheroidals, and dwarf irregulars. The Milky Way has nearly 60 satellite dwarf galaxies (Fig 32), and as of 2018 more continue to be discovered.[33] Many of these galaxies are in various stages of being absorbed by and/or torn apart by the Milky Way.

Figure 32-The Sagittarius Dwarf Irregular Galaxy, a satellite galaxy of the Milky Way. (NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

Galaxy clusters

Much like stars, galaxies are often found in groups known as **galaxy clusters** (Fig 33). Our Milky Way Galaxy is part of the **Local Group,** which contains more than 50 galaxies including two other large spirals: the Andromeda Galaxy and the Triangulum Galaxy. Most of the galaxies in the Local Group are

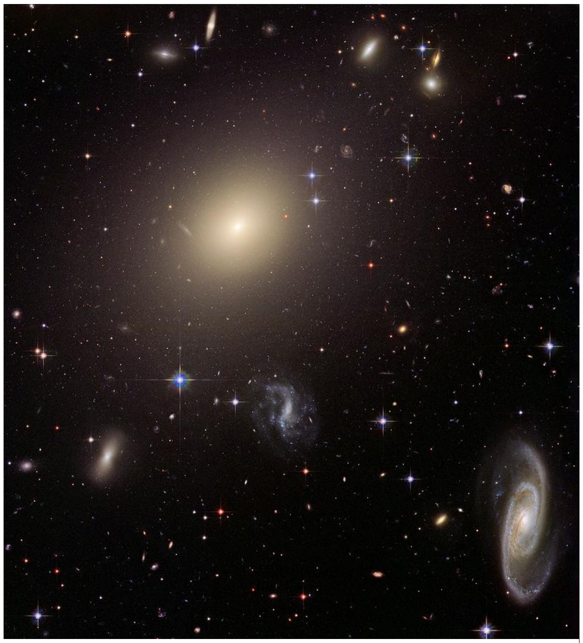


Figure 33-The galaxy cluster Abell S0740 in the constellation Centaurus. (NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

dwarfs that are very difficult to see with backyard telescopes.

When we look towards the constellation Virgo in the spring, we can see the Virgo Cluster which contains more than 1,000 galaxies, dozens of which are visible with a small telescope. Both the Virgo Cluster and our own Local Group are in turn part of a larger conglomeration of galaxies known as the Virgo Supercluster. **Galaxy superclusters** are among the largest known structures in the universe.

Sky catalogs

Throughout this chapter, we have referred to objects by both common names (the Ring Nebula) and catalog numbers (M57). The sheer number of stars and deep-sky objects prevents each one from being given a common name; only the best and the brightest receive one. Instead, for hundreds of years, astronomers have used a variety of catalogs and numbering systems to keep track of celestial objects. The two catalogs most commonly encountered in backyard astronomy are the **Messier Catalog** and the **New General Catalog**.

The Messier Catalog (M)

Charles Messier was a well-known 18th century French astronomer and comet hunter (Fig 34). In the course of his search for comets, Messier kept coming across fuzzy objects that looked like comets, but remained fixed relative to the stars over time. In Messier's own words:

> What caused me to undertake the catalogue was the nebula I discovered above the southern horn of Taurus on 12 Sept. 1758, while observing the comet of that year….This nebula had such a resemblance to a comet, in its form and brightness, that I endeavored to find others, so that astronomers would not confuse these same nebulae with comets just beginning to shine.[34]

Figure 34-Charles Messier (Public domain)

Messier and his associates eventually compiled a list of more than 100 “impostor comets,” now known as the Messier Catalog. While these objects were annoyances to Messier, the mere fact that he could see them using the inferior telescopes of his time means that the objects he cataloged are actually among the brightest and most spectacular galaxies, star clusters, and nebulae in the night sky. All 110 Messier objects are within reach of a small backyard telescope, and are traditionally the first deep-sky objects viewed by beginning astronomers.

To this day, Messier is remembered not for his comet discoveries (of which there were 13), but for his catalog: a “Greatest Hits of the Night Sky” that he had, ironically, intended to be a list of things *not* to look at.

The New General Catalog (NGC)

While the Messier catalog contains nearly all the deep-sky jewels of the Northern Hemisphere sky, many fine objects were either missed by Messier or reside in the southern sky.

In the late 1800s, English astronomer John Dreyer compiled a list of all 7,840 star clusters and nebulae known at the time. His list is known as the **New General Catalogue (NGC)** and is the most commonly encountered catalog of deep-sky objects after Messier’s.

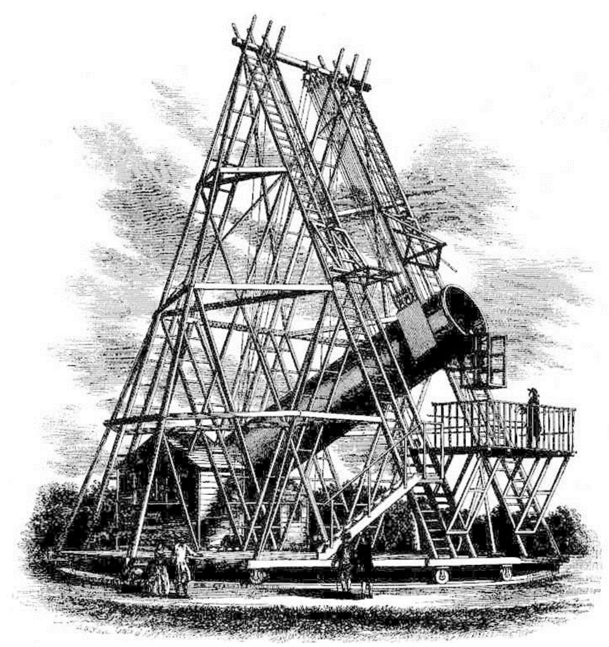


Figure 35-William and Caroline Herschel's 47" reflecting telescope, used in the late 1700s and early 1800s to discover many of the objects that eventually became part of the New General Catalog (NGC). (Public domain)

Many of the objects in the NGC are faint and push the limits of a backyard telescope. However, a handful of NGC objects rival (or even exceed) Messier objects in both brightness and beauty. The NGC also includes objects in the southern sky that were invisible to Messier from his perch in France.

Review

Common Misconceptions

Below is a list of commonly encountered misconceptions about the night sky and its contents. As a way to review content from this chapter, see if you can explain why each misconception is inaccurate:

- Shooting stars are actually stars.
- Meteors are only visible during meteor showers.

- Aurorae can only be seen near the poles.
- The moon is larger when it is near the horizon.
- The stars in the night sky are part of other galaxies.
- Planetary nebulae have something to do with planets.

Questions for thought

- Imagine you are an astronomer looking at “nebulae” through your telescope hundreds of years ago. What might your thoughts about their true nature have been?

- How far out into the universe can we see? With the naked eye? With binoculars? With a telescope? How does light pollution affect the answer?

- Many amateur astronomers spend countless hours hunting down faint galaxies and nebulae with their telescopes. Why do you think this is? What is it about these faint, fuzzy smudges that captures their attention so strongly?

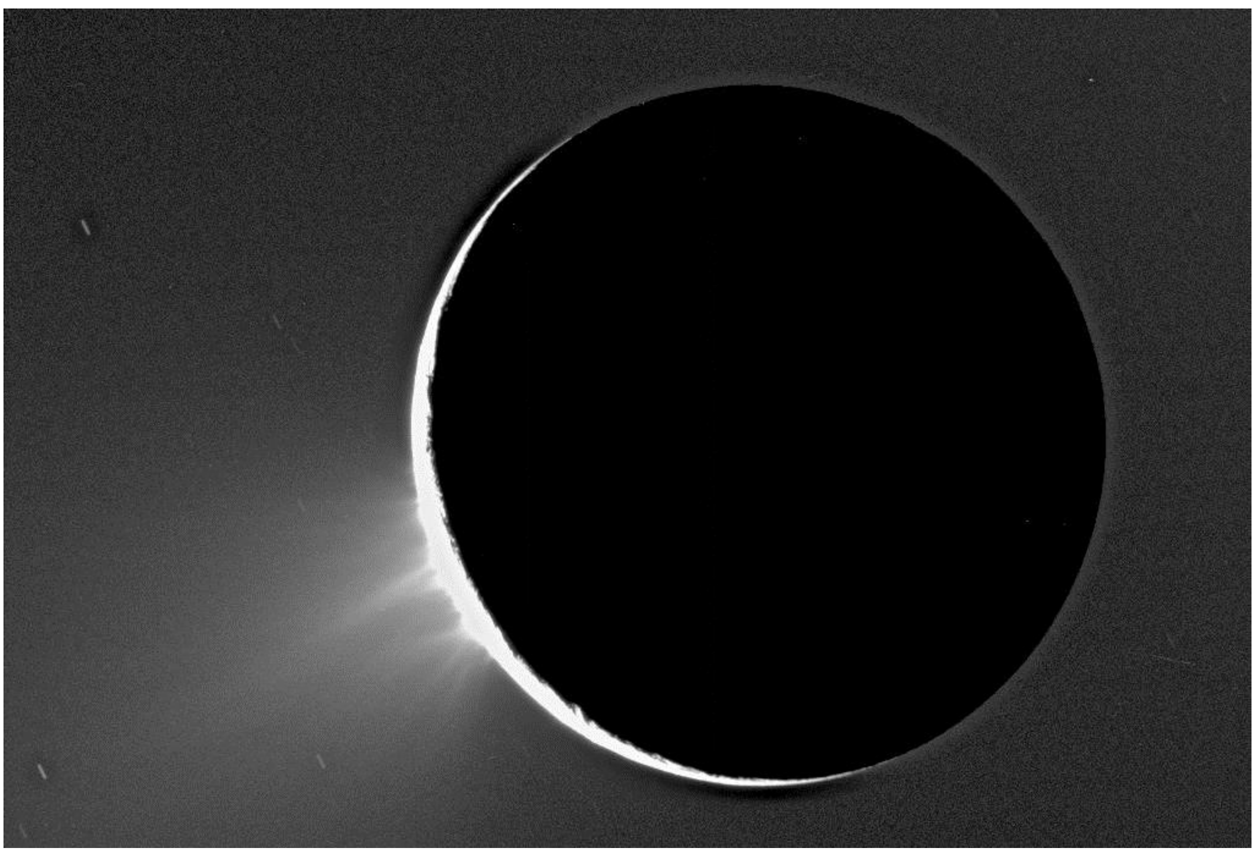
- Many celestial objects appear bright and colorful in photographs, but dim and fuzzy even with a large backyard telescope. What might you say to someone who is used to seeing these photographs, and subsequently disappointed with their view of a nebula or galaxy through your telescope?

- In most cases, larger telescopes lead to progressively better views, except with stars, which remain as points of light even with the largest telescopes on Earth. Why do you think this is? Are there any other objects where increasing the size of the telescope doesn’t necessarily result in a better view?

For More Information

- A guide to the Messier Objects: http://www.messier.seds.org/objects.html
- *Deep-Sky Companions: The Messier Objects*, by Stephen James O’Meara, 1998
- *Heavens-Above.com* (location specific satellite predications and other stargazing info): http://www.heavens-above.com
- Interactive Scale of the Universe web app: http://htwins.net/scale2/
- *SpaceWeather.com* (information on meteor showers and aurorae): http://www.spaceweather.com
- “Tonight” (daily article on what to look for in the sky tonight): http://earthsky.org/tonight

CHAPTER 2.6: OUR SOLAR SYSTEM



Ice geysers on Enceladus, a moon of Saturn. (NASA/JPL).

Chapter 2.6 Goals

After reading this chapter and participating in the corresponding workshop activities, you should be able to:

- Compare and contrast Earth and its properties to other bodies in our Solar System, with a focus on conditions that are needed for life.

Putting the "Solar" in Solar System

Our universe emerged almost 14 billion years ago in the **Big Bang**. Within a few hundred million years, our Milky Way Galaxy began to form. Enormous stars were born, lived short active lives, and then exploded. The remains of these early stars eventually collapsed into other, smaller stars. Finally, about 4.5 billion years ago, one of the stars emerging from the wreckage of past stellar generations became our **Sun**.

Our **Solar System** consists of the Sun and all the objects gravitationally bound to it. Most of this chapter focuses on the **planets**, **moons**, and other objects that orbit the Sun, but it is important to realize that the Sun is both literally and figuratively the star of our Solar System. 99.8% of the mass in our Solar System is contained within the Sun. Everything else accounts for just 0.2%. On a very large scale, the Sun is a single-object system.

Most, if not all, cultures recognized the Earth-Sun connection long before we realized that it was the center of our Solar System. Humans have long known that the Sun is related to the seasons, plant growth, and temperature. Interest in the Sun as a powerful object is seen in cultures worldwide. Solar deities were so common that "the Sun as a god" is practically a universal concept (Table 1).

Our ancestors had it right when they connected the power of the Sun with life on Earth. Earth's seasonal changes, weather, water, and diversity of life are all dependent on our closest star. Without the Sun, life as we know it would not exist. At the same time, the Sun can also be a hazard. Energetic particles and X-rays emitted during solar storms can interfere with power grids, radio communications, and satellites.

Table 1: Selected Sun Gods

Culture	Deity	Description
Aztec	Tonatiuh	Sun god/personification of the Sun.
Kamilaroi	Yhi	Solar deity who personified the Sun and brought life to the world.
Egyptian	Amun, Aten, & Ra	At various times, these gods were associated with the Sun and had varying levels of power and fame.
Inca	Inti	God of the Sun.
Japanese	Amaterasu	Ruled not only the Sun but also the heavens.

Formation of the Solar System

Roughly 4.5 billion years ago, a giant **molecular cloud** made mostly of hydrogen gas began to collapse under its own gravity. This molecular cloud was not unlike the star forming regions we see in the Orion Nebula today. As the cloud collapsed, it fragmented into smaller pieces, one of which became our Sun and the planets, dwarf planets, moons, asteroids, and comets that make up our Solar System. Other fragments collapsed to form other stars and solar systems.

As molecular cloud fragments collapse and shrink, conservation of angular momentum requires that they rotate faster. The collapsing cloud eventually forms a flattened rotating disk of gas and dust surrounding the young star in the center (for more on star formation, see *Chapter 2.7*). This is known as a **protoplanetary disk** (Fig 1). Within this disk planetary formation occurs, primarily via a process called **accretion**, in which dust grains gradually clump together and collide to form larger bodies. Because of the disk's rotation, all of the planets orbit the Sun in the same direction that the Sun spins.

Figure 1-Possible protoplanetary disks surrounding young stars in the Orion Nebula, a gigantic star-forming region about 1500 light-years away. (C.R. O'Dell/Rice University; NASA)

While we can't go back in time to see our own protoplanetary disk, we can see them around other young stars (Fig 1). The temperature inside a protoplanetary disk increases as you move closer to the young star in the center. This temperature gradient explains the stark differences between the inner and outer planets. In the hot inner part of the disk, the only materials that could exist as solids were rock and metals. The accretion of these relatively rare materials formed small **terrestrial planets** like the Earth. In the cooler outer portions of the disk, temperatures were cold enough for compounds such as water, carbon dioxide, and methane to exist as solids. Because these compounds were more abundant than rock and metals, the outer planets grew larger, and accreted enough mass to also capture gaseous hydrogen and helium from the surrounding disk, forming the **ice and gas giants** of the outer Solar System.

We know that our Solar System formed about 4.5-4.6 billion years ago primarily because we don't find **meteorites**, rocks, or objects of any kind older than that anywhere in the Solar System. In particular, a class of meteorites known as **chondrites** appears to be made of primitive Solar System material formed directly via accretion in the early Solar System. Nearly all chondrites are ~4.56 billion years old, providing one of the most reliable estimates for the age of the Solar System.[1]

Table 2: A Brief History of Solar System Discoveries	
Year	**Discovery**
----	The Sun, Moon, and naked eye planets (Mercury, Venus, Mars, Jupiter, and Saturn) have been known since antiquity, although the concept of a "solar system" is relatively new.
1610	Galileo documents the **first four moons of Jupiter**, showing that smaller bodies travel around more massive ones and that other planets besides Earth have moons.
1655	Christiaan Huygens discovers that Saturn also has at least one moon, **Titan**.
1684	Giovanni Cassini had discovered **four more moons of Saturn**, Iapetus, Rhea, Tethys, & Dione, by this year.
1705	Edmund Halley recognized repeated sightings of **a comet** as the same object, the first evidence of an object other than a planet orbiting the Sun.
1781	William Herschel accidentally discovers the planet **Uranus** with his telescope, the first planet not known to the ancients.
1801	The first asteroid, **Ceres** (now also considered a **dwarf planet**), is discovered by Giuseppe Piazzi and initially classified as a planet. Three more asteroids are discovered by 1807.
1845	The 5^{th} asteroid, **5 Astraea**, is discovered. The nearly 40 year gap between the discoveries of 4 Vesta and 5 Astraea was the result of the Napoleonic Wars.
1846	Urbain Le Verrier and John Adams mathematically predict the existence of a planet beyond Uranus. Johann Galle and Heinrich d'Arrest discover **Neptune** on their advice.
1846	The largest moon of Neptune, **Triton**, is found just weeks after the planet is discovered by William Lassell.
1877	Mars' two moons, **Phobos and Deimos**, are discovered by Asaph Hall.
1892	E.E. Barnard discovers the 5^{th} moon of Jupiter, **Amalthea**, almost 300 years post-Galileo.
1901	The asteroid **464 Megaira** is discovered, bringing the total number of asteroids discovered in a 100 year period to 464.
1930	Clyde Tombaugh discovers **Pluto**, the most distant Solar System object known at the time.
1959	Humans begin sending **probes** to other Solar System bodies (Luna 1, Pioneer 4 to the Moon).
1977	The **rings of Uranus** are discovered, making it the second planet (after Saturn) known to have a ring system.
1978	48 years after the discovery of Pluto, James Christy discovers Pluto's largest moon, **Charon.**
1992	The first **Trans-Neptunian Object** discovered after the Pluto/Charon system, **1992 QB_1**, is discovered.
2004	**Haumea**, the first **plutoid** (dwarf planets past Neptune) after Pluto, is discovered.
2005	**Makemake and Eris** (more plutoids) discovered. Eris is more massive than Pluto, motivating astronomers to define the word "planet" for the first time.
2011	Between 1610 and 1999, 67 solar system moons were discovered. In the 11 years after that, 2000-2011, **111 moons** were discovered.
2018	As of March 2019, the Minor Planet Center reports that nearly **790,000 asteroids** have been documented to date.

The Solar System Today

At first glance, our Solar System consists of the Sun, four inner terrestrial planets, Mercury, Venus, Earth, and Mars, all of which you can stand on and only one of which is habitable, the gas giants Jupiter and Saturn, and the ice giants Uranus and Neptune. Innumerable small Solar System bodies, such as asteroids, comets, dwarf planets, and moons, round out the roster.

Distances in our Solar System are usually measured in **astronomical units (AU)**. One astronomical unit is the average distance between the Earth and Sun, about 150 million km (93 million mi). We use the average distance because objects in orbit around the Sun do not travel in perfect circles, but rather in ellipses. As a result, the distance between a planet and the Sun is not constant. When a planet is closest to the Sun, we say it is at **perihelion**. When it is furthest, we say it is at **aphelion**.

Table 3: The Planets of the Solar System

Planet	Orbital Period	Avg. distance from Sun (AU)	Atmosphere	Moons	Avg. Temp (°F)	Mass (Earths)	Magnetic Field
Mercury	88 days	0.38	Trace	0	333°	0.05	Yes
Venus	225 days	0.72	97% CO_2	0	867°	0.81	No
Earth	365 days	1	78% N	1	57°	1	Yes
Mars	2 years	1.52	96% CO_2	2	-85°	0.1	No
Jupiter	12 years	5.20	90% H	79	-166°	318	Yes
Saturn	30 years	9.58	96% H	61	-220°	95	Yes
Uranus	84 years	19.20	83% H	27	-320°	14	Yes
Neptune	164 years	30.05	80% H	14	-330°	17	Yes

Mercury

Mercury boasts a number of Solar System superlatives, including:

- Closest planet to the Sun
- Fastest planet (88 day year)
- Smallest planet
- Largest and most metallic core proportional to its size
- Most cratered planet
- Highest orbital **eccentricity**

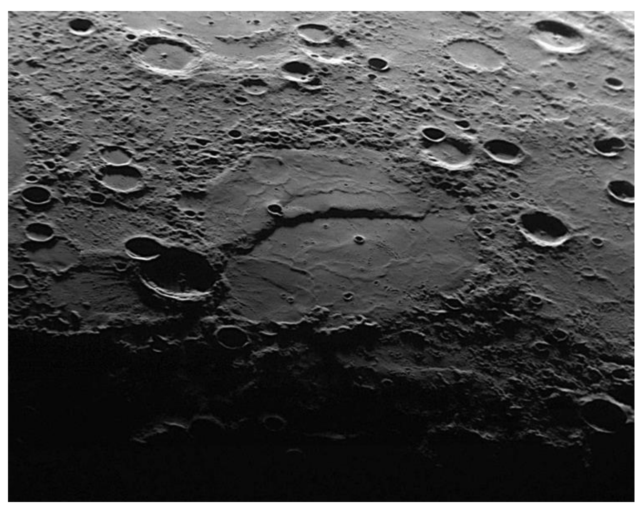
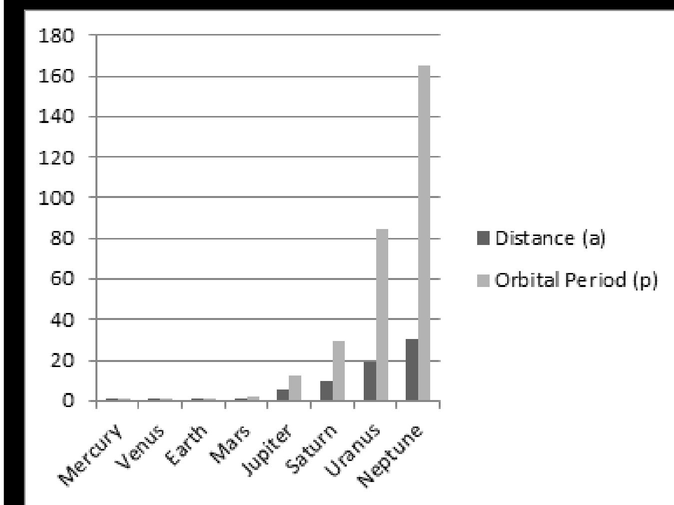


Figure 2-The heavily cratered surface of Mercury, as seen by NASAs MESSENGER spacecraft. (NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington)

Mercury's heavily cratered surface is an important clue about its current state (Fig 2). Much like our Moon, Geologic processes such as volcanism and erosion fill in or erase craters over time, which is why the Earth has so few. Mercury's abundance of impact craters suggests that it doesn't have an atmosphere, and that is lacks any recent geologic activity. If Mercury had an atmosphere, many impacting objects would disintegrate before reaching the surface, as they do on Earth. Without an atmosphere, there is also no weather to erode craters once they form.

Mathematical Morsels

It's not surprising that Mercury is the fastest planet. According to Kepler's Third Law, the distance between a planet and the Sun is directly proportional to the orbital period of the planet. More precisely, the square of the orbital period of a planet (p) is directly proportional to the cube of the average distance to the Sun (a): $p^2 \propto a^3$. The closer a planet is to the Sun, the faster its orbit. Mercury is the fastest planet not because of chance, but because of physics.



This makes Mercury inhospitable to life as we know it. Mercury does have some water ice on its surface, left behind by comets that have impacted the planet. How is ice able to exist so close to the Sun? Mercury has the smallest **axial tilt** of any planet. Earth's rotational axis is tilted 23.5° to the plane of our orbit around the Sun. Mercury's is tilted just 0.034°, meaning that the planet rotates almost straight up and down. This ensures that Mercury doesn't experience **seasons** like Earth or Mars, and that sunlight never reaches the bottom of craters near Mercury's poles. It is here, in these perpetually dark and shadowed crater floors, that water ice is able to survive on the planet closest to the Sun.

While Mercury is the smallest and least massive planet in our Solar System, you would actually weigh more on Mercury (38% of your Earth weight) than you would on Mars. This is because Mercury is denser; more than half of Mercury's volume is occupied by an iron-rich core. In contrast, Earth's iron core occupies just 15% of its total volume. Why is Mercury's core so large? The planet may have been rich in iron to begin with, or large impacts may have ejected most of its rocky mantle early in its history, leaving behind a disproportionally large core.

Mercury's high orbital **eccentricity** is also noteworthy. Eccentricity is a measure of how circular an orbit is. Values closer to zero indicate more circular orbits: 0 is a perfect circle and 1 is a parabola. Mercury has the highest eccentricity of any planet, at 0.2. Earth's orbital eccentricity is just 0.016. Still, Mercury's eccentricity is low compared to most dwarf planets and comets.

Exploring Mercury

Many aspects of Mercury remain a mystery. To date, only two probes have been sent there: Mariner 10 (1973), and MESSENGER (2004). A third, the joint Japanese-European orbiter BepiColombo, is scheduled to arrive in 2025. No probe has yet landed on Mercury, and it remains by far the least explored and understood of the terrestrial planets.

The Closest Thing to Our Sun?

What's the closest object to the Sun? Most of us would say Mercury, but this answer ignores a family of Mercury-crossing asteroids, as well as the story of the hypothetical planet Vulcan.

In 1859, astronomer Edmond Lescarbault thought he saw a planet closer to the Sun than Mercury. The famous mathematician Urbain Le Verrier, who accurately predicted the existence of Neptune from behind a desk using only mathematics, believed Lescarbault and took up the cause. Soon, people all over the western world were obsessed with planet "Vulcan." James Watson, director of the Ann Arbor Observatory, even claimed to have seen it in 1878 during a solar eclipse.

Le Verrier believed strongly in the planet's existence, partly because he had predicted Neptune's existence by showing that another gravitationally large object must be pulling on Uranus' orbit. Similar calculations caused him to believe the same thing was happening to Mercury. But by 1915, Einstein showed that gravity worked differently than previously thought, and Vulcan was no longer needed to explain Mercury's motions. Furthermore, modern solar probes like SOHO and STEREO have found no such planets, hammering the last nail in the coffin for Vulcan.

While no Solar System objects exist entirely within Mercury's orbit, several asteroids do pass closer to the Sun as they cross over Mercury's path. These objects include 1566 Icarus, the first Mercury-crossing asteroid discovered in 1949, and 2005 HC4, an Apollo asteroid with the closest **perihelion** of any orbiting body yet discovered in the Solar System (Fig 3).

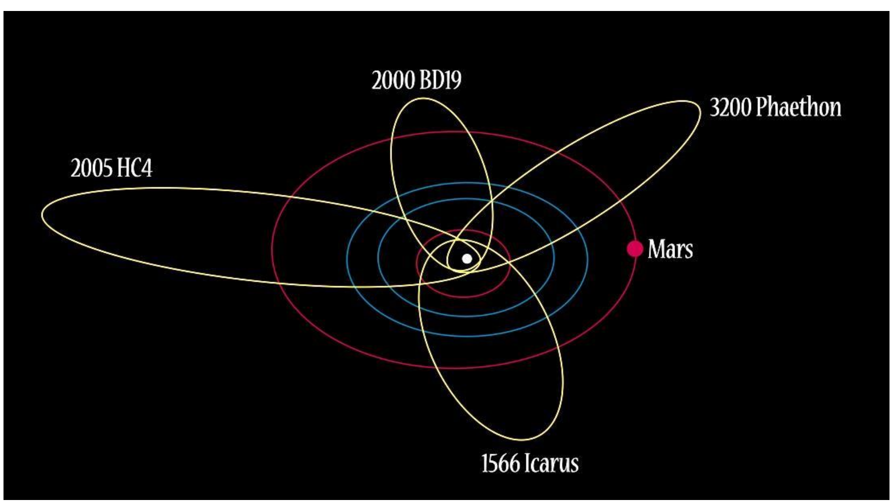


Figure 3-The orbits of several Mercury crossing asteroids. (NPS/Leesa Ricci)

Venus

Figure 4-A true-color image of Venus from the Mariner 10 probe. (NASA, image processing by Ricardo Nunes)

Venus is sometimes called "Earth's twin" or our "sister planet," mostly because it is almost exactly the same size as Earth. Venus has 95% the radius and 82% the mass of Earth, and is also very similar in terms of density, composition, and gravity.

The similarities to Earth end there however. Venus has an atmosphere so thick that the surface pressure is about 92 times greater than on Earth at sea level. On Earth, you would have to dive 1 km (0.6 mi) below the surface of the ocean to experience the same pressure you would standing on the surface of Venus. And while Venus is not the closest planet to the Sun, it is definitely the hottest. The carbon dioxide in Venus' atmosphere traps heat, resulting in an average surface temperature of 471 °C (880 °F), hot enough to melt lead and zinc.

Astronomers have known about Venus' atmosphere for at least 250 years, well before humans sent probes there. In 1761, Mikhail Lomonosov theorized that Venus must have an atmosphere, due to the apparent blurry edges of the planet as it crossed in front of the Sun. These rare crossings of Venus in front of the Sun are called **transits** and were extremely important in understanding Venus and the distance between the Earth and the Sun prior to the space age. The next Venus transit will occur in 2117.

Because it has an axial tilt of less than 3°, Venus, like Mercury, has virtually no change in seasons. It does have weather, and lightning has been observed in its atmosphere. Venus also rotates from east to west, making it the only planet to rotate completely backward, that is, in the direction opposite of its orbit. (Technically, Uranus also rotates "backward," however its axial tilt is 98° meaning that it essentially rotates on its side.) Not only does Venus rotate backwards, it also rotates very slowly; so slowly that its day (243 Earth days) is longer than its year (225 Earth days).

Venus is usually the closest planet to Earth and is often the third brightest object in the sky after the Sun and Moon. Its average distance from the Sun is 0.7 AU so at its closest, Venus is only 38 million km (24 million mi) away from Earth. That's almost four times closer than Earth is to the Sun. When Venus is on the opposite side of the Sun from us, it is considerably farther away and Mars can temporarily become our closest planetary neighbor.

From Earth, Venus appears white and bright because of its reflective cloud cover (Fig 4). If you were standing on the surface however, the clouds would filter out so much light that it would appear a dingy orange. Radar imaging can see through the clouds, revealing Venus' surface (Fig 5). The planet is home to more than one thousand volcanic features, but very few craters. In stark contrast to Mercury, few impacting objects make it through Venus' thick atmosphere. Even accounting for the atmosphere, Venus shows a remarkable lack of impact craters. This, along with the presence of volcanoes, tells us that Venus is geologically active and that craters are being quickly erased from its surface. Venus' handful of impact craters are spread uniformly over its surface, which means that the surface is of a similar age everywhere. Crater counts suggest the surface is less than 750 million years old all over the planet, and it's possible Venus underwent a planet-wide resurfacing event as little as 300 million years ago.[2]

Figure 5-Radar imaging by the Magellan probe revealed the complex surface terrain below Venus' thick clouds. (NASA/JPL)

Radar imaging has revealed highland regions somewhat reminiscent of Earth's continents, but that are probably formed by very different types of geologic activity. Aphrodite Terra and Ishtar Terra are the two largest highland areas. Aphrodite Terra is about the size of the South American continent, and Ishtar Terra is the size of Australia.

Exploring Venus

Venus poses a serious challenge to spacecraft engineers; the heat, acid rain, and intense pressure makes it a difficult planet for a probe to explore. Strong winds in the upper atmosphere also make the descent to the surface perilous.

Humans have attempted to send about 40 probes to Venus so far. While not all were intended to be landers, only eight probes have successfully sent back data from the surface of the planet. These probes have had an average lifespan on the surface of about half an hour before succumbing to the heat and pressure. There's no way around it: Venus eats probes. The longest lasting probe on Venus was Venera 13, which returned data for 127 minutes. Surviving the brutal conditions on Venus may be possible someday in the future, but for now it would be a suicide mission to send humans to Venus.

Earth

Figure 6-Earth, as seen from Apollo 8 as it orbited the Moon. (NASA/Bill Anders)

Earth is a unique planet, at least in the context of our Solar System. It is a water world, mostly covered in a salty ocean, with pieces of land jutting out in a handful of areas. It is the most massive of the terrestrial planets, and you weigh more on Earth than you would on Mercury, Venus, or Mars. While Earth does not have as much atmosphere as Venus, it has an incredibly active atmosphere where phenomena such as wind, rain, snow, hail, lightning, tornadoes, and hurricanes are common.

By far the biggest difference between Earth and the other planets is the presence of life. Earth is overrun with living organisms, and has been for at least 3.5 billion years, possibly longer.[3] At no point in the last ~3.5 billion years has Earth been completely free of living organisms, although the Permian Extinction nearly restarted the process about 250 million years ago. Life has taken over Earth and is a fundamental aspect of the planet. Life has even changed the Earth's atmosphere, beginning with the microbes that pumped tons of oxygen into the atmosphere as a waste product about 2.5 billion years ago, forever changing the way life would evolve.

Earth's Moon

Another unique aspect of Earth is our Moon. Earth is the only planet in the Solar System with a single moon. Lying just 384,600 km (239,000 mi) from the Earth, our Moon is, by far, the largest satellite compared to its host planet in the entire Solar System. The diameter of the Moon is about 27% that of Earth, slightly narrower than the width of the lower 48 states. While Jupiter and Saturn have moons larger than ours, they are much smaller relative to their host planet. Many astronomers believe that the large size of our Moon has had a stabilizing influence on Earth and its climate over time, minimizing changes in our orbit and axial tilt, and possibly making life more likely to develop.[4]

Where did our gigantic moon come from? Many of the satellites in our Solar System either formed alongside their parent planet directly from the protoplanetary disk (such as Jupiter's **Galilean moons**) or are small bodies captured by the planet's gravitational pull (Mars' two moons, most of Jupiter's and Saturn's moons, Neptune's Triton). However our Moon exhibits some characteristics that make both of these scenarios highly unlikely.

Our Moon is a regular, **prograde orbiting**, **tidally locked** moon. Its bulk composition is similar to Earth's, except the Moon is depleted in metals (such as iron) and volatiles (such as water). The composition of the Moon is very similar to Earth's mantle, but the Moon has a much smaller core in proportion to its overall size.

The best explanation for the formation of our Moon is currently the *giant impact model*. In this model, the early Earth was struck by a Mars-sized object, ejecting material into Earth's orbit that eventually coalesced into the Moon. This model explains the "missing" components of the Moon. Earth's heavier metals had already sunk to the center of the molten early-Earth, forming the core and shielding them from the collision, while materials such as water would have been vaporized in the impact, allowing them to escape into interplanetary space.[5]

The Lunar Surface Today

The Moon has been geologically dead for millions of years; the footprints left by the Apollo astronauts are as fresh today as the day they were formed. Like Mercury, the Moon's lack of an atmosphere or recent geologic activity combine to create a surface riddled with impact craters. The Moon's surface can be broadly divided into two distinct types of topography: **highlands** and **maria** (Fig 7).

The lunar highlands are bright, rugged, mountainous, and heavily cratered, indicating their older age. In contrast, the maria (singular=**mare**, from the Latin for "sea") appear dark, smooth, and lack many large impact craters, indicating that they are younger than the highlands. Most of the maria have a circular shape; they are enormous impact basins that filled in with lava flows more than three billion years ago.

The contrast between the highlands and maria is readily apparent even to the naked eye: the dark, circular maria form the familiar "man in the moon." The maria appear darker because they are filled with a dark-colored volcanic rock called basalt. Basalt is the most common rock on Earth's surface and is abundant in Southern Utah. In contrast, the highlands consist of a lighter colored igneous rock called anorthosite.

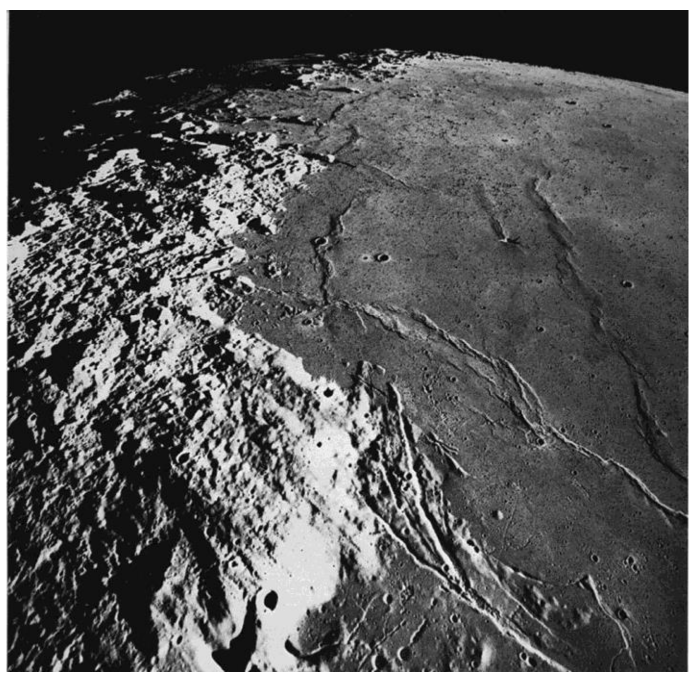


Figure 7-The old and rugged lunar highlands (left) meet the comparatively young and smooth lunar maria (right) at the edge of Mare Serenitatis. (NASA)

Mars

Mars has been an object of human fascination since antiquity. Named for the Roman god of war, its ruddy hue sets it apart from the other naked eye planets (Fig 8). Mars is red for the same reason that much of Southern Utah is red: many of its rocks contain small amounts of iron oxides and hydroxides. In other words, Mars is rusty.

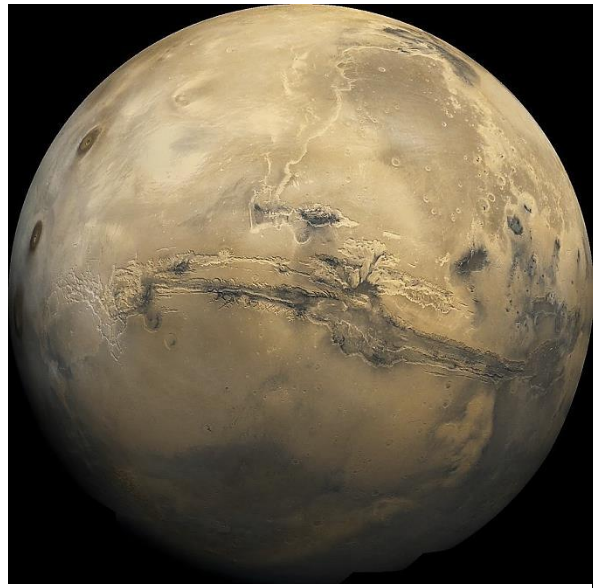


Figure 8-Mars as seen by Viking 1 in 1980. The vast Valles Marineris rift system, nearly as long as the United States is wide, is front and center. (NASA/USGS)

Furthering interest in Mars is the fact that it is arguably the most Earth-like planet in the Solar System. Its day is just 40 minutes longer than ours and its axial tilt nearly identical. While it is quite a bit smaller than Earth (you would weigh about 38% of your Earth weight), the conditions on the surface are not *quite* as inhospitable as those on Venus or Mercury. While Mars is quite cold, with an average surface temperature of -60 °C (-80 °F), temperatures can range from -140 °C to as high as 30 °C on a balmy summer day near the equator (-284 °F to 86 °F) (Fig 9). These temperatures may not sound appealing, but unlike Venus they are survivable for humans and downright pleasant for machinery.

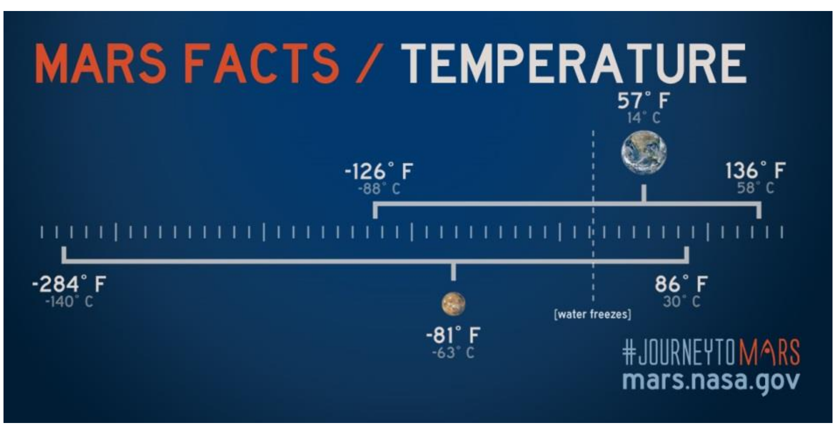


Figure 9-The relative temperatures of Earth and Mars. (NASA)

Geologically, Mars is similar to the Moon and Mercury at first glance. It seems mostly dead today, but yet is home to the largest volcanoes in the Solar System. Olympus Mons, for example, would nearly cover the state of Arizona. Evidence now suggests that some of these volcanoes have been active as recently as 180 million years ago, while studies done in the last decade reveal that there may have been volcanism as recently as a few million years ago, challenging our perception of Mars as a geologically dead world.[6]

Mars has a thin carbon dioxide (CO_2) atmosphere and a pair of polar ice caps that change seasonally and consist of a combination of water ice and dry ice (frozen CO_2).

Water on Mars

Figure 10-An outcrop of conglomerate, a sedimentary rock formed by the action of flowing water, on Mars. (NASA/JPL-Caltech/MSSS)

The idea of Mars as a habitable world has long fascinated astronomers and the general public. Several late 19th and early 20th century astronomers, such as Giovanni Schiaparelli and Percival Lowell, observed a network of dark linear markings on Mars. Lowell famously interpreted these as a network of irrigation canals built by an intelligent civilization of Martians, kicking off a frenzy over the possibility of life on Mars that persists to this day. While the markings turned out to be an optical illusion, determining whether Mars could have once hosted life has remained a central question of Martian research for more than a century.

Orbiters, landers, and rovers have found abundant geologic evidence suggesting that Mars used to be a warmer and wetter world (Fig 10). While liquid water cannot exist on the surface today (due largely to the low atmospheric pressure), prior to three billion years ago Mars likely had a much thicker atmosphere. It was eventually stripped away by the **solar wind** after Mars' interior cooled and lost its ability to generate a protective **magnetic field.** Just how much water once existed on Mars, for how long, and what other compounds were present is still debated.

Moons

Mercury and Venus have no moons, Earth has one, and Mars has two (Fig 11). This may seem like a pattern until the moons of Mars are revealed to be extremely tiny, and probably captured asteroids. The closest moon, Phobos, has a maximum diameter of 27 km (16.7 mi). Deimos is about half that size. Both moons were discovered in 1877 by Asaph Hall. If you were to stand on Mars and watch Phobos, it would appear to rise in the west and set in the east. This is not because Phobos is traveling in **retrograde**

Figure 11-Phobos (left) and Deimos (right). (NASA/JPL-Caltech/University of Arizona)

orbit, but because Phobos travels so quickly around Mars that it outpaces the planet's rotation. A single Martian day is just slightly longer than an Earth day, but Phobos takes less than eight hours to orbit Mars, giving the false appearance of a retrograde orbit.

Exploring Mars

An enormous number of successful probes have been sent to Mars (more than 20) and even more have been unsuccessful. It's no mistake that far more probes have been to Venus and Mars than Mercury. Landing a probe on a planet without an atmosphere is much harder to do – and much more expensive. The only way to land on a rock with no atmosphere is with rockets, but Venus and Mars both have enough of an atmosphere that landers can float down via parachute with comparative ease.

Table 4: Partial List of Martian Probes

Probe	Type	Notes
Mars 1	Flyby	First flyby of Mars but a partial failure; it got within 193,000 km (120,000 mi) of Mars' surface and returned some data before losing communications. Mission Date: November 1, **1962** (launched).
Mariner 4	Flyby	First successful flyby. Returned 21 pictures and 634 kB of data. Mission Date: November 28, **1964** (launched).
Mariner 9	Orbiter	First successful Mars orbiter. Mission Date: November 14, **1971** (entered orbit).
Mars 2	Lander	First object to reach the surface of Mars. Unfortunately it was a crash landing and no data was returned. Mission Date: November 27, **1971** (landed).
Mars 3	Lander	First "soft" landing on Mars, but stopped working 20 seconds later. Mission Date: December 2, **1971** (landed).
Viking 1	Lander	First successful lander on Mars. Viking carried out its mission until late 1982. Mission Date: July 20, **1976** (landed).
Pathfinder /Sojourner	Orbiter/ Rover	The first successful Mars rover, Sojourner sent back over 500 pictures of the Martian surface. Last contact was in 1997. Mission Date: December 4, **1996** (launched).
Mars Climate Orbiter	Orbiter	Most expensive Martian probe failure to date. A discrepancy in units (using pound seconds instead of Newton-seconds) caused the $327.6 million probe to be destroyed after returning just a single photograph. Mission Date: December 11, **1998** (launched).
Mars Exploration Rovers	Rovers	The Opportunity rover has spent over 4600 days on Mars alive and well, and is the longest lasting rover ever. Mission Date: January 25, **2004** (landed)
Curiosity	Rover	Largest, most advanced rover sent to Mars. Many instruments to assess Martian climate and geology, and whether past conditions were ever favorable for life. Mission Date: August 6, **2012** (landed)

The proximity of Mars and its relatively benign surface conditions have led to lots of speculation about sending humans to Mars. The biggest problem with sending humans to Mars and staying for an extended period of time is not the lack of air, water, or warmth, but rather the lack of gravity. Gravity affects us in ways that are so obvious we don't even think about them. For example, the height of mountains is not solely dependent upon geology, but also on gravity.

The tallest mountain in the Solar System is Rheasilvia, a peak within a crater on the asteroid Vesta, at 14 miles high. The volcano Olympus Mons on Mars is a close second, coming in at 13.2 miles. On Earth, the tallest mountain is technically Mauna Kea (6.3 miles) but it's mostly under water. With less gravity to pull them down, smaller bodies like Mars and asteroids can support mountains far taller than those found on Earth. Because Earth has more mass, and thus more gravity, it is unlikely Earth will ever be able to sustain mountains as tall as Rheasilvia or Olympus Mons.

Table 5: Highpoints of the Solar System

Mountain	Location	Height in Miles
Rheasilvia	Vesta (asteroid)	14
Olympus Mons	Mars	13.2
Iapetus Ridge	Iapetus (Saturn moon)	12
Boosaule Montes	Io (Jupiter moon)	11.3
Ascraeus Mons	Mars	9.3
Mauna Kea	Earth	6.3
Mount Everest	Earth	5.5

The height of mountains isn't the only thing gravity has a firm dominion over. Without gravity, our bodies do not have to work as hard to pump blood or lift weight, and astronauts in zero gravity environments rapidly develop biological problems. We evolved to work against our gravity, and without it, we deteriorate. Humans in space have suffered muscle atrophy, bone deterioration, swelling of the face, heart enlargement, and ocular degeneration due to the microgravity.

And yet, we don't often think about this. Think about all the science fiction you've watched or read where the human explorers had to wear specialized suits to combat the environment (lack of oxygen, toxic atmosphere, increased radiation, etc.) Now think of the last time you saw fictional characters in space have to deal with a decrease in gravity.

This problem is not limited to Mars, but it's an important thing to consider before sending people there. John B. Charles, chief of the international science office of NASA's human research program, has said that NASA could already send astronauts to Mars and bring them back alive. He also stressed that it was crucial that the astronauts arrived productive and in good health, given that any such mission would be incredibly expensive. "My goal," he said, "is to see a program that doesn't deliver an astronaut limping to Mars."[7]

We cannot *currently* combat some health risks due to space travel, such as increased risk of getting cancer or Alzheimer's due to radiation, but we may *never* be able to combat health risks related to lower gravity. Growing food, reusing water, and all the other things Mark Watney had to do in *The Martian* are really the least of our worries. These are obstacles humans can overcome, but lowered gravity is a virtually insurmountable obstacle, because how does one increase the gravity of a planet?

The Main Asteroid Belt

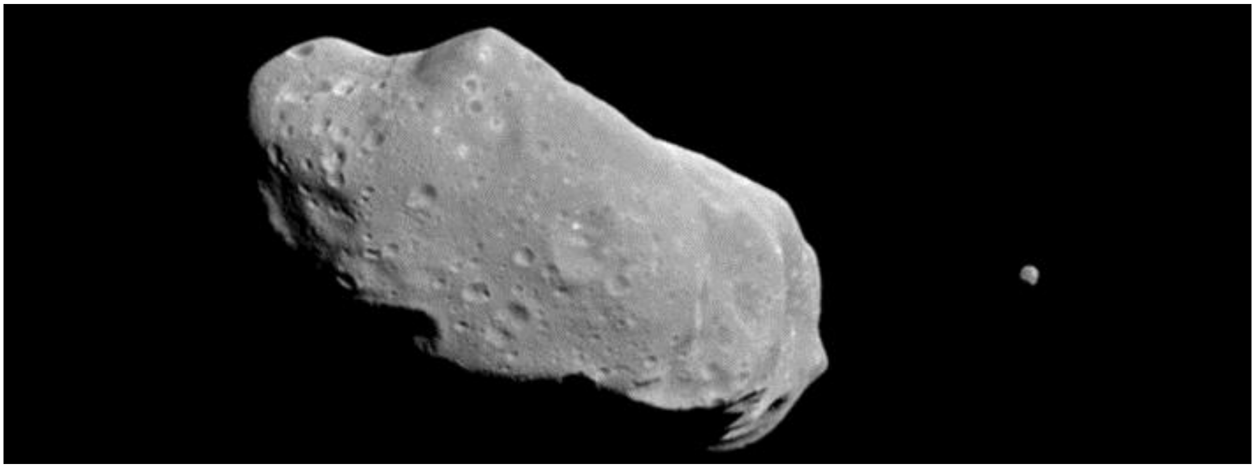


Figure 12-The main belt asteroid 243 Ida (about 59 km (37 mi) long), along with its moon Dactyl, as seen by the Galileo probe in 1994 en route to Jupiter. (NASA/JPL)

Asteroids are small Solar System bodies, most of which inhabit a zone between the orbits of Mars and Jupiter known as the main **asteroid belt** (Fig 12). The first asteroid, Ceres, was discovered on New Year's Day in 1801 by Italian astronomer Giuseppe Piazzi. As of March 2019, nearly 790,000 asteroids had been discovered and numbered.[8] Astronomers estimate that the asteroid belt contains well over one million asteroids greater than 1 km (0.6 mi) in diameter.[9] Despite this large number, the asteroid belt encompasses a vast area of the Solar System, from 2.0 to 3.3 AU from the Sun, and thus is mostly empty space. You could fly a hypothetical spaceship through the main asteroid belt and never even see a single asteroid, let alone hit one.

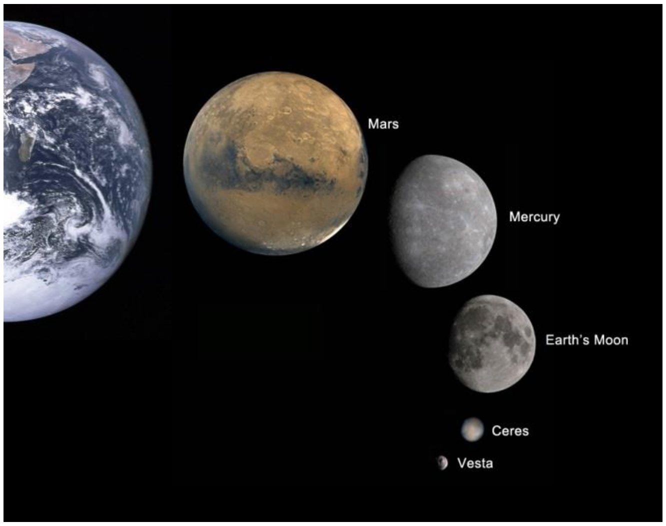


Figure 13-The size of the largest two asteroids, Ceres & Vesta (bottom two objects) compared to Earth, Mars, Mercury, and the Moon. (NASA/JPL-Caltech/UCLA)

When the first asteroids were discovered, many astronomers assumed they were new planets. However, even with large telescopes, they wouldn't resolve into a disk like other planets, but rather remained points of light, just like the stars. They had orbits like planets, so they were eventually named "asteroids" which means "star-like." We now know that asteroids are small rocky bodies of varying composition, left over from the protoplanetary disk that formed our Solar System. The largest, Ceres, is only a fraction the size of our Moon (Fig 13). Many are the fragmented remains of bodies that never became large enough to be planets.

Asteroids differ from **comets** primarily on the basis of composition. Asteroids are typically made of rock and metal, whereas comets have lots of dust and ice. The largest asteroid, Ceres, is large enough to be spherical and is also classified as a **dwarf planet.**

Near-Earth Asteroids

Worth a special mention are the **near-Earth asteroids (NEAs)**, classified by NASA as any asteroid that comes within 1.3 AU of the Sun. Many of these bodies cross Earth's orbit, while others do not (Table 6). More than 19,000 NEAs have been discovered as of March 2019.[10]

Near-Earth asteroids are a concern because Earth has collided with some of them in the past, and will certainly again in the future. A collision with a NEA just 1 km (0.6 mi) in diameter would result in global devastation. Even the impact of an 20 meter (66 ft) wide NEA like the one that exploded over Chelyabinsk, Russia in 2013 could wipe a large city off the map. NASA has a congressional mandate to find and catalog all NEAs greater than 1 km in diameter, and estimates place progress at ~90%.

Table 6: A Guide to the Nomenclature of Asteroids

Term	Description	Examples
Asteroid	Any small, inner Solar System body orbiting the Sun that does not display characteristics of a planet or comet.	
NEA	A near-Earth asteroid (NEA) is any asteroid whose orbit brings it close to Earth (within 1.3 AU of the Sun.) NEAs are divided into four groups (see below).	2062 Aten, 1862 Apollo, 1221 Amor
Atira	NEAs that orbit the Sun entirely inside of Earth's orbit.	163693 Atira.
Aten	NEAs that cross Earth's orbit with a semi-major axis of less than 1 AU.	99942 Apophis
Apollo	NEAs that cross Earth's orbit with a semi-major axis of more than 1 AU.	3200 Phaethon
Amor	NEAs that approach Earth's orbit but remain outside it. Most cross Mars' orbit, but not Earth's.	433 Eros, 1036 Ganymed
Trojan	Trojans are asteroids that share the orbit of a planet at stable positions called "lagrangian points" 60° ahead or behind the planet. Earth has one Trojan, Mars has several, and Jupiter has many.	2010 TK_7

Jupiter

After crossing the asteroid belt, the characteristics of the planets change dramatically. Jupiter is, by far, the largest planet in our Solar System and the first of the **gas giant** planets. 318 times more massive than Earth, and 5,700 times more massive than the smallest planet Mercury, Jupiter is more than twice as massive as all the other planets combined.

About 90% of Jupiter's volume is hydrogen and helium in varying states. Modeling suggests that Jupiter has a core that is less than 10 Earth masses, however some models don't give it a core at all and still manage to explain its outward appearance and behavior. Assuming that Jupiter does have a core of ice and rock, we know that surrounding it is an envelope of liquid hydrogen (and a little helium) condensed under the intense pressure and heat.

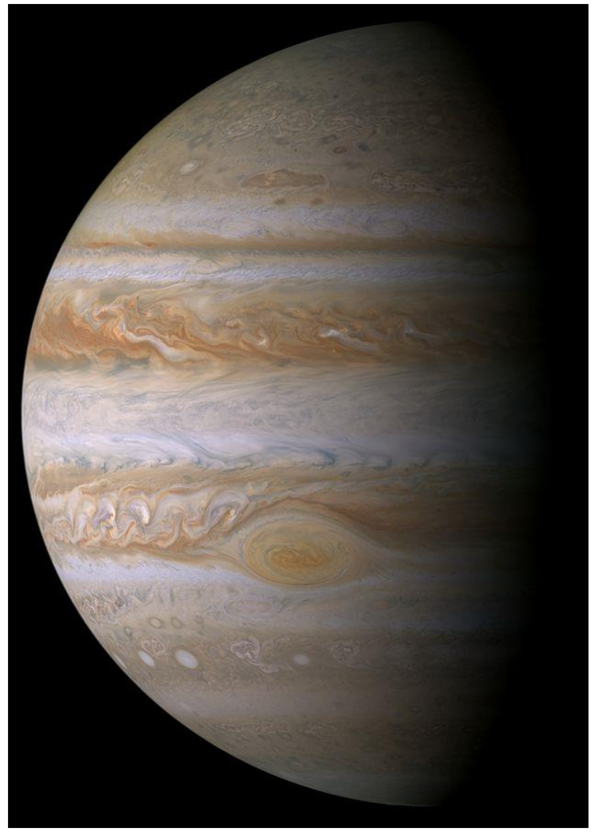


Figure 14-Jupiter, as seen by NASAs Cassini Probe. (NASA/JPL/Space Science Institute)

Table 7: Jovian Discoveries	
365 BCE	Gan De notes a star following the planet Jupiter (possibly the moon Ganymede).
1610	Galileo Galilei turns his telescope toward Jupiter and finds it has four moons.
1676	Ole Roemer uses irregularities in the eclipses of Jupiter's moons to deduce that light must have a finite speed.
1831	Samuel Schwabe records Jupiter's Great Red Spot in detail.
1979	Voyager 1 and 2 pass the planet in 1979 and find that Io is an active volcanic world, Callisto is icy, and Europa is covered in scars.
1995	The Galileo probe begins orbiting Jupiter, providing even more information about the planet and its moons.
2016	The Juno probe enters the Jovian system to learn more about Jupiter's interior and formation.

We are used to hydrogen and helium existing as gasses here on Earth, but deep within Jupiter, the pressure becomes extreme. If you could stand on the surface of Jupiter's core, you would experience 40 million times the pressure you experience at sea level on Earth. At these pressures, hydrogen is no longer a gas. It becomes **metallic hydrogen**, a liquid capable of conducting electricity that generates Jupiter's intense magnetic field. Saturn too has metallic hydrogen, but you have to go down much further to get to it.

The most distinctive features of Jupiter are the spectacular red and white clouds bands in its upper atmosphere (Fig 14).

White clouds are made of water and ammonia, while darker clouds are due to the presence of ammonium hydrosulfide. In fact, the entire planet is covered in these ruddy clouds, but white clouds form above them in areas where rising air promotes the cooling and condensation of ammonia. These white bands of ammonia clouds are known as zones, while the darker bands represent descending air are known as belts. Jupiter's atmosphere is also famous for large, powerful, long-lived storms such as the Great Red Spot, itself more than twice the diameter of Earth.

Could Jupiter have become a Star?

Technically, any planet could have become a star…if only it had managed to accrete more mass during Solar System formation. Jupiter is big, but it is nowhere near large enough to be a star. We would need 80 more Jupiters combined to make even the smallest object capable of **nuclear fusion** (the definition of a star). Even then, depending on how voluminous (or "fluffy") the object was, it might just be a brown dwarf, a "failed star."

Jupiter's Moons

Jupiter the planet is interesting, but Jupiter the system is perhaps even more astonishing. Jupiter has the most known moons, 79, of any planet in our Solar System, not surprising given that it has the most extreme gravitational pull. The vast majority of Jupiter's moons are small and probably captured asteroids, but the four **Galilean moons**, Io, Europa, Ganymede, and Callisto, are unique worlds in their own right and among the most interesting objects in the Solar System.

The Galilean moons, so-named because Galileo recorded and observed them in the early 1600s with one of the first telescopes, can be easily seen in binoculars or a small telescope. The dimmest, Callisto, has an **apparent magnitude** of 5.65 while the brightest, Ganymede, is magnitude 4.6. Humans with good eyesight can see objects down to 6th magnitude, so how is it that these moons are invisible to the naked eye?

The problem is not the moons, but Jupiter itself. Jupiter and the Galilean moons appear very close together in the sky and, as bright as Ganymede is, Jupiter is 760 times brighter. Without the aid of a telescope, the moons are just too close to Jupiter for our eyes to resolve them in Jupiter's bright glare.

Table 8: Apparent magnitude of select Solar System moons

The Moon (Earth)	-12.74
Ganymede (Jupiter)	4.6
Io (Jupiter)	5.0
Europa (Jupiter)	5.3
Callisto (Jupiter)	5.7
Titan (Saturn)	8.4
Rhea (Saturn)	9.6
Tethys (Saturn)	10.2
Dione (Saturn)	10.4
Iapetus (Saturn)	11
Phobos (Mars)	11.5
Deimos (Mars)	12.5
Titania (Uranus)	13.5
Triton (Neptune)	13.5
Oberon (Uranus)	13.7
Amalthea (Jupiter)	14.1
Charon (Pluto)	17.3

In 365 BCE, the Chinese astronomer Gan De observed and recorded Jupiter's behavior and wrote the book *Suixing Jing* (Treatise on Jupiter). He noted that he could see a star following the planet Jupiter, and called their relationship "an alliance."[11] Could Gan De have seen a moon of Jupiter 2,000 years before the telescope was invented? Yes, he could have. If you use an object, such as a dowel or even a tree branch to block out Jupiter's light, you can see Ganymede with the naked eye, albeit with some difficulty. Callisto is also visible using this method, because even though it is fainter than Ganymede, it gets quite a bit farther away from Jupiter. Good eyesight, no light pollution, and looking when the moons are at their farthest point from Jupiter will increases your odds of seeing them with the naked eye. No other moons in the Solar System (besides our own) are this highly visible.

Galilean Moons

Jupiter and its Galilean moons are essentially a Solar System in miniature (Fig 15). All four have a **prograde orbit** around Jupiter and orbit in Jupiter's equatorial plane. These factors suggest that the moons formed directly from the protoplanetary of the early Solar System, as opposed to being captured later by the planet like the rest of Jupiter's moons. The Galilean moons orbit Jupiter quickly – the closest, Io, orbits in less than two days and the furthest, Callisto, in 17 – and their motion around Jupiter can been seen in a matter of hours through any backyard telescope.

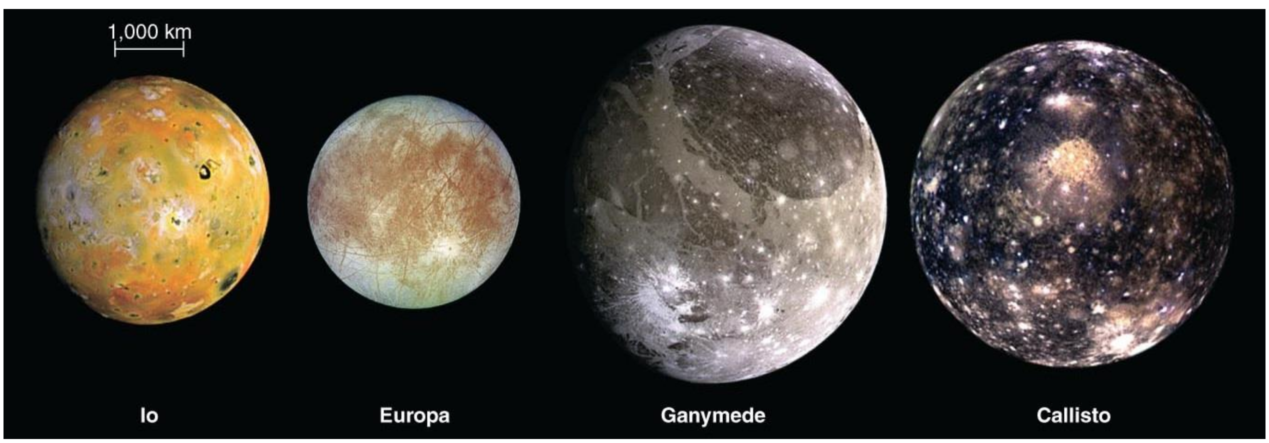


Figure 15-Jupiter's Galilean moons shown with correct relative sizes to each other and, from left to right, in the proper order from Jupiter. (NASA/JPL/DLR)

Io is the closest Galilean moon to Jupiter and is the most volcanically active body in the Solar System. Volcanoes cover the moon, and volcanic plumes can be seen spewing material 300 km (190 mi) above Io's surface. Sulfur compounds deposited onto the surface during these eruptions make Io a colorful moon. Io's volcanic activity is due to **tidal heating** from being caught in a gravitational tug-of-war between Jupiter and the outer Galilean moons. Io is constantly flexed or "kneaded," creating friction which warms the interior and causes it to be molten.

Europa is the smallest of the Galilean moons and, in stark contrast to Io, is covered not in volcanoes but a relatively fresh layer of water ice. Europa also experiences tidal heating, although not to the same degree as Io, and this heat likely melts underlying ice forming a subsurface liquid water ocean. Like our own ocean, this water is likely salty but lies beneath several kilometers of ice, making it impossible to observe directly from orbit. Current estimates suggest that Europa's ocean may contain two to three times as much water as all of Earth's oceans combined. In 2013 it was discovered that Europa is venting plumes of water, much like Saturn's moon Enceladus.

Could life swim in Europa's oceans? The scenario is realistic enough that NASA deliberately crashed the Galileo probe into Jupiter at the end of its life in 2003, rather than risking a possible collision with Europa that could contaminate the moon with Earth bacteria stowed away on the spacecraft. A probe capable of exploring Europa's ocean is a top NASA priority for future interplanetary missions.

Ganymede is the largest moon in our Solar System, larger than the planet Mercury, far larger than Pluto, and three-quarters the size of Mars. While Ganymede is larger than Mercury, it is less dense and has less mass. Like Europa, Ganymede has a surface made mostly of water ice, although some patches appear young while others areas have more craters and appear older. Ganymede may also have a subsurface saltwater ocean, although if so, it is likely much deeper beneath the surface and thus harder for us to get to. Ganymede has a metallic iron core, like Earth, which astronomers know because it generates its own magnetic field. It also has a *very* thin oxygen atmosphere and terrain that indicates a complex and active geologic history.

The outermost Galilean moon, Callisto, is the third largest moon in the Solar System (after Ganymede and Saturn's Titan) and is similar in size to Mercury. Unlike the other three Galilean moons, Callisto is heavily cratered, leading astronomers to conclude that it hasn't been geologically active for a very long time. It is the largest body in the Solar System that shows no signs of geologic activity, and appears to have been dead for the last 4 billion years – almost as old as the Solar System itself. Because of Callisto's extremely old surface, it could give a window into the past, particularly what was going on in the early Solar System.

Other Moons

Jupiter's other 75 moons are all very small. The largest, Amalthea, has a maximum diameter of just 250 km (155 mi). These moons are likely all either captured asteroids, or the shattered remains of small moons that have collided with asteroids and been broken into even smaller pieces. Small Jovian moons continue to be discovered. The most recent batch of 10 were announced in July 2018.

Saturn

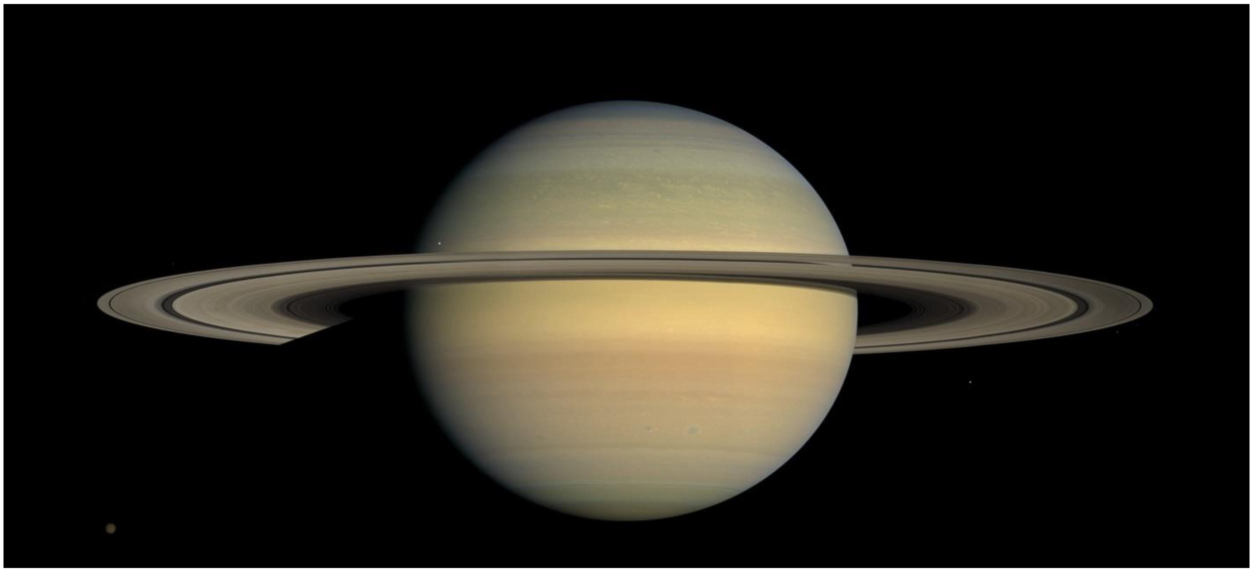


Figure 16-A true color view of Saturn, its ring system, and its largest moon, Titan (lower left) from the Cassini probe. (NASA/JPL/Space Science Institute)

Saturn is a strikingly beautiful sight even in small backyard telescopes. It is the most distant planet in the Solar System visible to the naked eye, lying almost twice as far from the Sun as Jupiter. Like Jupiter, it is a gas giant composed primarily of hydrogen and helium, and has a metallic hydrogen envelope on the inside. Saturn, the second largest planet in the Solar System, is nearly as large as Jupiter in radius (9.4 Earths as opposed to Jupiter's 11) but is much less massive (95 Earth masses instead of 318). Because of its large volume and low mass, Saturn is an extremely "fluffy" planet and would float in water. Saturn also has cloud layers similar to Jupiter, but they lie deeper within its atmosphere, making its outward appearance more muted.

Saturn's Rings

Saturn is known for its complex ring system (Fig 16), first observed by Galileo through his telescope in 1610. Galileo did not fully comprehend what he was seeing. He described Saturn as having "ears," and it was not until 1655 that Christiaan Huygens proposed that Saturn was surrounding by a ring.

While the other three giant planets also have ring systems, Saturn's are the most extensive and the only ones large and reflective enough to be easily seen from Earth. The rings are composed of small particles of water ice (mixed with some dust and rock) all orbiting Saturn like innumerable tiny moons. Most of the ring particles are confined to a very thin plane: the rings are more than 250,000 km (155,000 mi) in diameter, but on average just 10 meters (33 ft) thick. In other words, the relation between the thickness of the rings and their diameter would be like stretching out one piece of printer paper so that it covered an entire football field.

Saturn's Moons

Saturn has the second highest number of known moons in the Solar System at 62. Like Jupiter, many are remarkable worlds in their own right, stranger than anything sci-fi authors came up with before we discovered them.

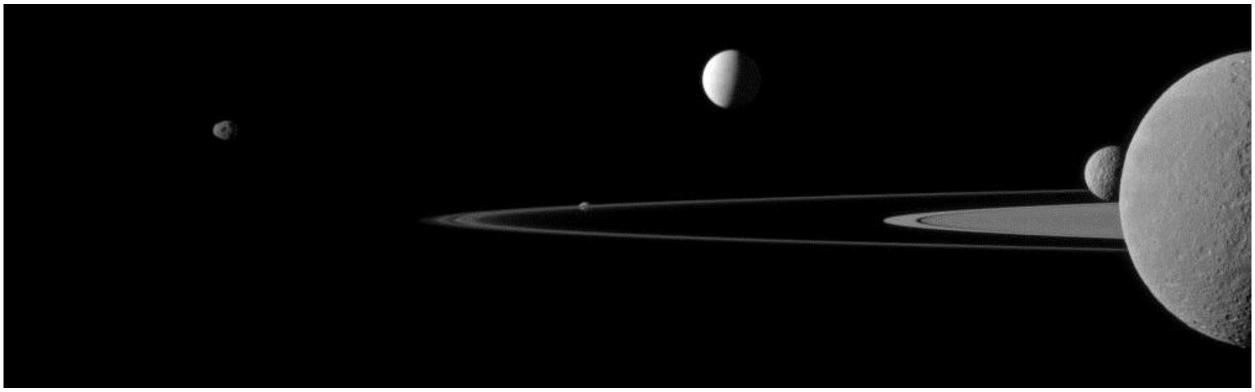


Figure 17-A quintet of Saturn's moons with rings in the background. From left to right: Janus, Pandora, Enceladus, Mimas, and Rhea. (NASA/JPL/Space Science Institute)

Titan

Titan is the second-largest moon in the Solar System (after Ganymede), and has a mean radius of 2,575 km (1,600 mi), making it larger than the planet Mercury. The majority of Saturn's moons are named after titans or giants, except Titan which is named after the generic term itself: the titans of Greek mythology.

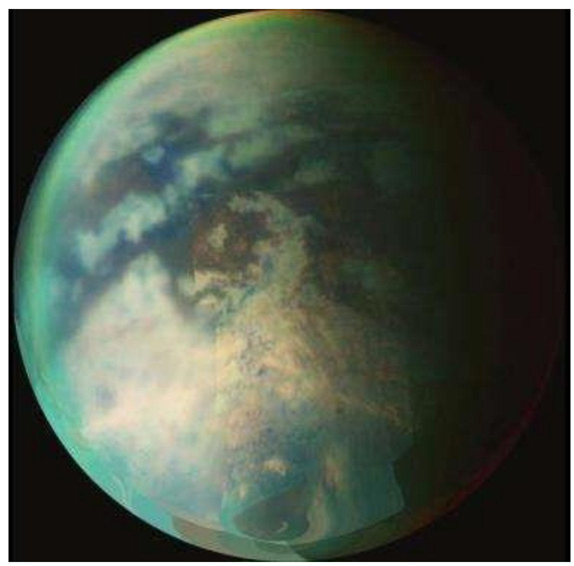


Figure 18-A view of Titan's surface captured by instruments on the Cassini probe that can penetrate Titan's thick, hazy atmosphere. (NASA/JPL/University of Arizona)

Titan is one of the strangest worlds in our Solar System. It is the only moon with a thick atmosphere, which extends more than 560 km (350 mi) above its surface due to its low gravity. The atmosphere is mostly nitrogen (like Earth's) but also has some argon, methane, and ethane mixed in as well. If you weighed 100 lbs. on Earth, you would only weigh 14 lbs. on Titan. This lack of gravity, combined with an atmosphere that is thicker than Earth's, means that many of the old-fashioned "flying machines" would actually work on the surface of this moon.

The average surface temperatures and pressures on Titan permit methane to exist as a solid, liquid, and a gas, just like water on Earth. The polar regions of Titan are home to lakes and rivers of liquid methane and ethane, and Titan likely has a methane/ethane cycle, much like Earth has a water cycle.

Titan is the only outer Solar System body to have a probe land on its surface. A joint mission between NASA and ESA (European Space Agency), the six-ton Cassini spacecraft (NASA) arrived at Saturn in 2004 carrying the Huygens lander (ESA). In January 2005, Huygens reached the surface of Titan (Fig 19). It found a dark world covered in thick clouds, great lakes of liquid natural gas, and dunes of hydrocarbon "sand."

Figure 19-The surface of Titan, from the Huygens lander. (ESA/NASA/JPL/University of Arizona)

Iapetus

Discovered by Giovanni Cassini in 1671, Iapetus, the third largest of Saturn's moons, is bright white on one side and black as coal on the other (Fig 20). It also has an enormous ridge along its equator, spanning an entire hemisphere of the moon (Fig 20). This mountain ridge is up to 20 km (12.4 mi) high, much higher than any mountains on Earth. The origin of the ridge is unclear.

Enceladus

Enceladus is one of the most reflective objects in our Solar System. Like a bright disco ball, Enceladus reflects nearly 100% of the sunlight that strikes it. Cryovolcanoes spew ice and water vapor from a subsurface ocean, coating the surface in a fresh layer of bright ice and contributing material to Saturn's E Ring (Fig 21).

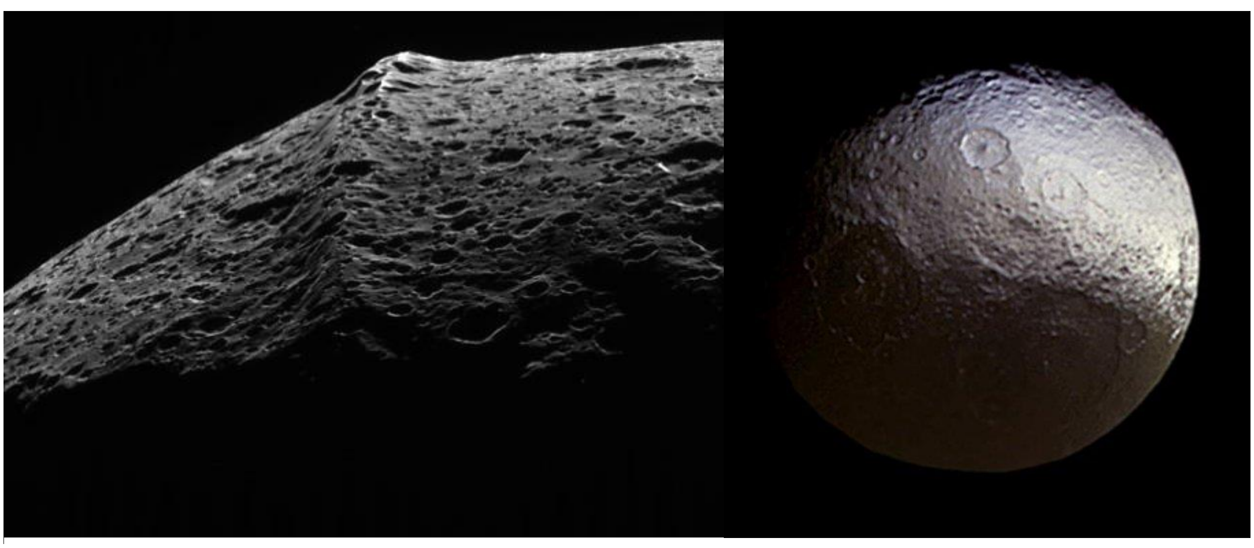


Figure 20-Iapetus' equatorial ridge as imaged by Cassini (left). Bright and dark hemispheres of Iapetus (right). (NASA/JPL/Space Science Institute)

Other Moons

Saturn has so many interesting moons that it would take an entire book to cover them all. A few other notable ones include:

- Hyperion, which is so heavily cratered it almost looks like a sponge. It is also the only regular moon in the Solar System that is not tidally locked to its planet.
- Telesto, Calypso, Helene, and Polydeuces, which are all Trojan moons. Trojan moons share the orbit of a larger moon (in this case, Tethys and Dione) but 60° ahead or behind.
- Janus and Epimetheus, which essentially share the same orbit.
- Mimas, the smallest object in the Solar System to be round, and which looks suspiciously like the Death Star due to a giant impact crater that spans nearly 1/3 of the moon's diameter (Fig 22).

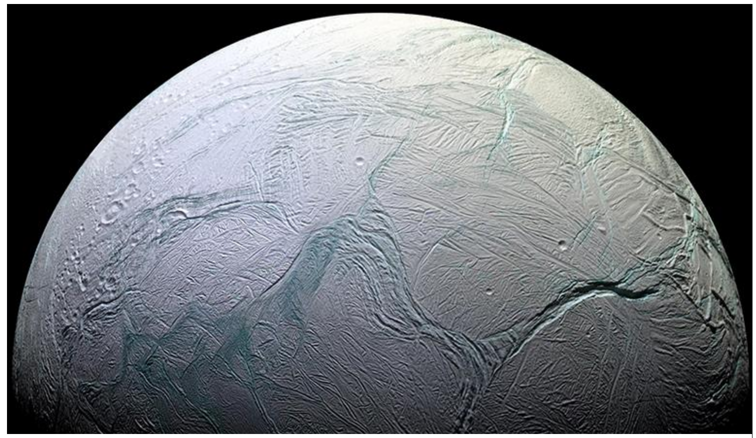


Figure 21-The craterless and complex surface of Enceladus indicates a geologically active world. (NASA/JPL/Space Science Institute)

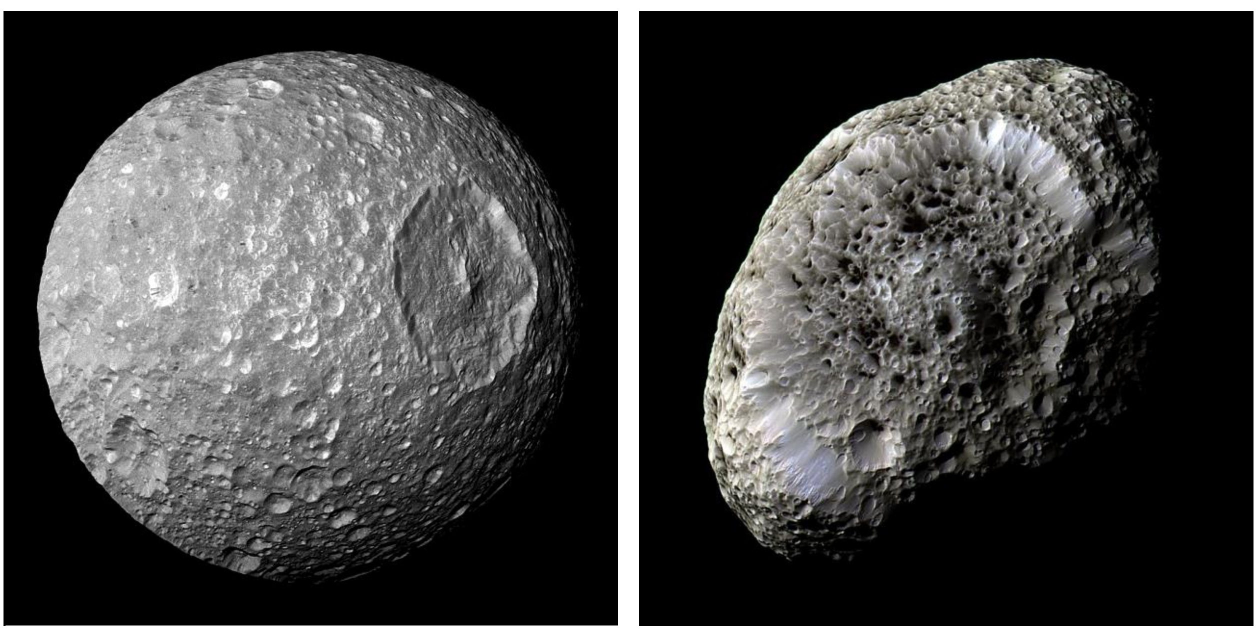


Figure 22-Saturn's "Death Star" look-alike, Mimas (left), and a false-color view of Hyperion (right). (NASA/JPL/Space Science Institute)

Uranus

Figure 23-The remarkably featureless blue disc of Uranus, as imaged by the Voyager 2 probe in 1986. (NASA/JPL-Caltech)

Uranus was discovered in 1781 by British astronomer William Herschel (who was also an accomplished composer), a discovery that ranks among the most surprising in the history of astronomy. Up until this time in the Western world, no one really expected to find anything new in the Solar System. All the planets known at the time were easily visible to the naked eye and no one had seriously explored the idea that there might be other planets out there that required a telescope to see. Herschel's discovery ushered in an era of planet hunting that continues to this day, both in our Solar System and in the search for others.

Herschel originally thought he had discovered a new comet, but by 1783 astronomers were convinced that Uranus was indeed a new planet. Herschel subsequently tried to name it after King George III, but no one went for that – certainly not outside England. The Seven Years War had ended less than two decades earlier, the Americans had declared their independence just five years ago, and France and the U.S. had absolutely no intention of naming the new planet after the current King of England. Johann Elert Bode named it Uranus, after the Greek god Ouranos. Uranus is the first planet to be named after a Greek god instead of a Roman one, but nevertheless still fits into the equivalent pantheon and is the primordial god of the sky. For all that kids make fun of it, "Uranus" is a much better name than "Georgium Sidus" (George's Star).

Along with Neptune, Uranus is the least explored planet in the Solar System, although thanks to Voyager 2, we do know a little bit about it. Uranus is the least massive of the giant planets, but slightly larger in diameter than Neptune. It is about four times wider than Earth, and 14 times as massive. Its equator is almost at a right angle to its orbit; that is, Uranus rotates on its side, rolling along its orbit like a big blue cue ball. Its unique color comes from methane in its upper atmosphere which absorbs red light and reflects blue light back toward its surface (Fig 23). Uranus contains a smaller proportion of hydrogen and helium compared to Jupiter and Saturn, and is instead made primarily of icy, swirling fluids of water, methane, and ammonia. Since the composition of Uranus and Neptune is distinct from the gas giants Jupiter and Saturn, the two outermost planets are better termed **ice giants.**

Uranus' moons

Uranus has 27 known moons, but the largest, Titania, is just 1,600 km (1,000 mi) in diameter, less than half the size of our own Moon. Uranus' moons are named mostly after Shakespearian characters. The first two discovered, Titania and Oberon, were found by William Herschel, and the names "Titania" and "Oberon" were suggested by Herschel's son John in 1852. It is ironic then that the discoverer of Uranus, who was not allowed to engage in nationalism and name his planet after the King of England, should get 25 moons named after England's most famous author.

The five largest of Uranus' moons are made primarily of ice, but have graphite or carbonaceous material covering their surfaces, giving them a dull gray appearance. Umbriel probably has the most rock of these medium-sized moons. Umbriel and Oberon may have a dark surface covered with the same compounds that Iapetus' dark side is coated with: tholins, a reddish-brown class of organic-rich compounds common in the outer Solar System.

While Saturn's moon Titan may be the weirdest moon in the Solar System, Miranda gives it a run for its money. It is covered in surface features that appear both very old and very young. Its piecemeal surface is reminiscent of Frankenstein's Monster (Fig 24). It is much smaller than Earth's Moon (less than 1/7th the size) and yet it seems to have had at least some geologic activity in its past, most likely due to tidal flexing.

Miranda has the tallest known cliff in the Solar System. Verona Rupes is about 20 km (12.5 mi) high, or roughly 10 times as deep as Earth's Grand Canyon. Amazingly, you might actually survive a fall (or jump) from it. Because of Miranda's low gravity, it would take about 12 minutes for anything to reach the bottom (including a person). You would be traveling at about 200 km/hr (125 mi/hr) per hour by the time you reached the bottom, so excessive padding would be necessary. A jump might be survivable, but the Master Astronomer Program recommends against this – maybe just watch a rock fall for 12 minutes instead.

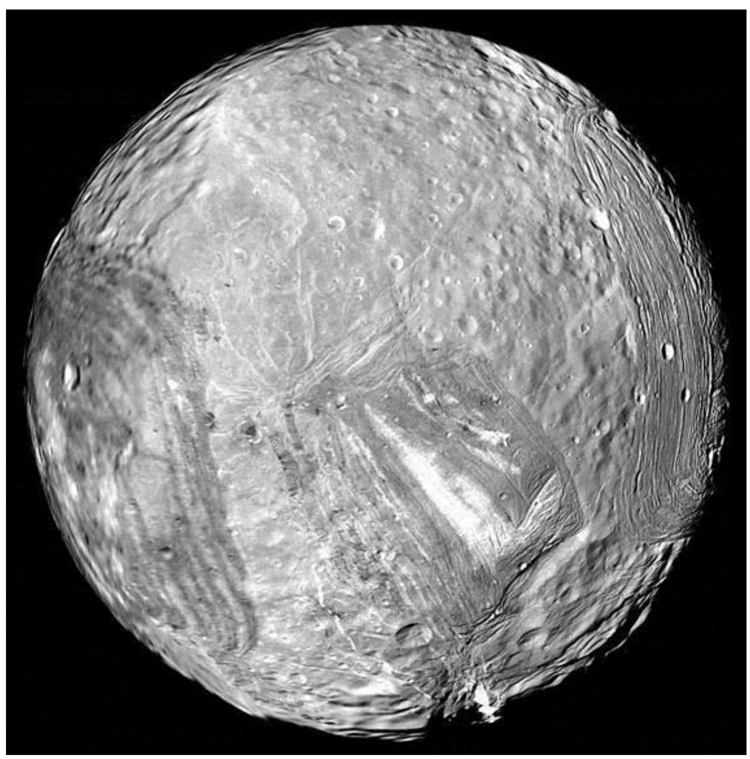


Figure 24-Uranus' moon Miranda. (NASA/JPL-Caltech)

Neptune

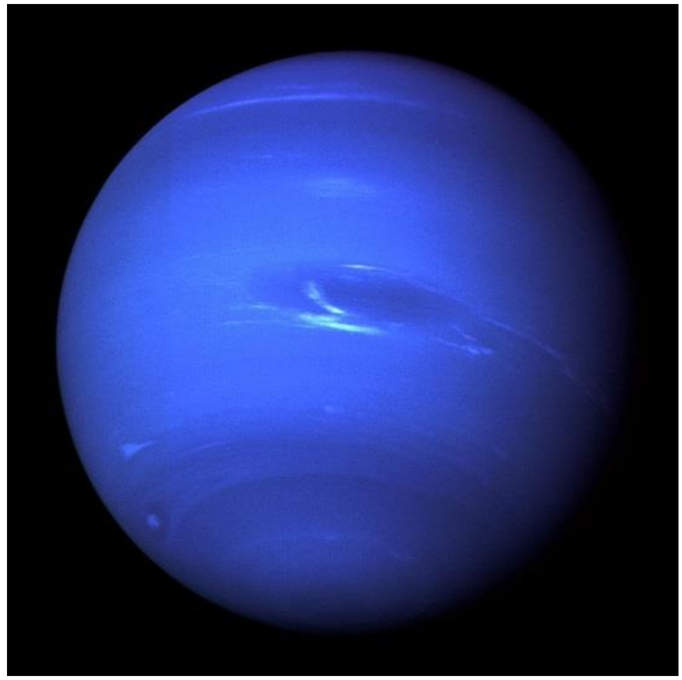


Figure 25-Neptune, as seen by the Voyager 2 probe in August 1989. (NASA/JPL)

Neptune, now officially the outermost planet in the Solar System after the reclassification of Pluto, is slightly more massive than Uranus (17 Earth masses) but slightly smaller in diameter.

Neptune was not “found” in the traditional sense. No astronomer stumbled upon it in a telescope by accident. Instead a mathematician predicted its existence using only observations of Uranus. The French mathematician Urbain Le Verrier realized that the orbit of Uranus did not quite match predictions, and postulated that there must be some massive body in the outer Solar System perturbing Uranus’ orbit. Le Verrier predicted Neptune’s location from these calculations and sent his findings to a German astronomer, Johann Galle. Galle found Neptune on his first night of searching, Sept 23, 1846, extremely close to LeVerrier’s predicted position. Galle wanted to name the planet after Le Verrier, but Le Verrier himself suggested Neptune. And besides, one does not simply get to name a planet after a Frenchman when one did not allow the previously discovered planet to be named after an Englishman.

The discovery of Neptune quickly fueled the flames of international rivalry. A twenty-something British mathematician named John Couch Adams had been working on similar calculations since 1841 and had forwarded his predictions to the Astronomer Royal, George Airy. However Airy did not take Adams’ calculations as seriously as he could have and neglected to have anyone search for the planet.[12] Only after the discovery of Neptune did Airy begin to publicize Adams’ work, which the French perceived as an attempt to claim credit for their discovery. Today, Le Verrier and Adams are often given joint credit for the discovery, along with Galle who was the first to actually observe it in a telescope.

Like Uranus, Neptune hasn’t been well explored and remains poorly understood. Voyager 2 passed about 4,400 km (2,730 mi) from its atmosphere in 1989, taking pictures of not only the planet (Fig 25), but some of its moons as well. Neptune is an ice giant with a similar composition and structure to Uranus. It boasts the fastest winds in the Solar System, with speeds of up to 2,100 km/hr (1,300 mi/hr) having been recorded.

Neptune's Moons & Rings

Neptune currently has 14 known moons, most of which were discovered after 1980, like many of the smaller outer Solar System moons (Fig 26). Triton is the only large moon and was found only 17 days after Neptune itself by astronomer William Lassell. Larger than the dwarf planet Pluto, but smaller than our own Moon, Triton is unique in that it is the only reasonably sized moon (about 2,700 km (1,680 mi) in diameter) that is traveling in a **retrograde orbit** around its host planet (Fig 27).

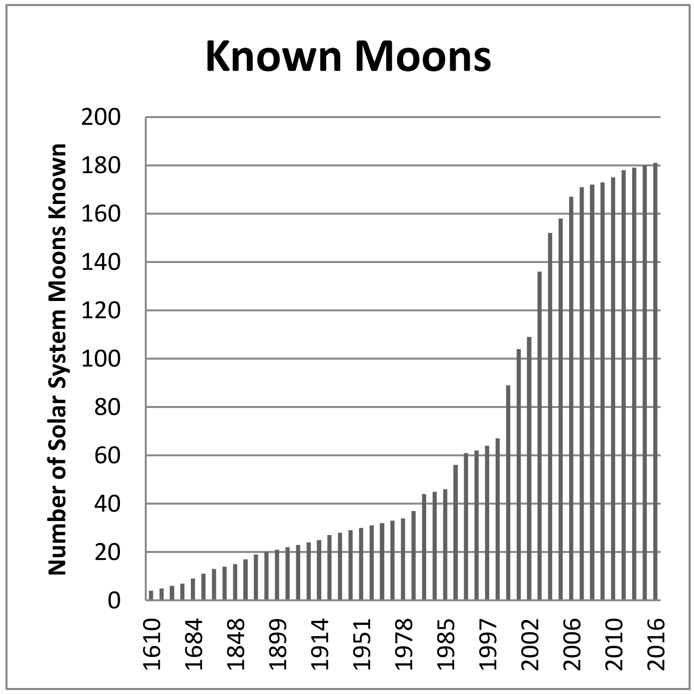


Figure 26-Chart showing the rapid increase in the number of known solar system moons in the 1980's and 90's. (NPS/Leesa Ricci)

Most large moons, including our Moon, Jupiter's eight largest moons, Saturn's eight largest moons, and Uranus' five largest moons, all travel in **prograde orbits** on their planets' equatorial planes. This suggests that they formed alongside their parent planet in the early protoplanetary disk. However, a moon traveling in retrograde orbit, that is, the opposite direction that the planet is rotating, is usually a dead giveaway that the moon did not form with the planet. Triton may actually be a captured **dwarf planet.** If it is, then it's the only moon of its kind.

Neptune not only has rings, but also arcs, or incomplete rings. While the discoverers of Neptune were not able to name the planet after themselves, we've gone ahead and named the rings after them: Galle, Leverrier, and Adams are all rings around Neptune.

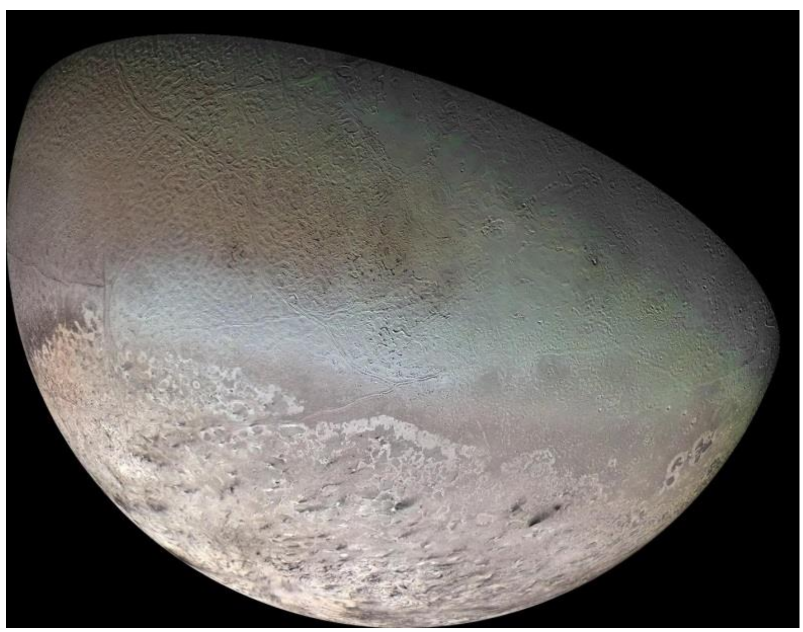


Figure 27- Neptune's largest moon Triton, is seen in this mosaic of images captured by Voyager 2 during the only visit thus far to the Neptune system. (NASA/JPL/USGS)

Pluto

Long the lovable misfit of the planetary club, Pluto is now officially classified as a **dwarf planet**. Of the five confirmed dwarf planets in the Solar System, Pluto is the largest in terms of diameter (about twice the diameter of Texas) and the second largest in terms of mass.

Pluto was discovered in 1930 by farmer turned astronomer Clyde Tombaugh at the Lowell Observatory in Flagstaff, Arizona. Tombaugh was continuing a search for “Planet X” initiated by observatory founder Percival Lowell decades earlier. Lowell, a mathematician by training, believed that the discovery of Neptune did not fully explain the irregularities in Uranus’ orbit (see previous section) and was convinced that another large planet lurked undiscovered in the outer Solar System. Lowell’s calculations were in error (Neptune turned out to be larger than everyone thought it was in the early 1900’s) but the search still turned up Pluto 14 years after his death, albeit entirely by coincidence.[13]

When Clyde Tombaugh discovered Pluto, no one knew just how small it was. The common assumption at the time was that the new planet was larger than Earth. The New York Times article announcing the discovery suggested that the new planet was “possibly larger than Jupiter and four billion miles away.”[14] We now know that was wishful thinking. Pluto is actually smaller than seven *moons* in our Solar System. It has just 0.2% the mass of Earth and 17% the mass of our Moon.

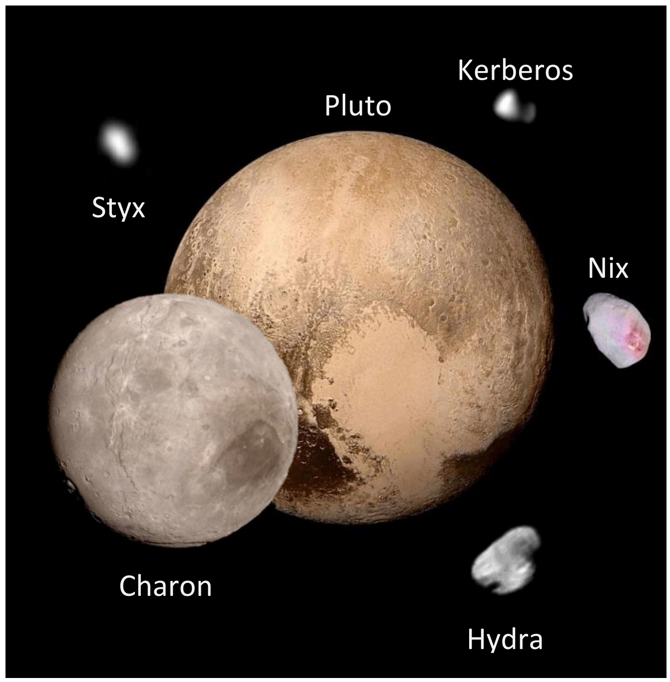


Figure 28-Composite image of Pluto and its moons. (Images: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute/Alex Parker. Composite: Leesa Ricci/NPS)

Pluto is particularly near and dear to Americans’ hearts. In 1930, it was the only planet to have been discovered by an American. Tombaugh was an amateur astronomer who had been working on his parent’s farm in Kansas when he was hired to search for Planet X. Although he later earned a Master’s degree in astronomy, his story painted a picture of passion over elitism, something European astronomy had never achieved. Prior to Tombaugh, nearly every well-known astronomer had been well-financed. Galileo was friends with the pope and worked for the Medicis. Newton was a lord. Herschel was sponsored by King George III. And here was Tombaugh, a farm boy with a passion for astronomy, working long nights to discover a new world. It’s easy to see why Tombaugh and Pluto are so beloved.

New Horizons

For 84 years following its discovery, Pluto remained a mystery. The best telescopes on Earth show Pluto as nothing more than a gray blob. After Voyager 2 visited Uranus and Neptune in the late 1980s, Pluto was the only planet to never have been visited by a probe. That changed in 2015 when NASA's New Horizons spacecraft flew past Pluto after a nearly 10 year journey.

New Horizons transformed Pluto from a blobby gray orb into a real world. Among the surprising discoveries made by New Horizons were:

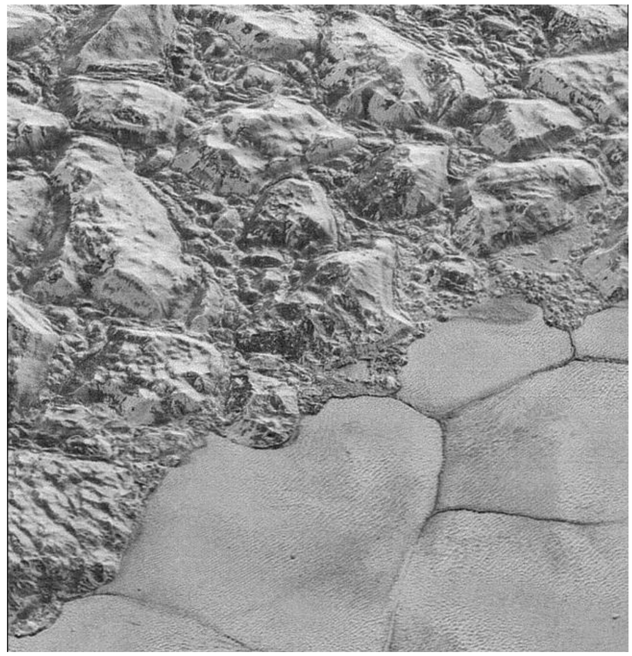


Figure 29-Water-ice mountains on the surface of Pluto, as seen by New Horizons. This view is about 80 km (50 mi) across. (NASA/JHUAPL/SwRI)

- That Pluto, despite its great distance from the Sun, is geologically active. Portions of the surface appear to be less than 10 million years old.
- A compositionally varied surface, with some areas covered in frozen nitrogen, and others composed of frozen methane and carbon dioxide. Numerous mountain ranges are made of water ice "rocks" (Fig 29).
- The largest glacier in the Solar System, a 1,000 km (620 mi) wide mass of nitrogen ice.
- Evidence of possible flowing or standing liquids on Pluto's surface in the past, something previously only seen on Mars, Titan, and Earth.

Beyond Pluto

Did you ever read astronomy books as a child? Remember how the Solar System just sort of stopped at Pluto? Pluto was one-of-a-kind for a very long time. When Pluto was discovered, it had no name. Instead it was referred to as "the Trans-Neptunian Planet" until Venetia Burney (at 11 years old) suggested the name Pluto, Roman god of the underworld.

Today, astronomers still call objects past Neptune **trans-Neptunian objects** (or TNOs). The difference is that Pluto is no longer alone in this category. Until recently, this section of the handbook wouldn't have existed; Pluto was the only TNO known. While some astronomers hypothesized that Pluto might have friends, there was no observational evidence to support this idea until James Christy discovered Pluto's largest moon, Charon, in 1978. About half the size of Pluto, Charon also made it easy to calculate Pluto's mass, confirming its small size.

In 1992, David Jewitt and Jane Luu discovered 1992 QB_1, the first TNO discovered other than Pluto and Charon. Unlike Pluto, which is sometimes closer to Earth than Neptune, 1992 QB_1 does not cross Neptune's orbit and stays firmly in the outer Solar System. While this discovery was intriguing, 1992 QB_1 is much smaller than Pluto and Charon, at less than 200 km (124 mi) in diameter. It's not surprising that astronomy texts still envisioned Pluto as the "end" of the Solar System as recently as the 1990s.

Table 9: Discovery Date and Diameters of Larger TNOs

Year of Discovery	Object	Diameter (km)
1930	Pluto	2,372
1992	1992 QB_1	<200
1998	Chaos	600
2000	Huya	450
2000	Varuna	670
2001	Ixion	650
2002	Quaoar	1,100
2003	Varda	700
2003	Haumea	1,240
2003	Eris	2,320
2003	Sedna	1,000
2004	Orcus	900
2004	Salacia	850
2005	Makemake	1,430
2007	2007 OR_{10}	1,540

Before long though, the pace of TNO discovery picked up (Table 9). In 1998 Chaos was discovered, an object larger than 1992 QB_1 at around 600 km (373 mi) in diameter. Then Varuna, 700 km (435 mi) in diameter, was discovered in 2000. While these objects were still smaller than Pluto, they were much larger than a typical asteroid or comet and forced astronomers to wonder: Could there be an entire population of Pluto-like objects inhabiting the outer Solar System?

The answer, it turned out, was yes. By the end of 1998, more than 40 small TNOs had been discovered. These objects lie within a region of the Solar System known as the **Kuiper Belt**. Extending from about 30 to 50 AU from the Sun, the Kuiper Belt contains more than 1,000 known TNOs and likely several hundred thousand others still waiting to be discovered (Fig 30).

By the early 2000s, larger TNOs were beginning to show up. In 2002, Quaoar (pronounced kwa-war) was discovered by Mike Brown and Chad Trujillo, and it was over 1,000 km (621 mi) in diameter. Mike Brown later called Quaoar a "huge icy nail in the coffin of Pluto as a planet."[15] Brown also said that he thought these new icy bodies would one day be called "Plutonians," giving a nod to the original object, and indeed TNOs large enough to be round in shape are now officially known as **Plutoids**. Finally in October 2003 came the real nail in the coffin for Pluto's planetary status: Eris.

Eris was discovered in 2003 and has a diameter of just over 2,300 km (1,430 mi), slightly smaller than Pluto, but with 30% more mass. Technically not part of the Kuiper Belt, Eris belongs to another family of TNOs known as *scattered disk objects*. The discovery of an object so similar in size to Pluto forced the astronomical community to ask: Had a new planet been discovered? Eris either had to be considered a new planet or Pluto had to be "demoted." There was simply no scientific rationale to keep calling Pluto a planet and not call Eris one as well.

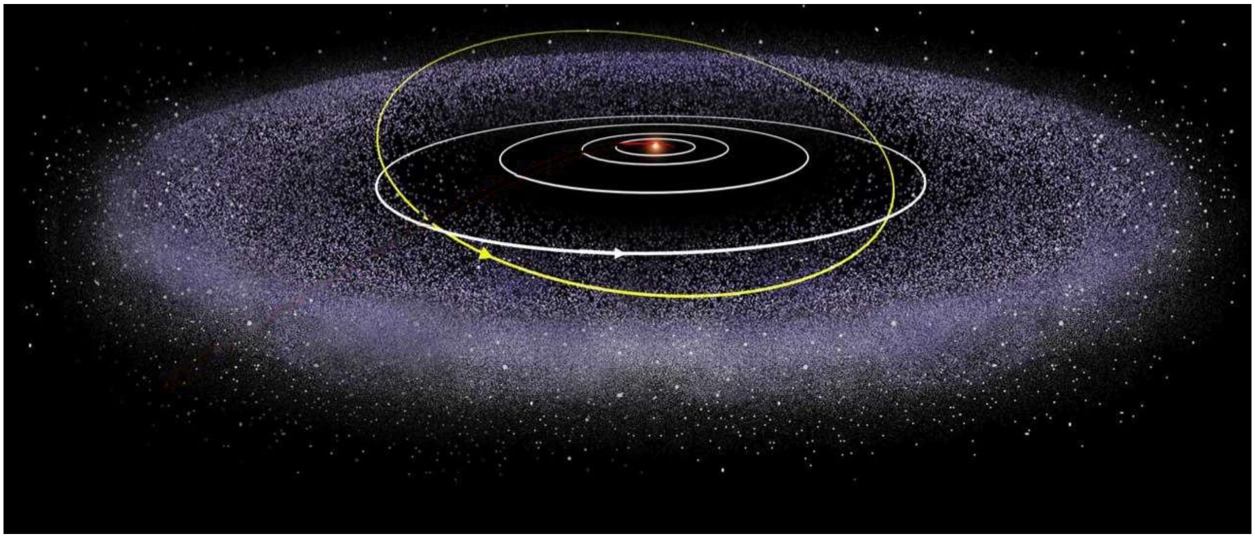


Figure 30-The Kuiper Belt is a vast, disc-shaped region of the outer Solar System beyond Neptune. The orbits of the outer planets (white) and Pluto (yellow) are shown for reference. Note how Pluto's orbit is inclined relative to the ecliptic. (NASA)

Up until this point, no TNOs were as large or massive as Pluto, so the International Astronomical Union (IAU), the organization responsible for categorizing astronomical bodies, never had to deal with this problem. Pluto could remain a planet, and new discoveries in the outer solar system could be categorized simply as TNOs – no planetary distinction required. But Eris changed all that.

Why is Pluto not a Planet Anymore?

In 2006, the IAU addressed the "planet problem" by establishing three criteria that an object must meet in order to be officially designated as a planet:

- The object must be in orbit around the Sun.
- The object must have sufficient mass to assume hydrostatic equilibrium (a nearly round shape).
- The object must have "cleared the neighborhood" around its orbit.

While Pluto satisfies the first two criteria, by virtue of its many friends in the Kuiper Belt and scattered disk, it has not "cleared its orbital neighborhood." Objects that meet the first two criteria but fail the third are now officially known as **dwarf planets**. The Solar System's roster of dwarf planets currently includes Pluto, three other round TNOs (Eris, Makemake, and Haumea), as well as the largest asteroid, Ceres. While the decision to reclassify Pluto was controversial both inside and outside the astronomical community, the reality is that dwarf planets, and particularly the Plutoids, are very different from the eight major planets:

- Even the largest dwarf planets (Pluto, Eris) are smaller than any of the terrestrial planets, and much smaller than the gas and ice giants.

- They do not orbit in the **ecliptic** plane like the eight major planets. Of these, Mercury has the highest inclination to the ecliptic plane at about 7°. Of the Plutoids, Pluto is the least inclined to the ecliptic at 17°. Haumea is 28° off, Makemake 29°, and Eris 44°.
- The Plutoids have eccentric orbits. Mercury has the most elliptical orbit (highest eccentricity) of the eight planets at 0.2 (where 0 is a perfect circle and 1 is a parabola). Haumea has an eccentricity of 0.2, Pluto 0.25, and Eris 0.43.

In some ways, Pluto's reclassification is simply a consequence of scientific progress. As our knowledge of the universe changes, so does our terminology. Pluto isn't even the first "ex-planet." When Ceres, the first asteroid, was discovered in 1801, astronomers thought they had discovered a new planet. In a striking parallel to the Pluto saga, it was not until several other objects were found in the same part of the Solar System that astronomers realized they were looking at a whole new class of objects. The name "asteroid" was coined and Ceres (as well as several other asteroids) lost their planetary status.[16]

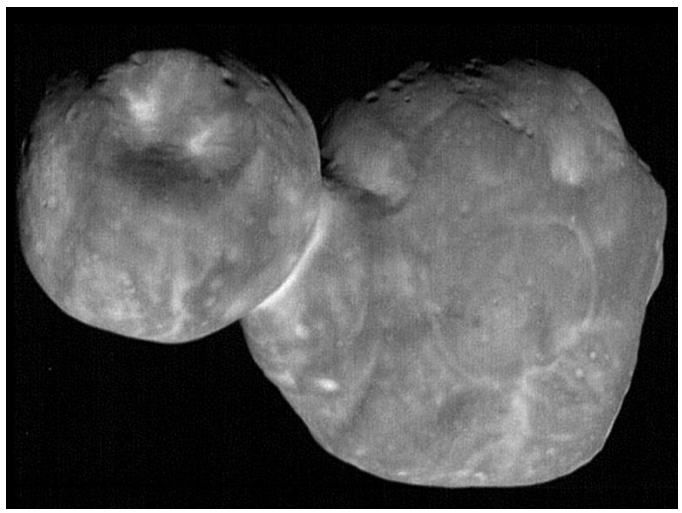


Figure 31-Kuiper Belt object 2014 MU69 as seen during the New Horizons flyby in 2019. This is the most distant object ever explored by a spacecraft. (NASA/Johns Hopkins Applied Physics Laboratory/Southwest Research Institute, National Optical Astronomy Observatory)

Outside of the Pluto system, only one Kuiper Belt object has been visited by a probe: New Horizons flew past 31 km (19 mi) long 2014 MU69 in January 2019 (Fig 31). Many more TNOs, Kuiper Belt objects, and dwarf planets still await discovery. Consider Sedna, a TNO with a diameter around 1,000 km (621 mi) and an extremely elliptical orbit that takes it more than 900 AU from the Sun at **aphelion**. In contrast, its **perihelion** distance is only 76 AU. When it was discovered in 2003, it was very close to perihelion, and even then barely visible. Objects like Sedna are impossible to see at aphelion using current technology. So were we just lucky to discover Sedna when it was at perihelion? Maybe. More likely there are lots of Sednas out there that we can't see precisely because they're closer to their aphelions than their perihelions.

After all this chaos, it is perhaps fitting that Eris was named for the Greek goddess of discord and strife and its tiny moon named Dysnomia, after the goddess of lawlessness. And if you still feel sad about Pluto, consider that Clyde Tombaugh's ashes are on board New Horizons and have now flown past the object he discovered so many years ago.

Comets & the Oort Cloud

At the edge of the Solar System, beyond the Kuiper Belt, lies an immense reservoir of billions (or perhaps trillions) of **comets** known as the **Oort Cloud**. Often described as "dirty snowballs," comet nuclei are chunks of ice, rock, and dust, typically about the size of a small city (Fig 32). Like planets and asteroids, comets orbit the Sun, but typically on very long and elongated paths that take them far into the outer Solar System.

Because of their highly elliptical orbits, most comets spend the vast majority of their lives hundreds or even thousands of astronomical units from the Sun. At this distance comets are essentially invisible to us. We generally see them only when one enters the inner Solar System and approaches the Sun.

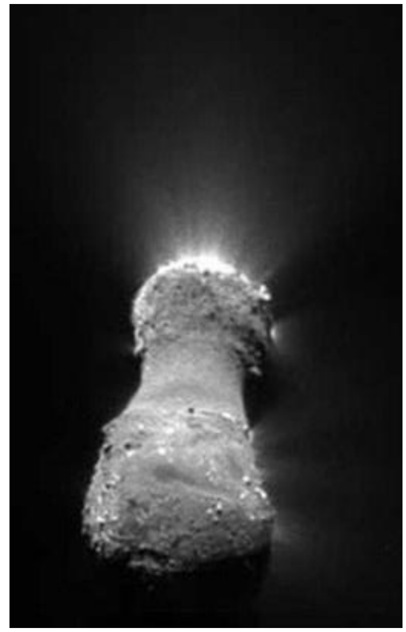


Figure 32-The nucleus of Comet Hartley 2, less than 1.6 km (1 mi) in diameter as seen by NASAs Deep Impact Spacecraft. (NASA/JPL-Caltech/UMD)

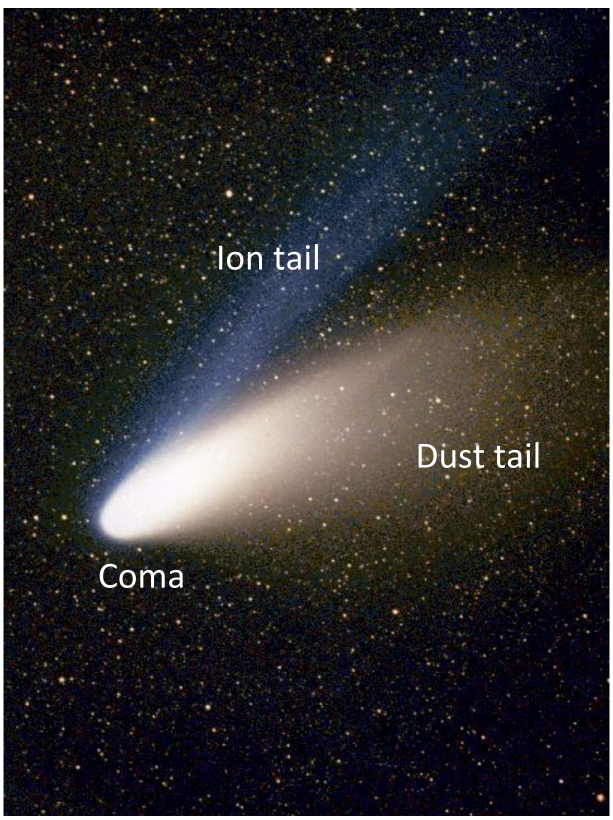


Figure 33-Comet Hale-Bopp was a long-period comet that graced the skies in 1997, becoming one of the brightest comets on record. (Geoff Chester/U.S. Naval Observatory)

When a comet enters the inner solar system and begins to warm up, ices within the comet begin to vaporize and/or sublimate and the comet takes on a new appearance. A comet approaching perihelion will often develop a **coma**, or atmosphere, and in many cases a tail (or two) (Fig 33).

There are two primary classes of comets. Short-period or periodic comets take less than 200 years to complete an orbit around the Sun. They appear in our night sky regularly, hence their name. Conversely, long-period comets have orbital periods ranging from 200 years to tens of thousands of years. These comets can have aphelion distances of tens of thousands of AUs from the Sun. When a long-period comet appears in the night sky, it may not be seen again for generations or even millennia.

The End of the Solar System

In September 2013, it was widely misreported that the Voyager 1 probe had left the Solar System. In reality, Voyager 1 had arrived, about a year earlier, at the **heliopause**, the outer limit of the Sun's solar wind and the beginning of interstellar space (Fig 34). While Voyager 1 was the first human-made object to reach this point, the heliopause is *not* the end of the Solar System.

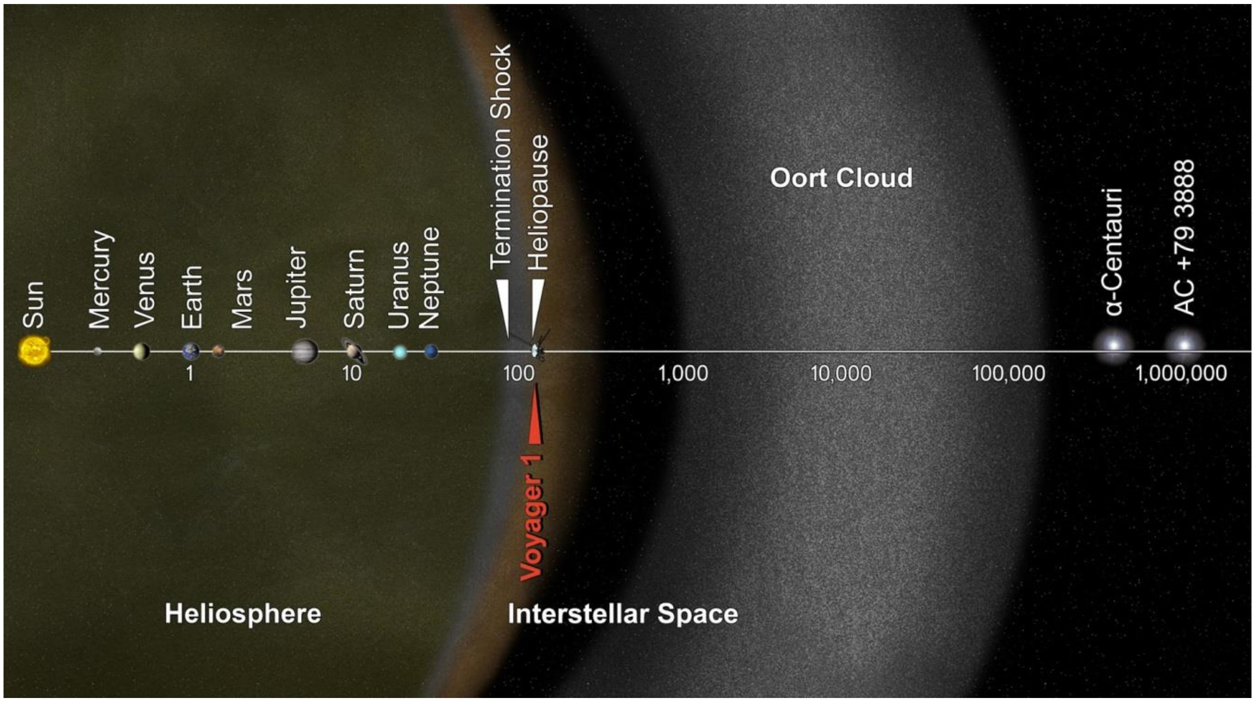


Figure 34-Illustration of the outer Solar System showing the heliopause, current position of Voyager 1, and the Oort Cloud. Distance bar is in astronomical units. (NASA/JPL-Caltech)

When it reached the heliopause, Voyager 1 was about 121 AU from the Sun. As of August 2018, Voyager 1 is now 143 AU from the Sun, placing it firmly in interstellar space. Although it is traveling many times faster than a speeding bullet, it will take hundreds of years just to reach the inner edge of the Oort Cloud, and tens of thousands of years to get to the outer Oort Cloud. Not until Voyager 1 reaches the outer edge of the Oort Cloud will it truly be free of our Solar System. Only here does the gravity of other stars become stronger than the pull of our Sun.

Conclusion

Our Solar System is vast and rich and interesting. It is full of water: on the moons of Jupiter and Saturn, in the Kuiper Belt, and the frozen cometary bodies of the Oort Cloud. There are chemical compounds out there that we don't have on Earth, like tholin in the outer Solar System, and states of matter we can't experience on Earth, like the deep seas of metallic hydrogen below Jupiter's clouds. We've found the building blocks of life in the most remote corners of the Solar System, but no life to go with it yet. We began sending probes to faraway worlds only half a century ago, and we've already peered beneath the clouds of Titan, discovered hundreds of moons whose chemistry and composition defy our imagination, and discovered that Pluto is stranger than we ever expected with a bunch of weird little friends.

Perhaps the most surprising picture to ever have been taken by a probe is one from Voyager 1. In 1990, astronomer Carl Sagan convinced NASA's administrator to turn the probe around at a distance of nearly four billion miles and take a picture of Earth. There was no plan to do this when the probe was initially launched in 1977, and Candy Hansen (of JPL) and Carolyn Porco (University of Arizona) went to work designing a new command sequence to get the spacecraft turned around and ready to shoot at just the right exposure time. The resulting picture is usually known as "The Pale Blue Dot" (Fig 35). In the image, Earth is almost invisible, and takes up a mere pixel. After seeing the photo, Carl Sagan had this to say:

Look again at that dot. That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives. The aggregate of our joy and suffering, thousands of confident religions, ideologies, and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilization, every king and peasant, every young couple in love, every mother and father, hopeful child, inventor and explorer, every teacher of morals, every corrupt politician, every "superstar," every "supreme leader," every saint and sinner in the history of our species lived there – on a mote of dust suspended in a Sunbeam.

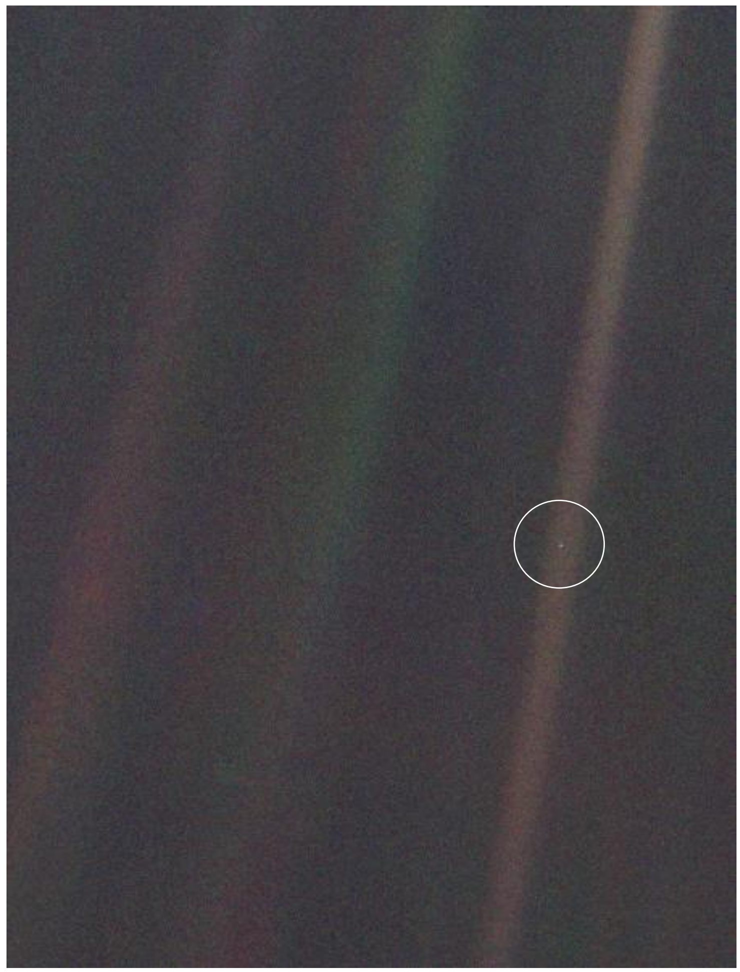


Figure 35-"The Pale Blue Dot,"an image of Earth taken by Voyager 1 when it was roughly 5.95 billion km (3.7 billion mi) from our planet. Earth is the tiny dot inside the circle. (NASA/JPL)

The Earth is a very small stage in a vast cosmic arena. Think of the rivers of blood spilled by all those generals and emperors so that, in glory and triumph, they could become the momentary masters of a fraction of a dot. Think of the endless cruelties visited by the *inhabitants of one corner of this pixel on the scarcely distinguishable inhabitants of some other corner, how frequent their misunderstandings, how eager they are to kill one another, how fervent their hatreds.*

Our posturings, our imagined self-importance, the delusion that we have some privileged position in the universe, are challenged by this point of pale light. Our planet is a lonely speck in the great enveloping cosmic dark. In our obscurity, in all this vastness, there is no hint that help will come from elsewhere to save us from ourselves.

The Earth is the only world known so far to harbor life. There is nowhere else, at least in the near future, to which our species could migrate. Visit, yes. Settle, not yet. Like it or not, for the moment the Earth is where we make our stand.

It has been said that astronomy is a humbling and character-building experience. There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we've ever known.[17]

Review

Common misconceptions

Below is a list of commonly encountered misconceptions about the Solar System. As a way to review content from this chapter, see if you can explain why each misconception is inaccurate:

- Planets shine the same way that the Sun does.
- Planets orbit the Sun in circles.
- Mercury is the hottest planet.
- The Solar System was created by the Big Bang.
- The Solar System is the center of the galaxy/universe.
- Earth is the only object in the Solar System with water/liquid water.
- The asteroid belt is densely packed, as in Star Wars.
- Only planets have moons.
- Jupiter almost became a star.
- Only Saturn has rings.
- Uranus and Neptune are gas giants.
- Pluto is always the farthest planet from the Sun.
- Pluto is no longer a planet because it’s not big enough.
- Pluto is the edge or “end” of our Solar System.

Questions for thought

- You are hosting a star party, looking at Saturn, Mars, and Jupiter through a telescope when a participant comments on how it is unfortunate scientists had to get rid of Pluto.

What do you say? Was the decision to reclassify Pluto as a dwarf planet a good one? Why or why not? Does it matter?

- Imagine that astronomers discovered an Earth or Mars-sized body in the Kuiper Belt. Would it be considered a planet? Why or why not?

- Suppose that you were placed in charge of prioritizing future planetary missions for NASA. What mission(s) would you prioritize and why? What unresolved questions about the Solar System would you want to answer?

- Aside from Earth, which other object in the Solar System is most Earth-like? Why? Could humans survive there?

- Astronomers have discovered more than 3,000 planets orbiting other stars. Do you think these planets and solar systems are similar to our own or different? Why?

- Venus and Jupiter are the two brightest naked eye planets, but Venus is very small and Jupiter is very far away. What factors determine how bright a planet appears from Earth?

- We've sent more spacecraft to Mars than any other planet. Why are humans so interested in Mars? What factors contribute to our extensive exploration of the red planet?

- Many conditions had to be just right here on Earth for life to take hold. Are we just lucky? Or are such conditions common throughout the Solar System and/or universe? What do you think? How can astronomers go about seeking the answer?

For More Information

- *How I Killed Pluto and Why It Had It Coming,* by Mike Brown, 2012
- The Planetary Society: http://planetary.org/
- "The Solar System": http://nineplanets.org/overview.html
- "Solar System Exploration" (NASA): https://solarsystem.nasa.gov/
- *Snapshots from Space* (Solar System exploration news from planetary scientist Emily Lakdawalla): http://www.planetary.org/blogs/emily-lakdawalla/

Chapter 2.7: Stars

An x-ray and infrared image of the Flame Nebula (NGC 2024) showing a cluster of young stars near the center of the nebula. (X-ray: NASA/CXC/PSU/K.Getman, E.Feigelson, M.Kuhn & the MYStIX team. Infrared:NASA/JPL-Caltech)

Chapter 2.7 Goals

After reading this chapter and participating in the corresponding workshop activities, you should be able to:

- Define a star and describe the basic processes that power them, as well as how stars are responsible for creating the building blocks of life.
- Explain how spectroscopy allows us to better understand and classify stars based on their physical properties.
- Compare and contrast our Sun with other types of stars, and describe how the lifecycle of a star varies based on its mass.

What is a Star?

No astronomy handbook would be complete without a chapter on stars. The very word "astronomy" is derived from the Greek *ástron*, meaning "star." Our nearest star, the Sun, allows life to exist on Earth and is the basis for much of what we know about stars in general.

Stars, like most objects in space, are objects dependent almost entirely on mass. Anything could be a star – as long as it was massive enough. A star is a body massive enough to generate its own energy and light via **nuclear fusion**. Most stars, including our Sun (Fig 1), fuse hydrogen atoms into helium atoms in their cores. This process releases copious amounts of energy and **photons** (light), giving stars their luminous nature.

Without sufficient mass and a high enough temperature, these nuclear reactions don't occur. The *minimum* mass required to achieve nuclear fusion and become a star is about 80 times the mass of Jupiter (about 0.075 times the mass of the Sun). The *maximum* mass of a star is less clear. We see very few stars that exceed 150 times the mass of our Sun. Those that do, like a handful of stars in the Tarantula Nebula that may be as much as 320 times more massive than our Sun, are extremely rare, short-lived, unstable, and atypical.[1] This means that stars are typically between 0.075 and 150 times the mass of the Sun, but as we'll see, most stars in our galaxy are much less massive than the Sun.

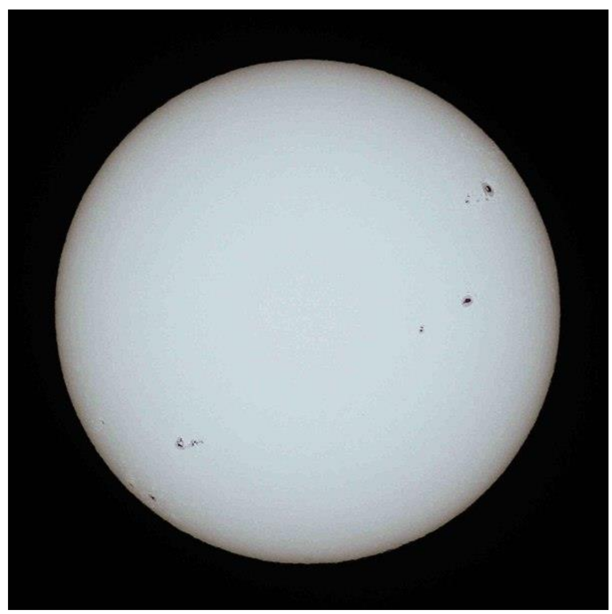


Figure 1-Our Sun, the closest star to the Earth, in visible light. The black spots are sunspots, cooler areas of the Sun's surface that are often larger than Earth. (Geoff Elston, [CC BY 4.0])

Early Ideas about the Sun and Stars

The true nature of stars eluded astronomers for a long time. After all, before **spectroscopy** took off in the 1800s there was no way to determine what stars were made of, and before the telescope started to be used for astronomy in the 1600s, there was no way to even see any celestial bodies up close. As a result, many erroneous ideas about the Sun and stars have popped up over the ages. For example:

- Xenophanes of Colophon (590-500 BCE) taught that the Sun was born every day when it rises, and flees every night into an infinite distance.
- Anaxagoras (499-428 BCE) taught that the stars were bodies ripped away from the Earth and that they shine because of the fire of the ether.
- Yang Xiong (53-18 BCE) wrote that night was caused by the Sun moving so far away that its rays could not reach Earth.
- Aristotle (384-322 BCE) wrote that large moving objects make sound, and the stars make no sound, therefore they don't move.

While odd ideas about stars abounded until only a few hundred years ago, there were also people from the distant past that had remarkably accurate ideas about stars. For example:

- Anaxagoras may have been wrong about what stars were made out of, but he believed the Sun and stars were the same kind of object.
- Cleomedes (~300 CE) stated that the fixed stars we see at night are as large as the Sun, and could be even larger.
- Aryabhata (476-550 CE) gave the distance to the stars as 4.4 million times the distance to the Sun (in modern terms, that's about 70 **light-years** away).

By the 1600s, the idea that the Sun was a star and that other stars had their own planets was common. While this did not go over well everywhere (Giordano Bruno and Galileo Galilei notably ran into major problems with it in Italy), it was being successfully popularized in France. For example, Rene Descartes, only 32 years younger than Galileo, was a popularizer of many of Bruno's and Galileo's principles and supported the idea of solar systems around other stars. Another science writer, Bernard Le Bovier de Fontenelle (1657-1757), took those ideas even further. In 1686 he wrote *Conversations on the Plurality of Worlds* in which he advocated that other stars are suns, that those suns must have their own planets, and why couldn't there be life on those planets? It was extremely popular.

Philosophy is based on two things only: Curiosity and bad eyesight. For if you had better eyesight you could see perfectly well whether or not these stars are solar systems, and if you were less curious you wouldn't care about knowing – which amounts to the same thing.

– Bernard Le Bovier de Fontenelle

However, no one was able to empirically support these ideas until 1838 when Friedrich Bessel became the first astronomer to accurately measure the distance to a star other than the Sun: 61 Cygni. Bessel's discovery that the stars were extremely far away demonstrated that they must be about the same size as the Sun. This lent the "Sun-as-a-star" idea an enormous amount of credibility. Once cameras were invented, it became even easier to find the distances and **luminosities** of stars. By the late 1800s, there was no doubt that the Sun was a star.

While Bessel had solved one problem, the inner workings of stars remained a mystery until even more recently. By the mid-1800s, astronomers had used mathematics to rule out the once prevalent idea that the Sun was a gigantic ball of burning coal or wood. For a few decades in the late-1800s, the leading hypothesis was that the Sun's energy came from gravitational contraction. This too was soon ruled out, on the basis that contraction could only power the Sun for *millions* of years, not the *billions* of years that geologists were now realizing was the true age of our Earth and Solar System.

Not until Einstein debuted his now famous equation, $E = mc^2$, in 1905 did we have the information necessary to develop a cohesive theory of how stars shine. In a nutshell, Einstein's equation states that mass (m) and energy (E) are equivalent. Nuclear fusion essentially converts small amounts of mass into large amounts of energy (because c, the speed of light, is a very large number). By the 1930s, astronomers had a working model for the Sun based on the idea of nuclear fusion.

Inside a Star

Astronomers now have a more complete understanding of how stars work. Stars have several layers: a core, where nuclear fusion takes place, an envelope (sometimes called a *shell*) where energy is transmitted to the surface by either radiation or convection, and an atmosphere.

Energy generation occurs in the core, where temperatures are extremely high. The core temperature of the Sun is about 15 million °C (27 million °F). Photons created here take tens or hundreds of thousands of years to work their way from the core up to the surface. In the process, the photons lose energy. While they may begin as energetic x-rays or gamma rays in the core, they emerge at the surface as photons of ultraviolet radiation, visible light, or infrared radiation. Thus the surface of the Sun that we see is "only" about 5,500 °C (10,000 °F). Once at the surface, these photons take just eight minutes to reach Earth.

Because of a star's immense mass, gravity constantly pulls material toward the core. How then does a star keep from collapsing in upon itself? The energy released by nuclear fusion exerts an outward pressure, known as gas pressure, on the collapsing material. This effectively prevents the star from collapsing by "pushing back" against gravity. When these two forces, the inward pull of gravity and the outward push of gas pressure, balance, we say that the star is in equilibrium (Fig 2). It is stable. Without *both* processes, the star would collapse or the gas would escape into space and dissipate. Stable stars that are fusing hydrogen into helium and in equilibrium are known as **main sequence stars**.

Note that not all stars are in equilibrium. Young stars and those near the end of their lives are often unstable. We'll learn more about these stars in the "Lifespan of a Star" section below.

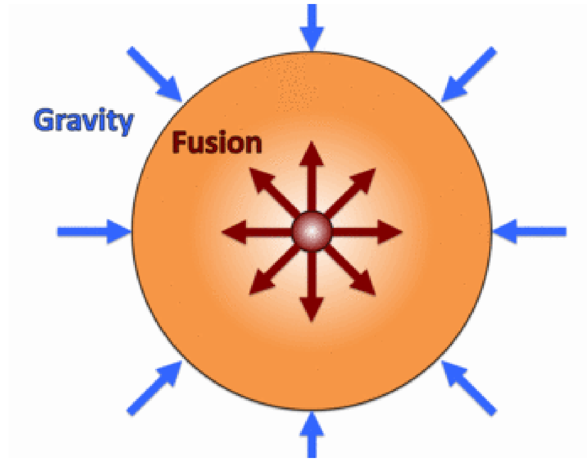


Figure 2-Stars are stable only when the inward pull of gravity is perfectly balanced by the outward push of radiation generated by nuclear fusion in the core. (Britton J. Olson)

Nuclear Fusion and Nucleosynthesis

The universe is mostly hydrogen (~74%) and helium (~24%) by mass, as are the giant **molecular clouds** which give birth to stars. As a result, stars are mostly hydrogen (the Sun is about 73% hydrogen by mass) so it is perhaps not surprising that hydrogen is a star's primary fuel source.

> ## Equilibrium in your Kitchen
>
> If you've ever heated atoms of water in a pan on a stovetop, you can understand the equilibrium between gravity and the outward pressure generated by internal heat. If you pour water into a saucepan and heat it up as hot as possible, the pan will overflow. Why? As the temperature rises, the atoms become more energetic and push away from each other, filling more space. If you put a lid on the pan and heat the water (and water vapor) until the lid is moving just enough to let out a little bit of vapor as it heats, the pan can be kept from overflowing. The water in the pan combined with the pressure from the lid can be thought of as having achieved equilibrium.
>
> In a star, the immense gravitational pull of the star's mass serves as the "lid" that keeps the stellar material from being blasted into space. While stars are not pans on stovetops, the equilibrium between the inward pressure of gravity and the outward heat pressure is somewhat analogous to the pan's dancing lid.

Over the course of a star's lifetime, nuclear fusion converts hydrogen atoms into helium atoms inside the core, releasing energy in the process. The scale of this process is staggering, even in a relatively modest star like the Sun. Our Sun fuses about 600 million tons of hydrogen into 596 million tons of helium each *second.*[2] In other words, the Sun gets about four million tons *lighter* each second due to nuclear fusion. The "lost" mass is converted into energy, which we see and feel as light and heat being radiated away from the Sun. As a star ages, its core becomes slowly enriched in helium. Eventually, many stars begin a phase where they fuse helium into carbon. Large stars will fuse carbon into a variety of other elements.

The process of converting elements such as hydrogen and helium into other, heavier elements inside stars is known as stellar **nucleosynthesis**. The universe was composed mostly of hydrogen and helium (and perhaps a bit of lithium) at birth, so all the other elements we know and love have been forged over the eons inside stars. As the late Carl Sagan once wrote: “The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars. We are made of starstuff.”[3]

Without stellar nucleosynthesis, we wouldn’t have carbon, and without carbon, there would be no life as we know it. Many different types of life occur on Earth and while some of this life is very strange, so far we’ve never found life that doesn’t contain carbon. Thus, all life as we know it is dependent on the nuclear processes that occur inside stars. Note that ordinary stars cannot manufacture any elements heavier than iron (element number 26 on the periodic table) via nuclear fusion. So where did Earth’s silver, gold, and uranium come from?

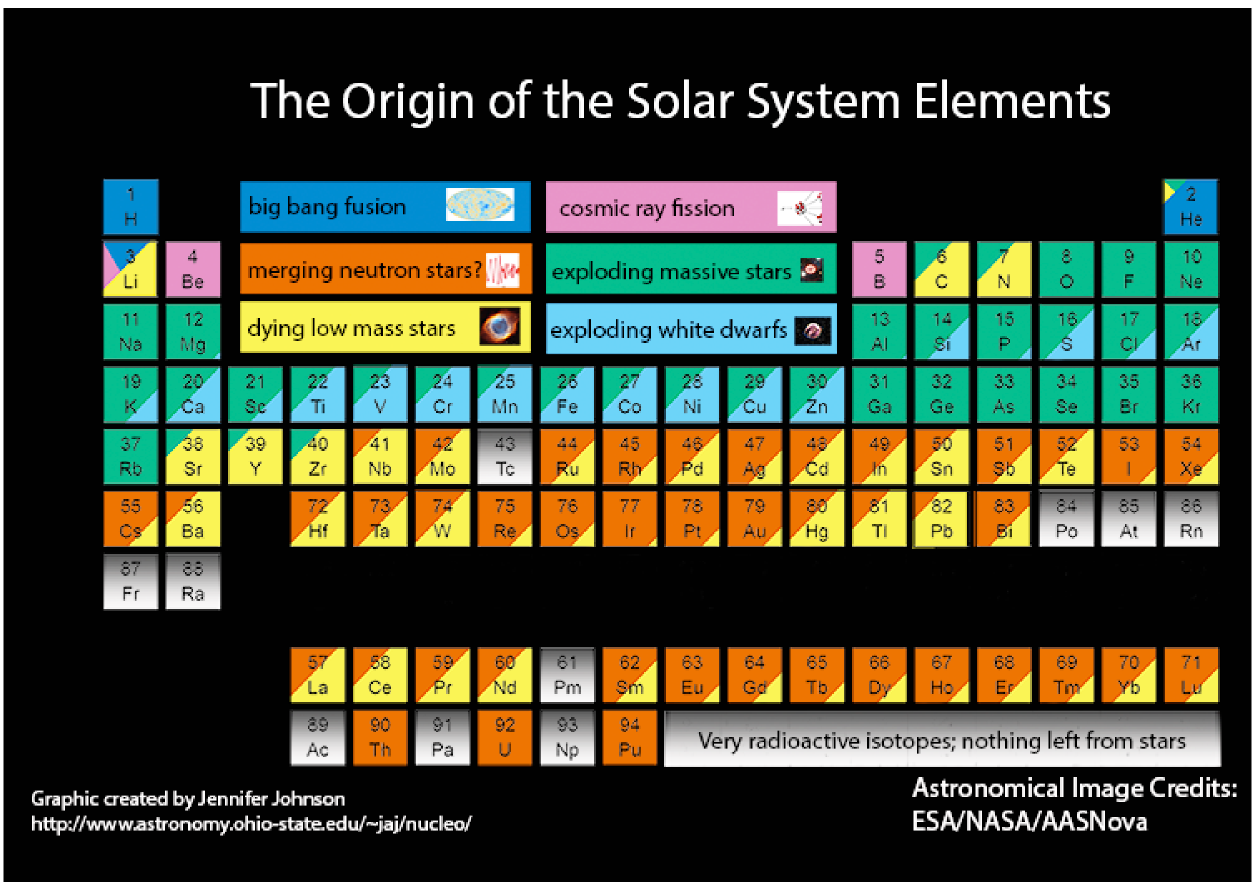


Figure 3-Origin of the elements on the periodic table. An element with multiple colors comes from more than one source, with the ratio of the colors indicating the approximately amount produced by each source. (Jennifer Johnson, Ohio State University, CC BY-SA 4.0)

Elements heavier than iron are produced in a variety of processes, most of which are associated with star death. **Supernovae** (exploding stars) and **neutron star** mergers are examples of the events responsible for the vast majority of elements on the periodic table (Fig 3). Explosive events like supernovae also help disperse and distribute these heavy elements (and those produced by nuclear fusion) throughout the galaxy to be incorporated into new stars and planets. The presence of heavy elements in our Solar System tells us that the Sun is at least a "second generation star"; that is, it formed only after older generations of stars had time to synthesize these heavy elements, die, and disperse them throughout the galaxy.

Spectroscopy: The Key to the Stars

Studying stars has always been a frustrating business, in part because they live for such a long time. If you did nothing but study a star your entire life in order to understand it, it would be like watching *The Godfather* for 0.2 seconds and then trying to explain the plot. Most stars just don't change appreciably on human timescales.

Until recently, all we knew about stars was that we see different ones throughout the year and that they move across the sky in slow measured motions throughout the night. However, both of these phenomena are caused by the Earth's motion, and tell us nothing about the nature of stars themselves. In fact, in 1835 the philosopher Auguste Comte stated about astronomical objects that "we can never by any means investigate their chemical composition or mineralogical structure…[nor] true mean temperatures."[4]

Fortunately, Comte turned out to be very wrong. Recall from *Chapter 2.1* that in the early 19th Century, William Wollaston discovered that the **spectrum** of the Sun contained dark **absorption lines**. It wasn't until 1860 that distinct chemical elements were found to produce distinct

Table 1: A Partial Timeline of Stellar Spectroscopy	
1800	William Herschel accidentally discovers the "invisible" infrared part of the spectrum.
1802	William Wollaston discovers dark lines (absorption lines) in the solar spectrum.
1828	Josef Fraunhofer describes over 500 dark lines in the solar spectrum, discovers bright lines in the spectrum, and develops a diffraction grating.
1859	Gustav Kirchhoff publishes a study on the chemical composition of the Sun.
1872	Henry Draper records the first spectrum of a star other than the Sun: Vega.
1890	Annie Jump Cannon & Antonia Maury publish a catalog of 10,000 stellar spectra.
1895	Henry Rowland produces a table showing 20,000 lines in the solar spectrum.
1912	Henrietta Swan Leavitt publishes her study of **Cepheid Variables**, which provide a method for calculating the relative distance of Cepheid stars.
1913	Ejnar Hertzsprung makes the first attempt to fix absolute instead of relative values to Leavitt's Cepheid data.
1913	Henry Russell presented his spectrum-luminosity diagram, which eventually became the Hertzsprung-Russell Diagram (HR Diagram).

absorption lines, leading to the realization that that **spectroscopy** could be used to determine which elements and compounds are present in the atmosphere of stars.

In 1872 Henry Draper photographed the spectrum of the star Vega, and found that the pattern of absorption lines was different from the Sun's. This discovery launched a race to classify stars based on the absorption lines present in their spectrum. Naturally, not all astronomers agreed on how to categorize the lines they saw. For decades, there were many confusing and competing systems for classifying stars, but eventually the Harvard system won out and it's the basis for the system astronomers still use today.

The Harvard System

One of the first things students learn if they ever study stars are these words: Oh Be A Fine Girl/Guy, Kiss Me. This is a mnemonic device for remembering the different **spectral types** (or **spectral classes**) of stars (Fig 4) popularized by the matron of stellar physics, Annie Jump Cannon (Fig 5). The Harvard system has several classes (O, B, A, F, G, K, and M) for categorizing stars based on features present in their absorption lines. The system was designed by Cannon, based on the earlier work of Williamina Fleming.

Cannon learned to recognize stellar spectra at a glance, a skill that could be compared to being able to read barcodes. She classified more stars using their spectral lines than anyone ever before her or since: at least a quarter of a million stars. We still use a modified version of Cannon's classification system today, although astronomers sometimes use additional letters and numbers to more accurately refine the system while still allowing astronomers to say "this is an A-type star" for simplicity's sake.[5]

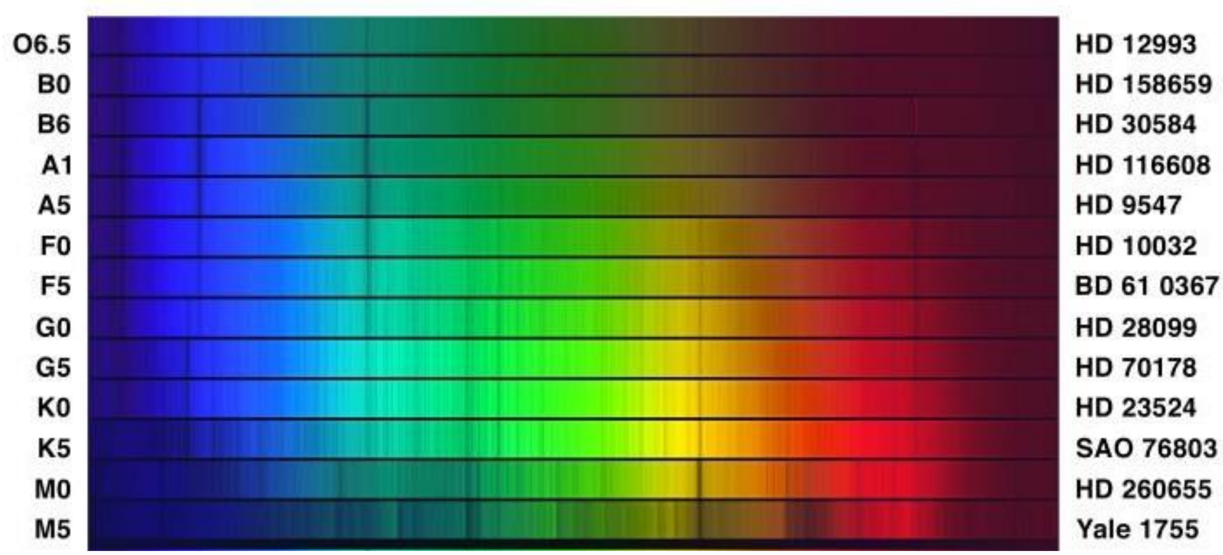


Figure 4-Spectra of various stars organized by spectral type. Spectral type is at left, and star catalog numbers are at right. Note how the intensity and presence of certain absorption lines change depending on the spectral type. (NOAO/AURA/NSF)

Understanding Spectral Type

Aside from composition, what else can the different patterns of absorption lines tell us about stars and their properties? Ultimately, the lines tell us the temperature of the star. In many ways, the spectral class of a star can be thought of as a "temperature class."

Figure 5-The "Harvard Computers" worked on stellar classification and other topics at the Harvard College Observatory in the early 20th century. Annie Jump Cannon is standing directly behind Mabel Gill, who is second from the right in the front row. (Public domain)

Remember from *Chapter 2.1* that absorption lines are caused by certain elements absorbing certain wavelengths of light (energy) within the star. The Harvard system originally divided up stellar spectra based on the relative strength of the absorption lines due to hydrogen. In extremely hot stars, most hydrogen is **ionized** and thus not very good at absorbing light. Consequently, extremely hot stars (O-type in the Harvard system) will lack prominent hydrogen absorption lines.

In very "cool" stars, hydrogen isn't very good at absorbing light either, because its electrons aren't excited enough. Only at just the right temperature is hydrogen able to absorb light and create prominent absorption lines in the spectrum of a star.[7] A-type stars happen to have this temperature, and thus their spectra have the strongest hydrogen absorption lines.

Table 2: The Harvard classification system for stars[6]

Spectral Class	Surface Temperature (K)	Color*	Naked Eye Examples
O	32,000-50,000	Blue-white	Alnitak, Mintaka
B	10,000-30,000	Blue-white	Rigel, Spica, Regulus
A	7200-9500	White	Sirius, Vega, Altair, Deneb
F	6000-7000	Yellow-white	Procyon, Polaris
G	5300-5900	Yellow	The Sun, Alpha Centauri
K	4000-5200	Orange	Arcturus, Capella, Pollux (all giants)
M	2000-3900	Orange red	Betelgeuse, Antares (both giants)

*The conventional star colors listed here are relative to the color of an average A-type star, such as Vega, which is considered to be white. The color of a star as perceived by the naked eye is affected by interstellar dust, the Earth's atmosphere, and our level of dark adaptation, and may not always match the colors listed here.

This general principle applies to other elements as well; an atom or molecule's ability to create absorption lines is heavily dependent on temperature. By looking at the relative strength of different absorption lines, astronomers can deduce both which atoms and molecules are present as well as the approximate surface temperature of the star.

A Tour of the Harvard System

O-type

O-type stars are always hot and blue. Most are also very massive, bright, and young. "Bright" in this context refers to **luminosity** – that is, how much energy a star emits relative to the Sun. Much of the light emitted by a typical O-type star actually lies in the ultraviolet.

O-type stars are not very common, in large part because they don't last very long. Massive stars fuse their hydrogen into helium much more rapidly than smaller stars and thus have shorter lifespans. Despite their rarity, the luminosity of O-type stars allows us to see them even from great distances. Two easy-to-find O-type stars are Alnitak and Mintaka in Orion's Belt. Alnitak is about 30 times the mass of the Sun, but thousands of times more luminous. Our Sun is already 4.5 *billion* years old, but Alnitak is less than 10 *million* years old and has already begun to die.

B-type

A typical B-type star is cooler and whiter in color than an O-type star, but still much hotter, more luminous, more massive, and shorter lived than our Sun. The stars Alnilam, Rigel, Saiph and Bellatrix in Orion are all B-type stars. Due to their short lifetimes, O and B-type stars are often found in close proximity to the **open clusters** or **associations** in which they were born.

A-type

A-type stars are even cooler, whiter, less luminous, and longer lived than B-type stars. At this point, you might have detected a pattern in the Harvard classification: as you progress from O-type to M-type, stars generally become cooler, redder, less luminous, less massive, longer lived, and more abundant. There are exceptions, usually involving giant and supergiant stars that are near death, but this rule holds for most stars. The bright naked eye stars Sirius, Vega, and Deneb, are all A-type stars.

F-type

O, B, and A-type stars are often giants or even supergiants. With few exceptions, they are massive, hot, short-lived stars that produce so much intense radiation that it doesn't make much sense for astronomers to look for planets around them. In contrast, F-type stars are cool enough that it is possible for F-type stars to have planetary systems (for example, Tau Bootis). They also live long enough (billions of years) that their planets could theoretically develop life. Polaris, our current north star, is a triple star system consisting of two F-type main sequence stars and one F-type supergiant.

G-type

Whether you know it or not, you are intimately familiar with a G-type star: the Sun. As a main sequence G-type star, we can expect the Sun to remain stable and viable for life on Earth for a total of about 10 billion years. Most other G-type stars are similar in luminosity and lifespan.

K-type

K-type stars are cooler and redder than our Sun. Main sequence K-type stars are also longer lived and less massive, however some K-type stars are giants. For example, the naked eye stars Pollux (the closest giant star to Earth at just over 30 light-years away) and Arcturus are K-type giants. These stars still have a cooler surface temperature than the Sun, but are much larger. In most cases, K-type giants were once Sun-like stars that are nearing the end of their lifetime and have swelled up and cooled as they enter their **red giant** phase. While these giants make up a small percentage of all K-type stars, the fact that they are larger and brighter means that most K-type stars we can see with the naked eye are giants as opposed to main sequence stars.

M-type

Finally we come to the M-type stars. For the most part, these are the coolest, reddest, least luminous, and least massive stars in the galaxy. Small M-type stars are often known as **red dwarfs** and are easily the most abundant type of star in the Milky Way Galaxy. These stars live for a very long time (hundreds of billions to trillions of years) and are a good place to look for life. Red dwarfs have luminosities so low that there are none bright enough to see with the naked eye.

As with K-type stars, some M-type giants do exist, again typically stars whose surface temperature has cooled as they near death. An example is Betelgeuse which is large, red, puffy, luminous, and in its final death throes.

Is Our Sun an Average Star?

No matter how you slice it, our Sun is not an average star. Although it is fairly close to the middle of the OBAFGKM classification system, the vast majority of stars in our galaxy, and likely other galaxies as well, are much smaller than our Sun. Of the ~350 closest stars to us, only 11 are in a hotter spectral class than the G-type Sun (Table 3). Within a 30 light-year radius of Earth, almost all of the stars are smaller and dimmer than the Sun, and most are of the dimmest, coolest, reddest variety around: the M-type red dwarfs. Of the 50 closest stars to Earth, our Sun is the fourth largest.[8]

However, when you look up at the night sky, most of the naked eye stars are much more luminous than the Sun, yet these types are rare when we look at catalogs of nearby stars. What's going on here?

Table 3: Spectral Types of Stars within 10 parsecs (32.6 light-years) of Earth[9]		
Type	**Quantity**	**Notes**
O	0	The closest O-type star to Earth is likely Zeta Ophiuchi (366 ly)
B	0	The closest B-type star to Earth is Regulus A (79 ly)
A	4	Includes Sirius and Altair
F	7	Includes Procyon
G	19	Includes the Sun
K	44	The closest is Alpha Centauri B
M	283	The closest is Proxima Centauri

What we see in the night sky vs. what's really happening in our galaxy is an almost perfect example of a sampling error. With the naked eye, we are naturally going to see the stars that are intrinsically bright, so it's easy to assume that most stars are a lot brighter (and hotter) than our Sun. However, as technology has improved and we have made a more complete survey of the stars around us, we have come to realize that while the bright O, B, and A-type stars hog the limelight, they are by no means representative of what's out there. Most of our closest stellar neighbors, like Proxima Centauri, Barnard's Star, and Luyten 726-8, are so small and dim that they are simply not visible to the naked eye, even though they aren't that far away.

Why are there so many red dwarfs out there? There are two reasons. The first is pretty straightforward: In any given star-forming nebula, exponentially more low-mass stars will form than high-mass ones.[10] The deck is stacked in favor of the low mass stars from the outset.

The second reason has to do with longevity. High mass stars use up their supply of hydrogen much more quickly than low mass stars. Thus, small M-type stars will outlive their larger, more luminous, hotter cousins. In a 2004 paper, astronomers showed that a star with 10% of the Sun's mass would be stable for about 5.74 trillion years, outliving our own Sun by 5.73 trillion years as well as the predicted age limit of the universe.[11] Massive O and B-type stars will live for 10-100 million years, but the very small M-type stars will live somewhere between ten thousand and a hundred thousand times longer. At any given time there are more small stars out there because once they're born they just keep going, whereas the O and B-type stars will have already come and gone.

Recent statistical analysis showed that M-type stars have a high probability of hosting planets.[12] Red dwarfs are the most common and longest lived type of star in the galaxy, can be stable for billions to trillions of years, and have a high abundance of planets. If life in the universe exists outside of Earth, it is a good idea to look for it around red dwarfs (see *Chapter 2.9: Exoplanets*).

Lifespan of a Star

Much like humans, stars have very distinct life phases. A typical star will be birthed from a giant molecular cloud, spend a few million or billion years as a stable star on the main sequence, and then swell up and die. Exactly what path a star takes through life depends largely on its mass.

Star Birth

We know that stars are massive (our own Sun is about 330,000 times as massive as the Earth), but where does all that matter come from? The life of a star begins inside large clouds of hydrogen gas and dust known as **molecular clouds**. The size of these clouds can be almost beyond comprehension. For example, the star-forming region 30 Doradus in the Large Magellanic Cloud (a satellite galaxy of the Milky Way) is about 650 light-years across (Fig 6). That's more than 40,000 times the size of our Solar System, if we define the edge of the Solar System as the **aphelion** of Sedna's orbit.

Figure 6-30 Doradus (also known as the Tarantula Nebula is a massive star forming region in the Large Magellanic Cloud, a satellite galaxy of the Milky Way. (ESO/IDA/Danish 1.5 m/R. Gendler, C. C. Thöne, C. Féron, and J.-E. Ovaldsen, CC BY 4.0)

If a molecular cloud becomes massive enough, or if some external event (such as the shockwave from a nearby supernova) compresses the cloud, portions of it will begin to fragment and then collapse. As the cloud fragments collapse under the influence of their own gravity, physics dictates that they get warmer as the gravitational energy of the gas is converted to kinetic energy. Fragments that reach a high enough density and temperature can become protostars and eventually fully-fledged stars. These young stars can be very unstable, randomly belching out gigantic bursts of **plasma** many times more massive than any plasma bursts our Sun currently puts out. Young stars are often **variable stars**, that is, their apparent magnitude can fluctuate as seen from Earth.

During star formation, a rotating disk of gas and dust known as a **protoplanetary disk** can form around the young star. This material can eventually form planets, asteroids, and comets around the primary star (see *Chapter 2.6: The Solar System*). Because the material in a protoplanetary disk comes from the surrounding molecular cloud, solar systems are typically the same age as their primary star and have a similar composition. This is true of our own Solar System: The Earth is about 4.5 billion years old, as is Jupiter, as is the Sun.

The Main Sequence

When astronomers refer to a **main sequence star**, they are talking about stars that are in the prime of their life. Main sequence stars are those not in the process of forming or dying, but rather those that are in a state of equilibrium, “quietly” fusing hydrogen into helium. Stars spend the majority of their lives on the main sequence. A main sequence star is a stable, happy star. Fortunately for us, our Sun is on the main sequence right now, and will remain there for roughly the next five billion years, at which point it will become unstable. Exactly what happens to a star after its main sequence phase depends on its mass (Fig 7). Let’s first explore what happens to a relatively low-mass star like our Sun when it leaves the main sequence.

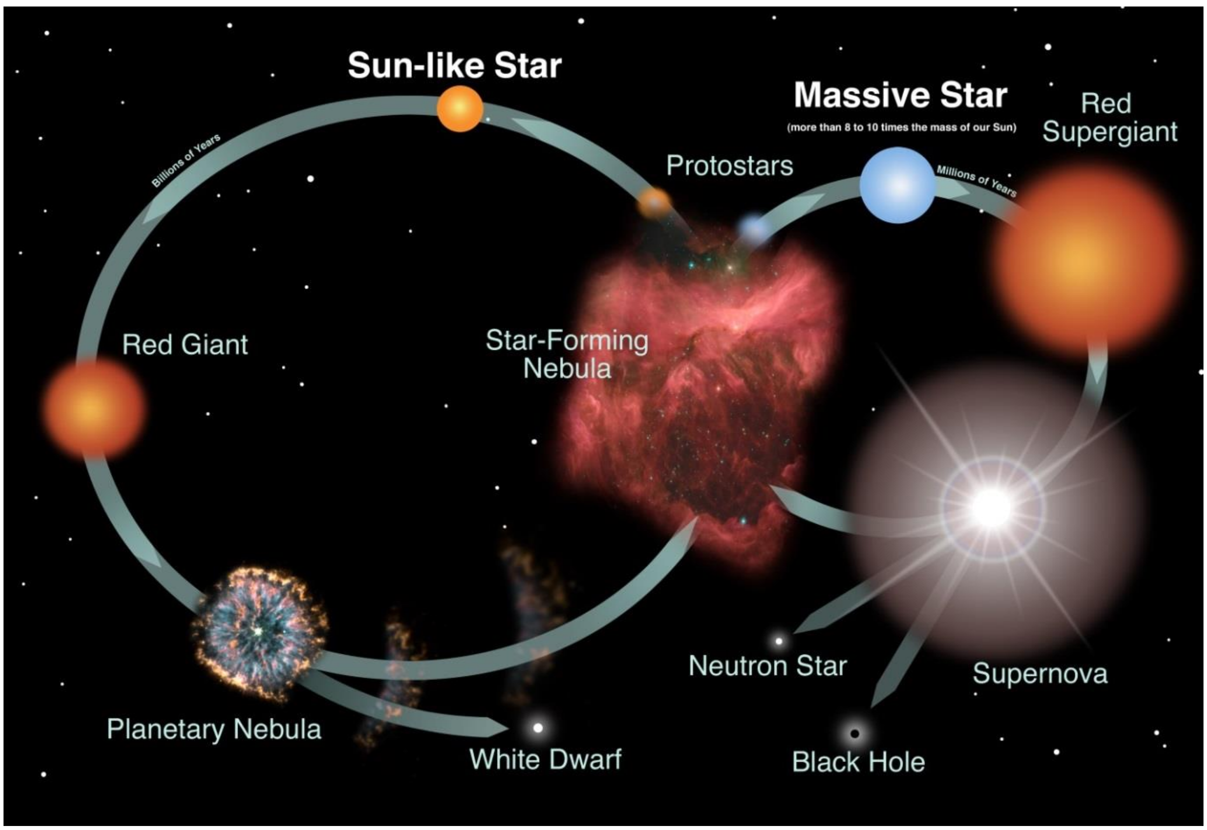


Figure 7-Diagram showing the lifecycle of Sun-like (low mass) and massive stars. (NASA and the Night Sky Network)

Death of a Low Mass Star

While all stars are essentially born the same way, the same is not true of death. For Sun-like stars, death begins when the star runs out of hydrogen in its core and nuclear fusion stops. With nothing to counteract gravity, equilibrium is lost and the helium-rich core begins to collapse. This increases the temperature of the star’s interior, causing unused hydrogen in a

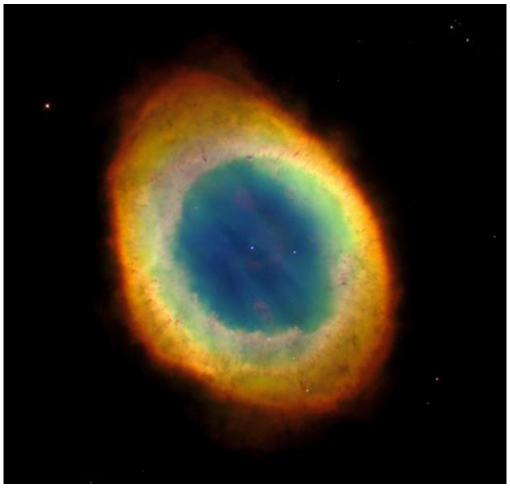


Figure 8-The Ring Nebula, the remains of a dead Sun-like star. Note the white dwarf core leftover at the center. (The Hubble Heritage Team-AURA/STScI/NASA)

shell surrounding the core to begin fusing into helium. The energy released by this process causes the star to swell into a **red giant** many times larger than the original star. Eventually, the helium core contracts and gets hot enough for helium to be fused into carbon and oxygen. When this happens, the star remains a giant, but shrinks and becomes hotter and bluer.

Once the helium is exhausted, the star's days are truly numbered. With a collapsing core of carbon and oxygen surrounded by shells of "burning" hydrogen and helium, the star becomes unstable and may begin to pulsate. The outer layers become effectively detached from the rest of the star and begin to expand outward into space. Astronomers call this expanding shell of gas a **planetary nebula** (although there is nothing planetary about them, see *Chapter 2.5*). In the center of many planetary nebulae sits the leftover core, a hot ball of carbon and oxygen known as a **white dwarf** (Fig 8).

Note that this description applies mainly to stars with 0.8 to 8 times the mass of the Sun. Stars smaller than about 0.8 solar masses live longer than the present age of the universe, so none have died to date.[13] Stars larger than about eight times the mass of the Sun put on a much more spectaculr show.

Death of a High Mass Star

In stark contrast to the relatively quiescent death of a small star, high mass stars, like the O and B-type supergiants and giants in the constellation Orion, explode when they die.

The death of a high-mass star starts in much the same way as a low-mass star. However, their larger mass and higher core temperatures permit the fusion of carbon and oxygen into additional elements, like silicon, sulfur, and eventually iron. Iron cannot be fused into heavier elements without an *input* of energy. Once the star has a core full of iron, nuclear fusion cannot proceed and the star has reached the end of its life. The iron core contracts under the influence of gravity until it can contract no more then "rebounds," sending a violent shock wave out through the rest of the star, generating the massive explosion that we call a **supernova** (plural=**supernovae**). A supernova can be billions of times more luminous than the Sun and momentarily outshine all the other stars in a galaxy combined. Note that several other processes can also generate supernovae. The specific type described here, those generated by the core collapse of a massive star, are known as *Type II* supernovae.

From Earth, a distant supernova typically looks like a star that suddenly grows brighter and brighter until it dims again (Fig 9). The process can take several weeks, and if you are not looking at the right spot every night, it can look as if a star just appeared out of nowhere. Supernovae also play an important role in the evolution of the universe. In these explosions, the elements produced by nucleosynthesis, and others forged in the supernova itself, are dispersed throughout the galaxy to eventually form new stars and planets.

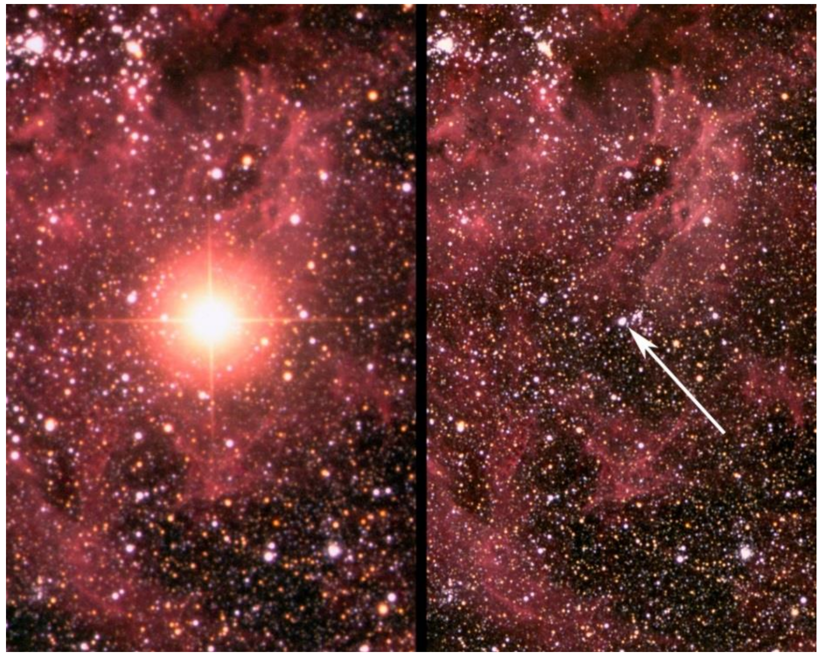


Figure 9-Supernova 1987A (left), the explosion of a massive star in a nearby galaxy witnessed in February 1987. The star, known as Sanduleak –69° 202, is shown in the "before" photo at right. The star increased in luminosity by a factor of 100 million during the supernova. (David Malin/AAO)

The Afterlife

Once stars die, they don't disappear entirely. They leave remnants of themselves that we can see long after the star is gone.

Low Mass Star: White Dwarf

A **white dwarf** is the leftover core of a low-mass star. Although white dwarfs are sometimes called "white dwarf stars," they are not stars in the true sense because there are no nuclear processes going on inside them. Thus, a white dwarf does not shine in the way that a star does. So how can we still see them? If you take a rock and heat it up until it glows, you can understand how we see white dwarfs. When we look at a white dwarf, we are essentially seeing a cooling cinder, nothing more than the intense heat left over from the extreme temperatures that occurred inside the star while it was still alive.

White dwarfs are very small, very hot, and very dense. A typical white dwarf might contain the mass of the Sun in an area only about the size of the Earth. Consequently, white dwarfs are also relatively dim, both in luminosity and apparent magnitude, because of their small surface area.

High Mass Star: Neutron Stars and Black Holes

The death of a high mass star will leave behind either a **neutron star** or a stellar mass **black hole** in the aftermath of a supernova.

A neutron star is an extremely dense object that does on a subatomic level what stable stars do on an atomic level: protons and electrons are literally squeezed into neutrons at the conditions inside a neutron star. Neutron stars are subject to a high gravitational pull because of their extreme density. A human would weigh many billions (or even trillions) of pounds on a neutron star.

The most massive stars collapse into stellar mass black holes instead of neutron stars. A black hole forms when gravity collapses a massive object into an area so small that the space surrounding it experiences such an extreme gravitational pull that nothing, not light, not sound, not smell, can escape from it. The object at the center of the black hole, the object that used to be a star, is called the singularity, and the area around the black hole that acts as a threshold from which nothing can escape is called the event horizon. Because no information of any kind can escape the event horizon, we can't study black holes the way we can study other objects in the universe.

It's important to note that there are several different kinds of black holes, including supermassive black holes at the center of **spiral galaxies**. These are millions of times more massive than the *stellar mass black holes* that come from collapsing stars. Stellar mass black holes are actually pretty common: the first one discovered and confirmed was Cygnus X-1, in the constellation Cygnus.

Conclusion

Stars are unique objects in astronomy because they were never "discovered." The study of stars has taken us from believing that they were immovable bright lights on a distant sphere to uncovering some of the most fantastic physics ever imagined. Humans have always known about stars, but until recently we didn't know how far away they really are, how enormous they really are, or how different they are from each other. Today we understand how old the Sun is, how different Betelgeuse is from Sirius, what stars are made out of, and how they will die, yet we still struggle to comprehend the physics of a star. Stars are probably the strangest objects that we see every day. The more we know about them, the more we know they're not like anything we experience on Earth. In short, we have no analog for a star. The night sky is populated by strange objects indeed.

Review

Common misconceptions

Below is a list of commonly encountered misconceptions about stars. As a way to review content from this chapter, see if you can explain why each misconception is inaccurate:

- The Sun is a large burning ball of gas and/or fire.
- The Sun is a unique object and not a star.

- The Sun and stars will last forever/don't change over time.
- All stars are "yellow."
- There are many stars in our Solar System.
- All stars explode in supernovae.
- Red stars are hotter than blue stars.

Questions for thought

- You are hosting a star party and have just explained how most of the elements on the periodic table come from the nuclear processes inside the core of stars. Someone says: "So a star takes hydrogen and turns it into something valuable, like gold?" What's the problem with this reasoning?

- You see a meme that says: "When you wish upon a star, it's too late because the star is dead." What's the problem with this reasoning?

- You'll often hear that the stars in the night sky are simply "other Suns." Such a statement is technically correct, but also a bit of an oversimplification. What does our Sun have in common with all the other stars in the night sky? How does it differ?

- Which type of star do you think is most conducive to a solar system capable of supporting life? Why?

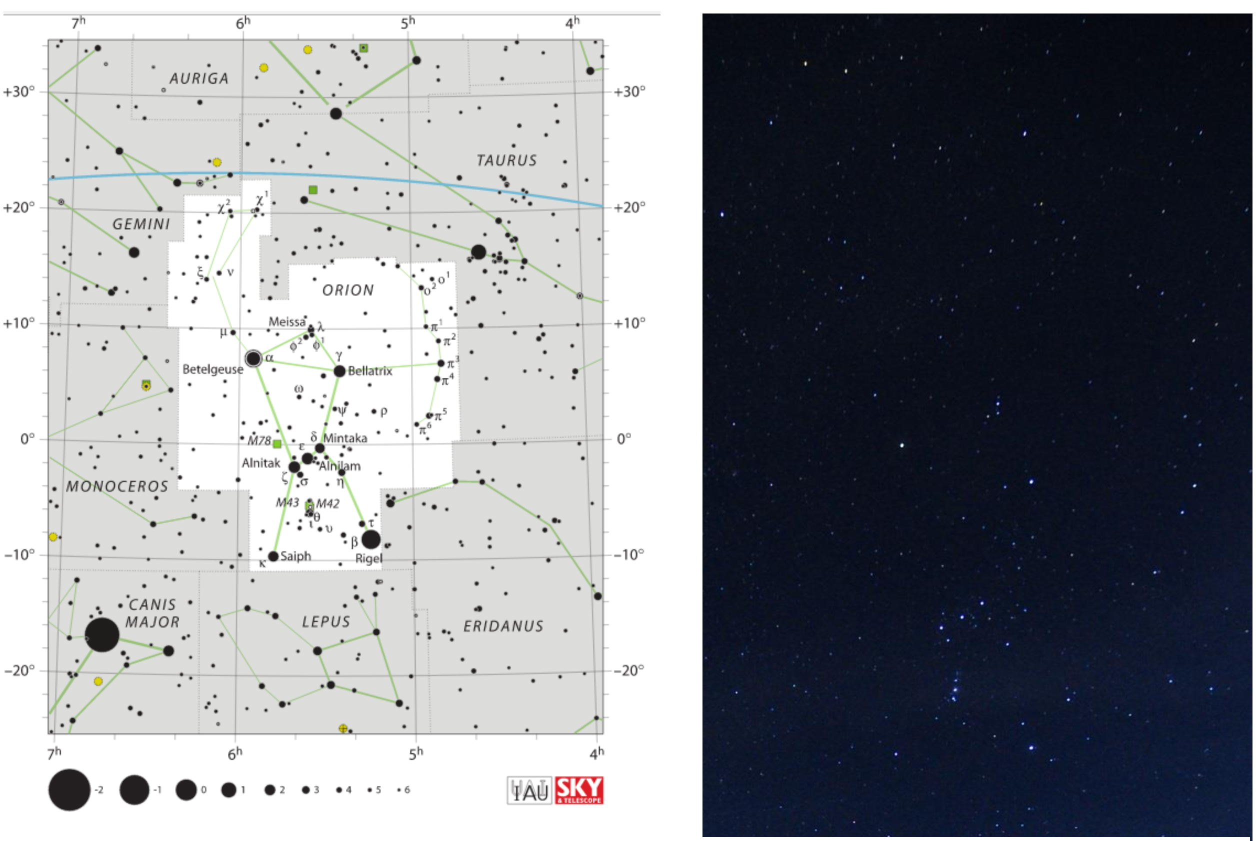
- How do stars currently forming differ from those formed in the early universe? Do any of these differences have consequences for planet formation and/or life?

- A single star lives much longer than a human, so how are astronomers able to decipher the evolution and lifespan of stars?

For More Information

- American Association of Variable Star Observers: https://www.aavso.org/
- *The Hundred Greatest Stars*, by James B. Kaler, 2002
- *The Little Book of Stars*, by James B. Kaler, 2001
- *Miss Leavitt's Stars: The Untold Story of the Woman Who Discovered How to Measure the Universe*, by George Johnson, 2006
- "Stars" (information from stellar astronomer James B. Kaler): http://stars.astro.illinois.edu/sow/sowlist.html
- "Stars" (NASA webpage on stars): https://science.nasa.gov/astrophysics/focus-areas/how-do-stars-form-and-evolve

CHAPTER 2.8: CONSTELLATIONS



The constellation Orion, represented on a star chart (left) and in a photograph (right). (Chart: International Astronomical Union/Sky & Telescope. Photo: Zach Schierl)

Chapter 2.8 Goals

After reading this chapter and participating in the corresponding workshop activities, you should be able to:

- Explain how constellations are two-dimensional patterns and provide examples of how different cultures have seen different patterns among the same stars.
- Identify and provide basic information about several prominent constellations, their brightest stars, and any significant deep sky objects within them.

Patterns in the Night

Historically speaking, **constellations** are the patterns that humans see among the stars in the night sky. They are not physical objects in space, but rather constructs of the human mind. Throughout history, virtually all well-documented civilizations had their own constellations, although today they are often hard to see due to the rising tide of light pollution.

While the idea of constellations is universal, not everyone saw the same figures in the sky. Nor was the idea of constellations strictly limited to connections between stars. Some cultures, such as the Quechua-speaking people of the Peruvian Andes, also identified figures, or "dark constellations," in the dark dust clouds of the Milky Way.[1] Can you see the giant llama in the dark voids of Figure 1?

Figure 1-Some cultures have seen "constellations" in the dark dust lanes of the Milky Way Galaxy. Can you? (Zach Schierl)

Constellations appear on the cover of a box found in the tomb of Zeng Hou Yi, a member of Chinese royal society buried around 433 BCE.[2] These constellations do not resemble those used by Western astronomers today, but instead reflect Chinese constellations. Constellations have also been found on the Egyptian tombs of Seti I (d. 1279 BCE), and Senmut (d. 1464 BCE). While some, such as the Big Dipper (depicted as part of a bull), are recognizable to us, many others would look odd, such as the crocodile, the bird above the lion's head, the god An, the goddess Serket, and the hippopotamus.[3]

Constellations in Three Dimensions

It is natural to assume that the stars within a given constellations are close to one another. But it is important to remember that a constellation is not a physical object or place in space. We see the stars on a two-dimensional bowl (the night sky) when in reality the universe is three-dimensional. Looking up at the night sky, we have few clues about the true distance of the stars. This makes many stars look like they are close together when in reality they are not.

Until recently, no one knew how far away the stars were. For most of human history, stars were seen as objects fixed to a celestial sphere that surrounded Earth. The concept of three-dimensional space did not exist. It's not hard to see why the idea of a celestial sphere was popular. After all, the stars all appear to move at exactly the same rate and distance, as though mounted onto a distant, slow-moving, enormous sphere. Not until the mid-1800s were astronomers able to begin accurately measuring the true distance to the stars.

We now know that the distances to the stars vary greatly, even within a single constellation. For example, in the constellation Cygnus the swan, the star Deneb (the tail) is more than 1,500 **light-years** away, while Epsilon Cygni (the left wing) is a measly 70 light-years away. These two stars appear close to either other on the sky, but aren't physically close to each other at all because they lie at vastly different distances from our Solar System.

Even today, we sometimes see the product of this confusion. In the 2012 film *Prometheus*, the characters use a depiction of a constellation as a navigational guide to a distant star system. In reality, this could not happen. Because constellations are two-dimensional representations of three-dimensional space, the ones we see are unique to our Solar System. Travel to even the nearest star and the patterns will look very different. As a result, constellations would not be useful as maps or navigational aids for hypothetical interstellar travelers.

In a few cases, stars that look like close together actually are. For example, many of the stars in Ursa Major (the constellation home to the Big Dipper) belong to the Ursa Major Moving Group. A **moving group** (or **association**) is a group of stars that are all moving together as a collective group through the galaxy. The Ursa Major Moving Group has at least 60 members, including all the bright stars in the Big Dipper, except for Alkaid and Dubhe.[4]

Constellations in Modern Astronomy

Historically, a constellation was a *pattern* seen by humans in the night sky. In modern astronomy, constellations are defined as an *area* of the sky. In 1928, the International Astronomical Union (IAU) standardized the constellations used by professional astronomers by carving up the night sky into 88 official constellations (see Table 1). In modern astronomy, a constellation is akin to a country on a world map, or perhaps a puzzle piece; a discrete region of the sky defined by often jagged boundaries (Fig 2).

As a result, every star and deep-space object in the sky “belongs” to one of the 88 constellations, even if it is not part of the traditional stick-figure pattern. Astronomers, professional and amateur alike, will often speak of a planet or star being “in” a particular constellation (e.g., “Mars is in Taurus right now”). This means that the object in question is within the boundaries of that particular constellation.

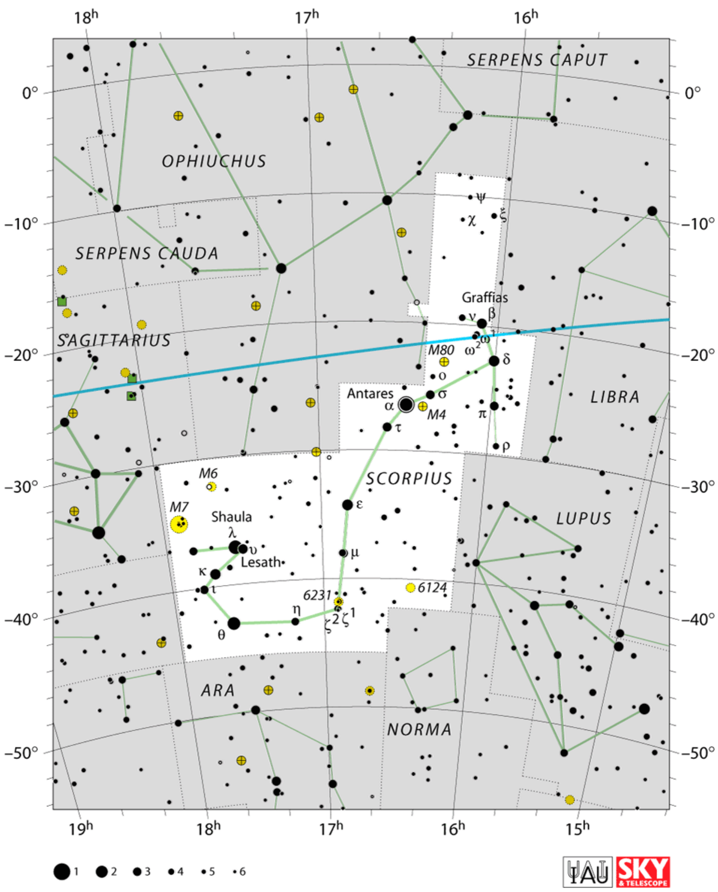


Figure 2-The constellation Scorpius. This chart shows both the traditional stick figure depiction of Scorpius, as well as the IAU constellation boundaries. (International Astronomical Union/Sky & Telescope)

Not all 88 constellations are visible everywhere on Earth. Constellations like Ursa Major, Ursa Minor, and Cassiopeia are too close to the **north celestial pole** to be visible from far southern latitudes. Similarly, those of us in the north never get the opportunity to see southern gems like Crux (the Southern Cross) and Carina (the Ship’s Keel). Even mid-southern constellations like Scorpius and Sagittarius only poke their heads (or stingers) above the horizon for a month or two from our latitude. Only from the equator are all 88 constellations visible at some point during the year.

Figure 3-The Big Dipper is an asterism, that is, a small part of the larger constellation Ursa Major, the Great Bear. (Lunar and Planetary Institute, Houston)

When is a constellation not a constellation?

Ask any large group of people what the most famous constellation is and you will likely be met with a chorus of “the Big Dipper!” But this is incorrect. Many well-known patterns of stars in the night sky are not officially recognized as one of the 88 constellations.

Table 1: The 88 Official Constellations (*italics* denote those never visible from Southern Utah)

Latin Name	English Name	Latin Name	English Name
Andromeda (And)	Princess of Ethiopia	Lacerta (Lac)	Lizard
Antlia (Ant)	Air pump	Leo (Leo)	Lion
Apus (Aps)	*Bird of Paradise*	Leo Minor (LMi)	Little lion
Aquarius (Aqr)	Water bearer	Lepus (Lep)	Hare
Aquila (Aql)	Eagle	Libra (Lib)	Balance/scales
Ara (Ara)	*Altar*	Lupus (Lup)	Wolf
Aries (Ari)	Ram	Lynx (Lyn)	Lynx
Auriga (Aur)	Charioteer	Lyra (Lyr)	Lyre or harp
Bootes (Boo)	Herdsman	*Mensa (Men)*	*Table mountain*
Caelum (Cae)	Graving tool	Microscopium (Mic)	Microscope
Camelopardalis (Cam)	Giraffe	Monoceros (Mon)	Unicorn
Cancer (Cnc)	Crab	*Musca (Mus)*	*Fly*
Canes Venatici (CVn)	Hunting dogs	*Norma (Nor)*	*Carpenter's Level*
Canis Major (CMa)	Big dog	*Octans (Oct)*	*Octant*
Canis Minor (CMi)	Little dog	Ophiuchus (Oph)	Holder of serpent
Capricornus (Cap)	Sea goat	Orion (Ori)	Orion, the hunter
Carina (Car)	*Ships keel*	*Pavo (Pav)*	*Peacock*
Cassiopeia (Cas)	Queen of Ethiopia	Pegasus (Peg)	Pegasus, winged horse
Centaurus (Cen)	Centaur	Perseus (Per)	Perseus, hero
Cepheus (Cep)	King of Ethiopia	Phoenix (Phe)	Phoenix
Cetus (Cet)	Sea monster (whale)	*Pictor (Pic)*	*Easel*
Chamaeleon(Cha)	*Chameleon*	Pisces (Psc)	Fishes
Circinus(Cir)	*Compasses*	Piscis Austrinis (PsA)	Southern fish
Columba (Col)	Dove	Puppis (Pup)	Poop deck
Coma Berenices (Com)	Berenice's hair	Pyxis (Pyx)	Ship’s compass
Corona Australis (CrA)	Southern crown	*Reticulum (Ret)*	*Net*
Corona Borealis (CrB)	Northern crown	Sagitta (Sge)	Arrow
Corvus (Crv)	Crow	Sagittarius (Sgr)	Archer
Crater (Crt)	Cup	Scorpius (Sco)	Scorpion
Crux (Cru)	*Cross (southern)*	Sculptor (Scl)	Sculptor's tools
Cygnus (Cyg)	Swan	Scutum (Sct)	Shield
Delphinus (Dep)	Dolphin	Serpens (Ser)	Serpent
Dorado (Dor)	*Swordfish*	Sextans (Sex)	Sextant
Draco (Dra)	Dragon	Taurus (Tau)	Bull
Equuleus (Eql)	Little horse	Telescopium (Tel)	Telescope
Eridanus (Eri)	River	Triangulum (Tri)	Triangle
Fornax (For)	Furnace	*Triangulum Australe (TrA)*	*Southern triangle*
Gemini (Gem)	Twins	*Tucana (Tuc)*	*Toucan*
Grus (Gru)	Crane	Ursa Major (UMa)	Great bear
Hercules (Her)	Hercules, son of Zeus	Ursa Minor (UMi)	Little bear
Horologium (Hor)	*Clock*	Vela (Vel)	Ship’s sail
Hydra (Hya)	Sea serpent	Virgo (Vir)	Virgin or maiden
Hydrus (Hyl)	*Water snake*	*Volans (Vol)*	*Flying fish*
Indus (Ind)	*Indian*	Vulpecula (Vul)	Fox

For example, the Big Dipper is a group of seven bright stars *within* the larger constellation of Ursa Major, the Great Bear (Fig 3). Well-known groupings of stars that are not official constellations are known as **asterisms**. Another well-known asterism is the Summer Triangle, which consists of the bright stars Vega, Deneb, and Altair, which themselves belong to three separate constellations.

Naming the Stars and Constellations

Of the 88 official constellations used by astronomers today, the majority (about 48) come to us from the Greeks.[5] One of the oldest records of constellations that we would be familiar with comes from the book *Phaenomena,* written by the Greek poet Aratus of Soli (ca 315-240 BCE). Though it is literary in nature, it describes many recognizable constellations including the bears (Ursa Major and Ursa Minor), the dragon (Draco), the virgin (Virgo), the queen (Cassiopeia), the serpent bearer (Ophiuchus), and Orion.[6]

Many Southern Hemisphere constellations were "invented" by European astronomers during expeditions to map the southern sky in the 15th through 17th centuries. Astronomers named many of them for contemporary inventions or pieces of navigational equipment. This is why the Southern Hemisphere sky is graced by constellations such as Sextans (the sextant), Circinus (the compasses), and Horologium (the pendulum clock). Other astronomers around this same time decided to fill in the gaps between the traditional Greek constellations with creations of their own, leading to northern constellations such as Lacerta (the lizard), Cameleopardalis (the giraffe), and Monoceros (the unicorn). These so-called "modern constellations" tend to be small, dim, and lacking in bright stars.

Many constellation names are quite long. To avoid writing out the whole name when referring to objects or stars within them, the constellations are often referred to in print by three letter abbreviations (see Table 1).

…it should be emphasized that the credit for the suggestion of such symbols belongs entirely to Professor Hertzsprung – to whom astronomers will be increasingly indebted as they contemplate their reduced bills for printing.

– Henry Norris Russell, 1922

Star names

While the constellations we're familiar with are most likely to be Greek, most common star names come from Arabic. For example, many star names begin with "Al" (Alcor, Algeiba, Altair, Alnitak) which literally translates to "the" in Arabic.

Only a handful of the brightest stars even have common names. The rest of the bright naked eye stars have formulaic names based on the Greek alphabet, shown in Table 2. This system was devised by astronomer and star mapper Johannes Bayer in 1603. Bayer decided to call the brightest star in a given constellation Alpha (α), the second brightest Beta (β), and so on. Thus, the North Star (Polaris), the brightest star in the constellation Ursa Minor (the little bear), is also known as "Alpha Ursa Minoris." This naming convention is known as the **Bayer System**.

Table 2: The Greek Alphabet	
α	Alpha
β	Beta
γ	Gamma
δ	Delta
ε	Epsilon
ζ	Zeta
η	Eta
θ	Theta
ι	Iota
κ	Kappa
λ	Lambda
μ	Mu
ν	Nu
ξ	Xi
ο	Omicron
π	Pi
ρ	Rho
σ	Sigma
τ	Tau
υ	Upsilon
ϕ	Phi
χ	Chi
ψ	Psi
ω	Omega

Table 3 (following page) lists the 25 brightest stars in the night sky, along with their Bayer System names and **apparent magnitudes**. Note that there are a few discrepancies in the Bayer System. Bayer, working in the 1600s, was not able to discern small differences in brightness between stars of very similar magnitudes. For example, Pollux is designated as Beta Geminorum, even though it is a few tenths of a magnitude brighter than Castor, which is Alpha Geminorum.

Variable stars also throw a wrench into the Bayer System. For example, Betelgeuse is a variable star and is designated as Alpha Orionis. However, its variability means that it is not always the brightest star in Orion. When Betelgeuse is at its dimmest, Rigel (Beta Orionis) temporarily becomes the brightest star in Orion until Betelgeuse brightens again and reclaims the title.

Learning the Constellations

Learning the constellations is much like moving to a new city and learning to navigate your way around town without a map. At first it seems overwhelming, but quickly gets easier as you learn to recognize new landmarks and gain familiarity with your surroundings. It does take time, especially when you consider that new constellations come into view each season, and that some are only visible for a few months of the year. Learning the constellations is rewarding, and is also a key skill you need to effectively operate a telescope.

Don't try to find and learn every constellation in the sky on a single night. Most people find it easier to focus on learning one or two new constellations each time they go outside to stargaze. By focusing on one or two new constellations at a time, and always revisiting old ones, you will gradually expand your constellation repertoire over time.

That's supposed to be a Herdsman?

At first glance, many constellations may seem to bear little resemblance to the animal, person, or thing they supposedly represent (Fig 4). This can be an obstacle to learning them; without a memorable pattern, it can be hard for many constellations to make a lasting impression. While it is tempting to make fun of the ancient Greeks for their overly imaginative constellations, let's take a few moments to consider why this might be.

Many of our most famous constellations had their origins thousands of years ago. Even the "modern" constellations are several hundred years old. All 88 come from a time before we had an armada of electronic devices to entertain us at night. They come from a time when humans spent much more time outside at night looking up at the sky than we do now. They come from a time when humans likely had a deeper connection to what they saw in the sky. Ask yourself: is the fact that we have trouble seeing a bear in the stars of Ursa Major a statement about the imagination of ancient skywatchers? Or is it a statement about us here in the 21st Century?

Table 3: The 25 Brightest Stars

Rank	Common Name	Bayer Name	Constellation	Apparent Magnitude	Best Season
1	Sirius	Alpha Canis Majoris	Canis Major	-1.46	Winter
2	Canopus	Alpha Carinae	Carina	-0.72	*Southern*
3	Rigil Kentaurus	Alpha Centauri	Centaurus	-0.27	*Southern*
4	Arcturus	Alpha Bootis	Bootes	-0.04	Summer
5	Vega	Alpha Lyrae	Lyra	0.03	Summer
6	Capella	Alpha Aurigae	Auriga	0.08	Winter
7	Rigel	Beta Orionis	Orion	0.12	Winter
8	Procyon	Alpha Canis Minoris	Canis Minor	0.38	Winter
9	Achernar	Alpha Eridani	Eridanus	0.46	*Southern*
10	Betelgeuse	Alpha Orionis	Orion	0.50 (var)	Winter
11	Hadar	Beta Centauri	Centaurus	0.61 (var)	*Southern*
12	Acrux	Alpha Crucis	Crux	0.76	*Southern*
13	Altair	Alpha Aquilae	Aquila	0.77	Summer
14	Aldebaran	Alpha Tauri	Taurus	0.85 (var)	Winter
15	Antares	Alpha Scorpii	Scorpius	0.96 (var)	Summer
16	Spica	Alpha Virginis	Virgo	0.98 (var)	Spring
17	Pollux	Beta Geminorum	Gemini	1.14	Winter
18	Fomalhaut	Alpha Piscis Austrini	Piscis Austrinus	1.16	Fall
19	Becrux	Beta Cru	Crux	1.25 (var)	*Southern*
20	Deneb	Alpha Cygni	Cygnus	1.25	Summer
21	Regulus	Alpha Leonis	Leo	1.35	Spring
22	Adhara	Epsilon Canis Majoris	Canis Major	1.50	Winter
23	Castor	Alpha Geminorum	Gemini	1.57	Winter
24	Gacrux	Gamma Crucis	Crux	1.63 (var)	*Southern*
25	Shaula	Lambda Scorpii	Scorpius	1.63 (var)	Summer
					Data:[7]

On a less philosophical note, consider also that many of the stars that make up the traditional constellation patterns are faint and easily washed out by **light pollution**, something that didn't exist when these constellations were first developed. (Moonlight can also cause many of these stars to disappear.) For example, Ursa Major is hard to pick out from Cedar City not because Cedarians lack imagination, but simply because most of its stars are masked by **skyglow**. It's hard to see a bear with 75% of its body erased by light pollution! Thousands of years ago, astronomers in the largest cities on Earth would have seen a darker night sky, and more stars, than folks in rural Utah do today.

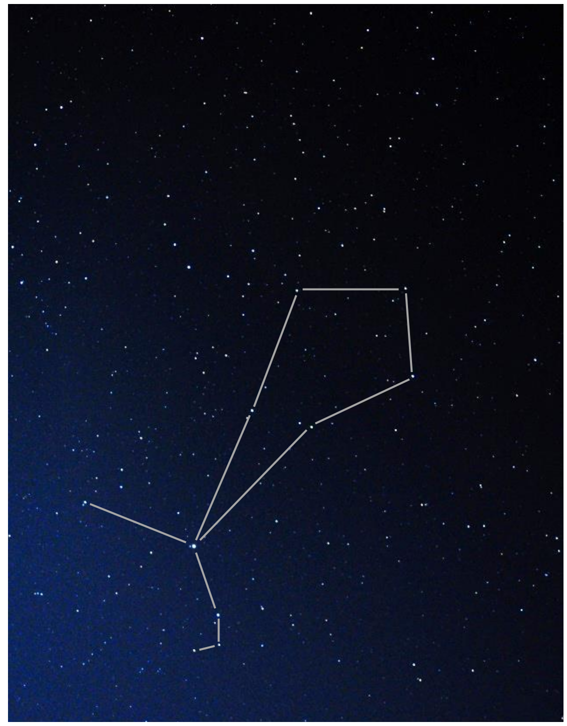


Figure 4-Traditional representation of the constellation Boötes, the Herdsman. (NPS/Zach Schierl)

All hope is not lost though. H.A. Rey (of *Curious George* fame), wrote a book on constellations called *The Stars: A New Way to See Them.* Rey redraws the traditional constellation stick-figures in an attempt to make each look more like its namesake. For the most part, he succeeds, making this a recommended resource for people who want their Cygnus to actually look like a swan. Rey's patterns are generally more memorable and easier to learn than those in typical constellation books, but not even the best field guide can bring back stars lost to light pollution. If you really want to see the constellations, there is no substitute for going somewhere truly dark. Dark sky stewardship truly is "constellation conservation"!

Using a Planisphere or Star Chart

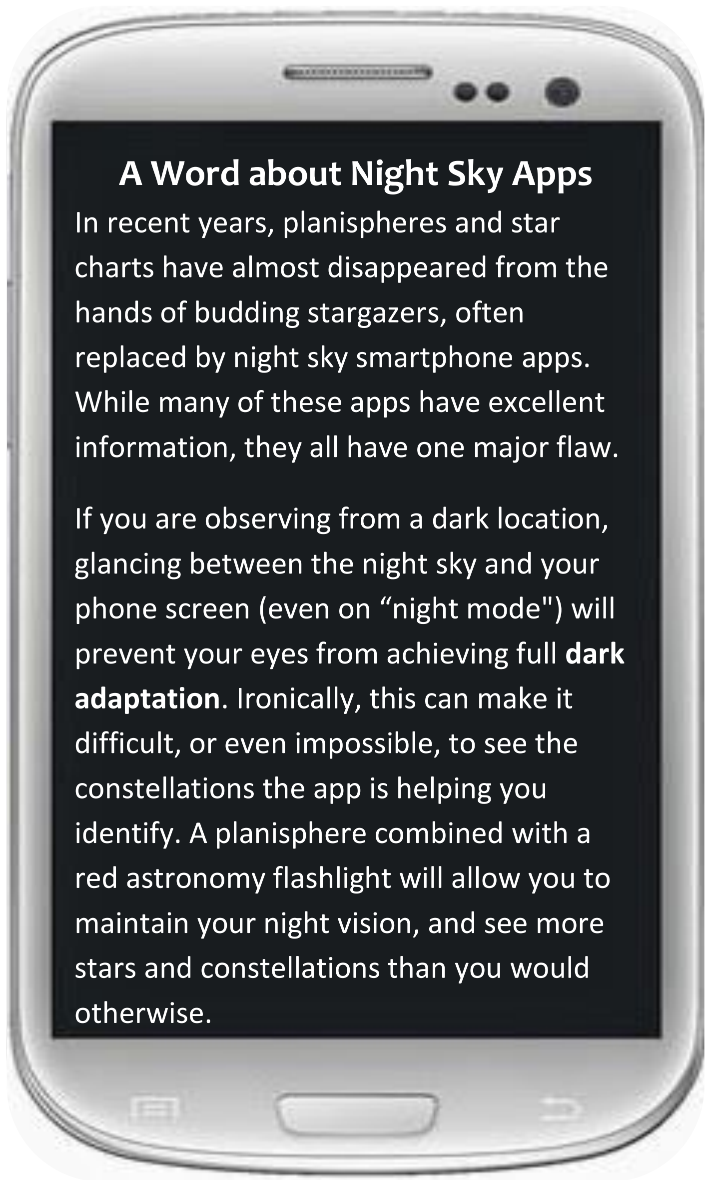
One of the best tools for learning constellations is a planisphere or star wheel. (See note on night sky apps on the next page.) A planisphere is a rotating disk that displays which stars and constellations are visible throughout the year (Fig 5). Many astronomy field guides and magazines have static sky maps that serve a similar purpose.

Because the sky you see depends on how far north or south of the equator you are, planispheres are not universal. For example, one designed for use in the continental United States will be useless in New Zealand, or even Hawai'i or Alaska. A given planisphere is typically useful for +/- 10° of the stated latitude. For example, the one shown in Figure 5 on the next page says "Latitude 40° North," so it would be useful for most of the continental U.S.

Figure 5-A typical planisphere (left) used to identify stars and constellations. To use, align the date and time along the edge. Here, the planisphere is set for observing on March 15th at 9 pm. (NPS/Zach Schierl)

All planispheres work the same way. Around the edges, you will see dates and times (Fig 5, right). Begin by lining up the current date with the time of night you plan to observe. (If your area is observing daylight savings time, you must subtract one hour. If it is 11 pm in mid-summer, set the planisphere to 10 pm.) Once the date and time are set, the sky in the circular window should match what you see outside.

To use the planisphere, you need to know which direction you are looking. If you can identify the North Star, this is easy. If not, use a compass or app. Find the edge of the planisphere that corresponds to the direction you are facing and hold that edge out in front of you. You've now oriented the planisphere, and can begin trying to match the patterns to those in the night sky. Start by identifying the brightest stars (the largest circles on the map) and using these as signposts to the constellations.



Green Laser Pointers

Green laser pointers are a ubiquitous sight at star parties and other astronomy outreach events these days. The lightsaber-esque beam, extending skyward seemingly to infinity, makes it easy to point out stars, planets, constellations, and satellites to large groups (Fig 6). For good reason, astronomy educators have fallen in love.

What sets these green lasers apart from their red brethren? Green lasers emit a very powerful and focused beam of light with a wavelength of 532 nanometers. At a given power, green lasers appear brighter than red ones because our eyes are more sensitive to this wavelength of green light. The beam reflects off particles in the atmosphere, allowing us to clearly see the beam.

While green laser pointers can be a wonderful educational tool, they also have the potential to be dangerous, and must always be used with caution! Lasers with a power output of more than 5 milliwatts are not legally considered "pointers" by the U.S. Food and Drug Administration and should be avoided for astronomy. Even a 5 milliwatt pointer can result in serious eye damage if used improperly. When using green lasers for astronomy education, follow all local laws and always take the following precautions:

Figure 6-A park ranger uses a green laser pointer to point out constellations at Rocky Mountain National Park in Colorado. (NPS/Jeff Zylland)

- Never look directly into the beam. At arm's length, a typical green laser pointer beam is as bright as the Sun.
- Never point the beam at terrestrial objects or in the vicinity of aircraft, especially low-flying aircraft. Avoid using green lasers near airports. Amateur astronomers have been arrested and prosecuted for inadvertently aiming green lasers at aircraft![8]
- Never allow a member of the public or someone you don't know to hold or operate the laser. Children should never use a green laser pointer.
- Always be aware of your surroundings when using a green laser. Stand with your back to your audience, and avoid aiming the laser at objects close to the horizon so you do not accidentally hit taller individuals with the beam.

Mythology

Many people find constellations easier to remember if they know a story or legend to go along with it. Most of the Greek constellations have elaborate stories behind them, as do constellations from other cultures. These stories can often help you remember important facts about a constellation or group of constellations.

For example, according to the Greek legend, Orion was hunting one day when Scorpius stung him. Both Scorpius and Orion died and were put into the night sky – but to avoid future conflict, Zeus placed them on exactly opposite sides of the night sky. To this day Orion and Scorpius are never visible in the night sky at the same time. From the Northern Hemisphere, Orion is visible in the winter and early spring, while Scorpius is highest in late summer. Orion is also chasing the bull, Taurus, and stepping on the hare, Lepus. His trusty hunting dogs Canis Major and Canis Minor are right below his feet, and behind him, respectively.

The Greek story of Andromeda's family also gives us clues to where these constellations are in the night sky. Cepheus the King and Cassiopeia the Queen are Andromeda's parents. These two constellations are right next to each other, a little to the north of Andromeda herself. Like many Greek stories, tragedy befalls them. Cassiopeia boasts of her daughter's beauty, saying she is more beautiful than the sea nymphs. Poseidon gets mad and sends a sea monster, the constellation Cetus, to ravage the shore of their country. To avoid this, Cepheus and Cassiopeia choose to sacrifice Andromeda to Cetus. At the last moment, Perseus the hero shows up on his flying horse, Pegasus, and saves her by aiming the head of Medusa (which he had just returned from severing) at Cetus, causing the sea monster to turn into stone and sink to the bottom of the sea. All these constellations are located in the same area of the night sky, and are best seen in the fall.

A good storyteller armed with a green laser pointer (and dark skies) can make learning the constellations easy by making stories like these come alive. A dramatic retelling of an epic Greek legend, or introducing an audience to the black constellations of the Inca are great ways to connect people to the night sky. Constellation stories show that humans have been looking up since the dawn of our species. Under dark skies, we see the same constellations as past generations of humans. Only in the last century of our existence has seeing these patterns in the sky become a struggle, as light pollution laps ever higher at the stars.

Review

Common misconceptions

Below is a list of commonly encountered misconceptions about constellations. As a way to review content from this chapter, see if you can explain why each misconception is inaccurate:

- The stars in a constellation are physically near each other.

- The Big Dipper is a constellation.
- The North Star is the brightest/closest/largest star in the sky.
- We see the same constellations throughout the year.

Questions for thought

- Given that constellations are such a universal concept among different cultures, why do astronomers today use primarily the ancient Greek constellations?
- What is the significance of constellations in modern astronomy? How do they help astronomers?
- Among the best known constellations are those of the zodiac. What is it about this group of constellations that sets them apart?
- What can we learn about different cultures by studying their constellations? If you were to make set of constellations for your family, what sorts of shapes might you include?

For More Information

Green Laser Pointers

- "All I Want for Christmas is a Green Laser: How to Choose and Use One": https://www.universetoday.com/128930/choosing-using-green-lasers/
- "Some Pointers on Using Laser Pointers" (Sky & Telescope): http://www.skyandtelescope.com/observing/some-pointers-on-the-use-of-laser-pointers/

Constellation images, stories, and history

- *A Constellation Album,* by P.K. Chen, Sky and Telescope Publishing, 2007
- *Dot to Dot in the Sky* (children's book series), by Joan Marie Galat
- "Figures in the Stars: How cultures across the World have seen their myths and legends in the stars": http://www.datasketch.es/may/code/nadieh/
- "The Origins of the Constellations": http://www.jstor.org/stable/27856779
- Photos of the constellations: https://stellarscenes.net/english/seiza.htm
- *Sharing the Skies: Navajo Astronomy*, by Nancy C. Maryboy and David Begay, 4th Edition, 2010
- *Star Names: Their Lore and Meaning,* by Richard H. Allen, 1963
- *Star Tales*, by Ian Ridpath, 1990
- *Stars of the First People: Native American Star Myths and Constellations*, by Dorcas Miller, 1997

- *Why the North Star Stands Still,* by William R. Palmer, 1978

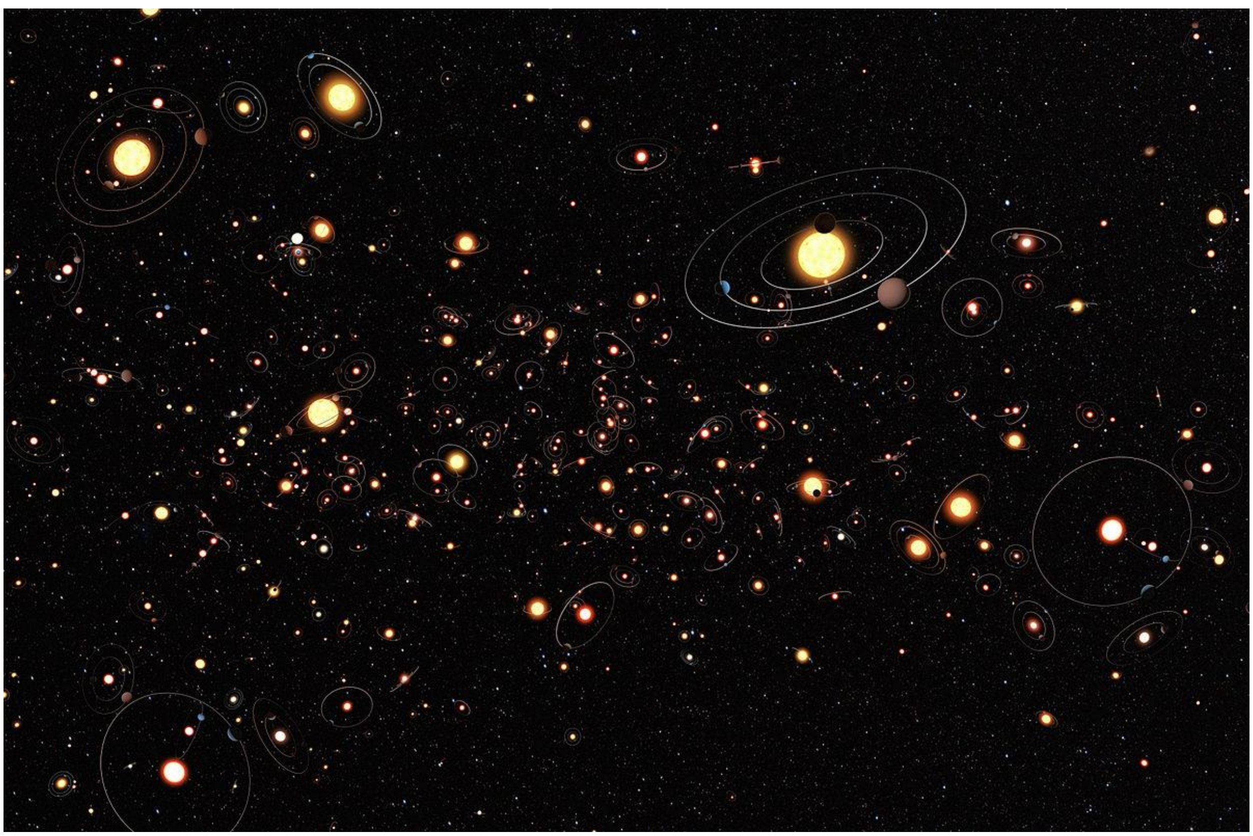
Constellation Field Guides and Star Atlases

- *Cambridge Star Atlas (4th Edition),* by Wil Tirion, 2011
- "The Evening Sky Map" (free monthly star charts): http://www.skymaps.com/downloads.html
- *Find the Constellations*, by H.A. Rey, 2016 edition
- *Sky & Telescope's Pocket Sky Atlas*, by Roger W. Sinnott, 2006
- *The Stars: A New Way to See Them*, by H.A. Rey, 2016 edition

Planispheres

- David H. Levy's Guide to the Stars: http://www.company7.com/books/products/graunplanispheres.html
- The Miller Planisphere: https://www.celestaire.com/product-category/astronomy-star-finding/miller-planisphere/
- "The Night Sky" planisphere: https://www.davidchandler.com/products/planispheres-star-charts/

CHAPTER 2.9: EXTRASOLAR PLANETS



Artist's impression of extrasolar planets; planets around stars other than our Sun. Over the past few decades, astronomers have come to realize that planets around stars are likely the rule rather than the exception. (ESO/M. Kornmesser, [CC BY 4.0](#))

Chapter 2.9 Goals

After reading this chapter and participating in the corresponding workshop activities, you should be able to:

- Discuss the primary motivations behind the search for extrasolar planets and how discoveries made to date compare with planets in our own Solar System.
- Explain the transit method of searching for extrasolar planets and describe its advantages, limitations, and biases.
- Provide a science-based summary of astrobiology, and discuss the basic prerequisites for finding life as we know it elsewhere in the universe.

An Infinity of Worlds

The space we declare to be infinite…In it are an infinity of worlds of the same kind as our own.

– Giordano Bruno, 1584

Extrasolar planets, or **exoplanets**, are planets outside of our Solar System, orbiting around other stars. More than 3,700 have been confirmed as of August 2018.[1] Of particular interest are exoplanets that might be similar to Earth and capable of hosting life. How do we find these planets? How do we determine their characteristics? What can exoplanets tell us about our own Solar System and planet? These are all questions that we will explore in this chapter.

The idea that stars are suns, and that those suns may have planets like our own is not a new one. Nor is the idea that other solar systems with Earth-like planets exist in the universe. Known as the Copernican Principle, the basic idea that we hold no special place in the universe became popular in Europe and the United States between the 1600s and 1800s. The common umbrella term for a belief that there are other solar systems, other Earth-like worlds, or other people (or aliens) living on other worlds is “pluralism,” and for several hundred years it swept through Western astronomy, philosophy, and religion like wildfire.

Pluralism became slightly less popular in the 1960s when the first probes sent to Mars and Venus returned a picture of dead worlds. The lack of water in the Solar System seemed to prove that Earth was special. But we now know that Mars, though dead and mostly dry now, was probably wet and warmer in the past. Then water began to be found all over the outer Solar System: Europa, Callisto, Ganymede, Enceladus, icy bodies in the Kuiper Belt, and the comets of the Oort Cloud. By the early 2000s, the idea that the Earth held no special significance in the galaxy was again gaining popularity.

Astronomers discovered the first exoplanets in 1992. In 1995, 51 Pegasi b became the first exoplanet discovered around a Sun-like star. Though 51 Pegasi b itself wasn’t Earth-like (it is about half the size of Jupiter and very close to its parent star, orbiting every 4 days), the discovery still changed astronomy forever.

As of August 2018, there are now 3,775 confirmed extrasolar planets, with the vast majority having been discovered in just the past few years (Fig 1). A little over two decades after the first discovery, astronomers are now confident that the majority of stars in our Milky Way Galaxy have their own planets, and that "stars are orbited by planets as a rule, rather than the exception."[2] Furthermore, estimates suggest that about 22% of Sun-like stars have a potentially habitable planet, that is, an Earth-sized planet at the correct distance from its parent star where liquid water could exist.[3] These are paradigm-altering conclusions that were completely unsupported just a decade ago. Given that there are hundreds of billions of stars in our Milky Way, the number of potentially habitable planets in the galaxy is truly vast.

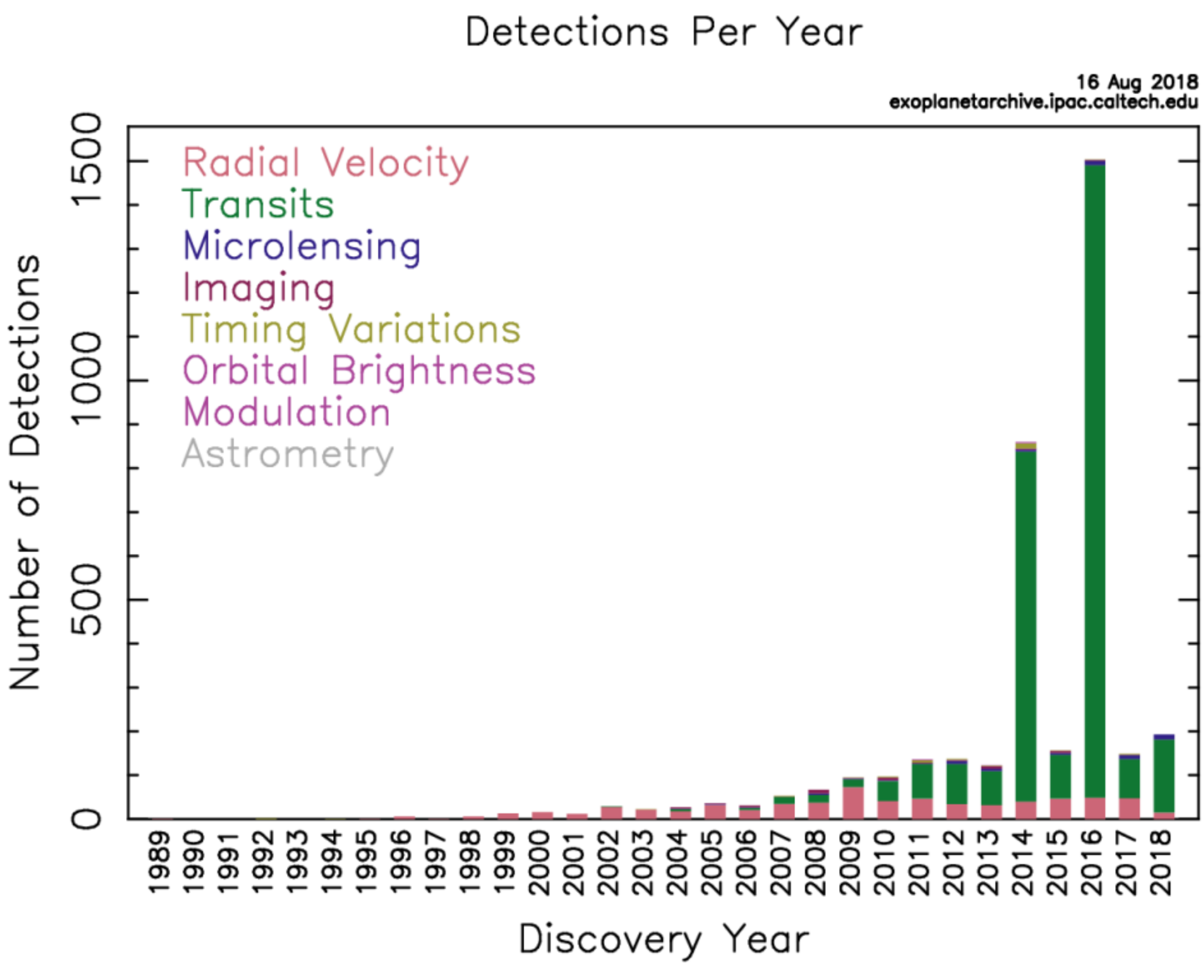


Figure 1-Graph showing the number of exoplanets discovered per year over the last two decades. The pace of discovery rose dramatically in the early 2010s, largely due to the success of NASAs Kepler mission. The color of the bars indicates the technique used to discover each planet. Green indicates the transit method, the technique used by Kepler. (NASA Exoplanet Archive)

Hunting for Exoplanets

The first detection of an extrasolar planet came in 1992 and it's easy to wonder, given the large telescopes and sophisticated cameras that astronomers had, what took so long?

Exoplanets are not easy to find. Seeing one directly is a bit like trying to spot a firefly in the glare of oncoming truck headlights. Because stars are so bright and planets shine only through reflected light, even a large exoplanet is going to be much, much fainter than its parent star. Furthermore, when seen from light-years away, the exoplanet and star will appear so close together that they essentially appear as a single object. Even today, most extrasolar planet "discoveries" have not been seen or photographed directly. Fortunately, astronomers have a variety of techniques that can be used to detect a planet's influence on its parent star.

Transit Method

The vast majority of confirmed exoplanets (2,951) have been detected using the **transit method** (Fig 1) so we'll explore this technique first.[4]

Imagine standing on a distant planet, one outside of our Solar System, and looking back at the Sun with a telescope. If your planet happened to be in the same plane as the Solar System, once per year, you would see the Sun dim very slightly as the Earth, itself invisible to you, passed between you and the Sun, momentarily blocking a miniscule amount of the Sun's light. Such an event is known as a **transit** (Fig 2**.** The Earth is so small that it would barely diminish the Sun's light, but if you kept watching, you might notice that the Sun's light dims a bit more noticeably every 12 years, the result of Jupiter transiting in front of the Sun. If you watched the Sun long enough, it would be theoretically possible to "discover" all of the planets in the **ecliptic** plane, without actually seeing any of them.

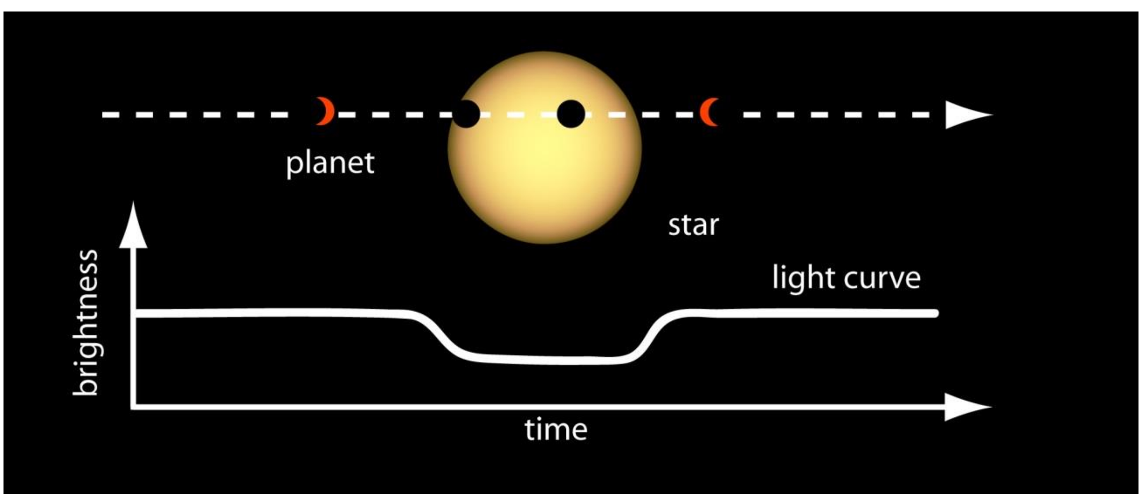


Figure 2-The transit method explained. As a hypothetical planet passes in front of its parent star from our point of view, the brightness of the star momentarily dips as the planet covers up part of the star. (NASA Ames)

Astronomers have been very successful searching for exoplanets using this concept. Sophisticated observatories can now detect the dimming of a star caused by the transit of a planet in front of it. In essence, astronomers carefully measure the light output of a star over a long period of time (often years) and watch for slight dips that could be the result of a planet passing in front of it. While other phenomena can cause a star to temporarily dim, a regular, periodic dimming is a pretty good sign that a planet is orbiting the star.

However, there are drawbacks to the transit method. In order to catch a planet transiting in front of its star, it needs to be in nearly the same plane as our Solar System. Therefore, a large percentage of planets, those that orbit on a plane perpendicular to our point of view, are undetectable using the transit method (Fig 3).

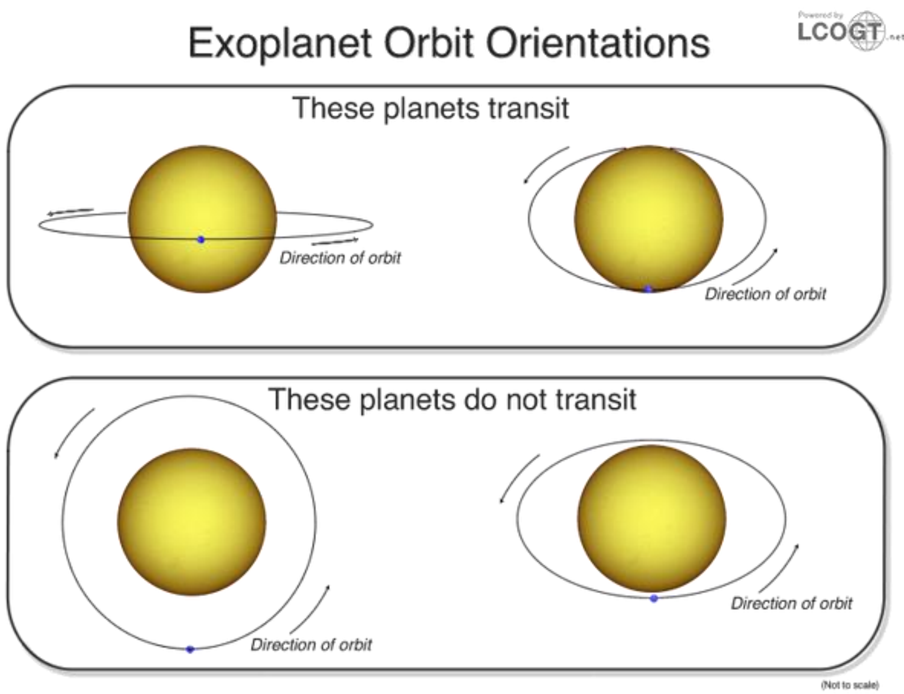


Figure 3-Not all planets can be detected using the transit method. Planets that orbit their parent star on a plane perpendicular to our line of sight (bottom) will not transit and cannot be detected using the transit method. (Las Cumbres Observatory)

NASA's **Kepler** mission, launched in 2009, features a space telescope that has been incredibly successful in using the transit method to discover exoplanets. From 2009 to 2013, the telescope monitored the brightness of 150,000 stars in the direction of the constellations Cygnus, Lyra, and Draco, every 30 minutes, looking for slight dips in brightness that could be caused by transiting planets. As of August 2018, Kepler had discovered 2,327 exoplanets and nearly 4,500 exoplanet candidates awaiting further study and confirmation.[5] For the first time, many of these discoveries are exoplanets similar in size to Earth (Fig 4). Prior to Kepler, most exoplanets discoveries were much larger than Earth, often the size of Jupiter or even larger.

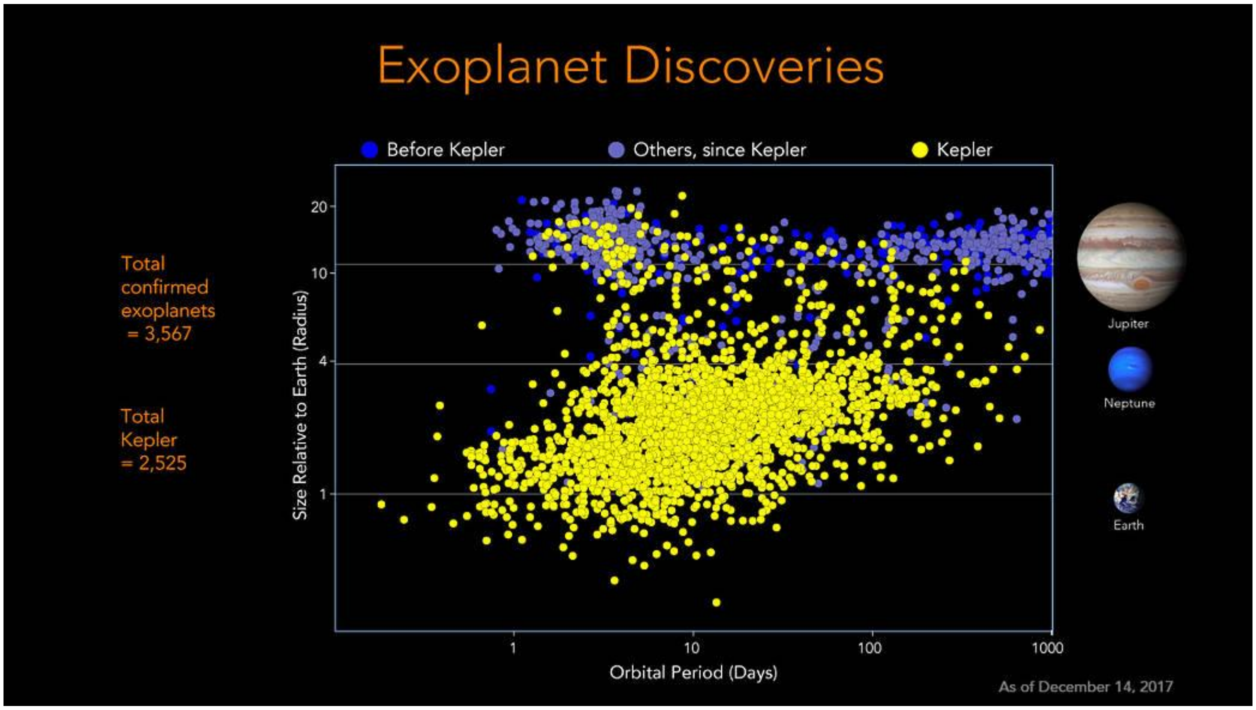


Figure 4-Graph showing the size of all discovered exoplanets (through Dec 2017) compared to Jupiter, Neptune, and Earth. NASAs Kepler mission has been responsible for the discovery of nearly all Earth-sized exoplanets found to date. (NASA/Ames Research Center/Jessie Dotson and Wendy Stenzel)

Radial Velocity Method

Prior to Kepler, the primary technique used to find exoplanets was the **radial velocity method**. This method is more complex to understand, but the underlying premise is that as planets, particularly massive ones, orbit around stars, they exert a slight gravitational tug on their parent star, causing the star to “wobble” around the center of mass of the star-planet system ever so slightly (Fig 5).

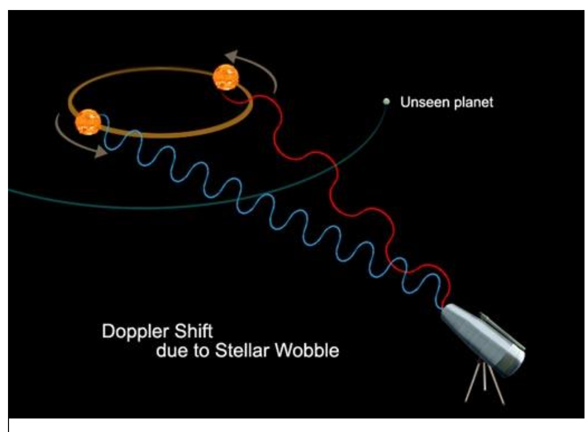


Figure 5-An exoplanet orbiting a star causes the star to “wobble” in a regular and detectable way. (NASA/JPL-Caltech)

Astronomers can detect this wobble, and determine whether or not it is regular and periodic. If the wobble occurs with regularity, just like with the transit method, this is good evidence that there is a planet going around the star. In our own Solar System, Jupiter causes the Sun to wobble on a detectable scale. The larger the planet, the larger the wobble, and thus the radial velocity method is much more likely to detect larger and more massive planets than smaller more Earth-like ones. As a result, few Earth-sized exoplanets have been discovered using the radial velocity method.

Direct Imaging

Both the radial velocity and transit methods are indirect; astronomers can't see the exoplanet itself, only its effect on the parent star. In contrast, direct imaging is exactly what it sounds like: taking an actual image of a planet around another star.

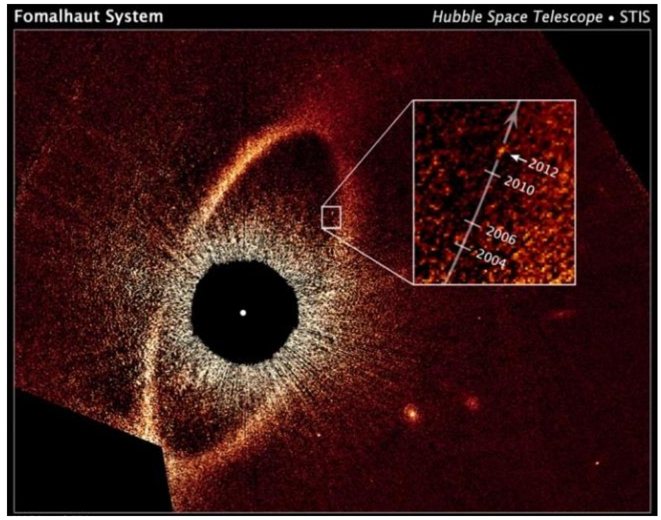


Figure 6-Image of the exoplanet Fomalhaut b (inset) obtained with the Hubble Space Telescope. The black circle blocks out the light from the parent star, Fomalhaut. (NASA, ESA, and P. Kalas (University of California, Berkeley and SETI Institute)

Remember that exoplanets are extremely difficult to detect directly because the parent star is so much brighter than the planet and the planets appear so close to the star. Because of this, exoplanets discovered via direct imaging are rare. Of the 3,775 confirmed exoplanets, only 44 have had their picture taken. Figure 6 shows one of the few directly imaged exoplanets: Fomalhaut b. Even though this exoplanet is just 25 light-years away and likely larger than Jupiter, it appears as nothing more than a pixel in the image, underscoring the challenge of directly photographing exoplanets.

Bias

All of the methods commonly used by astronomers to detect exoplanets are biased. For example, consider the transit method. It takes Earth approximately 365 days to go around the Sun. Thus, an astronomer on a distant planet trying to find planets around the Sun may need to observe the Sun *continuously* for up to an entire year in order to spot the Earth passing in front of it. Focusing a telescope on a single star for a full Earth year would be expensive, time consuming, and challenging. Consider: How do you monitor the star during the day or when it is cloudy? That's where space telescopes like Kepler come in.

But even one year wouldn't be enough because a dimming episode tells us nothing about periodicity. Perhaps the dimming was caused by a stray comet passing in front of the star. To confirm that an exoplanet is present, astronomers need to see the light from a star dim regularly and consistently, which can take many years. It's easier to find planets that are going around their stars much faster than Earth is going around the Sun. Because there is a direct correlation between the orbital period of a planet and how close it is to the star (Kepler's Third Law), there is a bias toward exoplanets orbiting very close to their parent stars at alarming speeds. For example, Kepler-78b orbits its star in less than 12 hours.[6] Those close planets are easier to track and establish as planets, but they are rarely suitable for life.

Massive planets are also easier to find. Planets with greater mass exert a greater pull on their parent star, and are easier to discover than low-mass planets using the radial velocity method. Prior to Kepler, virtually all exoplanets had been discovered using the radial velocity method and were Jupiter-sized or larger. The first rocky, Earth-sized exoplanet discovered was in fact Kepler-78b with a mass of 1.7 $M_\oplus$ (1 $M_\oplus$ = 1 Earth mass) and 1.2 $R_\oplus$ (1 $R_\oplus$ = 1 Earth radius). Even with the transit method though, larger planets are still easier to find. Planets with a large diameter, like Jupiter, block out more light and cause more obvious dimming of their parent star than smaller planets like Earth or Mars.

Looking for Life in All the Right Places

One of the primary reasons for the intense interest in exoplanets over the past few decades is the idea that we could find an Earth-like planet capable of supporting life. Before we visit some of these exoplanets, it is worth taking a closer look at life here on Earth and taking a moment to think about what exactly we are looking for. After all, defining "life" has become much more complicated in the past few generations.

Diversity of Life on Earth

If a common theme can be found among the living organisms of Earth, it is to create more copies of the species, and stay alive as long as possible. The point of life seems to be to continue living. However, most organisms on Earth have already failed in this, as an estimated 99% of species that have ever lived have also gone extinct.[7]

Life on Earth is also incredibly diverse. Even organisms in the same kingdom vary wildly in size. The largest *animals* that have ever lived, blue whales, measure in at about 109 feet, or 1.5 million times longer than the smallest living animals, Myxozoa, tiny parasitic jellyfish that measure about 0.02 millimeters.

As far as all organisms go, plants and fungi compete for the title of largest living thing on the planet. Pando, a single, enormous aspen colony near Fish Lake, Utah, covers about 107 acres.[8] It is very old, clones itself, and unfortunately has been declining in recent years due to encroachment of campers and deer. But this is nothing compared to a specimen of *Armillaria ostoyae* in Oregon's Blue Mountains. This fungal colony covers 2,384 acres and like Pando, has been around for a long time, at least 2,400 years and possibly as long as 8,650 years.[9] Life forms on Earth can also be extremely long-lived, as in the case of the Great Basin bristlecone pines (*Pinus longaeva*) which can live for thousands of years.

Where Can Life Live?

Much of our exploration of the Solar System and our search for exoplanets has focused on looking for places where life could possibly exist, either at present or in the past. Unfortunately, we've only found life on Earth meaning that Earth is our only data point, so this search is effectively for the conditions needed for *life as we know it*.

On Earth, we find life everywhere. At the bottom of the deepest oceans, on the highest mountain peaks, in the most arid deserts, and in the frozen wastelands near the poles, we find life. We often think of life as fragile and reliant on a comfortable environment, however many organisms can live in incredibly inhospitable environments. For example, Strain 121 (*Geogemma barossii*) is a microorganism in the archaea domain found near hydrothermal vents. It's known as Strain 121 because it survives just fine at 121 °C (250 °F).[10] *Thermococcus gammatolerans* can not only survive in temperatures up to 95 °C (203 °F), but can also withstand intense doses of radiation.[11] Other organisms can survive the extreme pressures of the deep ocean. For example, some Foraminifera live at the bottom of the Mariana Trench, beneath 10,896 meters (6.7 miles) of water, at more than 1,000 times the pressure we experience at sea level.[12]

There are even some animals (not just bacteria) that can withstand extreme environments. The live-bearing Sulphur Molly (a fish), lives in springs containing otherwise toxic amounts of hydrogen sulfide. *Spinoloricus cinziae*, a microscopic marine-dwelling animal, lives without any oxygen at all.[13] And perhaps most impressively, in 2007 two different species of tardigrade (microscopic water-dwelling animals), *Richtersius coronifer* and *Milnesium tardigradum*, were exposed to the vacuum, radiation, and cold of space in the Biopan-6 experiment. Both were sent up in a natural state of cryptobiosis and had stopped all metabolic activity. Although *M. tardigradum* fared better than *R. coronifer*, when some of the ultraviolet light was filtered out, both species survived.[14]

What does life need?

The diversity of life on Earth is staggering, but so is its mundanity. Not a single organism on this planet is formed without carbon. Could life-as-we-don't-know-it spring up in a place that is chemically different? It's impossible to know. We just don't have any frame of reference. While some sci-fi writers insist on parading silicon-based life on television, there is currently no evidence for non-carbon based life. Silicon is hundreds of times more common in Earth's crust than carbon, and yet, not a single silicon-based organism has ever been discovered. Life as we know it is simply not possible without carbon.

We also have yet to discover life that does not need liquid water at some point in its lifecycle. Water is an essential element in the biologic processes taking place inside every organism on Earth. As we've seen, life can survive in an incredible array of extreme environments, but as far as we know, life needs liquid water and it needs carbon.

The Habitable Zone

Because of the apparent importance of liquid water for life, a central concept in the world of exoplanets is the idea of a **habitable zone**, sometimes called HZ or the "goldilocks zone." The habitable zone is the region around a star where liquid water could theoretically exist on the surface of a planet (Fig 7). Obviously Earth is in the Sun's habitable zone; we are at the right distance from the Sun for water to neither be a constant solid (ice) or gas. Move Earth further from the Sun and much of its water would freeze; move it closer and much of our water would boil away and escape the planet entirely.

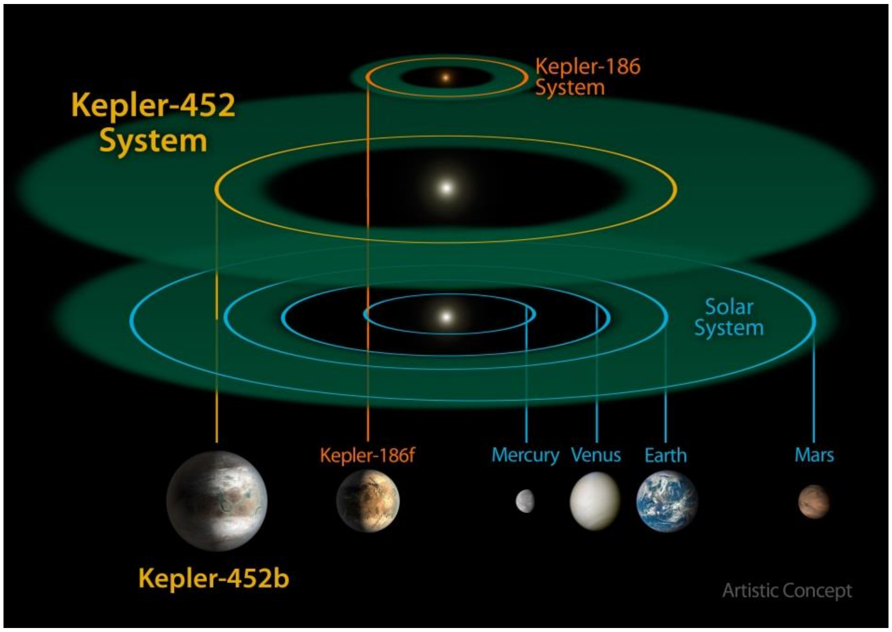


Figure 7-The green doughnut represents the habitable zone of our Solar System compared to the habitable zones of two other exoplanet systems, Kepler-452 and Kepler-186. (NASA/JPL-Caltech/R. Hurt)

There are several other factors to consider when thinking about habitable zones as well. Our distance from the Sun is not the only thing that controls how warm it is, or over what temperature range water is a liquid. For example, adding salt to water will lower the temperature at which liquid H_20 will freeze, and increase the temperature at which it will boil. Adding or removing pressure will alter the boiling and freezing points of water as well.

As such, the habitable zone is a general rule. For example, Venus, Mars, and our Moon are all technically within the Sun's habitable zone, but none have liquid water on their surface (at least not today; Venus and Mars may have had liquid water in the distant past). This is largely due to varying atmospheric conditions on these worlds. Venus' thick CO_2 atmosphere makes the surface of the planet extremely hot, whereas Mars' thin atmosphere retains little heat. Greenhouse gases, like carbon dioxide (CO_2) and methane (CH_4) will make a planet warmer than an equivalent atmosphere of nitrogen and/or oxygen. Venus, Earth, and Mars are all significantly warmer than they would be in the absence of any greenhouse gasses in their atmospheres.

There are also ways for liquid water to exist on a planet or moon that have nothing to do with being in the habitable zone. For example, Jupiter's moon Europa and Saturn's moon Enceladus are far outside of the Sun's habitable zone, and yet we know they have liquid water beneath their surface. This is because of **tidal heating**, a concept discussed in *Chapter 2.6: Our Solar System*.

While the habitable zone concept is a useful framework for thinking about which planets might be likely to have liquid water, and by extension life, it is not foolproof. We must remember that there are many, many factors that will determine whether or not liquid water could exist on the surface of an exoplanet.

The Habitable Zone and the Parent Star

The location of the habitable zone depends largely on the parent star itself. Not all stars are like our Sun. Our habitable zone extends (very roughly) from the orbit of Venus to Mars, a distance of about 120 million km (74.5 million mi). However, the size and location of the habitable zone is different for different stars. Stars that are hotter and more luminous than our own will have a habitable zone that is much further from the parent star. And stars that are colder and dimmer will have a habitable zone that is closer to the star. A planet orbiting a **red dwarf** star could be habitable at the distance that Mercury lies from our Sun.

In reality, astronomers aren't even looking for life-bearing planets around O, B, and A-type stars. Not only are these stars hotter, brighter, and shorter lived (not as much time to build a solar system and evolve life), but they also typically emit a lot of light at extreme wavelengths. Ultraviolet light is just not good for life. Even on Earth we have to take precautions against the UV light emitted by our own Sun by wearing sunscreen to protect our skin cells, and the Sun emits relatively little UV light. Any star putting out a lot of X-rays or UV rays isn't going to be great for life as we know it.

In summary, right now we are looking for life that's carbon-based (the only life we've ever encountered), on a planet with liquid water, that is protected from harmful stellar radiation, and is on a planet that's been around long enough to evolve at least single-celled organisms.

Notable Extrasolar Planets

Even though most of the extrasolar planets discovered so far can't be seen directly, we can learn a lot about them by studying their gravitational influence on their parent star, or the amount of light they block out during a transit. Things like orbital period, distance from their star, size, mass, composition, and atmospheric properties can be inferred, at least approximately, for many exoplanets. Let's learn a bit more about some of the most intriguing exoplanet systems.

What's in a Name?

At first glance, many exoplanets have confusing and strange names, like Gliese 667 Cc, Kepler-452b, and WASP-33b. While these names may seem arbitrary, in many cases they can actually tell us a lot about the planet itself. Exoplanet names are often a nod to their catalogs or the missions/projects that led to their discovery. Here are a few examples:

- **Gliese:** Exoplanets orbiting stars in the *Gliese Catalogue of Nearby Stars* organized in 1957 by German astronomer, Wilhelm Gliese. Stars in this catalog are nearby, usually within 60 light-years, and most are dim, M-type, red dwarf stars.
- **HD:** Exoplanets orbiting stars in the *Henry Draper Catalog*, a repository of 225,300 stars and their spectra published beginning in 1918. Many HD exoplanets were detected using the radial velocity method.
- **OGLE:** Exoplanets discovered by the Optical Gravitational Lensing Experiment using either the transit method or the gravitational microlensing method. OGLE planets are usually very distant, because the OGLE project was originally designed to look for dark matter, not exoplanets. In fact, OGLE currently holds the record for discovery of the farthest known extrasolar planet: *OGLE-2005-BLG-390Lb*, at about 22,000 light-years away.
- **Kepler/KOI:** Exoplanets discovered by NASAs Kepler Space Telescope. Nearly all Kepler and KOI (Kepler Object of Interest) exoplanets were discovered using the transit method and are located in the constellations Cygnus, Lyra, or Draco (the field of view of Kepler's telescope).
- **WASP:** Exoplanets discovered by the Wide-Angle Search for Planets, which uses the transit method and an international array of robotic telescopes to detect exoplanets.

Let's try an example. What can we learn about the exoplanet **Gliese 667 Cc** just from its name?

- **Gliese:** From above, we know that its parent star is likely a nearby red dwarf.
- **667:** This number means that the parent star was the 667th entry in the Gliese catalog.
- **C:** In the case of a binary or multiple star system, an uppercase letter indicates which star in the system the planet is going around. Gliese 667 is a triple star system (A, B, and C), so this exoplanet is orbiting star C.
- **c:** The final, lowercase letter always indicates the planet itself. Somewhat confusingly, exoplanet lettering always starts with "b." The letter of the planet indicates *in what order it was discovered, not the order from the star*. So this planet was the second exoplanet discovered around the star Gliese 667 C (the first would be Gliese 667 Cb).

Now it's your turn. What can you tell just by looking at the names of the following exoplanets?

- Gliese 581 e
- Gliese 86 Ab
- Kepler 174d
- HD 187123 b

Kepler-452b

This exoplanet is in the habitable zone of a G-type star (like our Sun), has a 385-day orbit (only 20 days longer than Earth's year), is about 60% larger in diameter than Earth, and is probably rocky (Fig 8).[15]

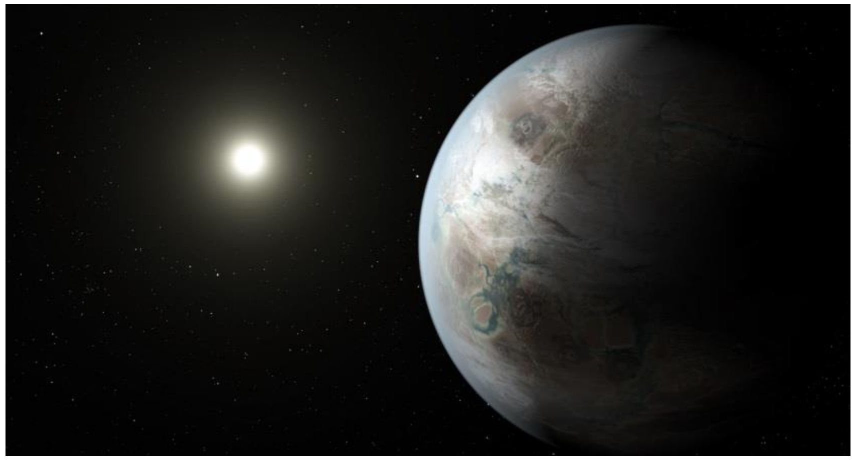


Figure 8-Artist's impression of Kepler-452b and its Sun-like parent star. (NASA Ames/JPL-Caltech/T. Pyle)

What is extra special about this planet is its star; Kepler-452. This G-type star is 1.5 billion years *older* than our own Sun, making this particular solar system a possible analog for our own Solar System, just 1.5 billion years in the future. We don't know if Kepler-452b has or has had life, but imagine that it did: What might it look like with all that extra time to evolve? What will life look like on Earth in 1.5 billion years?

Gliese 667 Cc

As we can see with Gliese 667 Cc, planets can orbit within **multiple star systems**. On a planet that orbits three stars, you would have three shadows, three sunrises and sunsets, or possibly never have night at all depending on how close the planet is to the parent stars (Fig 9).

Figure 9-Artist's impression of a sunset on Gliese 667 Cc. Note the three suns in the sky. (ESO/L. Calçada, [CC BY 4.0](CC BY 4.0))

Gliese 667 Cc is in the habitable zone of the red dwarf star Gliese 667 C. The two other stars in this system are further off in the distance and the planetary system truly belongs to the one star. Even so, there are two stars that are much closer to the exoplanet than any other star system is to our Sun. It is unknown what effect this might have on the planet and any life that could exist there.

Proxima Centauri b (The Pale Red Dot)

Proxima Centauri b is the closest exoplanet to Earth, which is not surprising given that Proxima Centauri is the closest star to Earth (other than the Sun). Proxima Centauri belongs to a triple star system, along with Alpha Centauri A and Alpha Centauri B. Proxima is the closest of the three stars to us, just a little over four light-years away. In fact, the star was named "Proxima" when it was discovered because of its proximity to us – which is going to be hilarious in 40,000 years when Ross 248 will be closer than four light-years away from us.

The planet Proxima Centauri b was discovered quite recently in 2016. The planet has a minimum mass of 1.3 Earth masses and orbits Proxima Centauri every 11 days. At that distance, it may seem like there is no way it would have liquid water on its surface, however the star Proxima Centauri only gives off 0.1% as much light as our Sun, and is only about 12% the mass of the Sun.[16] Because Proxima Centauri is so dim, cool, and small (a red dwarf star), Proxima Centauri b is actually in the star's habitable zone. This means that theoretically liquid water could exist on the surface of Proxima Centauri b.

Figure 10-Artist's impression of the surface of Proxima Centauri b. (ESO/M. Kornmesser, [CC BY 4.0](#))

Before we try to get humans out to Proxima Centauri b, we have to recognize that even if we could cross the vast distance that is four light-years, there are problems awaiting us once we get there. Even though Proxima Centauri b is in the habitable zone, we know that its host star is subject to flares. Although our Sun also has flares, Proxima Centauri b is much closer to its parent star and we don't know whether it has an atmosphere or a magnetosphere to protect any life that could occur on the surface. Additionally, it's in a three-star system; Alpha Centauri A is more luminous than the Sun, and Alpha Centauri B is about half as luminous as the Sun, so there may be some issues with the amount of radiation the planet receives. We just don't know how well-protected the planet is from its parent and auntie stars.

Gliese 581

The Gliese 581 system appears regularly in the news because it just can't stop producing exoplanets – and it's historically interesting (Fig 11). Gliese 581 b was discovered in 2005, and was one of the smallest planets to be discovered at that time. Even though its mass is over 15 times that of Earth's, in 2005, a planet that "small" was a big deal. Gliese 581 (the star itself) is a red dwarf, so it is a good place to look for potentially life-bearing planets, but Gliese 581 b just wasn't a good candidate for anything humans might be interested in for themselves.

Then in 2007, Gliese 581 c was discovered, which was even smaller (about 5 times the mass of Earth), but like Gliese 581 b, it was too close to the parent star to support liquid water on its surface. But again, at the time, Gliese 581 c was one of the most Earth-like planets ever discovered. Then Gliese 581 d was discovered, and even though it was 7 times more massive than Earth, it was in the star's habitable zone (a little on the cold side, but still). Gliese 581 e was then discovered in 2009, and at only about 2 times the mass of the Earth, it definitely seems to be terrestrial/rocky. However, it is too close to the star to be inside the habitable zone. Then Gliese 581 f and 581 g were discovered, but unfortunately Gliese 581 f is from data that was spurious, and it's currently debatable whether 581 g and 581 d exist as well.

These controversial planets didn't stop a huge number of people from collecting and packaging a digital message to the Gliese 581 system in 2008, and which should arrive in 2029.

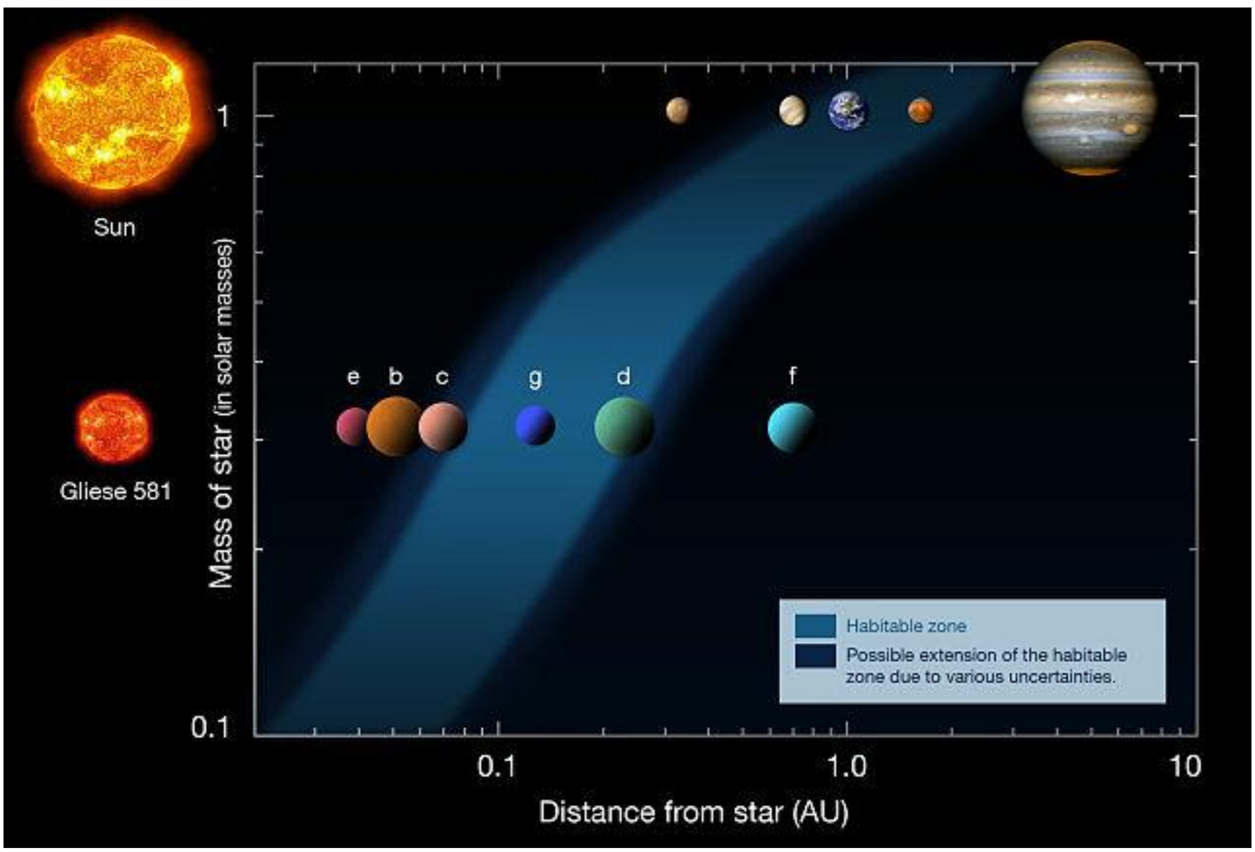


Figure 11-Habitatble zones of our Solar System compared to the Gliese 581 system. Smaller, cooler red dwarf stars such as Gliese 581 have larger habitable zones that lie closer to the star. Several of the exoplanets discovered within this system appear to lie in the habitable zone. (ESO, CC BY 4.0)

TRAPPIST-1 System

On February 23, 2017, astronomers published a paper in the journal *Nature* detailing seven terrestrial planets around a nearby dwarf star. What is amazing about the Trappist-1 system is that all seven of the planets are small enough to be terrestrial. Some are even less massive than Earth but still more massive than Mars (Fig 12). They also orbit a red dwarf star that's very cool, which makes their close orbits (TRAPPIST-1 b for example orbits in 1.5 days, and TRAPPIST-1 h orbits in 19 days) still within the habitable zone of the star. Additionally, they are very close to each other. The distance between b and c is about 650,000 km (404,000 mi) – that's only about three times the distance between Earth and the Moon.

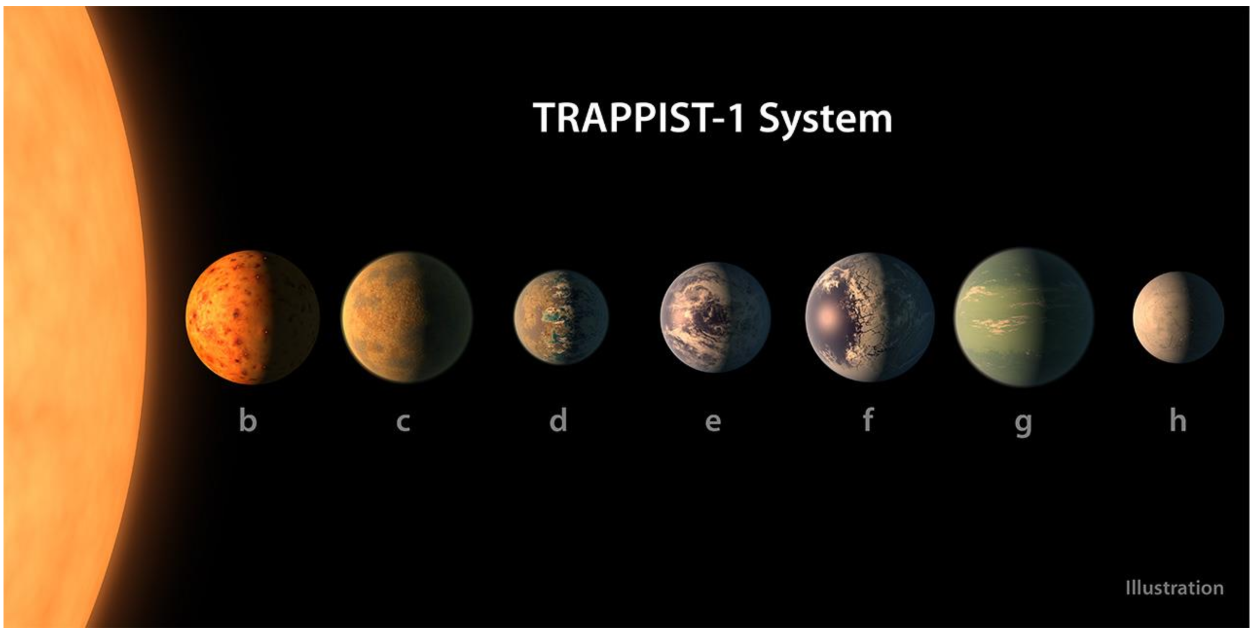


Figure 12-Artist's impression of the TRAPPIST-1 System. (NASA/JPL-Caltech)

The absolute largest distance between the rocky planets, (between TRAPPIST-1 b and TRAPPIST-1 h) is about 8,000,000 km (4,970,000 mi). This means that all of the TRAPPIST-1 system planets are close to each other. At the very closest between Earth and our nearest neighbor Venus (on average), we are about 24,000,000 km (14,900,000 mi) away from Venus. The absolute largest distance you'd have to go if you were living on TRAPPIST-1 to the very farthest planet away from you in your solar system (to TRAPPIST-1 h) would be less than the distance between Earth and its closest planetary neighbor. If we had experienced the space age in the TRAPPIST-1 system, we'd be on all the other planets by now. And the best news is the star system is only about 40 light-years away.

These are the exoplanets that are making the news today, but in 10 or 20 years, what new planets will we find out there?

Review

Common misconceptions

Below is a list of commonly encountered misconceptions about extrasolar planets. As a way to review content from this chapter, see if you can explain why each misconception is inaccurate:

- Planets are rare and most stars don't have them.
- Earth is unique; there are no other planets similar to it out there.
- We can see most of the exoplanets that have been discovered.

Questions for thought

- Why did it take so long for astronomers to start discovering planets around other stars? What changed that has allowed so many to be found in such a short amount of time?

- What are some limitations of using the transit method to detect extrasolar planets? Are there certain types of planets that we are more or less likely to find using this method? Could a ground-based telescope use the transit method to search for exoplanets? Why or why not?

- How do the extrasolar planets we've found so far compare to the planets in our Solar System? Is our Solar System "normal?" Why or why not?

- Even the closest extrasolar planets are so far away that we will likely never be able to visit them. Given this information, why is the search for exoplanets important? How does their discovery and study benefit humans?

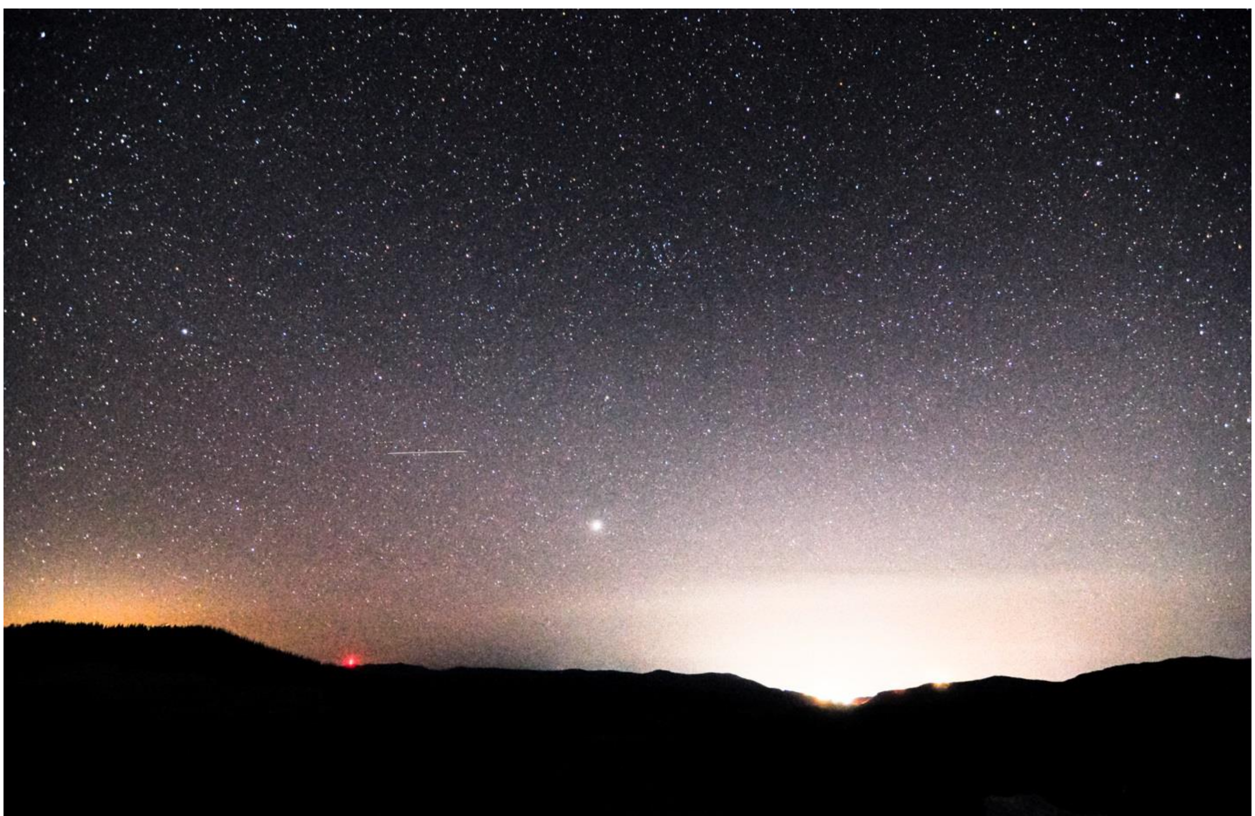
- Do you think we will ever find life somewhere else in the universe? Why or why not? What do you think it will look like?

For More Information

- "250 Years of Planetary Detection in 60 seconds": https://www.universetoday.com/118925/250-years-of-planetary-detection-in-60-seconds/
- The Extrasolar Planet Encyclopedia (database with information on all currently confirmed exoplanets): http://exoplanet.eu/catalog/
- Planet Hunters TESS (citizen science project to look for new exoplanets): https://www.zooniverse.org/projects/nora-dot-eisner/planet-hunters-tess

SECTION 3: **PROTECTING THE NIGHT SKY**

Chapter 3.1 – Introduction to Light Pollution



Light pollution degrades the night sky even at many International Dark Sky Parks like Cedar Breaks National Monument. In this photo, the lights of Cedar City (pop ~32,000) 21 km (13 mi) away illuminate the western horizon from Cedar Breaks. (NPS/Zach Schierl)

Chapter 3.1 Goals

After reading this chapter and participating in the corresponding workshop activities, you should be able to:

- Define and readily recognize the three main types of light pollution: skyglow, glare, and light trespass.
- Describe the extent to which light pollution degrades the visibility of the night sky on a global scale, and become familiar with skyglow conditions in your city or region.

What is Light Pollution?

As we saw in *Chapter 2.1*, light is the foundation of astronomy. Ironically, light is also the greatest threat to astronomy, astronomers, and anyone who enjoys looking at the night sky.

Artificial light at night (often abbreviated as **ALAN**) is an integral part of modern society. The ability to flip a switch and get light on command at any time of day or night has revolutionized our society in a way that few other inventions have. Much of the light we use at night is useful and necessary; our 21st century society could not function without artificial light at night.

Unfortunately, we don't use all our artificial light wisely. Many outdoor light fixtures waste a significant percentage of the light they emit. This squandered light escapes into the sky or the surrounding environment, where it serves no useful purpose. The glow of the escaped light can make observing stars, galaxies, and even our own Milky Way difficult or impossible (Fig 1), even in rural areas far from large cities (cover photo). This unwelcome form of light, the bane of astronomers for more than a century now, is commonly known as **light pollution**.

Figure 1-The night sky from Toronto, Ontario before and after the 2003 Northeast blackout, a massive power outage that affected 55 million people. The Milky Way and most other celestial objects are invisible prior to the blackout, due to light pollution. (Todd Carlson)

The International Dark Sky Association defines light pollution as "the inappropriate or excessive use of artificial light."[1] Others define it more broadly as "the alteration of natural light levels in the outdoor environment owing to artificial light sources."[2] Note that in the second definition there is no mention of excess or inappropriate use; light pollution occurs whenever we light up an environment that would otherwise be dark.

Regardless of definition, light pollution is a growing problem. Our use of artificial light at night is increasing at a rate that is disproportionate to population growth. Earth's nighttime brightness due to artificial light is increasing at ~2% per year[3], while world population increases by ~1.1% per year.[4] While astronomers were the first to sound the alarm about light pollution decades ago[5], it is no longer purely the concern of stargazers. We now know that light pollution has consequences that extend far beyond the night sky. Fortunately, as we will see, it is an easy problem to solve.

How Can Light be "Pollution"?

Many people find the term "light pollution" confusing. After all, when we talk about air or water pollution, it is the water and air that are *being* polluted. With light pollution, light itself *is* the contaminant or pollutant.

How can light, something so seemingly "normal" and prevalent, be a pollutant? Pollution is defined as "an impairment of the purity of the environment." Before the advent of artificial lighting, the only night lights on Earth were natural sources like starlight, moonlight, aurorae, and fires. Artificial light impairs our planet's natural nighttime environment by adding light at times and in places where previously there was none.[5]

While light easily meets the definition of a pollutant, confusion over the term remains. Can you think of a better term to describe this phenomenon?

Effects of Light Pollution

Perhaps the most obvious consequence of light pollution is the loss of the night sky. As of 2016, an estimated 77.6% of Americans could not see the Milky Way from their backyard due to light pollution.[6] About 37% of Americans live under skies so light polluted that **dark adaptation** is not possible for the human eye.[7] True night, as it has existed for billions of years, no longer exists for those living under such conditions.

Stars and galaxies are not the only casualties of light pollution. The illumination of the natural nighttime environment is one of the most significant changes that humans have made to planet Earth, yet one whose consequences are only now becoming clear. As of 2019, we know that combating light pollution and preserving natural darkness not only saves the night sky, but also:

Protects nocturnal wildlife: Most animal species on Earth are **nocturnal**, and depend on either natural darkness or natural cycles of light and dark to time activities such as sleep, hunting, migration, and reproduction. A rapidly growing body of research is uncovering the effects of artificial light on nocturnal ecosystems around the globe.[8]

Improves human health: Excessive exposure to artificial light at night has been linked to a variety of human health concerns. Exposure to even low levels of blue light at night inhibits the production of the hormone **melatonin**, causing sleep disorders and suppressing the immune system. Many studies also suggest a link between prolonged exposure to artificial light at night and the risk of diabetes, various cancers, and other disorders.[9]

Saves energy and money: Poorly designed outdoor lighting wastes light, electricity, and ultimately money. **Dark-sky friendly lighting** uses light strategically to illuminate only what needs to be lit, saving energy and reducing emissions. Places with good lighting and dark skies are attracting growing numbers of **astro-tourists**, creating an extra economic benefit.[10]

We'll discuss these topics at more length in *Chapter 3.2: Why Protect the Night Sky?*

Types of Light Pollution

Astronomers and other scientists typically recognize three distinct varieties of light pollution: **skyglow**, **glare**, and **light trespass.** We'll take a closer look at each on a hypothetical stargazing trip to Olympic National Park in Washington.

Skyglow

It is 10:00 pm in late-May as you step out of your car at the summit of Hurricane Ridge in Washington's Olympic National Park. You have come for a night of stargazing and astrophotography, and are eagerly awaiting the end of twilight, which lasts late into the evening at this high latitude. A brisk wind whips around you as you take note of the snowbanks still lingering in the surrounding alpine meadows. The daytime crowds have departed and you are alone as darkness falls and your eyes start to adapt to the darkness. Before long, you begin to notice a yellow-ish glow materializing along the eastern horizon (Fig 2).

Your first thought as you observe the rising Milky Way disappear into the glow is that the Moon is rising. You quickly set up your camera and tripod, hoping to capture a dramatic photograph

Figure 2-The mysterious glow visible from Hurricane Ridge, Olympic National Park, Washington. (Zach Schierl)

of the lunar orb rising above the foothills of the Olympic Mountains. You wait, and wait, but the Moon never comes. In fact, the strange glow will persist, unchanging in its appearance, for the entire night. Only the onset of morning twilight finally erases the glow.

Before long, you realize the glow is not a natural phenomenon, but rather the **skyglow** from the Seattle metropolitan area, nearly 100 km (62 mi) and a three hour drive plus ferry ride away. The skyglow is an omnipresent mark of modern society, visible even here, on the doorstep of one of the most wild and remote wilderness areas in the lower 48 states.

Skyglow is the brightening of the night sky that occurs when light emitted upward from Earth's surface is **scattered** by particles in Earth's atmosphere.[11] Skyglow *can* be caused by natural processes, but for the most part it is the result of stray light escaping into the night sky from residential, commercial, and industrial lighting in populated areas.[12]

If Earth had no atmosphere, this escaped light would continue onward into space never to be seen again. However, we do have an atmosphere, one filled with gas molecules, aerosols, and particulates. All of these scatter the escaped light, some of which gets directed back towards the ground, making the sky itself appear to glow (Fig 3). As a result, skyglow brightens the night sky, making it harder to pick out stars, the Milky Way, and other celestial objects against the luminous background.

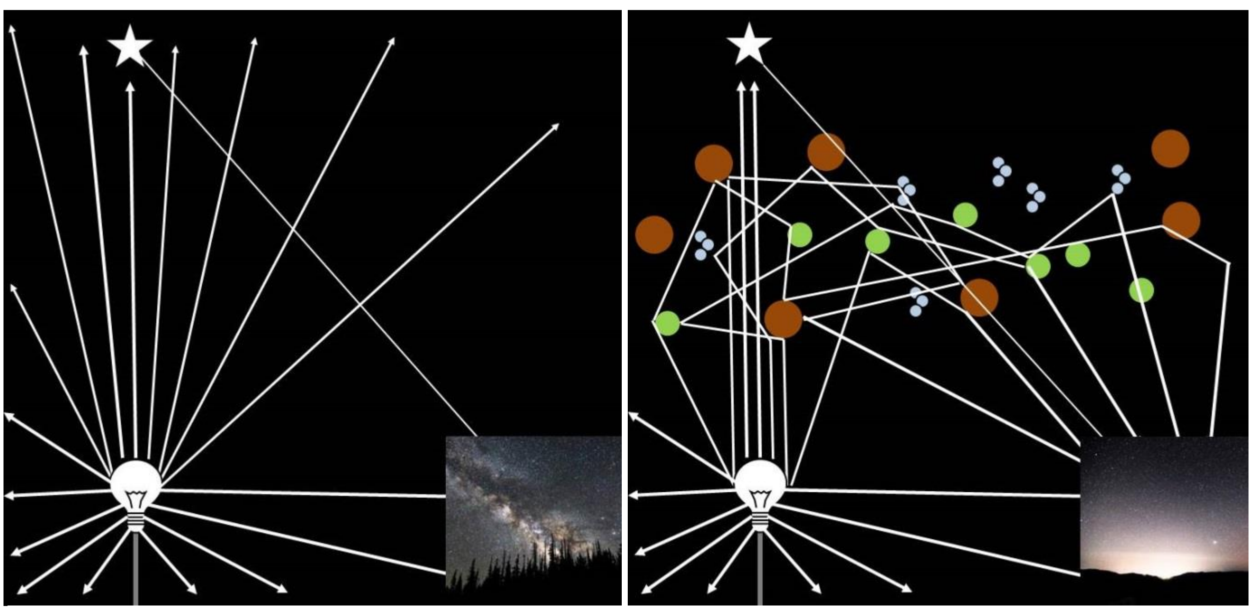


Figure 3-If Earth had no atmosphere, most artificial light emitted into the sky would simply escape into outer space (left), minimally impairing stargazers. In reality, our atmosphere contains molecules and particles that scatter light emitted upwards back toward Earth's surface (right), causing skyglow that degrades the view of the night sky in many areas. (NPS/Zach Schierl)

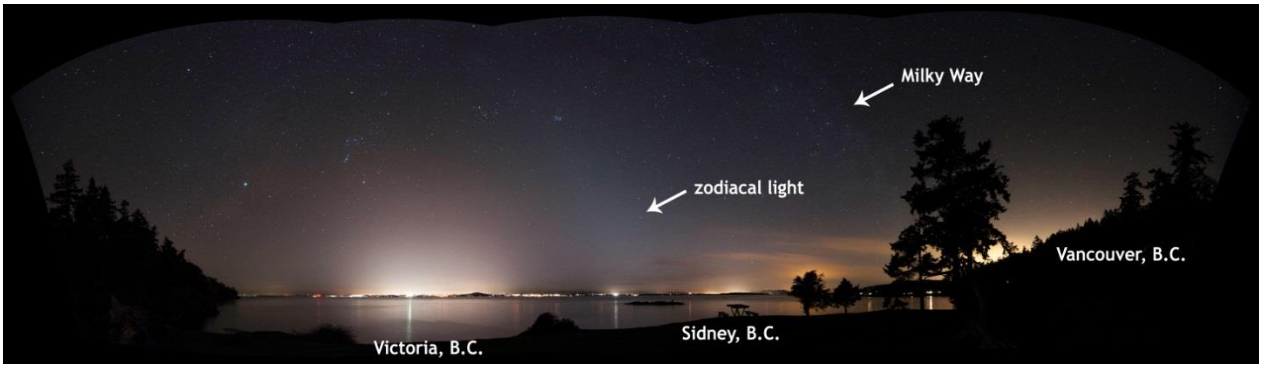


Figure 4-Skyglow from Victoria, British Columbia (metro population: 344,000) as seen from San Juan Island, Washington, approximately 19 km (12 mi) away. Note the faint appearance of the Milky Way and zodiacal light. (Zach Schierl)

Skyglow is perhaps the most pervasive form of light pollution because it can affect such a large area. Skyglow from even a small to medium-sized city, such as Cedar City or St. George, is bright enough to erase diffuse celestial objects such as the Milky Way. Skyglow from larger cities, such as Las Vegas or Los Angeles, decimates the night sky for dozens of kilometers or miles in all directions, and can be visible from more than 240 km (150 mi) away.[13] Skyglow over a distant city is commonly known as a **light dome.** For example, the light dome of Phoenix, AZ, is visible from Grand Canyon National Park, more than 320 km (200 mi) to the north. The light dome of Honolulu is visible from the great observatories on Mauna Kea, also roughly 300 km (185 mi) away.[14] Skyglow can be so bright and pervasive in many cities, and even in some suburban areas, that true **dark adaptation** is not possible.[15]

Humid air, clouds, poor air quality, and snow cover all exacerbate skyglow.[16] While clouds historically made the night sky *darker*, in the presence of skyglow they *brighten* it, a complete reversal of natural conditions.[17] Skyglow can also vary over the course of a single evening. It is generally brightest just after sunset and becomes dimmer as some city lights shut off later in the night.[18]

Glare

It is early morning, a few hours before sunrise, and you're headed back down the tortuous mountain highway that led you up to Hurricane Ridge for a great evening of stargazing. As you creep your way along the narrow, two-lane road, you diligently scan the shoulder in front of you, looking for the furry woodland creatures you know are waiting to dart into your path.

As you round a tight curve, an oncoming truck appears. Blinded by its blue-white headlights, your woodland creature watch is involuntarily placed on hiatus as you struggle just to see the road in front of you. You apply the brakes out of caution, knowing that a sheer cliff lies a few feet off the right shoulder. The truck quickly passes but it takes some time to regain your eyesight and view of the dark road. You've just experienced a classic example of **glare**, excessive brightness that causes visual discomfort or disability.[19]

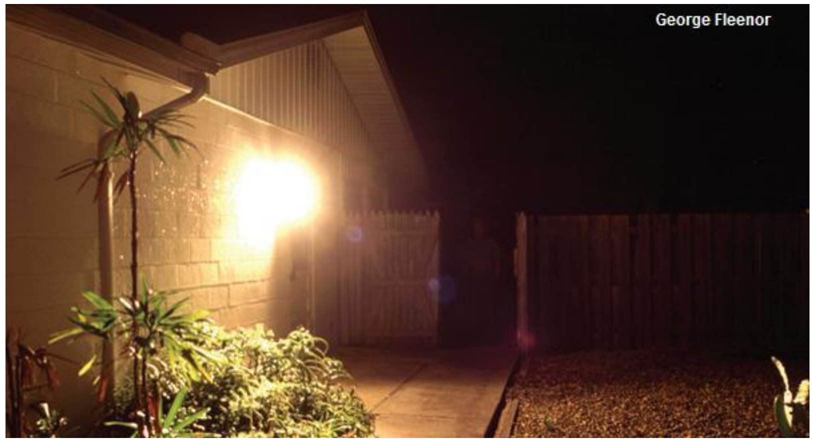


Figure 5-This unshielded floodlight on a residence is a classic example of glare. Note the human figure standing in the open gate. Glare prevents the eye from seeing into darker areas of the scene. (George Fleenor)

While headlight glare is hard to avoid, glare is also rampant in our towns and cities, the result of poorly designed lighting fixtures that often direct light into our eyes instead of onto what needs to be lit (Fig 5). The purpose of outdoor lighting is to help us see at night, yet light fixtures like the one in Figure 5 (colloquially known as "glare-bombs") actually *inhibit* our visibility because of extreme glare. Older individuals are especially sensitive to glare due to changes in the physiology of the eye that occur naturally with age.[20]

Stray light from glare sources also escapes into the sky, contributing to skyglow. Glare can be a significant problem for stargazers and astronomers. Even under dark skies free of skyglow, a single bright glare source can be enough to ruin your **dark adaptation** and prevent you from seeing the stars.

Figure 6-Light trespass from a nearby development illuminates the normally dark desert landscape at Death Valley National Park in California. (NPS/Dan Duriscoe)

Light trespass

You've safely navigated back to your hotel room in the charming seaside town of Port Angeles. Aside from the glaring truck headlights and a sharp swerve to avoid a mountain goat licking salt off the road, your trip down the mountain was uneventful. Bleary eyed, you look forward to a few hours of sleep before heading home later in the morning.

You open the door to your room and are greeted by an immense amount of light for such an early hour. You swat at the light switches on the wall but quickly realize that's not the issue. The light is entering the room through the window, and appears to be coming

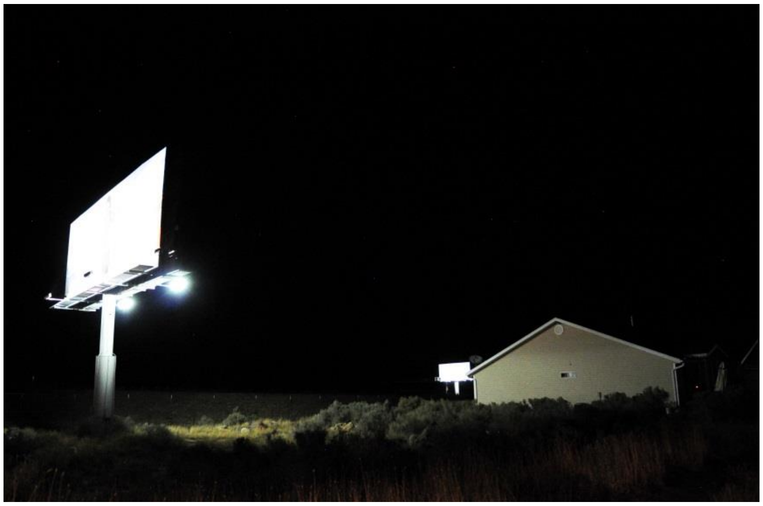


Figure 7-Light trespass from a billboard along Interstate 15 in Cedar City, UT illuminates this property all night, every night. (Zach Schierl)

from an egregiously bright floodlight attached to the restaurant adjacent to the hotel. Exactly why so much light is bursting into your second-floor room is unclear; the floodlight seems to be aimed more in the direction of your window than toward the restaurant itself. You close the flimsy drapes but are dismayed to discover that the light continues to leak both around and through the curtains. Even in your drowsy state, you are conscious enough to realize that, between the skyglow on the mountaintop, the glare of the truck headlights, and now this **light trespass**, you will not experience true darkness on this night.

Light trespass is artificial light cast into a location where it is unwanted. Other examples of light trespass might be a streetlight that shines unwanted light into an apartment window, or your neighbor's bright floodlight that illuminates *your* yard. Any artificial light that spills beyond intended boundaries and illuminates an area where the light is not wanted or desired is light trespass (Figs 6-7).[21] Indoor lighting can also be a source of light trespass if windows allow too much light to escape into the surrounding environment or sky (Fig 8).

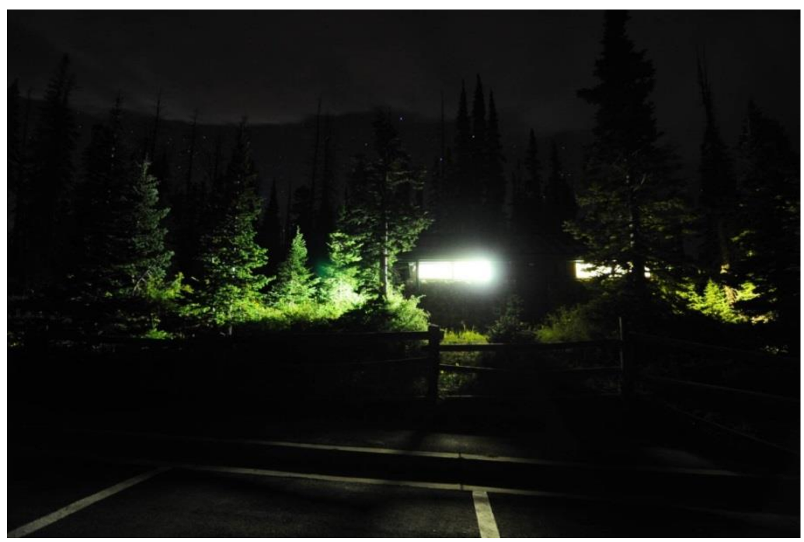


Figure 8-Light trespass from interior lights inside a restroom facility at Cedar Breaks National Monument, Utah. (NPS/Zach Schierl)

Light trespass is a growing problem for protected areas such as national parks, whose goal is to protect naturally dark nighttime ecosystems. Poorly designed lighting on developments within national parks can result in light trespass that illuminates an otherwise naturally dark landscape (Fig 6).

What's the Solution?

Now for some good news: skyglow, glare, and light trespass can all be minimized or eliminated without having to turn off the lights. The key is to use well-designed light fixtures that direct light onto what needs to be lit rather than letting it escape into the night sky or the surrounding environment. This is the main principle of **dark-sky friendly lighting**, which we'll discuss at length in *Chapter 3.4*.

For now, think of artificial light like a drug. Most drugs have potential benefits, but also possible negative side effects. Artificial light is no different. Light has innumerable benefits for our society, but can have damaging side effects if not used carefully. As we will see, combating light pollution is all about mitigating or minimizing the side effects, and keeping the night sky dark for future generations to enjoy.

Review

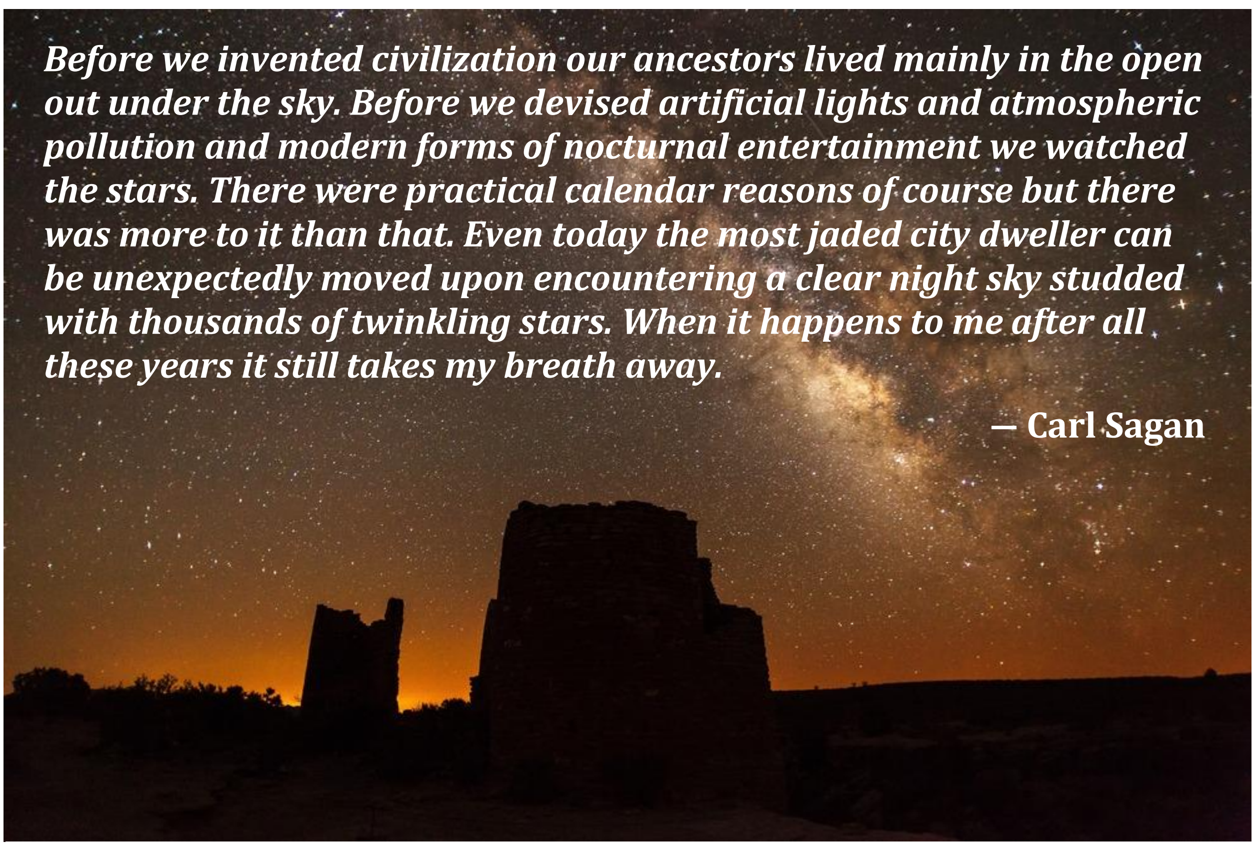
Questions for thought

- While astronomers were the first to sound the alarm about light pollution, who (or what) else might be affected by skyglow, glare, and light trespass? Can you think of any examples other than those discussed in this chapter?
- Consider the role of artificial light at night in our modern society. What do we use artificial light for? Why is light at night important? Could we live without light at night?
- As population continues to grow across the world, is it inevitable that light pollution will continue to grow and that we will eventually lose the night sky?
- Imagine you are on a multi-day backpacking trip in a large wilderness area and the only sign of human society you can see is the bright light dome of a distant city. How would this impact your experience? How would you feel?
- Imagine a hypothetical day in the future when humans have settled large portions of the Moon. Would skyglow be an issue? How about on Mars?
- Astronomers estimate that ~30% of outdoor light is wasted. Consider other resources such as water, food, or shelter. Would we tolerate letting 30% of these resources go to waste? Do we? Why or why not?

For More Information

- *The City Dark*, directed by Ian Cheney, 2011
- Consortium for Dark Sky Studies (University of Utah): http://darkskystudies.org/
- International Dark Sky Association: https://www.darksky.org/
- Light Pollution Overview (Florida Atlantic University): http://cescos.fau.edu/observatory/lightpol.html#LPfObM
- "Rate Your Skyglow" (Sky & Telescope): http://www.skyandtelescope.com/astronomy-resources/rate-your-skyglow/
- *What is Light Pollution?* (video): https://vimeo.com/325249584

CHAPTER 3.2 - WHY PROTECT THE NIGHT SKY?



The Milky Way arcs above ancestral Puebloan structures at Square Tower Group, Hovenweep National Monument, Colorado/Utah. Skyglow from distant cities is visible on the horizon, a new feature of a landscape that people have called home for thousands of years. (NPS/Jacob W. Frank)

Chapter 3.2 Goals

After reading this chapter and participating in the corresponding workshop activities, you should be able to:

- Describe the effects of artificial light at night on night sky visibility, cultural heritage, astronomical research, and natural ecosystems.
- Discuss economic considerations related to light pollution, including energy waste and the rise in astro-tourism.
- Summarize the physiological effects of artificial light at night on humans and how to mitigate them.
- Describe the role of the National Park Service and International Dark Sky Parks in raising awareness of and protecting dark night skies.

The Disappearing Night

Light pollution is not a new phenomenon. In a 1906 book on his studies of Mars, American astronomer Percival Lowell wrote: "Not only is civilized man actively engaged in defacing such part of the Earth's surface as he comes in contact with, he is equally busy blotting out his sky. In the latter uncommendable pursuit he has in the last quarter of a century made surprising progress."[1]

As this passage illustrates, astronomers have been watching the night sky disappear behind a veil of artificial light since the early 20th century. Over the past 100 years, those who study the sky have been driven far from the cities to seek places free of light pollution and **artificial light at night**. While professional astronomers are a tiny segment of the population, there are few people that *don't* enjoy the sight of a star-filled night sky. We don't preserve places like the Grand Canyon or Yosemite strictly for the benefit of geologists, nor is protecting the night sky solely about astronomy. Light pollution and the loss of the night have far-reaching effects that touch many elements of our society. In this chapter, we ask: "What are the consequences of light pollution for astronomers, for us, and for our planet?"

To answer that question, we must first understand just how prevalent and pervasive light pollution is. In 2016, a team of researchers released the *New World Atlas of Artificial Night Sky Brightness.* This atlas (discussed more thoroughly in *Chapter 3.3*) uses satellite data combined with ground-based measurements of light pollution from the **National Park Service** to quantify the extent of **skyglow** around the globe. Among their striking findings:

- 83% of the world's population, and 99% of those in the U.S. and Europe, live under light-polluted skies.
- 77.6% of people in the United States, and more than a third of the world's population, live under skies too light polluted to see the Milky Way, our home galaxy.

- In the U.S., 37% of the population lives under skies so bright that complete dark adaptation is not possible.
- Residents of northwestern Switzerland would have to travel more than 1,300 km (807 miles) to find a pristine night sky.[2]

Compared to an earlier skyglow atlas released in 2001, many of these figures have jumped significantly in the past decade and a half.[3] It is now clear that "night" has been eliminated from a large portion of the United States, and a significant swath of the planet. We are losing the night sky and natural darkness at an alarming rate.

But the question remains: "Why should we care?" In an era when our lives increasingly take place indoors at night, under the glow of artificial light, it isn't always obvious how the stars benefit us. What is the night sky good for? Why is natural darkness important? Light pollution is an existential threat to the night sky. If we are to save the night, astronomy communicators at all levels must do a better job of addressing these questions and facilitating connections with the night sky. This chapter will begin to explore some answers to these questions and more.

"More Alive and Richly Coloured than the Day"

Thanks to newfangled technologies like compasses, clocks, and smartphones, few of us still rely on the stars to find our way around town or know when it's time to meet a friend for dinner. While civilizations of the past used the stars for navigation and timekeeping, most modern-day activities don't require a crystal clear view of the night sky. Yet the allure of the stars remains.

Many astronomy communicators have stories about city-dwellers brought to tears by their first view of the Milky Way. Even on full moon nights, visitors to Cedar Breaks National Monument (which has dark, but not 100% pristine, skies) will often remark how they've never seen so many stars in their lives. Light pollution has become so widespread that skies most of us would consider "dark" are in fact awash with skyglow. This is due to a psychological and sociological phenomenon called **shifting baseline syndrome**, in which each new generation perceives the environmental conditions they were raised in as normal.[4] As a result, our standards for the environment continually get lower, as we collectively forget what things were like in the past. In other words, we've become so accustomed to light pollution that we don't know any better.

Consequently, a *truly* dark night sky is something that few people alive today, even those living in rural areas, have ever experienced. Yet few human experiences are as primal, awe-inspiring, and humbling as standing beneath a dark, clear, star-filled night sky and gazing up at the heavens. The sight of a dark night sky has inspired countless playwrights (William Shakespeare), scientists (Carl Sagan, Edwin Hubble), philosophers (Plato), and artists (Vincent Van Gogh) throughout history. Beautiful and poignant odes to the night are a staple of literature from the 19th and early 20th centuries:

If the stars should appear one night in a thousand years, how would men believe and adore; and preserve for many generations the remembrance of the city of God which had been shown! But every night come out these envoys of beauty, and light the universe with their admonishing smile.

—Ralph Waldo Emerson, *Nature and Selected Essays,* 1836

Though my soul may set in darkness, it will rise in perfect light;
I have loved the stars too fondly to be fearful of the night.

—Sarah Williams, *The Old Astronomer (To His Pupil),* 1868

Too wonderful the April night,
Too faintly sweet the first May flowers,
The stars too gloriously bright,
For me to spend the evening hours,
When fields are fresh and streams are leaping,
Wearied, exhausted, dully sleeping.

—Claude McKay, *Spring in New Hampshire*, 1920

It often seems to me that the night is much more alive and richly coloured than the day.

—Vincent Van Gogh, Letter to Theo Van Gogh, 1888

No sight that human eyes can look upon is more provocative of awe than is the night sky scattered thick with stars.

—Llewelyn Powys, *Impassioned Clay*, 1931

Outside of astronomy-specific texts, such glowing tributes to the heavens are harder to find today. Has the age when our preeminent writers, painters, and poets could so easily draw their inspiration from the night sky passed us by? Would Vincent Van Gogh still be inspired to paint *Starry Night Over the Rhone* (Fig 1) today, given that the path of the Rhone River is now one of the most egregiously light polluted corridors in the world? If you lived in a city blanketed by skyglow, could you identify with the sentiments expressed in these passages?

Figure 1-Vincent van Gogh's *Starry Night over the Rhône*, depicting a nighttime scene in Arles, France in September 1888. Today, Arles lies in one of the most light-polluted corridors in Europe, with light pollution washing out all but the brightest stars. (Public domain)

The loss of the night sky can be especially striking in places otherwise renowned for their natural state or lack of human habitation, such as national parks and wilderness areas. While we expect a light polluted sky above San Francisco or Los Angeles, what about when skyglow from such cities intrudes into places deliberately set aside for their wilderness character? For example, National Park Service measurements show that the night sky at Yosemite and Joshua Tree National Parks is significantly degraded, primarily due to skyglow from cities more than 160 km (100 mi) away.[5] Much like air, water, or noise pollution, too much artificial light can affect the fundamental character of natural places. As we will see later in the chapter, many national and state parks are now emphasizing the stewardship of natural darkness and nighttime scenery in an attempt to stave off the effects of light pollution.

History in the Skies

When you look up at the sky tonight, you're seeing the same stars and the same patterns that the Buffalo Soldiers saw while protecting Yosemite National Park from vandalism more than 100 years ago. You're seeing the same stars and constellations the signers of the Declaration of Independence saw in 1776. You're seeing the same stars that Polynesian peoples relied on to navigate the vast Pacific Ocean nearly 1,000 years ago. You're seeing the same stars that the mysterious erectors of Stonehenge saw more than 5,000 years ago. You're even seeing the same stars, albeit with subtle changes in familiar patterns like the Big Dipper (Fig 2), as humans saw migrating across the Bering Land Bridge into North America more than 15,000 years ago.

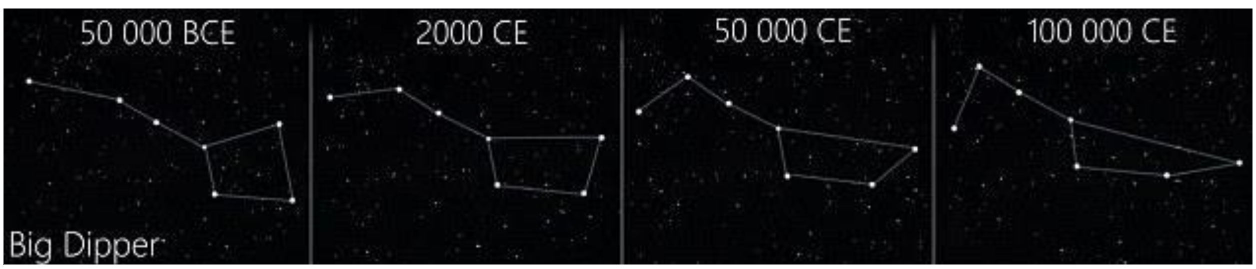


Figure 2-Star patterns change very slowly over time. The grouping we know as the Big Dipper has appeared virtually the same throughout recorded history, and would have appeared only slightly different to humans of 50,000 years ago. (Martin Vargic)

We see the same sky today that our ancestors saw, relied on, and looked to for inspiration. The stars are more than a pretty sight; they are an important link to our past. No matter where your ancestors hailed from, one thing is certain: they depended on the night sky and the stars in many ways. As we learned in *Chapter 2.3: History of Astronomy*, the stars were the basis for critical elements of human society that we take for granted today, such as calendar systems, navigation, and time keeping.

While we all see the same stars, different cultures have seen different patterns in those stars. Nearly every culture has their own set of constellations, whose origins are often deeply rooted in their values and traditions (Fig 3). These patterns offer a glimpse into cultures past and present. For example, in the stars that the Greeks saw as Scorpius, the Maori of present-day New Zealand saw a large canoe, an object of great significance to a society that navigated the many islands and atolls of the Pacific Ocean using the stars. Somewhat surprisingly, we also see many similarities. The stars of Ursa Major were seen as a great bear by cultures as disparate as the Ancient Greeks and the Iroquois of North America.

Figure 3-Two Diné (Navajo) constellations, Náhookòs Bi'áád (Female Revolving One) and Tiníléí (Gila Monster or Lizard). These patterns correspond in part to the western constellations of Cassiopeia and Andromeda. (NPS/Stellarium)

From stately monuments in our capital cities, to museums that chronicle the development of our society, to the protection of portals into the past like Ancestral Puebloan cliff dwellings and major battlefields, humans are no strangers to preserving our history. The night sky is a treasure trove of cultural history in its own right, and many entities are working to protect it on that basis alone. In 1999, the state of New Mexico placed the night sky on its list of "Most Endangered Historic Places." Three months later, Governor Gary Johnson signed the *New Mexico Night Sky Protection Act* into law, making New Mexico the first state to pass a statewide initiative aimed at protecting dark night skies and promoting **dark-sky friendly lighting**.[6]

Science in the Sky

We know more about the universe today - its contents, how it formed, and our place in it – than ever before. Ironically though, public knowledge of the importance of astronomy and the relevance of the night sky seems to be on the decline.

In 1994, the infamous Northridge earthquake knocked out power to most of the Los Angeles metro area. In the days that followed, the director of the famed Griffith Observatory in LA received numerous phone calls asking about the odd appearance of the night sky following the earthquake.[7] What the callers were seeing was nothing other than the Milky Way and several thousand stars, sights which had not been visible over Los Angeles for decades. Stories like this, while anecdotal, suggest that the loss of the night sky is impacting more than just our view of the stars. Tangible connections to the cosmos, such as the ability to see our own galaxy, help us better understand our place in the universe, and give us an important perspective on life itself.[8]

Light pollution severs these connections, and jeopardizes astronomers' ability to study the universe. Astronomers *need* dark skies now more than ever. The objects at the forefront of scientific discovery today are distant, faint, and washed out by even small amounts of skyglow. Most bright objects, those that can shine through the city lights, had most of their scientific insights wrung from them long ago. Space telescopes, one way to escape the clutches of light pollution, are prohibitively expensive in most situations, meaning that most astronomical research continues to take place on *terra firma.*

Why should we care about this research? Consider the threat posed by **near-Earth asteroids**. As of December 2018, astronomers have discovered more than 19,000 asteroids that approach, or even cross, Earth's orbit (Fig 4).[9] While our planet collides with small **meteoroids** regularly, producing harmless **meteors,** collisions with larger near-Earth asteroids have caused or contributed to mass extinctions in Earth's history. Such collisions will certainly happen again in the future. How we fare will depend on our ability to give ourselves plenty of advance warning.

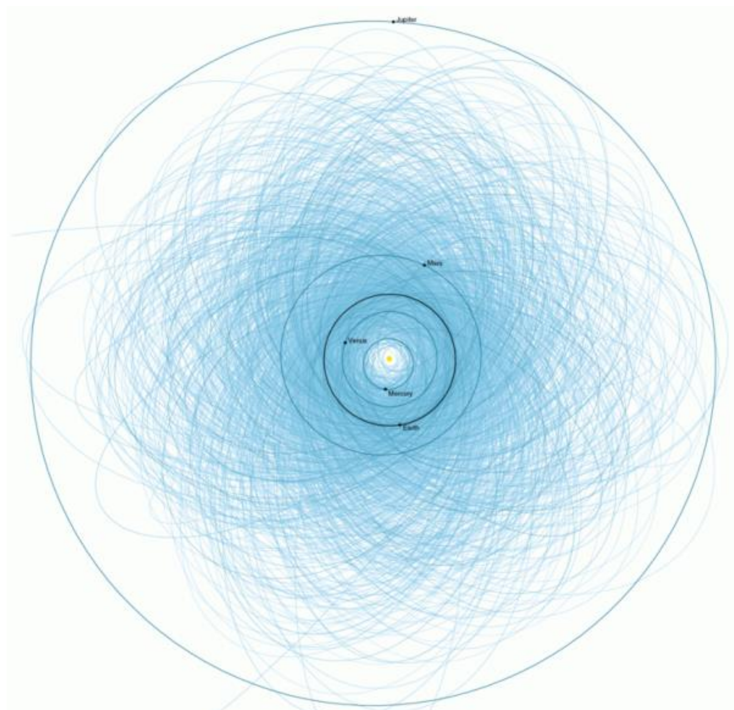


Figure 4-The orbits of all known (as of 2013) potentially hazardous asteroids over 460 feet in diameter. Earth's orbit is the thicker black circle near the center of the plot. (NASA/JPL-Caltech)

While this scenario may seem hyperbolic, we've had several close calls in the past century alone. In 2013, a 20 meter (~66 feet) wide near-Earth asteroid exploded about 32 km (20 mi) above Chelyabinsk, Russia. The shock wave and falling glass injured more than 1,000 people, and damaged more than 7,000 buildings. And yet these impacts were minor compared to what would have been wrought had the asteroid made it all the way to the ground. In 1908, a similar but even larger event occurred over Eastern Siberia, flattening more than 2,000 km^2 (770 mi^2) of forest along the Tunguska River, roughly equal to the size of the entire Phoenix metropolitan area. In both cases, we never saw the asteroids coming.

Earth isn't the only target; we've also observed major impacts on other planets, providing even more evidence that we live in a cosmic shooting gallery. In 1994 and 2009, astronomers watched in amazement as Jupiter was bombarded by pieces of a fragmented comet, Shoemaker-Levy 9, leaving behind blemishes larger than Earth itself.

Near-Earth asteroids are dark, dim, and difficult to spot in the best of circumstances. Light pollution only makes the challenge more difficult. If we brighten the sky to the point where we can only detect incoming asteroids after it is too late, then light pollution could literally be obscuring objects with the potential to erase entire cities or species (and ironically, our concerns about light pollution) from our planet.

Most observatories established in the late 19th or early 20th centuries were built in rural areas not all that far from major cities. With few exceptions, these facilities are now shrouded by skyglow and essentially unusable (Fig 5). Percival Lowell, the astronomer we met at the beginning of this chapter, was one of the first to seek a location for his observatory far from modern civilization. By doing so, he hoped to escape the air and light pollution that plagued his studies of Mars in New England.[10] After an arduous scouting mission, he founded the Lowell Observatory in Flagstaff, AZ in 1896. Flagstaff's ongoing commitment to preserving its dark night sky (see *Chapter 3.4*) has allowed Lowell Observatory to remain at the forefront of astronomical research over a century later.

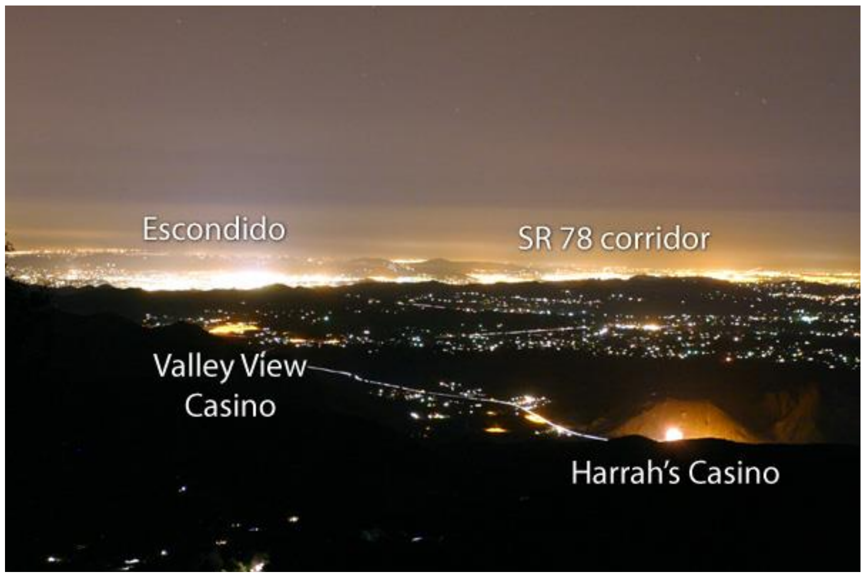


Figure 5-Light pollution (skyglow and glare) as seen from the Palomar Observatory in Southern California. (Palomar Observatory/Caltech)

Contemporary astronomers face essentially the same dilemma that Lowell struggled with in the 1890s. The only difference? Finding truly dark skies is no longer as easy as hopping on the train to Arizona. From Galileo in the 1600s to Annie Jump Cannon and Henrietta Leavitt in the early 1900s, most astronomers of the past didn't have to contend with light pollution. Only in the last century has it begun to stand in the way of scientific discovery. What discoveries might we prevent future astronomers from making if we continue to light up the night sky and obscure the cosmos?

A world without the night sky

So what do we lose when we blot out the stars? We lose one of the most breathtakingly beautiful sights on the planet. We lose the inspiration and the sense of wonder and discovery that comes with viewing the night sky. We lose the ability to peer into the universe, searching for both other life forms and threats to our existing society. We lose a night sky that is sacred to many cultures and a treasure trove of information about our past. We lose the ability to see the next frontier of discovery, and perhaps the desire to explore our cosmos beyond the boundary of our own planet. We lose the ability to look up at the Milky Way and ponder our place in space and the meaning of it all. We lose the ability to feel a part of our cosmic home.

Economics of Light Pollution

Of all the phenomena of nature, the celestial appearances are, by their greatness and beauty, the most universal objects of the curiosity of mankind.

—Adam Smith (1723-1790)

Why quote the father of modern economics and free market theory in an astronomy handbook? So far we've focused on how artificial light at night affects the sky, but now we turn our attention to some non-astronomical ramifications of light pollution, including economics.

As an integral element of modern society, electric lighting consumes a tremendous amount of energy and money. As of 2006, electric lighting consumed ~19% of global energy production, at a total cost of $360 billion.[11] Outdoor lighting accounts for about 8% of this figure, mostly in the form of street and parking lot lighting.[12]

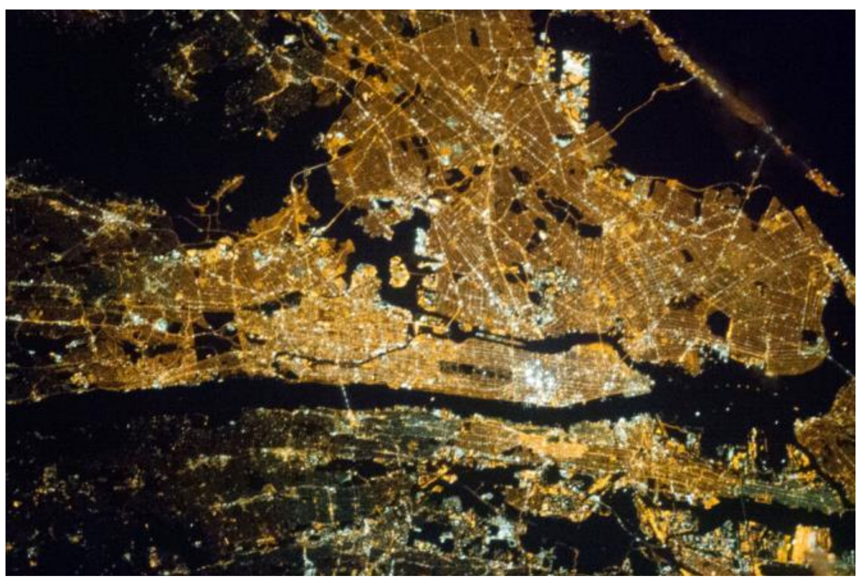


Figure 6-New York City at night, as seen by astronauts aboard the International Space Station. (NASA)

As the satellite image of New York City in Figure 6 shows, a significant proportion of outdoor lighting is emitted upward, where it serves little use. **Photons** visible from space are less likely to be serving a useful purpose on the ground, and yet are the primary cause of light pollution. Energy and money used to shine light into the sky is simply wasted. The International Dark Sky Association estimates that at least 30% of all outdoor lighting in the United States is wasted…that is, allowed to escape into the atmosphere by unshielded fixtures instead of being directed at what needs to be lit. [13] The cost of this wasted light in the U.S. alone is ~$3.3 billion per year, and the energy used to produce it releases 21 million tons of carbon dioxide into the atmosphere annually.[14]

Consequently, the night sky isn't the only thing we lose to light pollution. We also squander energy and money when we use light carelessly. Using well-designed **dark-sky friendly lighting** can provide the same level of illumination on the ground using less energy by eliminating wasted light, saving significant amounts of money in the process. These savings are among the factors behind the increasing number of municipalities around the world adopting dark-sky lighting codes (See further discussion and examples in *Chapter 3.4: Dark-Sky Friendly Lighting*).

Astro-Tourism

Saving money is great, generating economic growth is even better. The rapid rise of **astro-tourism** is demonstrating the vast economic potential of dark places. In a classic case of supply and demand, as dark skies become scarce in places like the eastern United States and Europe, more and more people are deliberately travelling to places free of light pollution while on vacation. Astro-tourism is increasingly seen as a potential economic driver in places, often rural, that are fortunate enough to still have dark skies. Astro-tourism inherently requires an overnight visit, which makes it attractive to communities that rely on tourism because it increases the average length of stay and overall tourist dollars spent.[15]

The Colorado Plateau, with its dark skies, good weather, high elevation, and vast tracts of public land, has already become a premier destination for those seeking a dark night. This is reflected in visitation statistics from places like Bryce Canyon National Park, which now draws ~30,000 visitors to its night sky programs (stargazing, full moon hikes, and annual astronomy festival) each year.[16] Many resorts and tour operators on the Colorado Plateau are now offering dark-sky specific packages, tours, and programs[17-18], while the Utah Office of Tourism has several pages and itineraries on its website devoted to promoting the numerous International Dark Sky Parks within the state.[19]

While monetization of dark night skies can help encourage their preservation, care is required to avoid unintended consequences. Artificial light and development associated with the rise in astro-tourism can inadvertently threaten the very thing that people come to see. States, cities, parks, and other groups promoting dark night skies as a tourist attraction must adhere to dark-sky friendly lighting principles in order for astro-tourism to be sustainable over the long term.

The Ecological Value of Darkness

Throughout the 4.56 billion year history of our planet, Earth has been a world of constant change. Entire continents merge, drift, and split apart. Erosion continually reshapes the Earth's surface. Global temperatures fluctuate with the composition of the atmosphere and orbital cycles. Aside from the occasional mega-eruption or asteroid impact, these changes occur slowly enough that life is able to evolve, adapt, and even thrive in the new conditions.

One of the few constants across geologic time has been the natural cycles of light and dark that result from the motions of the Sun, Earth, and Moon.[20] For eons, our bright day has been followed by a dark night, punctuated only by a short period of bright moonlight each month. Given Earth's dynamic state, it is remarkable how little these cycles have changed. For example, the length of our day has increased by just 3 hours since the beginning of the Cambrian Period 541 million years ago, when life on Earth began to rapidly diversify.[21] In other words, our night naturally gets about one second shorter every 50,000 years.

Today however, night is disappearing much faster. As artificial light encroaches upon the night, we eliminate these natural rhythms of light and dark from vast swaths of our planet. In many places "night" no longer exists at all. Skyglow combined with clouds or snow cover can light up the nighttime environment to a level far greater than eve the full moon.[22-23] Loss of the night is a phenomenon completely unprecedented in the history of our planet. Few were concerned until researchers began to discover that natural cycles of light and dark control a multitude of biological and ecological processes, both in humans and other organisms.[24]

Creatures of the Night

Perhaps the importance of darkness shouldn't be such a surprise. After all, many species, such as those that dwell in caves or on the ocean bottom, are accustomed to perpetual darkness. In contrast, no organism on Earth has evolved in a regime of perpetual light. Darkness is something every organism ever to inhabit Earth has experienced in common…until now.

The study of how darkness (or the lack of it) affects different species is known as **scotobiology**. More than 30% of vertebrates and 60% of invertebrates are **nocturnal**, and depend on darkness for foraging, mating and other functions.[25] Even diurnal species such as ourselves still need periods of darkness, even if we tend to sleep through most of it. Scotobiology has revealed that artificial light at night can affect organisms in several distinct ways.

First, artificial light at night illuminates the environment at *times* that are unnatural. Many species use celestial patterns of light (e.g., the lunar phase cycle, starlight, or the glow of the Milky Way) to navigate or time certain activities. Light pollution can mask or eliminate natural lighting cues that have been consistent for millions or billions of years, affecting the species that rely on them. For example, many species of reef-forming corals reproduce only once per year, releasing their eggs and sperm on the same night. The timing of this mass-spawning event appears to be controlled by moonlight.[26] Light pollution in coastal areas can mask this natural signal, prevent the corals from reproducing effectively, and potentially contributing to the worldwide decline of coral reefs.[27]

Secondly, the **spectrum** of artificial light at night is often very different from natural sources like moonlight and starlight. For example, our Moon, long the brightest source of light at night, shines via reflected sunlight. Sunlight (and thus moonlight) contains a broad spectrum of different wavelengths and collectively appears white. In stark contrast, most artificial light at night has a narrower spectrum while some, such as LEDs, emit a high proportion of blue light compared to other colors (Fig 7). This is notable because there are virtually no natural sources of blue light at night. Moonlight, starlight, and even the firelight humans have used to ward off the night for thousands of years all emit very little blue light. Numerous studies have found that blue light plays a major role in regulating biological processes and that its use at night has profound effects on animals and humans.[28]

Table 1 lists some examples of species shown to be affected by *ecological light pollution*, and offers a glimpse at the rapidly expanding field of scotobiology.

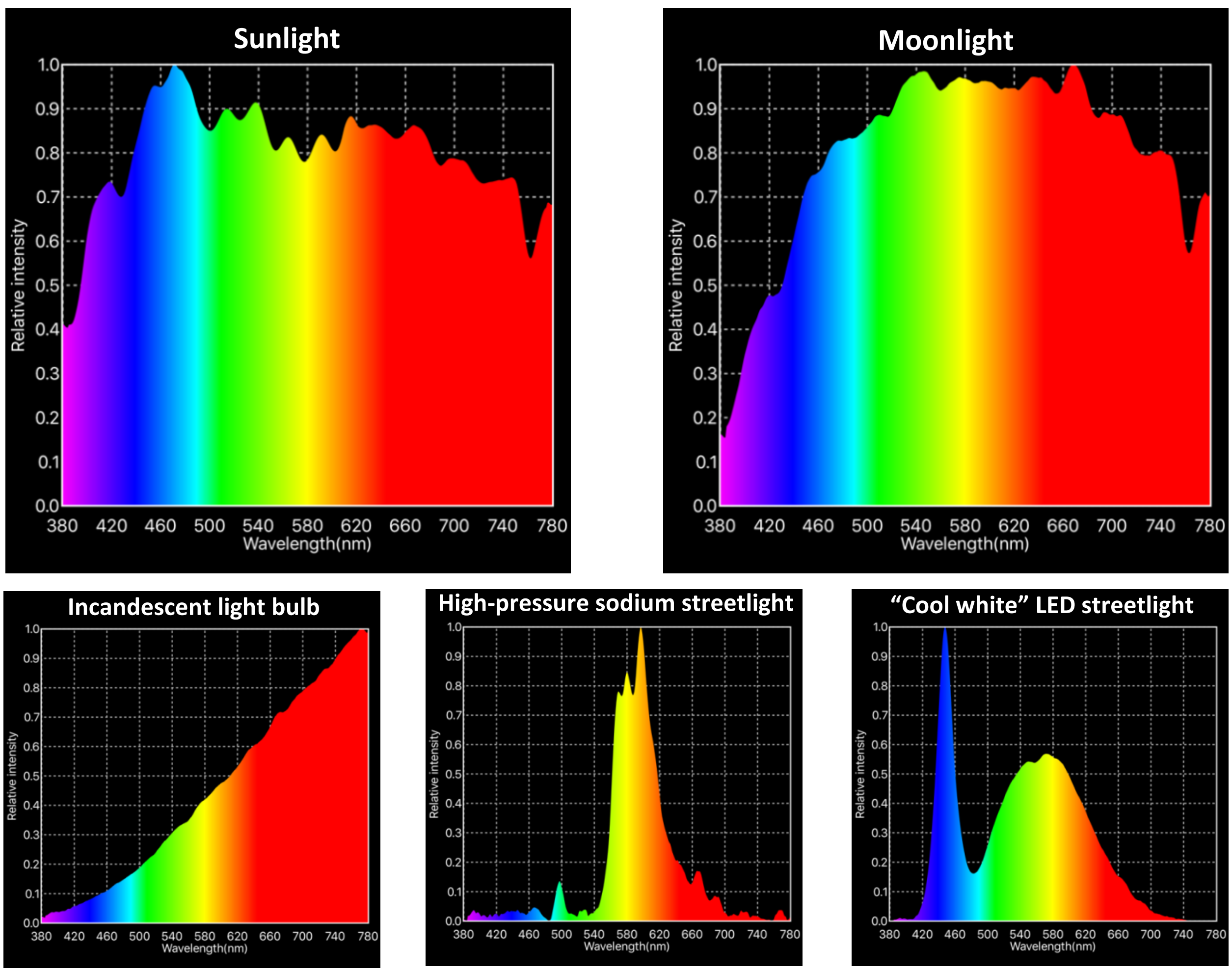


Figure 7-Observed spectra of moonlight, sunlight, and several different sources of artificial light at night. Diagrams show the relative amount of light emitted at different wavelengths by each light source. Note the large proportion of blue light emitted by the LED streetlight. (NPS/Zach Schierl)

Table 1: A Partial List of Species Affected by Artificial Light at Night	
Sea turtles	Hatchling sea turtles navigate to the safety of the ocean using natural lighting cues, namely, moon and starlight reflecting off the ocean surface. Many species of sea turtles will avoid nesting on brightly lit beaches, and hatchlings will crawl towards artificial light when it is present, drastically decreasing their odds of survival.[29]
African dung beetle *(Scarabaeus satyrus)*	Biologists have discovered that this species of dung beetle uses the diffuse light of the Milky Way as an orientation marker. Decreased visibility of Milky Way implies that the beetles lose their ability to orient.[30] Dung beetles are considered a "keystone species" because of their ability to facilitate decomposition and nutrient cycling.
Zooplankton *(Daphnia)*	*Daphnia* live in a variety of aquatic environments, and reside deep below the water during the day. Darkness triggers their migration to the surface to feast on algae. Marine ecologists have found that urban light pollution inhibits the zooplankton from migrating to the surface to feed, which can lead to algae blooms that affect negatively affect water quality as well as other lifeforms in the lake.[31]
Lesser horseshoe bat	Global populations of the lesser horseshoe bat are decreasing and it is classified as endangered in many areas. Studies have found that this species avoids heavily lit areas, and that artificial light at night interferes with feeding activities and decreases overall fitness of the bats.[32]
Beach mice	Studies of beach mice show that artificial light at night negatively affects their ability to gather food. Mice forage for food less often and for shorter periods of time in areas affected by artificial lighting.[33]
Various species	Moonlight is strongly polarized and many species use this polarized signal for navigation. Urban skyglow is un-polarized, and dilutes the signal used by many nocturnal species to navigate, potentially reducing the fitness of these organisms.[34]
Moths	In an agricultural area in England, moth activity, abundance, and species diversity was significantly lower at lit sites than unlit sites. Moths carried less pollen and fewer pollen types at the lit sites, suggesting that artificial lighting may be a mechanism contributing to moth declines.[35]
Migrating birds	Many species of birds migrate at night and use natural lighting cues (such as moonlight and starlight) to navigate. Migrating birds regularly travel over heavily lit areas where artificial light can disorient birds, and cause collisions with buildings and towers.[36]
Trees	Artificial light has been associated with earlier deciduous tree budburst across multiple species in the United Kingdom.[37] Normally controlled by temperature and day length, premature budburst can increase risk of frost damage.

While some of these species may seem small and insignificant, all are an integral part of the natural world around us. Many provide important **ecosystem services**, functions such as nutrient recycling, pollination, and water purification that help create an environment in which humans have the resources necessary for survival. Without ecosystem services and the species that provide them, we would not have food to eat, air to breathe, or nutrient-rich soil to grow food. For example, moths are an important pollinator yet studies show that both moth activity and the variety of pollen they carry are depressed around highly lit areas.[38] This can have a ripple effect on species that rely on moths for pollination, which are often important food sources for humans.

When we try to pick out anything by itself, we find it hitched to everything else in the universe.
—John Muir (My First Summer in the Sierra, 1911)

When we think about elements of a healthy ecosystem, the night sky might not be the first thing that jumps to mind. However the research is clear: natural darkness is important for a wide-variety of organisms both large and small.

Humans and Artificial Light at Night

Except for astronomers, humans are not nocturnal animals. Still, we evolved in the same cycles of light and dark as most other organisms and are far from immune to the effects of artificial light at night. The idea of light as a human health hazard may seem strange given that we are bathed in it every day of our lives. Historically though, humans have been exposed to bright sunlight during the day and low levels of light at night. In today's society, this regime is often flipped on its head. Light polluted cities can be brighter than the Full Moon at night, indoors and out, while many individuals work inside under lights much dimmer than the Sun during the day. This is a monumental shift away from the natural rhythms of light and dark that humans have experienced for millennia.

There is growing concern that exposure to artificial light at night, particularly blue light, has an impact on human health. In 2012, the American Medical Association weighed in, stating that: "The power to artificially override the natural cycle of light and dark is a recent event and represents a man-made self-experiment on the effects of exposure to increasingly bright light during the night as human societies acquire technology and expand industry."[39]

The results of this experiment, like so many, are mixed so far. We know that light plays a significant role in the regulation of our **circadian rhythm**. Consistent exposure to light and dark matches our circadian rhythm to the 24-hour day.[40] In addition to **rods** and **cones**, our eyes contain a third type of cell that is light-sensitive (but non-image-forming) and controls the release of a hormone called **melatonin**.[41] Typically, melatonin is produced at night when it is dark, while exposure to light during the day suppresses production. These cells are most sensitive to light with a wavelength of 459 nanometers: blue light.[42] Exposure to even very low levels of blue-rich artificial light at night can suppress melatonin production and disrupt circadian cycles, which in turn has been linked to a variety of harmful health effects.[43]

A growing body of evidence associates intense or prolonged exposure to artificial light at night, particularly blue light, with an array of human health issues.[44-45] Melatonin appears to have an anti-carcinogenic effect in humans and other species, while numerous epidemiological studies have found links between greater exposure to artificial light and the incidence of various cancers, most notably breast and prostate cancer. [46-47] In 2007, the International Agency for Research on Cancer (IARC) stated that “shift-work that involves circadian disruption is probably carcinogenic to humans.”[48] Research into *how* and *why* artificial light at night might cause these effects is ongoing. Artificial light at night can also affect human health in indirect ways. For example, artificial light at night contributes to air pollution in urban areas by breaking down natural compounds that “scrub” pollutants from the atmosphere during nighttime hours.[49] While a thorough discussion of the human health effects of artificial light is beyond the scope of this handbook, extensive information can be found in the links at the end of this chapter.

Artificial light at night is one of the most significant modifications that we have made to our planet, with wide-ranging impacts across many facets of society and the environment. As humans continue to blur the line between night and day, the value of darkness becomes increasingly clear. Light pollution is no longer just the concern of astronomers: it affects all of us. While light at night nearly universal, the good news is that there are still a handful of places left where we can experience a naturally dark night and a star-filled sky.

The Last Refuge of Night: Dark Skies in the National Parks

It is now easy to find artificial day, but what about a natural night? Many U.S. national parks and monuments, particularly those in the western U.S. located far from urban areas, remain relatively dark (Fig 8). These places are some of the best remaining oases from which to experience a nighttime environment relatively free of light pollution.

The **Organic Act of 1916,** which established the U.S. **National Park Service** (NPS), directs the agency to “conserve the scenery and the natural and historic objects and the wild life therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations.”[50] Park managers are increasingly realizing that a naturally dark night is a vital part of an unimpaired environment. As a result, more and more national parks are getting involved in dark sky stewardship, both to preserve the view of the night sky for visitors, and to maintain a naturally dark environment for plants and animals.

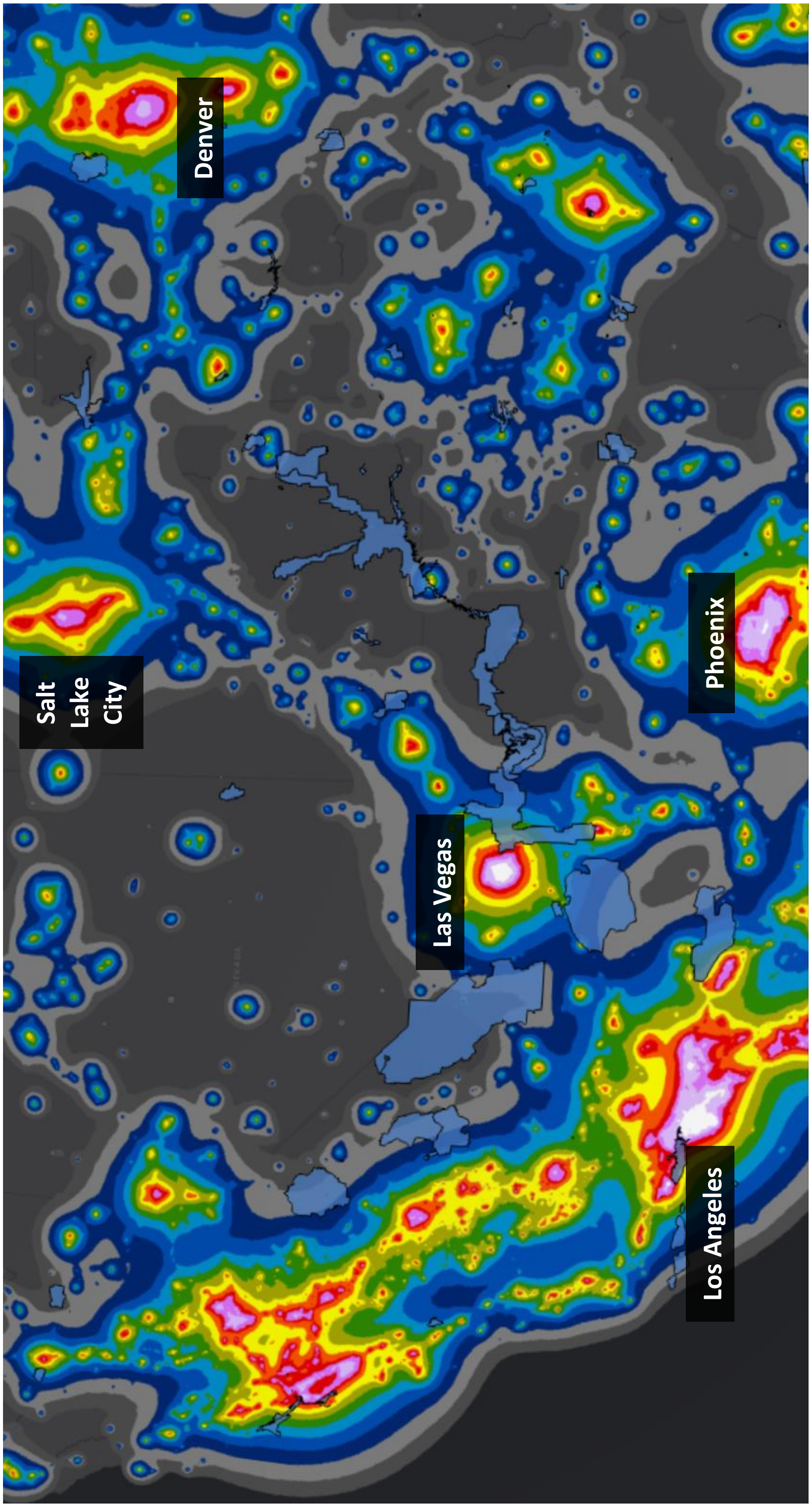


Figure 8-Map of skyglow intensity in the western United States, with an overlay of units in the U.S. National Park system (light blue). Note that many national parks in the western U.S. are located in areas relatively free from the effects of skyglow and other forms of light pollution. An explanation of the colors and construction of these maps can be found in Chapter 3.3. (Falchi et al. 2016, Science Advances e1600377)

Figure 9-The Summer Milky Way seen through Delicate Arch, Arches National Park, Utah. (NPS/Jacob Frank)

As light pollution takes over the cities, more and more people are turning to national parks and other protected areas to see the stars. A dark night sky is an integral part of the scenery and wilderness character that visitors expect to find in these places (Fig 9). Anyone who has spent time in a dark national park at night knows that the scenic value of a star-filled night sky is on par with anything a visitor can see by day. Dark national parks allow us to experience nighttime in a way no longer possible in most of the developed world.

Surveys of national park visitors support the idea that a dark night sky enhances the visitor experience (Table 2). In a survey of nearly two hundred groups who spent the night in a campground at Acadia National Park in Maine, 89.6% of respondents said that being able to view the night sky was important to them, while 34.2% said they would be less likely to visit the park if the quality of the night sky became more degraded.[52] In another survey of 1,179 visitors to Bryce Canyon National Park and Cedar Breaks National Monument in Utah, 89.1% of respondents agreed or strongly agreed that national parks should be preserved for their dark skies, while 90.3% said that communities surrounding parks should help preserve those skies.[53]

Table 2: Survey of 194 overnight visitor groups at Acadia National Park, Maine[51]

Statement	Strongly disagree/ disagree	Neutral	Strongly Agree/ Agree
Viewing the night sky (stargazing) is important to me.	1.0	9.4	89.6
The National Park Service should work to protect the ability of visitors to see the night sky.	1.1	8.9	90.0
The National Park Service should conduct more programs to encourage visitors to view the night sky.	2.6	27.1	70.3
One of the reasons I chose to visit Acadia is to view the night sky.	16.3	39.5	44.2
I would visit Acadia less often if it became more difficult to see the night sky.	25.8	40.0	34.2

While it is tempting to think of our national parks as untrammeled wilderness free of light pollution and other signs of human activity, in reality, not even remote national parks are completely immune from artificial light. Even from national parks famed for their dark skies, such as Bryce Canyon or Great Basin, **light domes** from distant cities or small communities just outside park boundaries are still visible on the horizon. Finding a truly pristine night sky, one comparable to what our ancestors even 150 years ago would have seen, is virtually impossible today.

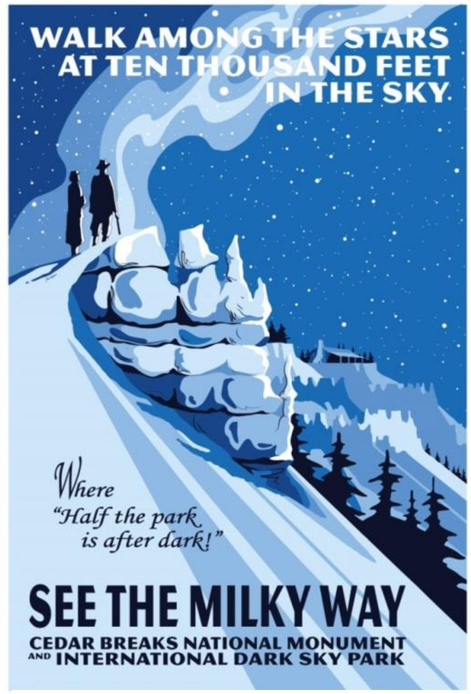


Figure 10-Poster art by University of Redlands astronomer Tyler Nordgren, promoting the nighttime wonders of America's national parks and monuments. (Tyler Nordgren)

With the influx of astro-tourism, National Park Service rangers and educators are increasingly at the forefront of the effort to educate the public about light pollution. As of 2011, more than 60 national park units regularly offer stargazing or astronomy programs.[54] At Cedar Breaks and many other parks, these night sky programs are by far the best attended programs on the menu. The slogan "Half the park is after dark!" and Milky Way poster art by astronomer Tyler Nordgren have contributed to a drastic rise in visitors seeking dark skies in national parks over the past decade (Fig 10). The National Park Service has also developed a Jr. Ranger Night Explorer program to introduce younger visitors to the night sky (Fig 11).

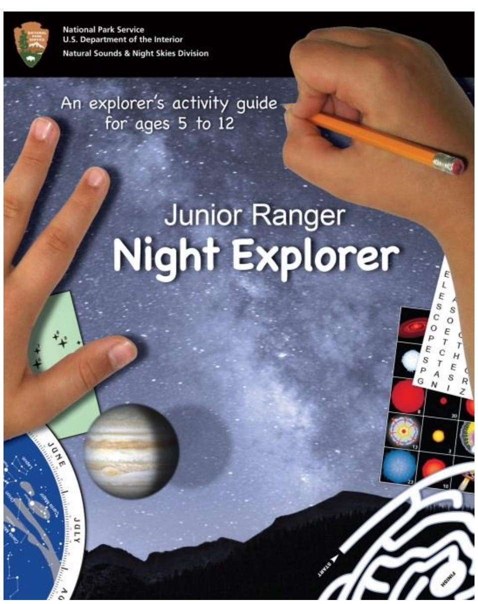


Figure 11-National Park Service Jr. Ranger Night Explorer program booklet. (NPS Photo)

Because they provide a partial respite from light pollution, dark national parks are a great venue for educating the public about the cosmos. Unlike in a planetarium, visitors get to experience the actual night sky instead of a virtual simulation. Astronomy educators have proposed that the authenticity of such an experience makes the audience more likely to be inspired by the significance of astronomy in their lives.[55] Research, although limited in scope, suggests that night sky programs in national parks are effective at increasing visitor understanding of the importance of dark night skies. A 2013 survey of night sky program attendees at Bryce Canyon NP and Cedar Breaks

NM showed that visitors came away from these programs feeling more knowledgeable about the impact of light pollution on the night sky, human health, and wildlife, how to improve outdoor lighting, and the cultural and historical value of the night sky and astronomy.[56]

Two national park units, Great Basin National Park in Nevada and Chaco Culture National Historical Park in New Mexico, are now home to permanent observatories (Fig 12). The Great Basin Observatory is a remotely operated research observatory used by undergraduate students at multiple universities around the western United States, while the observatory at Chaco Culture is used in the park's night sky education and outreach program.

Figure 12-The Great Basin Observatory (left) and Chaco Observatory (right). (GBO: Great Basin National Park Foundation, Chaco: NPS Photo)

In addition to education, the National Park Service has also taken a leading role in developing cutting-edge methods for monitoring light pollution and ascertaining its effects on the natural environment. The National Park Service's Natural Sounds and Night Skies Division, based in Fort Collins, Colorado, has quantitatively documented skyglow conditions at more than 100 parks since 2001.[57] Repeat measurements over time have revealed significant degradation of night sky quality at several parks, including Theodore Roosevelt National Park, Carlsbad Caverns National Park, and Chaco Culture National Historical Park (See *Chapter 3.3: Measuring and Monitoring Light at Night*). NPS skyglow data has also been used to validate satellite measurements of light pollution, helping create maps such as the one in Figure 8.[58]

Finally, many national park units are installing dark-sky friendly light fixtures and bulbs on buildings within park boundaries. This enhances the view of the night sky for visitors, maintains a naturally dark night for nocturnal animals, and, perhaps most importantly, serves as a model for surrounding communities. While improving lighting within parks is important, the reality is that most of the threat to dark skies in national parks comes from cities outside park boundaries. Moving into the future, parks will have to work closely with such communities in order to preserve their dark skies for future generations. In fact, this very handbook is a step in that direction. The Master Astronomer Program was originally created by Cedar Breaks National Monument as a way to promote dark sky stewardship in cities and towns throughout Southern Utah. By introducing people to the wonders and benefits of a dark night sky, we hope to increase the odds that the skies over Cedar Breaks will remain dark for decades to come.

International Dark Sky Places

To encourage the protection and stewardship of dark places around the world, the **International Dark Sky Association (IDA)** established the **Dark Sky Places** program in 2001.[59] This program certifies interested parks (national, state, & local), communities, and other entities as "International Dark Sky Places" presuming they meet and uphold a strict set of criteria. In general, potential dark sky places must:

- Possess an exceptional dark sky resource, relative to the surrounding area.
- Serve as a model example of dark-sky friendly lighting.
- Be actively engaged in education and outreach pertaining to dark skies and astronomy

Figure 13-Cedar Breaks National Monument International Dark Sky Park logo (NPS/Shannon Eberhard)

Flagstaff, AZ became the world's first International Dark Sky City in 2001, while Natural Bridges National Monument in southeast Utah was named the world's first **International Dark Sky Park** in 2007. To date, the IDA has designated more than 100 dark sky places around the world, including several parks and protected areas on or near the Colorado Plateau.[60] Cedar Breaks National Monument was designated as an International Dark Sky Park in March of 2017 (Fig 13), and Utah currently has more designated International Dark Sky Parks than any other state with 10.

Review

Common misconceptions

Below is a list of commonly encountered misconceptions about protecting the night sky. As a way to review content from this chapter, see if you can explain why each misconception is inaccurate:

- Light pollution is only an issue for astronomers who study the night sky.
- Light pollution doesn't directly affect humans.
- Light pollution is a problem not worth the time and money to solve.

- We can experience a pristine night sky just by going to the closest national park.

Questions for thought

- Is there an argument for dark sky stewardship that you personally feel is most compelling? Why? Would your neighbors, parents, or spouse feel the same way?

- You've been asked to give a talk on dark skies to the city council in your home town. How would you approach this talk? What information would you highlight? Would your approach differ if asked to give a talk for an astronomy club, a Rotary Club, or a local environmental organization?

- What are some challenges associated with educating the public about the importance of dark skies when most Americans have never experienced a truly dark sky? What is the role of education in the effort to save dark places?

- What is your favorite memory involving the night sky? How much light pollution was present? Would the experience have been different if there had been more or less light pollution? How so?

- How does light pollution affect our ability to solve current questions in astronomy? What can astronomers do about it?

- The full moon is often described by astronomers as a "natural" source of light pollution because of how it lights up the night sky but this ignores the fact that moonlight is very different than skyglow. How so?

For More Information

Light Pollution and the Night Sky

- Colorado Plateau Dark Sky Cooperative: https://cpdarkskies.org/
- *Dark Skies (*a film by *RadioWest* and *Science Friday*): https://films.radiowest.org/film/dark-skies
- *The End of Night: Searching for Darkness in an Age of Artificial Light*, by Paul Bogard, 2014
- *Let There Be Night: Testimony on Behalf of the Dark*, edited by Paul Bogard, 2008
- "Losing sight of the stars": http://theweek.com/articles/579064/losing-sight-stars
- *The New World Atlas of Artificial Night Sky Brightness* (interactive map of skyglow): http://cires.colorado.edu/Artificial-light

- *Night Spoken* (video series from Grand Canyon National Park exploring our relationships, or lack thereof, with natural darkness): https://www.youtube.com/channel/UCTm5qDFwhtV3HhNwver8-4Q
- *Protecting Dark Skies* (Colorado Plateau Dark Sky Cooperative)*:* https://vimeo.com/328258998
- *"*Why Astronomy Matters": http://www.deepastronomy.com/astronomy-education-01.html

Ecological & Human Health Effects of Light Pollution

- Artificial Light at Night (ALAN) Research Literature Database: http://alandb.darksky.org/
- *Blue Light Aotearoa: Impacts of artificial blue light on health and the environment*, 2018, Royal Society of New Zealand: https://royalsociety.org.nz/assets/Uploads/Blue-light-Aotearoa-evidence-summary.pdf
- *Dark Matters: Nature's Reaction to Light Pollution*, by Joan Marie Galat, 2017
- *Ecological Consequences of Artificial Night Lighting*, edited by Catherine Rich & Travis Longcore, 2006
- "Ecological light pollution": http://www.urbanwildlands.org/Resources/LongcoreRich2004.pdf
- "Human and Environmental Effects of LED Community Lighting" (American Medical Association): http://darksky.org/wp-content/uploads/bsk-pdf-manager/AMA_Report_2016_60.pdf

Night Skies in the National Parks and Dark Sky Parks

- "Stargazing in Utah" (Utah Office of Tourism): https://www.visitutah.com/things-to-do/dark-sky-parks
- International Dark Sky Places Program: http://darksky.org/idsp/
- National Park Service Night Skies Program: https://www.nps.gov/subjects/nightskies/index.htm
- *Stars Above, Earth Below: A Guide to Astronomy in the National Parks*, by Tyler Nordgren, 2010

CHAPTER 3.3 - MEASURING & MONITORING LIGHT AT NIGHT

Images of Earth at night from orbiting satellites can help visualize the extent of light pollution. These satellites can also help track changes in the amount of light being emitted into space from Earth's surface over time. (NASA Earth Observatory)

Chapter 3.3 Goals

After reading this chapter and participating in the corresponding workshop activities, you should be able to:

- Describe the most significant natural sources of light at night and how these phenomena can affect measurements of light pollution.
- Make and record basic measurements of night sky quality using limiting magnitude, the Bortle Scale, and a Sky Quality Meter.
- Accurately differentiate between a truly dark night sky and a night sky affected by skyglow.

Why Measure Light Pollution?

Measuring and monitoring are crucial to managing any type of environmental degradation, be it air pollution, water pollution, or **light pollution**. Without a way to accurately measure light pollution, we have no way to tell if conditions are improving or deteriorating over time, and no way to judge the effectiveness of efforts to combat it. Effective monitoring of light pollution requires both an objective method for measuring it, as well as some sort of reference condition—that is, "What should the night sky look like in the absence of light pollution?"

Unfortunately, both of these requirements are more complicated than they might seem. Human eyesight varies considerably at night, so our eyes are of limited use as a measuring tool. Plus, so many of us live under chronically light polluted skies that it can be difficult to recognize a truly dark sky when we see one.

Nevertheless, scientists have developed a host of techniques and metrics for monitoring light pollution and **artificial light at night**. Some are simple and require no special equipment, but suffer from human biases. Others are more objective and precise, but are complex and measured using dedicated instruments. Many do not measure light pollution itself per se, but rather the extent to which it degrades the visibility of stars and other objects in the night sky. This chapter will introduce you to some of each, and equip you to make some basic measurements of night sky quality from your own backyard.

Natural Light vs Artificial Light

A major challenge associated with measuring light pollution is distinguishing between *artificial* light and *natural* light. Despite our common language ("protecting *dark* skies"), the night sky is not actually "dark" at all in the absence of light pollution. It is filled with things that emit light, such as stars, planets, and the Milky Way (Fig 1). Ironically, it can often seem like the darker a sky is, the brighter it becomes with starlight! Thus, measuring light pollution is not as simple as measuring how bright the night sky is. For example, to accurately measure how much skyglow there is above a city, we need to be able to distinguish between actual skyglow and other natural sources of light that might masquerade as skyglow.

Figure 1-Even in the absence of light pollution, the night sky appears bright compared to the landscape in the foreground. (NPS/Zach Schierl)

The brightest source of natural light in the night sky is the Moon. Avoiding its light is as simple as not taking light pollution measurements on nights when the Moon is up. Other natural phenomena, such as **aurorae**, wildfires, and snow cover, can also brighten the night sky, although these too can be avoided by taking measurements at the right time of year. However, several lesser known phenomena light up the night sky every night of the year, and must be taken into account if we want accurate measurements.

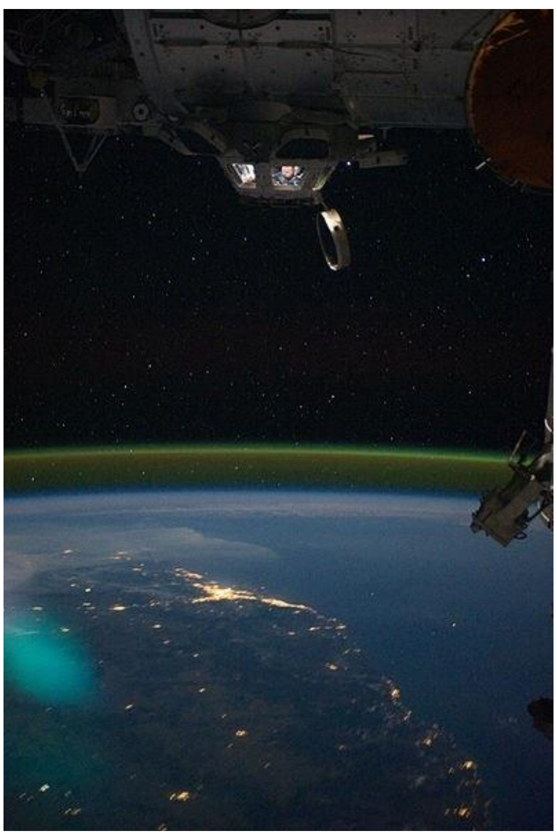


Figure 2-Airglow as seen from the International Space Station over the coast of Australia. (NASA)

Airglow

Airglow is the result of solar radiation exciting air molecules in the Earth's upper atmosphere. When the molecules de-excite, they emit a faint glow (Fig 2) that naturally brightens the night sky.

Airglow is seldom perceptible to the naked eye, but it is always there. (Airglow is actually brightest during the daytime, but is rendered completely invisible by bright sunlight.) More often, it shows up in long-exposure photographs of the night sky, where it appears as a ghostly green and/or reddish glow pervading the sky (Fig 3). The brightness of airglow varies over time, tied in large part to the 11 year solar cycle. Airglow is generally brightest during periods of increased solar activity, but its intensity also varies significantly on a night to night basis.[1] In the absence of moonlight, airglow is the single most significant source of natural night sky brightness (Table 1).[2,3]

Table 1: Median % contribution to natural night sky brightness[4]	
Airglow	45.3%
Zodiacal light	28.7%
Galactic light	19.5%
Starlight	5.2%

Figure 3-Long exposure photograph of the night sky from western Colorado showing prominent green airglow. The airglow was undetectable to the naked eye when this photo was taken. (NPS/Zach Schierl)

Zodiacal Light

The second largest contributor to natural night sky brightness is the **zodiacal light**, an elliptical band of sunlight reflecting off small dust particles in interplanetary space.[5] These dust grains are concentrated in the plane of our Solar System, so the zodiacal light appears as a pyramid of light stretching along the **ecliptic** and zodiac constellations, hence its name (Fig 4).

The zodiacal light is always present, though usually masked by light pollution in urban and suburban areas. Like airglow, it often appears in long-exposure photographs even when not visible to the naked eye. In fact, naked eye visibility of the zodiacal light can be used as an indicator of night sky quality (see "Bortle Dark Sky Scale" below). From a dark site, it can be easily seen with the naked eye and resembles the skyglow of a distant metropolis. The zodiacal light is brightest near the horizon and is best seen either just after sunset or just before sunrise. The changing angle of the ecliptic with respect to the horizon means it is most prominent in Northern Hemisphere spring and autumn.

Figure 4-The zodiacal light as seen from Grand Staircase-Escalante National Monument, Utah in mid-spring. The dashed line represents the approximate path of the ecliptic. (Zach Schierl)

Fun Fact

Brian May, the lead drummer of *Queen*, wrote his PhD thesis in astrophysics on the velocity of particles in the zodiacal dust cloud.

Galactic Light & Starlight

The third most significant source of natural light in the night sky is **galactic light** from our Milky Way Galaxy.[6] This light consists of **photons** scattered and reflected by interstellar dust, as well as the combined light from all the unresolved stars (stars too faint or close together to see without a telescope) in the Milky Way, known as *integrated starlight*.[7] The brightness of galactic light varies throughout the year. For example, in Northern Hemisphere summer the brightest portion of the Milky Way is high overhead, leading to more ambient galactic light at this time of year compared to winter.[8]

Surprisingly, the light from stars visible to the naked eye accounts for only about 5% of the photons entering your eyes on a dark, moonless night.[9] While the stars at night may seem big and bright, they are actually a lessor contributor to the brightness of the night sky than airglow, zodiacal light, or galactic light (Table 1). In other words, the combined light of all the stars you *can't* see is greater than the combined light of the stars you *can* see.

Accounting for Natural Light

Advanced methods of light pollution monitoring use sophisticated computer models to effectively subtract natural light sources, leaving only the artificial light behind.[10] However, the more basic methods simply record the overall brightness of the night sky and leave the interpretation up to us humans. To make good interpretations, we have to be familiar with these natural sources of light that can brighten the night sky.

Measuring Night Sky Quality with the Naked Eye

The simplest way to gauge the severity of light pollution is to make careful observations of the night sky with the naked eye. We'll focus on two metrics that require no special equipment to measure: **naked eye limiting magnitude (NELM)** and the **Bortle Dark Sky Scale.**

Naked Eye Limiting Magnitude (NELM)

Imagine gazing up at the night sky from downtown Los Angeles. Only a handful of stars, perhaps those of first and second **magnitude**, are visible, while the rest lie hidden in the haze of artificial light. The apparent magnitude of the *faintest* star visible to the naked eye from a given location is a common metric of night sky quality. In this case, if second magnitude stars are the faintest you can see, we would say that the **naked eye limiting magnitude (NELM)** of the sky is 2.0.

Now imagine travelling to a remote corner of Southern Utah. Many more stars are now visible; the bright ones you saw from L.A., plus thousands of third, fourth, fifth, and sixth magnitude stars. So many stars are visible that you may have trouble picking out the traditional constellation patterns. If stars of sixth magnitude are the faintest you can see with the naked eye, then the limiting magnitude is 6.0 and you are in for a fantastic night of stargazing.

Figure 5-Photos of the constellation Sagittarius, taken from Cedar City, UT (left) and Cedar Breaks NM (right). Note the Milky Way in the image from Cedar Breaks. Images were taken with the same camera, lens, and exposure settings. (NPS/Zach Schierl)

It's no secret that more stars are visible from darker locations. As seen in Figure 5, **skyglow** decreases the contrast between stars and the background sky, rendering fainter stars (and the Milky Way) invisible. Under a dark sky, these fainter stars pop out against the dark background and the limiting magnitude will be higher. (Remember that magnitudes are backwards and that fainter stars have higher magnitudes.) The NELM in a large city might be 3.0 or 4.0, while at a very dark site it might be as high as 6.0 or 6.5.[12] Some experienced observers can detect stars as faint as magnitude 7.0 or 7.5 from very dark locations.[13-14] An accurate limiting magnitude also tells you approximately how many naked eye stars are visible from a given site (Table 2).

Table 2: Number of Stars Visible to Naked Eye[11]

Naked eye limiting magnitude	Approximate # of naked eye stars:	Examples:
0	2	
0.5	5	
1	8	
1.5	12	
2	25	
2.5	47	
3	87	
3.5	144	Large city core (Las Vegas)
4	260	
4.5	463	Medium city core (St. George)
5	816	Small city core (Cedar City)
5.5	1,433	
6	2,534	Rural area (Three Peaks)
6.5	4,456	Dark site (Cedar Breaks)
7.0	7,794	Pristine dark sky site

Determining NELM

Limiting magnitude can be measured in several ways. All you need is a moonless sky, dark adapted eyes, and knowledge of a few constellations; no special equipment is required.

One technique for estimating NELM is a **star count**. A star count involves carefully counting all visible stars in one of several designated sections of the night sky, and then using a chart to look up the corresponding limiting magnitude. The more stars you see, the higher the limiting magnitude and the darker the sky. Detailed star count instructions can be found in the links at the end of this chapter and printed for use outside.

Two global citizen science projects can also help stargazers determine the limiting magnitude of their sky. Contributing to these projects builds a global database of night sky quality measurements and helps scientists track changes in light pollution over time on a large scale.

Globe at Night is a program of the National Optical Astronomy Observatory started more than a decade ago. The *Globe at Night* website contains star charts showing what different constellations look like under skies of different limiting magnitudes. Simply download the charts for a constellation currently visible in the night sky, and then see which one best matches your view. To contribute, you can submit your estimated limiting magnitude using an online form and compare your results to other observers from your area and around the world.

For those with smartphones, *Loss of the Night* is an app available for both Android and iOS devices. The app uses an interactive star chart to help you identify a series of fainter and fainter stars. For each star, you tell the app if it is clearly visible, barely visible, or not visible at all from your location. Using this information, the app is able to estimate your limiting magnitude. The *Loss of the Night* app works best in moderately to heavily light polluted areas. In extremely dark locations, the screen inhibits your night vision and prevents an accurate measurement of limiting magnitude. Links to both of these projects can be found at the end of the chapter.

Limitations of Limiting Magnitude

While limiting magnitude is a simple way to estimate night sky quality, it is far from perfect. First of all, NELM is not technically measuring light pollution at all, but rather how many stars are visible to the naked eye. Light pollution isn't the only factor that controls this number. High clouds, haze, smoke, humidity, bright airglow, and moonlight can all affect the visibility of faint stars at night. Thus, it is standard practice to only take NELM measurements on clear, moonless nights and sky conditions should be always be carefully documented.

Dark adaptation is also essential for obtaining an accurate limiting magnitude. Even then, everyone's eyesight is different. Two dark-adapted observers in the same location on the same night may arrive at different limiting magnitudes.[15] Finally, limiting magnitude varies depending on where in the sky you are measuring. NELM at the **zenith**, typically the darkest part of the sky, might be 6.0, but will likely be much lower along the horizon, where skyglow is most likely to be present.

Ultimately, NELM is one in a series of metrics that can help gauge the impact of light pollution. In conjunction with other measurements, it can be very useful. The primary advantage of NELM is that, while only semi-quantitative, it can be used by anyone with basic knowledge of the night sky to estimate night sky quality.

The Bortle Dark-Sky Scale

Introduced in 2001 by amateur astronomer John Bortle, the **Bortle Dark Sky Scale** is a nine-point rating system used to characterize night sky quality. In addition to limiting magnitude, the scale takes into account the amount of detail visible in the Milky Way, the visibility of the zodiacal light, and other naked eye observations. Lower Bortle numbers indicate more pristine skies (Fig 6), with "Class 1" defined as a pristine dark sky and "Class 9" representing an inner city sky. Since 2001, the Bortle Scale has seen widespread use among astronomers and light pollution scientists. It is arguably the most comprehensive and widely used method for estimating night sky quality using only the naked eye. A link to a detailed description of the Bortle Scale can be found at the end of this chapter.

Figure 6-Illustrations showing the appearance of the night sky in each of the nine Bortle Classes. (NPS/Chad Moore)

Limitations

In many ways, the Bortle Scale is an improvement over NELM, as it involves making a series of observations instead of just one. The appearance of features like the Milky Way and zodiacal light can be telling of sky quality, as their visibility deteriorates quickly with increasing skyglow. Despite these advantages, the Bortle Scale is still not a purely objective or quantitative measurement of light pollution. Bortle Scale observations still fall prey to the fact that human eyesight varies and many of the other pitfalls of using limiting magnitude.

When making any visual observations of night sky quality, the importance of dark adaptation cannot be overstated. Remember from *Chapter 3.1* that it takes at least 20-30 minutes for our eyes to become dark adapted. Even a quick glance at a bright object (such as a phone screen or white flashlight) can ruin your dark adaptation. Limiting magnitude and Bortle Scale measurements taken before dark adaptation is complete, or after dark adaptation is ruined, are essentially useless.

Measuring Night Sky Quality with Machines

Limiting magnitude and Bortle Scale measurements are inherently limited by human biases, so many scientists prefer to monitor night sky quality with specialized instruments. While these approaches are more objective, the numbers they spit out are still subject to human interpretation, and do not automatically distinguish between artificial and natural light.

Sky luminance

Sky luminance is a quantitative metric of night sky brightness that can be measured using a variety of instruments. On a very basic level, these instruments simply measure the amount of light emanating from the night sky and convert this into a number that can give us a general idea of how light polluted a sky is.

Astronomers typically express sky luminance in units of **magnitudes per square arcsecond (mag/arcsec^2)**. An **arcsecond** is an angle equal to 1/3600 of a degree. For reference, the full moon occupies more than 2.5 million arcsec^2, so one square arcsecond is a very small patch of sky. Just like fainter stars have higher magnitudes, dark skies have higher sky luminance values. As the night sky becomes brighter, due to skyglow or other factors, the sky luminance value will go down (Fig 7).

Figure 7-Sticker on the front of a Sky Quality Meter showing sky luminance values (in mag/arcsec^2) along with a representation of corresponding night sky conditions. (NPS/Zach Schierl)

Table 3 shows typical values of sky luminance in mag/arcsec^2 for different environments. Sky luminance at the zenith of a naturally dark moonless night sky is approximately 22.0 mag/arcsec^2, although this number is highly variable (between ~21.3-22.3) depending on the presence of airglow, zodiacal light, the position of the Milky Way, one's latitude, and several other factors.[16] For this reason, interpreting sky luminance values can be tricky. A value *slightly* below 22.0 could indicate the presence of skyglow, or may simply be due to natural variability in the brightness of the night sky.[17] Sky luminance values *significantly* lower than 22.0 are usually indicative of skyglow while values lower than ~20.0 indicate that the sky is light polluted enough to begin inhibiting dark adaptation.[18] Like with NELM and the Bortle Scale, measurements of sky luminance should only be taken on cloud-free moonless nights.

Table 3: Typical sky luminance values in magnitudes per square arcsecond[19]

Sky luminance (mag/arcsec^2)	Example Environment
22.0	**Night sky with no light pollution (no moon)**
21.0	Rural area near moderate sized city
20.0	Outer suburb of a major metropolis
19.0	Suburban area
18.0	Bright suburb or dark urban setting
18.0	**Night sky with no light pollution (with full moon)**
17.0	Bright urban setting (i.e. Downtown L.A. or New York)
13.0	Sky ½ hour after sunset
7.0	Sky at sunset

Sky luminance measurements are usually recorded at the zenith (typically the darkest part of the sky) in which case the result is known as **zenith sky luminance.** A more comprehensive metric is the **average all-sky luminance**, which involves measuring luminance at many points across the entire sky, and then calculating an average. Because skyglow preferentially affects areas of the sky closer to the horizon, zenith sky luminance will often underestimate the amount of light pollution present. Average all-sky luminance is more difficult and time-consuming to measure, but presents a more complete picture of sky quality.[20]

Sky Quality Meters

The easiest way to measure zenith sky luminance is the Unihedron **Sky Quality Meter (SQM)** (Fig 8)**.** The SQM is a commercially available device (~$100) that measures sky luminance in mag/arcsec^2. Using a SQM is as simple as pointing the detector at the zenith and pressing a button. After a few seconds, the sky luminance value is shown on the display. When using a SQM, it is best to hold the meter above your head in a location far from any streetlights, car headlights, or other **glare** sources that could skew the measurement.

Figure 8-Unihedron Sky Quality Meter (SQM). (NPS/Zach Schierl)

While quantitative and free of human biases, SQM measurements still have limitations. The SQM cannot measure average-all sky luminance because its field of view is restricted to, at most, an 80° swath of sky. This prevents them from capturing sources of skyglow near the horizon.

SQMs also cannot discriminate between artificial light and natural light; they merely tell you how bright the sky is. As a result, they are more adept at measuring differences in sky quality among urban and suburban sites. In these locations, natural light is negligible compared to skyglow. However, at extremely dark sites variations in natural sky luminance (due to airglow, position of the Milky Way, etc.) can be significant compared to any light pollution that is present, making SQM measurements difficult to interpret.[21] Ideally, SQM measurements should be combined with visual observations (NELM, Bortle Scale) to paint a more complete picture of night sky quality from a given site.

CCD Imaging

One of the most advanced and sophisticated techniques for measuring and monitoring light pollution was developed by the National Park Service's Night Sky Team in the early 2000s.[22] This method uses a **CCD camera** on a robotic telescope mount (Fig 9) to record sky luminance across the entire night sky. Using an automated script, the camera can image the entire night sky in less than an hour. Software is used to calibrate and stitch the images together into a single panorama.

Figure 9-NPS CCD camera setup for measuring sky luminance. (Natural Sounds & Night Skies Division/NPS)

Like a Sky Quality Meter, the camera measures sky luminance in units of mag/arcsec^2, but does so over the entire sky, allowing average all-sky luminance to be calculated. The panoramic images are color-coded based on sky luminance, creating a powerful visual that indicates which portions of the sky are darkest and which are brightest (Fig 10). Warmer colors represent brighter areas of the sky, such as the Milky Way and light domes, while darker portions of the sky are shown in blues, purples, and black.

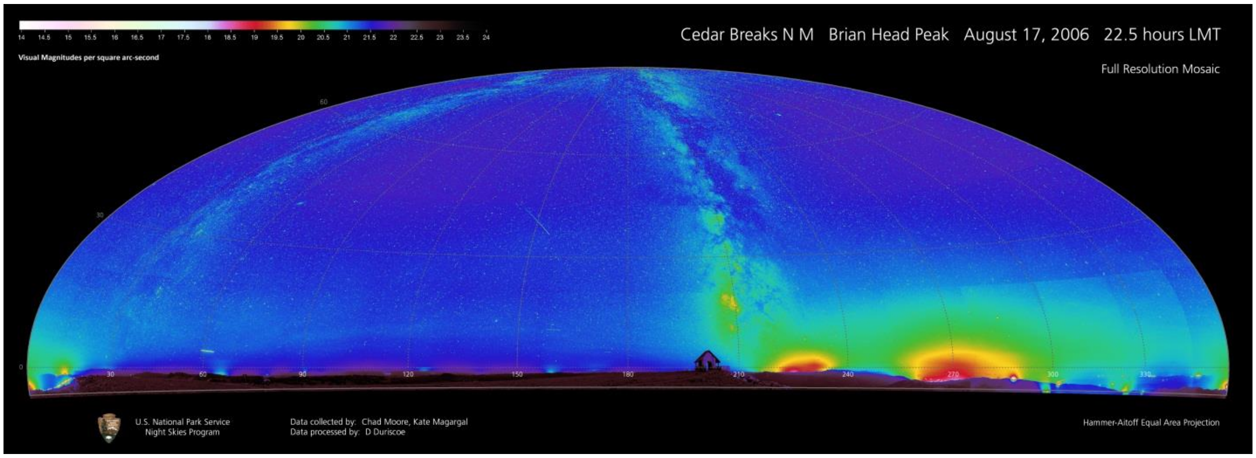


Figure 10-Panoramic image of sky luminance from Brian Head Peak, just outside Cedar Breaks National Monument, taken in 2006. The yellow and red blobs represent skyglow from St. George and Cedar City, UT. Note that natural sources of light, such as the Milky Way, also appear in warmer colors in the image. (Natural Sounds & Night Skies Division/NPS)

Like a SQM, the camera records both natural and artificial sources of light at night. However, computer modeling allows natural sources of sky luminance, such as airglow, zodiacal light, stars, and the Milky Way, to be subtracted from the images, leaving only the artificial sky luminance behind.[23] The result is an image of the night sky that shows only artificial skyglow (Fig 11). In these images, black represents portions of the sky unaffected by light pollution, whereas skyglow shows up as distinct, brightly colored blobs along the horizon.

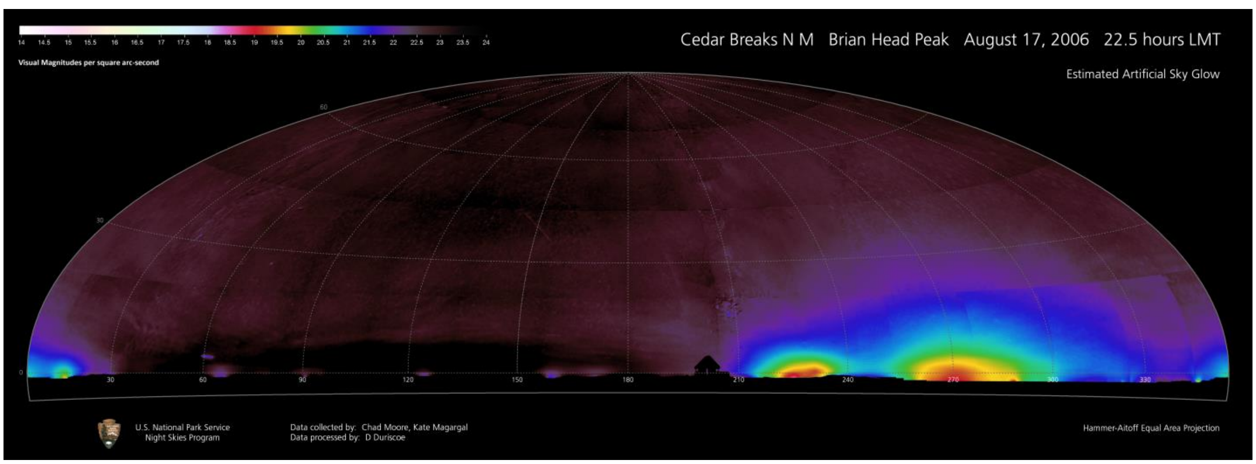


Figure 11-Panoramic image of <u>artificial</u> sky luminance from Brian Head Peak, UT. This image was created by subtracting natural sky luminance from Figure 10. Note how the skyglow of Cedar City and St. George remains prominent, while all natural sources of light in the night sky have disappeared. (Natural Sounds & Night Skies Division/NPS)

The next three images (Figs 12-14) show additional examples of data produced by this method. In each image, the natural sky brightness has been subtracted to leave only artificial light behind. These images represent the spectrum of night sky conditions documented at national parks across the country, from extremely dark (Fig 12) to extraordinarily light polluted (Fig 14).

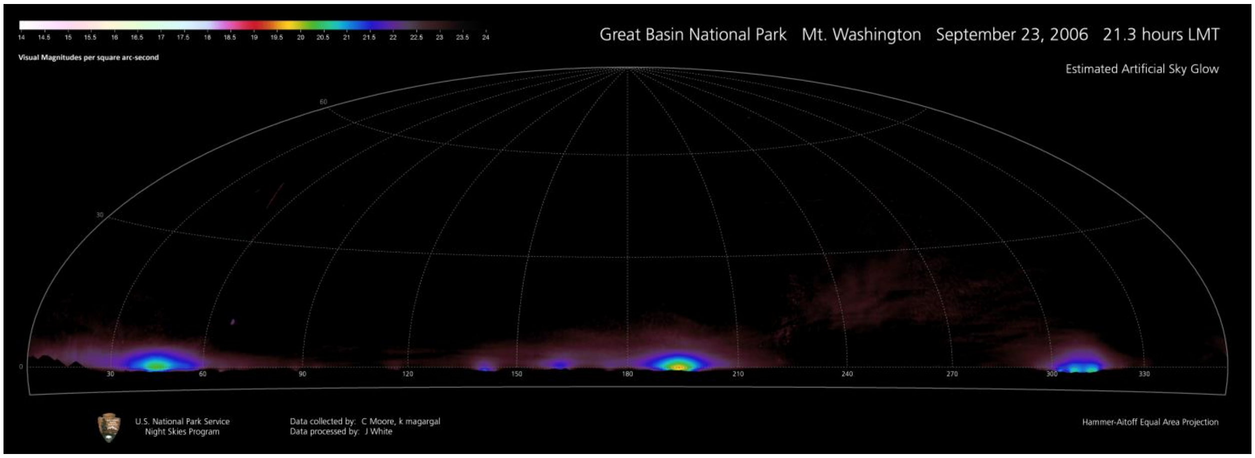


Figure 12-Artificial sky luminance panorama from Great Basin National Park, Nevada, one of the darkest national parks in the U.S. (Natural Sounds & Night Skies Division/NPS)

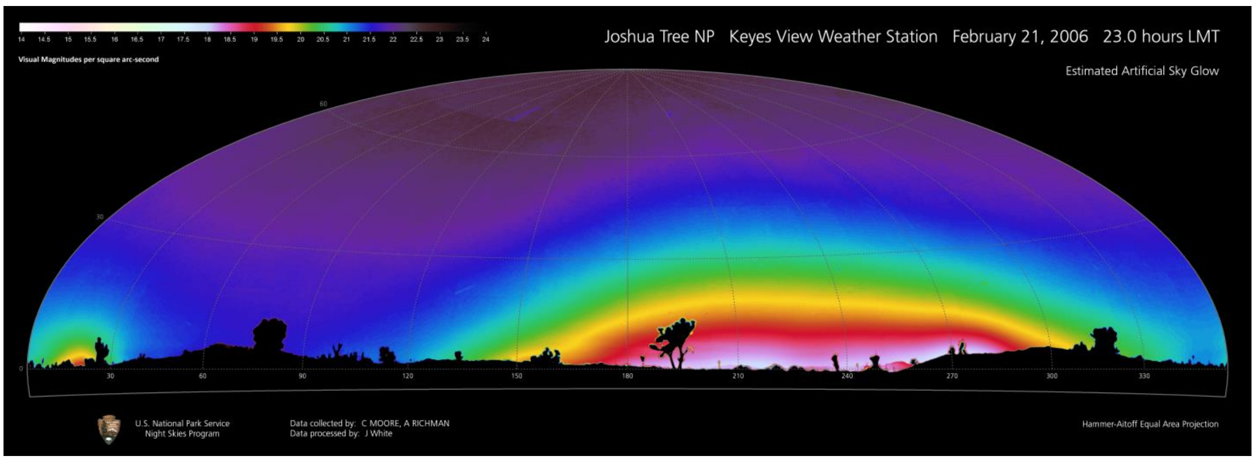


Figure 13- Artificial sky luminance panorama from Joshua Tree National Park, California. The sky here is severely degraded by skyglow from Palm Springs and Los Angeles, but is still "dark" by 21st century standards. (Natural Sounds & Night Skies Division/NPS)

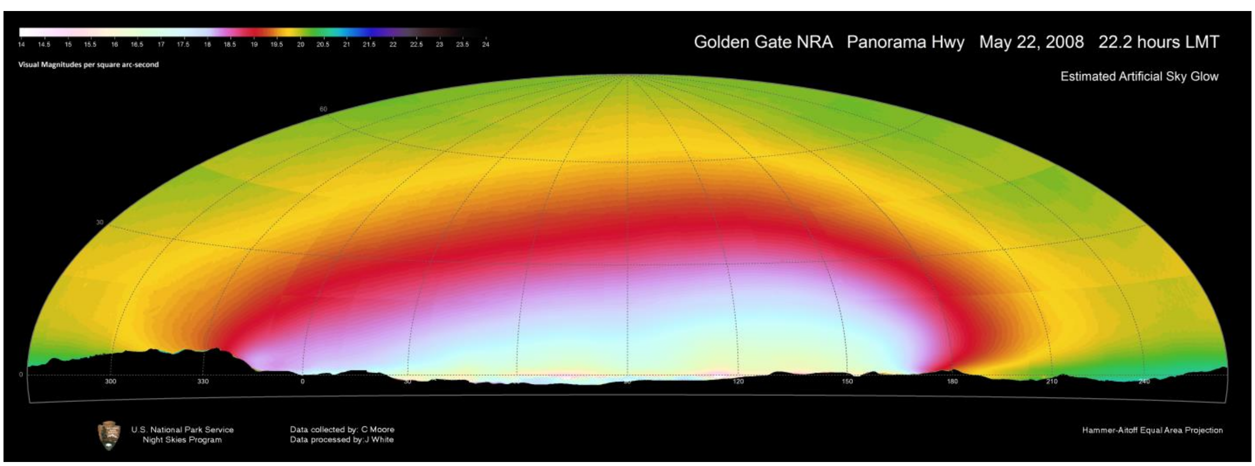


Figure 14- Artificial sky luminance panorama from Golden Gate National Recreation Area, California. Skyglow from the San Francisco Bay Area dominates the night sky at this urban national park. (Natural Sounds & Night Skies Division/NPS)

The National Park Service has used this method to document night sky conditions at more than 100 national park sites across the U.S.[24] Repeat measurements across several years clearly show how expanding light pollution is threatening the dark skies at many parks (Fig 15).[25]

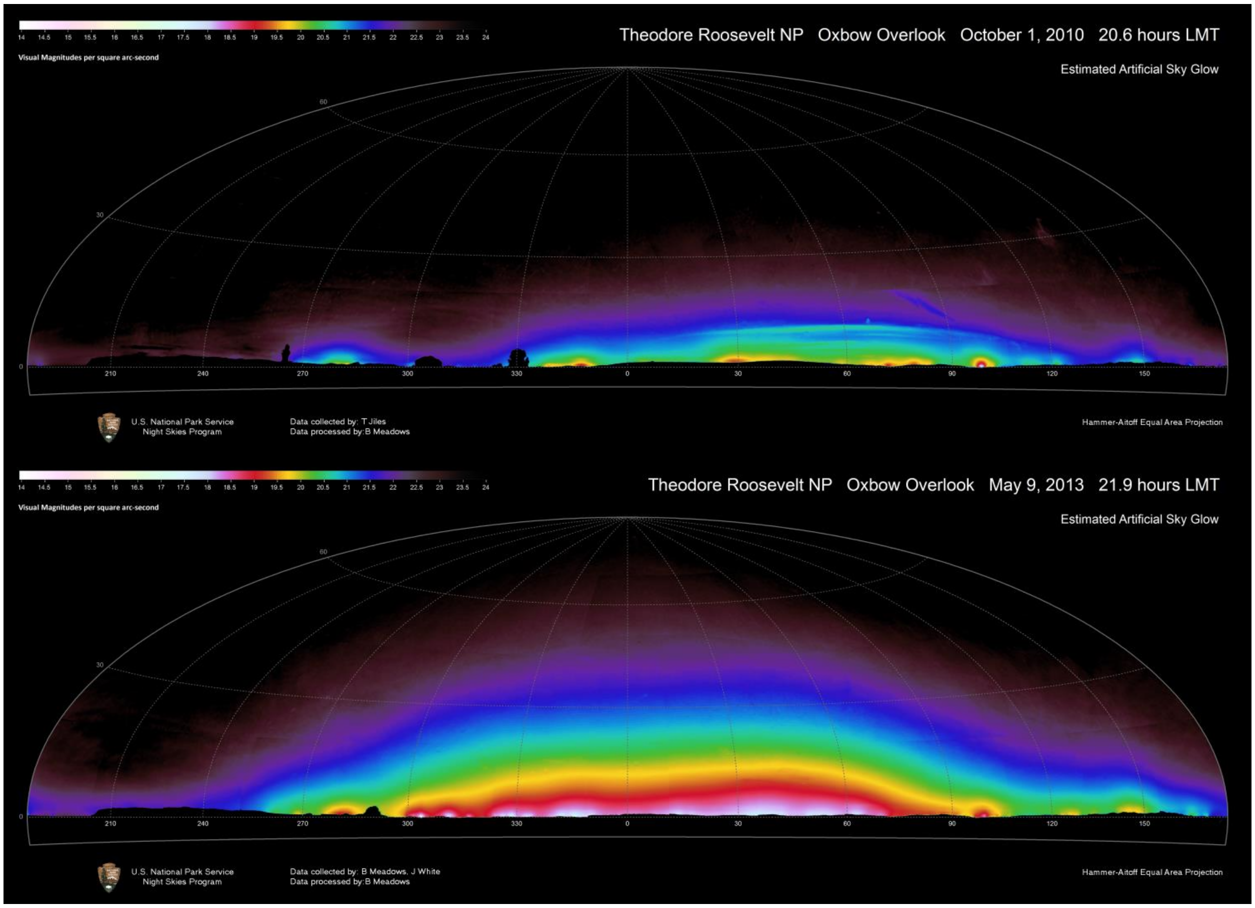


Figure 15- Artificial sky luminance panoramas from the same location in Theodore Roosevelt National Park, ND, taken less than three years apart. In this instance, night sky quality deteriorated due to increased skyglow from oil & gas development near the park. (Natural Sounds & Night Skies Division/NPS)

Satellite Imagery

Images from Earth-orbiting satellites are another powerful tool for measuring and monitoring light pollution. For example, the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument on NASAs Suomi NPP spacecraft generates a monthly, cloud-free image of the world at night (Fig 16). Astronaut photographs taken from the International Space Station are also a valuable source of information about artificial light emissions.[26]

These images record only **upward radiance**, that is, light from Earth's surface that escapes directly into the sky. While such images are useful and visually stunning, they do not capture the extent to which skyglow alters the night sky, and can make it appear as though there are more dark places left that there really are. For example, Figure 16 shows vast tracts of "dark"

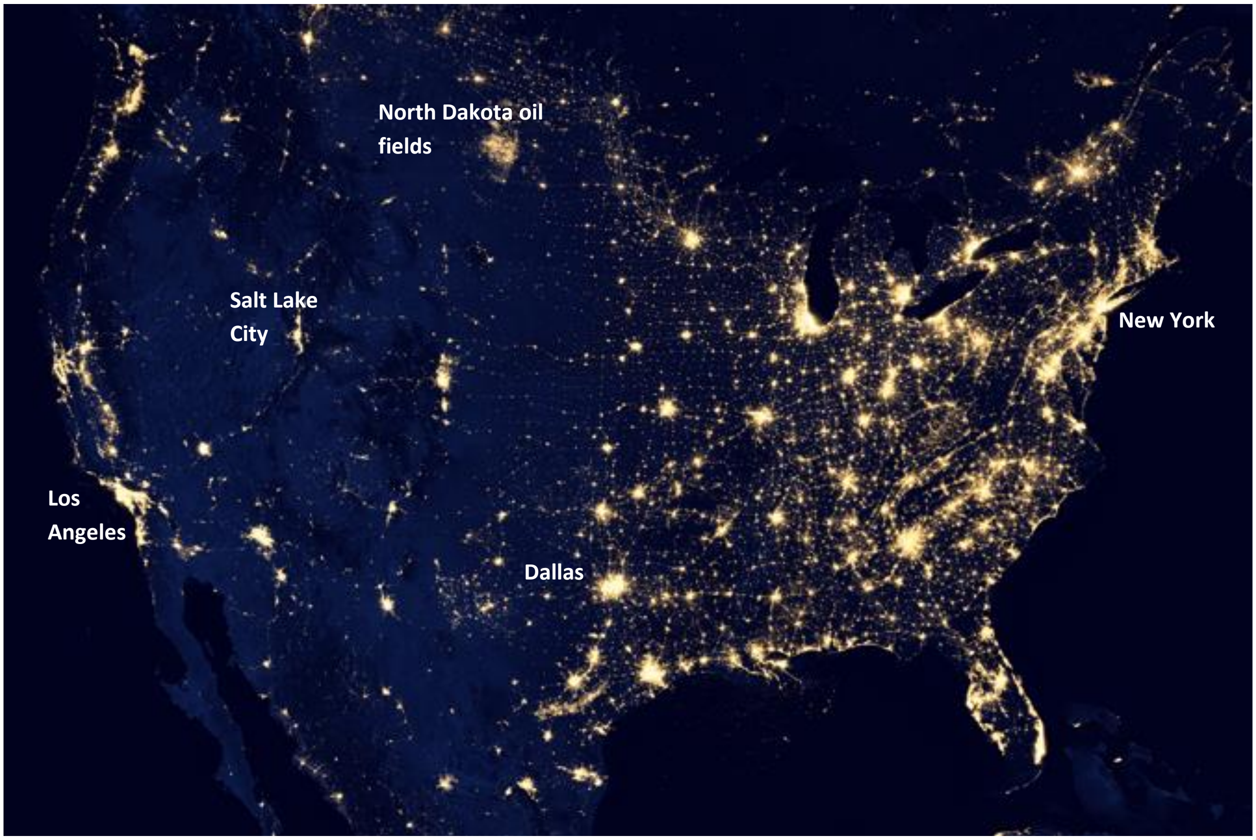


Figure 16-Image of the continental United States at night assembled from data acquired by the VIIRS instrument on the Suomi NPP satellite in 2012. (NASA Earth Observatory)

land in the western United States, but in reality the night sky in these areas is often affected by skyglow emanating from nearby, and often distant, cities.

Fortunately, by combining satellite images, ground based measurements of sky luminance, and models of how skyglow propagates through the atmosphere, we can make maps that take skyglow into account.[27] Examples include the maps in the *New World Atlas of Artificial Night Sky Brightness* (Figs 17-18), which use colors to indicate sky luminance at the zenith: black indicates a relatively pristine dark sky, while warmer shades represent a night sky severely degraded by skyglow. Yellow and orange are particular significant as they mark the approximate threshold at which the Milky Way is no longer visible to the naked eye.

When looking at these maps, it becomes obvious that very few places (especially in North America and Europe) remain truly dark. Large cities produce enough skyglow to degrade the night sky for several hours and several hundred miles in all directions. For example, residents of central Switzerland would have to travel nearly 1370 km (850 mi) to find a night sky that is essentially free of light pollution.[28] Additionally, because these maps indicate the sky luminance at the zenith only, even places that appear black on these maps may still have significant sources of skyglow on their horizon.

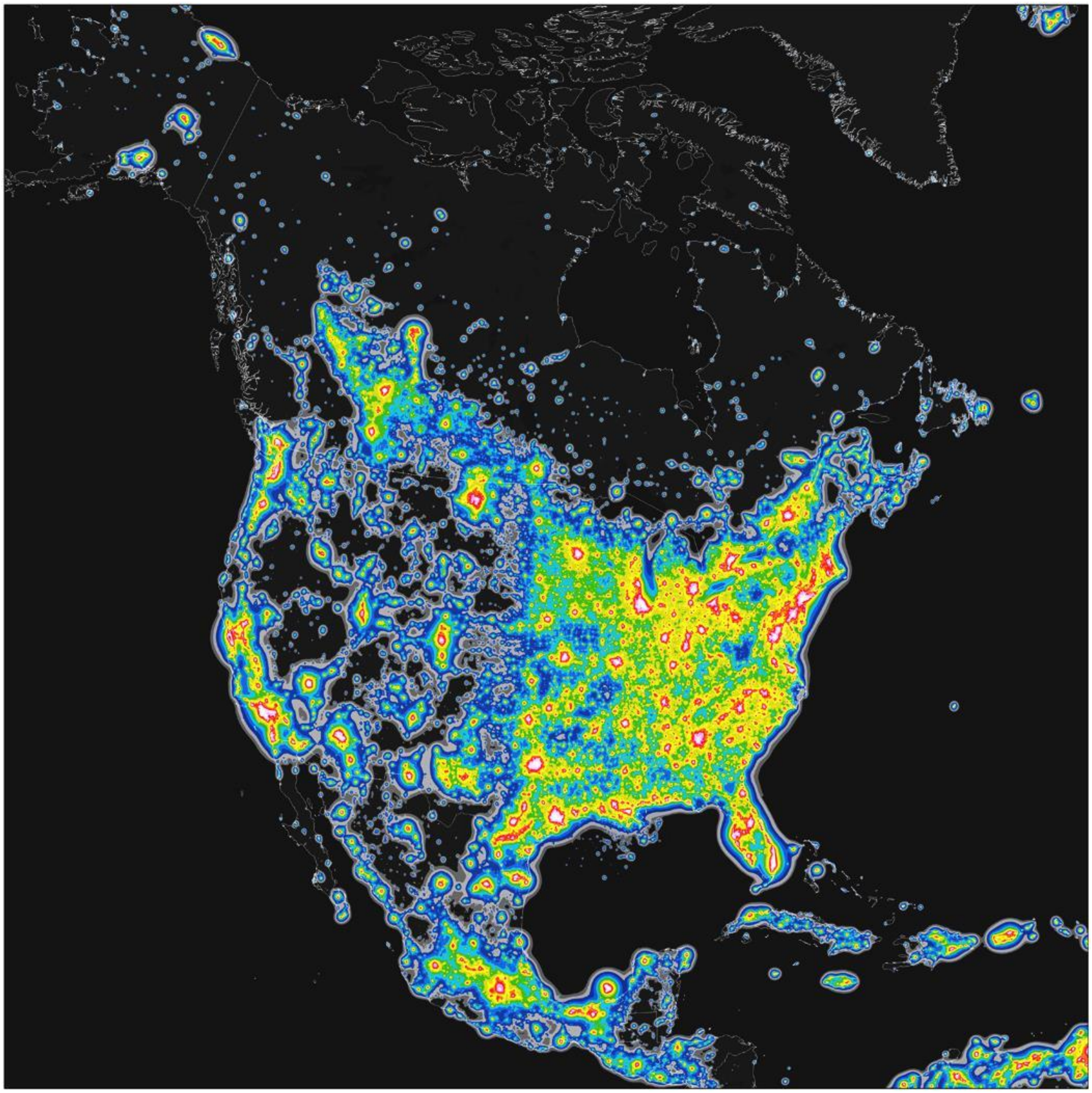


Figure 17-Map of North America's artificial night sky brightness. Warmer colors indicate increasing amounts of skyglow and light pollution. Note that the darkest remaining areas in the United State include the Colorado Plateau, northern Nevada, eastern Oregon, and portions of Alaska. (Falchi et al. 2016, Science Advances e1600377)

How dark is your sky?

Figure 19 shows a comparison of the various measuring and monitoring methods discussed in this chapter. How dark is the night sky from your backyard? Make a prediction based on what you've read, then try using some of these methods to find the answer. How does the sky over your home compare to a nearby large city or your favorite stargazing location?

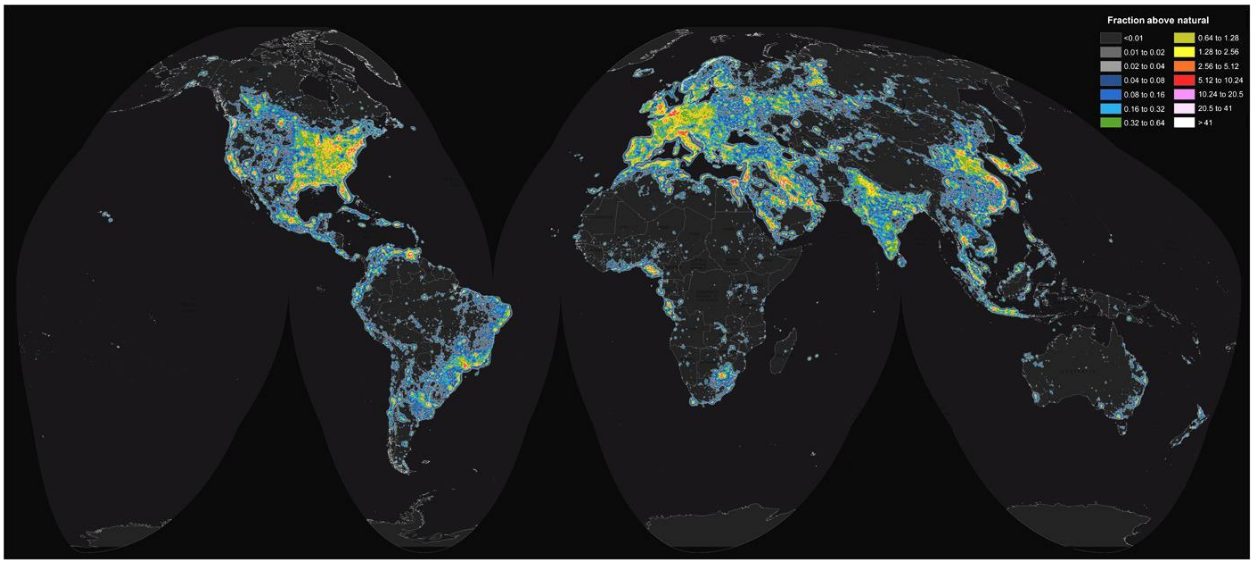


Figure 18- World map of artificial night sky brightness. Warmer colors indicate increasing amounts of skyglow and light pollution. (Falchi et al. 2016, Science Advances e1600377)

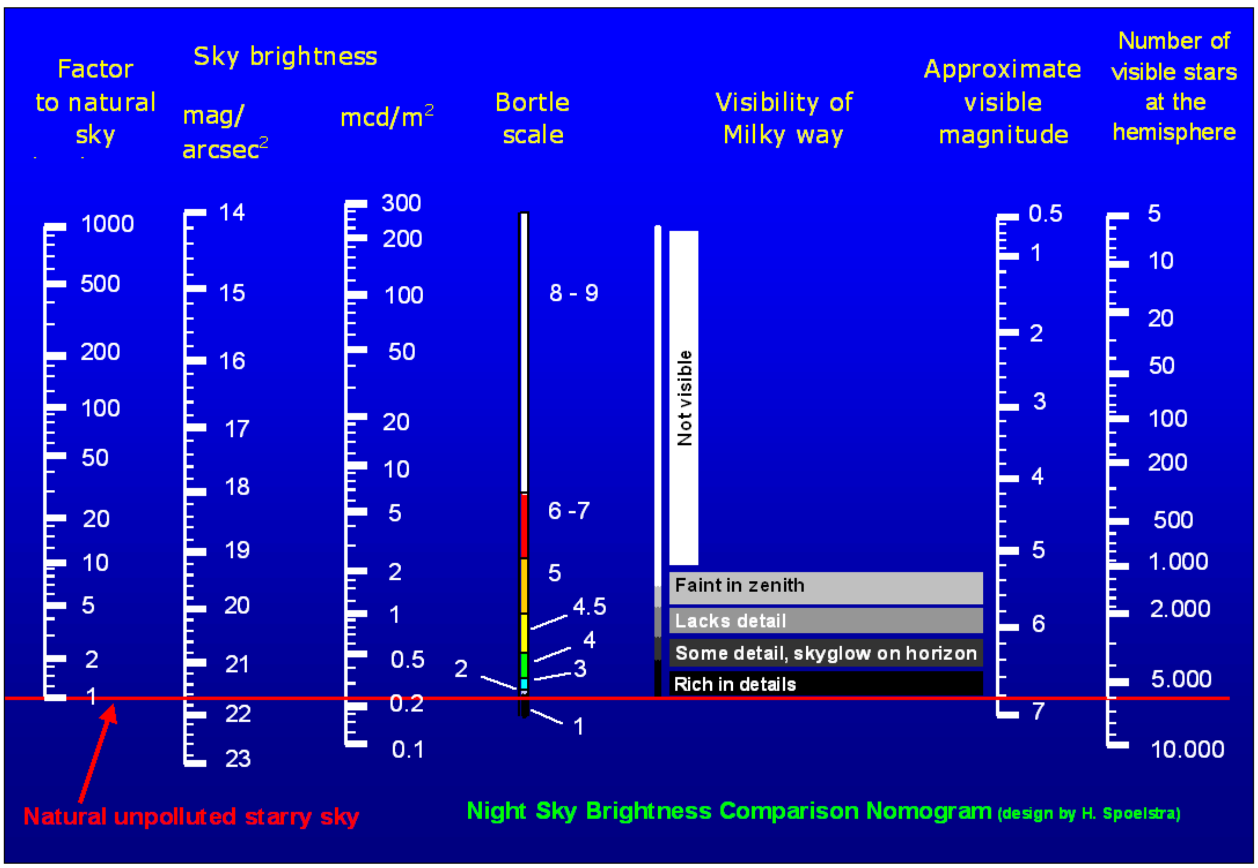


Figure 19-Chart showing an approximate comparison of the various metrics used to measure night sky quality. (Henk Spoelstra)

Review

Common misconceptions

Below is a list of commonly encountered misconceptions about measuring and monitoring light pollution. As a way to review content from this chapter, see if you can explain why each misconception is inaccurate:

- The night sky is “dark” in the absence of light pollution.
- All you need to do is drive a few miles outside of town to see a dark sky.
- We can see millions of stars with the naked eye.

Questions for thought

- How could you use some of the measurements of night sky quality discussed in this chapter to educate the public about light pollution?
- Where was the darkest night sky you’ve ever seen? How do you think it would measure up using the metrics discussed in this chapter?

For More Information

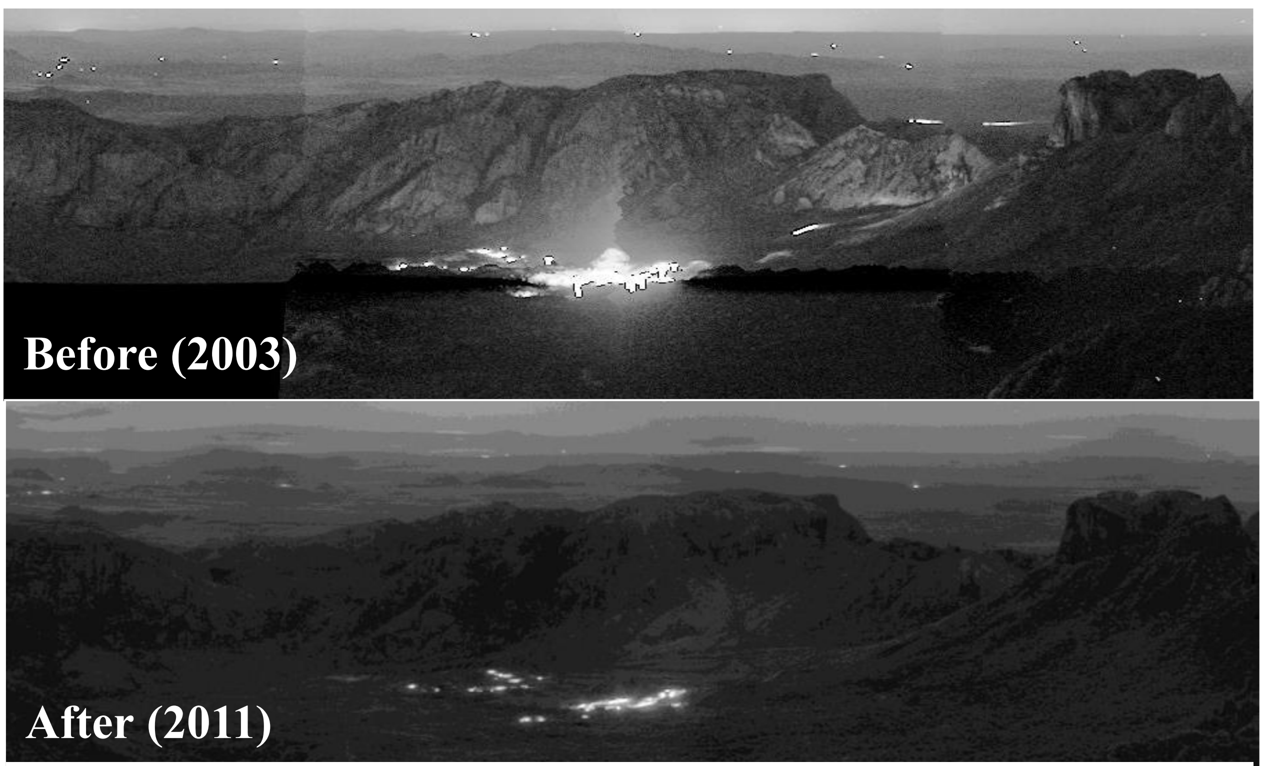
Measuring Your Night Sky

- “Gauging Light Pollution: The Bortle Dark-Sky Scale” (Sky & Telescope): https://www.skyandtelescope.com/astronomy-resources/light-pollution-and-astronomy-the-bortle-dark-sky-scale/
- *Globe at Night* (citizen science project for monitoring light pollution): https://www.globeatnight.org
- Instructions for performing a star count and estimating limiting magnitude: http://www.project-nightflight.net/limiting_mag.pdf
- *Loss of the Night* app: http://lossofthenight.blogspot.com/2015/01/brief-introduction-to-loss-of-night-app.html
- Unihedron Sky Quality Meters: http://unihedron.com/projects/darksky/
- “Using Sky Quality Meters to Measure Sky Brightness”: https://www.globeatnight.org/sqm.php

Global Measurements of Light Pollution

- National Park Service Night Sky Monitoring Database: https://www.nps.gov/subjects/nightskies/skymap.htm
- *The New World Atlas of Artificial Night Sky Brightness* (interactive map of skyglow): http://cires.colorado.edu/Artificial-light
- *Radiance Light Trends* web app (analyze light pollution trends in satellite imagery): https://lighttrends.lightpollutionmap.info/

CHAPTER 3.4: DARK-SKY FRIENDLY LIGHTING



Nighttime images of Chisos Basin in Big Bend National Park, Texas, before and after a dark-sky friendly lighting retrofit. The project minimized light pollution and reduced annual energy costs for outdoor lighting by 98% (from $3,293 to $164), all while maintaining a safe and sufficient level of illumination for park staff and visitors. Note how the mountainside is illuminated in the first photograph due to light trespass, but remains dark in the "after" photo. Images closely approximate how the scene would appear to the human eye. (Natural Sounds & Night Skies Division/NPS)

Chapter 3.4 Goals

After reading this chapter and participating in the corresponding workshop activities, you should be able to:

- Describe the six principles of dark-sky friendly lighting and how they can minimize light pollution and improve night sky quality.
- Identify dark-sky friendly lighting and suggest concrete ways that poor lighting could be improved.
- Provide examples of municipalities that have enacted dark sky lighting codes and the effect such codes have had on night sky quality.
- Address commonly cited safety and cost concerns related to dark-sky friendly lighting.

Daylight fades. The Sun drops below the tree-lined horizon and the sky transforms into vibrant shades of dark purple and blue. The brightest planets, Jupiter and Venus, burst into view as the sky darkens. People from around the world begin gathering around an armada of telescopes—computerized Schmidt-Cassegrains, hulking Dobsonians, small but elegant refractors—hoping for a view of a famous celestial object (or two, or three...) Nearby, at the crest of a small hill, sits a large white telescope dome, a string of people lined up in front of the door. The roof panels creak open revealing a large lens tucked just inside, reflecting the last shades of blue in the darkening sky. The dome begins to rotate as the telescope inside, a massive 24-inch wide, 40-foot long silver refractor, seeks its first target of the evening. The crowd waits excitedly for a view of the Great Hercules Globular Cluster, a conglomeration of perhaps 500,000 stars on the fringe of our galaxy. While they wait, an amateur astronomer uses a green laser to point out constellations, the Milky Way, and the Andromeda Galaxy, all visible to the naked eye in the sky overhead.

At first, this scene may not seem unique. This could describe a star party in just about any dark place on Earth. However, this particular event occurs nightly less than one mile from the center of an American city home to nearly 100,000 people. Yet the wonders of the night sky are on full display for all to enjoy. Even sights like the Milky Way and the Andromeda Galaxy, often obscured by light pollution in urban and suburban areas, are clearly visible here. In this chapter we'll discover how, why, and where a scene like this is possible.

Fear of the Night

Humans have always been scared of the dark. After all, we are a diurnal species, with eyes optimized for sight during the day, not at night. Historically, night has been the home of darkness, thieves, calamities, and danger.[1] The ability to produce light on command to ward off darkness has long been an important and treasured element of human society. From fires and torches, through the days of whale-oil and kerosene lamps, to the modern era of electric lighting, human progress has long been in step with advances in lighting technology.

Electric lighting has revolutionized the way humans live as much as any other invention. With the advent of cheap, easily accessible lighting, humans can now, for the first time in our history, function and perform almost any task both day and night, indoors and out. Most of us now spend the majority of our lives exposed to some sort of artificial light, whether it is the fluorescent bulbs in our homes and offices, the soft-orange glow of streetlights on an evening stroll, or the transfixing glow of our countless devices and screens. For better or worse, our modern lifestyle is dependent on artificial light.

But must we sacrifice the night sky and natural darkness in exchange? Must we give up the night that has existed on this planet for 4.56 billion years? The answer it turns out, is no. Around the world, cities, towns, parks, and neighborhoods are realizing that night, despite its historically bad reputation, has value (see *Chapter 3.2*). Fortunately, a dark night sky and a well-lit world are not incompatible. The solution is **dark-sky friendly lighting** (sometimes called "night-sky friendly lighting," or "good neighbor lighting").

Dark-Sky Friendly Lighting

There are many misconceptions surrounding dark-sky friendly lighting. A common one is that, to restore the night sky, we must turn off all our lights and return to the dark ages. Nothing could be further from the truth. As we will see, a dark sky does not require a dark ground.

Also prevalent is the idea that dark-sky friendly lighting is simply a product you can grab off the shelf at the local hardware store. Unfortunately, it's not quite that simple. Dark-sky friendly lighting is best described as a *philosophy* that informs the decisions we make about outdoor lighting. Through careful thought about the types of light bulbs and fixtures that we use, dark-sky friendly lighting saves energy and money, gives us the light we need for safety & security on the ground, and prevents wasted light from escaping into the night sky or spilling into the natural nighttime environment — all at the same time! In essence, dark-sky friendly lighting acknowledges that light shone upward into the night sky does no one any good, and is nothing more than a waste of money and electricity.

Six fundamental principles define the philosophy of dark-sky friendly lighting.[2-3] The best outdoor lights conform to all six, but even incorporating a few can significantly reduce light pollution. We'll now discuss each principle in detail, and then explore a few more dark-sky lighting myths at the end of the chapter.

1: Direct light downward where it is needed

If you want to make your lights more dark-sky friendly, the most important action you can take is making sure that lights illuminate what needs to be lit, and nothing else. Unfortunately, many outdoor light fixtures fail this principle. Poorly designed fixtures often cast light upwards into the night sky, or spray it horizontally creating **glare** (Fig 1). This light is wasted: light emitted upwards illuminates nothing besides treetops and the underside of low-flying aircraft, while horizontal glare actually i*nhibits* visibility at night.

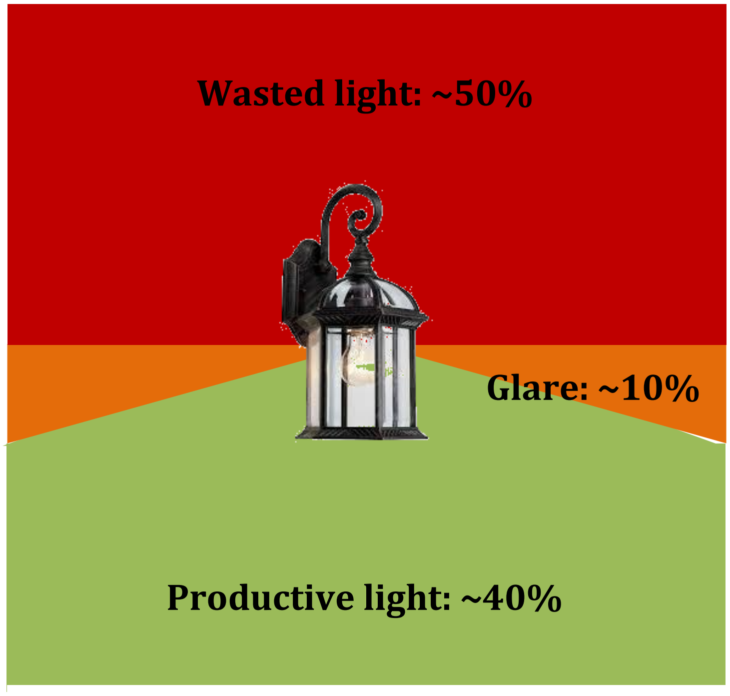


Figure 1-A typical, unshielded outdoor light fixture emits most of its light upward into the sky or sideways as glare. (NPS/Zach Schierl)

We need light at night. We need it on our front porch, on the road in front of us, perhaps even on a billboard we've bought to advertise a business. We need light at night for safety. We need it so we don't trip over a curb while walking into the grocery store to buy a midnight snack. We need it so we can walk down the street at night without fear of a villain jumping out of the shadows. With few exceptions, we need light at night on or near the ground, not in the sky. Rare is the attacker that jumps out of a dark tree onto an unsuspecting victim!

For a classic example of wasted light, consider the billboards that line many of our interstates and highways. These billboards are typically illuminated from *below*. While some of the light hits the billboard, most escapes directly into the night sky, exacerbating skyglow and wasting energy (Fig 2). In contrast, a billboard illuminated from *above* directs light downward, is less wasteful, and more dark-sky friendly. Such billboards are common in other countries, yet rare in the United States.

Figure 2-Billboards along Interstate 15 in Cedar City, UT are illuminated from below, with a significant percentage of light escaping into the night sky. (Zach Schierl)

Light emitted upward or horizontally by **unshielded fixtures** is the primary cause of night sky-erasing **skyglow** (Fig 3). (Light reflecting off the ground and back into the sky is a comparatively minor contributor to skyglow.[4]) We can minimize or eliminate wasted light by using **fully shielded light fixtures** that point light downward where it is

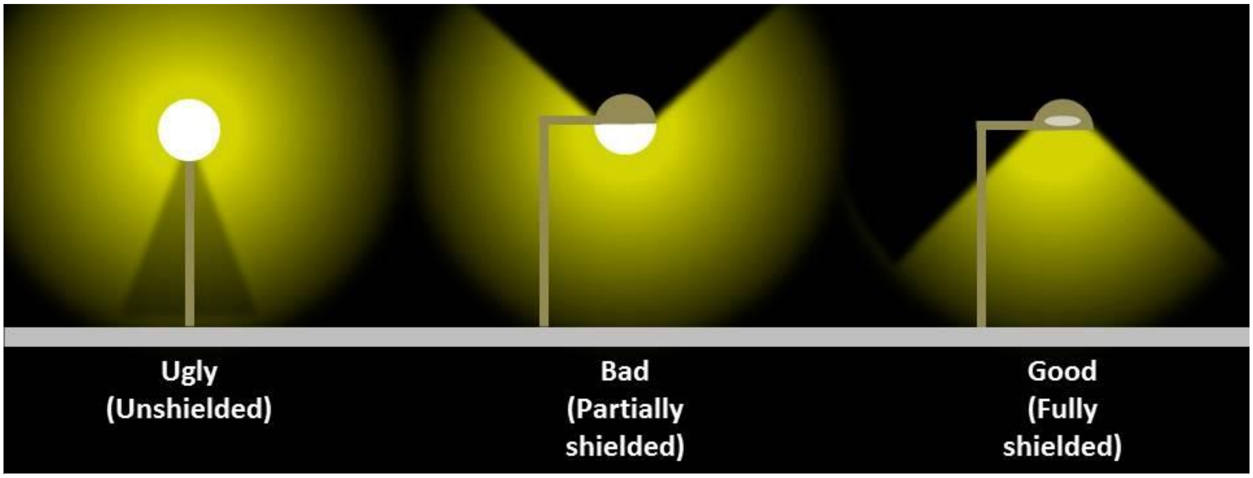


Figure 3-Diagram showing the difference between shielded and unshielded light fixtures. Note the "cone of darkness" beneath the streetlight at left. Light goes in all direction <u>except</u> down where it is needed. (NPS/Zach Schierl)

needed instead of letting it escape into the sky where it isn't. Compare the light fixtures shown in Figures 3 and 5 to get a better idea of the difference between shielded and unshielded outdoor light fixtures.

While this solution is simple in theory, in practice it can be a challenge to find fully shielded fixtures. A visit to your local hardware or lighting store will reveal that many, if not most, of the fixtures for sale are *not* fully shielded. Fortunately, the tide is slowly turning. Over the past decade there has been a drastic increase in the number of fully shielded fixtures on the market, as home and business owners realize the aesthetic and economic benefits of dark-sky friendly lighting. Many national retailers now stock a much wider variety of fully shielded fixtures for both residential and commercial applications than they did 10 years ago.

Figure 4-Fully shielded outdoor lighting products certified by the International Dark Sky Association bear this logo. (International Dark Sky Association)

To help consumers identify dark-sky friendly fixtures, the **International Dark Sky Association** (IDA) created the "Fixture Seal of Approval" program. While IDA does not sell lighting, they certify products that are fully shielded and have a low color temperature (*see principle #4*) with the seal shown in Figure 4. While not all fully shielded and dark-sky friendly products bear this seal (a manufacturer must first go through the certification process), the list of certified products on the IDA website is a good place to begin your search. A link is at the end of this chapter.

Figure 5-Examples of poorly designed light fixtures (left column) and dark-sky friendly light fixtures (right column). Note that many newer LED fixtures behave differently with regards to glare and light trespass, and are not depicted here. (Robert Crelin)

2: Use light only where it is needed

Fully shielded light fixtures prevent useful and necessary lights from contributing to light pollution. Take a walk around your neighborhood at night though and chances are you'll notice more than a few lights that don't seem to be useful *or* necessary (Fig 6).

The second principle of dark-sky friendly lighting is that every outdoor light should have a concrete purpose or task. When examined closely, you may find that some lights don't. We can further reduce all three types of light pollution by turning these lights off or removing the fixtures entirely. Eliminating unnecessary lights also saves energy and money.

Once again, a commitment to dark-sky friendly lighting *does not* require turning off useful lights that have a specific function. It *does* ask us to think carefully and critically about our lights, what their purpose is, and to remove them if they are not needed or redundant.

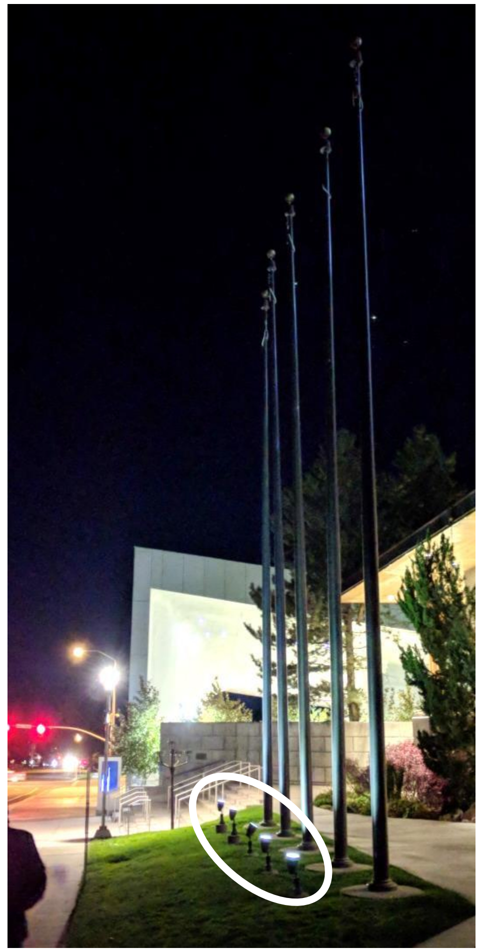


Figure 6-Unnecessary lights in front of a theater in Cedar City, UT. Note the five flagpole lights pointing up into the sky, even though there are no flags on the poles. (NPS/Zach Schierl)

3: Use light only when it is needed

Some outdoor lights have a concrete purpose, but only at certain times of night, or when people are present. In this situation, devices such as timers and motion sensors are an important element of dark-sky friendly lighting. Such devices are inexpensive, and reduce light pollution and energy waste by shutting off lights at times when they are not needed. For example, a floodlight over your garage door may only be needed when you are entering or exiting your garage, and not all night long.

Lights attached to well-calibrated motion sensors can also be more effective from a safety standpoint because they alert owners and law enforcement to unusual activity. Many newer LED light bulbs have integrated timers and/or motion sensors, eliminating the need for a separate device or wiring changes.

4: Use warmer colored bulbs

Entering the light bulb aisle at a hardware store can be overwhelming these days. With an endless array of bulbs to choose from, perhaps the most important factor to consider with regard to dark-sky friendly lighting is *color*.

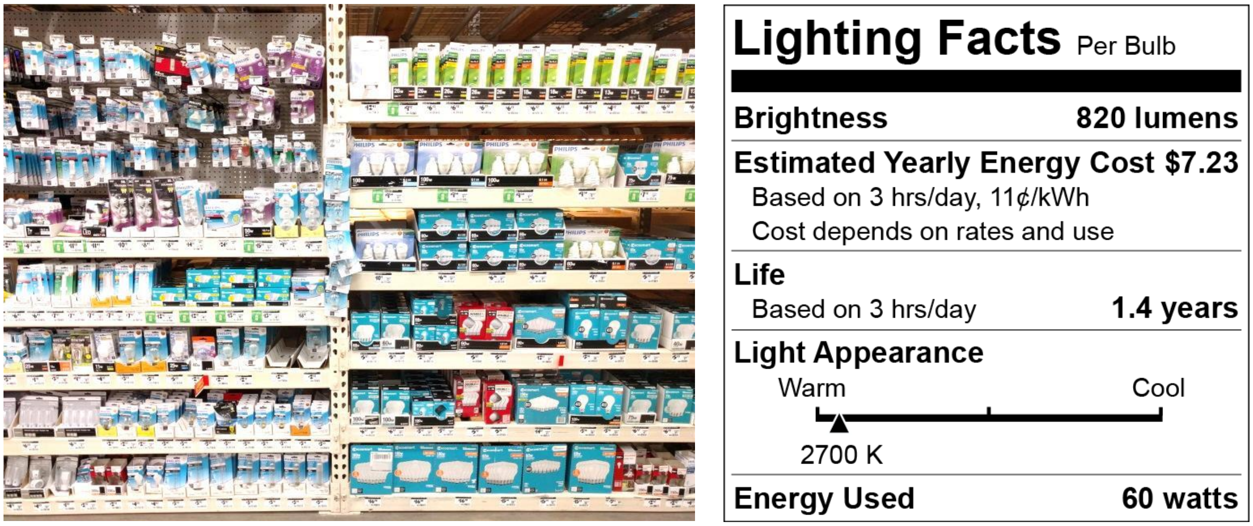


Figure 7-Light bulb options can be overwhelming! The "Lighting Facts" label required on most bulbs by federal law gives information about the cost, energy usage, and color of each bulb. (Photo: NPS/Zach Schierl, Label: U.S. Federal Trade Commission)

Most light bulbs are labeled with a **correlated color temperature (CCT)**. You can find this in the "Lighting Facts" section of the packaging, often under the heading "Light Appearance" (Fig 7). Color temperature gives a sense of a bulb's overall appearance and color and is expressed in degrees Kelvin (K) (Fig 8). Bulbs with a low color temperature (~3000K or below) are said to emit **"warm" light**, mostly from the red, orange, and yellow portions of the visible spectrum. These bulbs are often labeled "soft white" or "warm white."

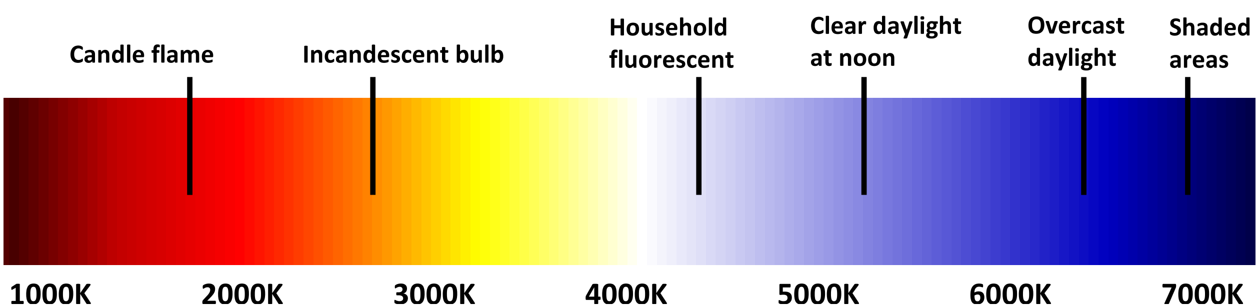


Figure 8-Color temperature of common light sources and light bulbs. (NPS/Zach Schierl)

Bulbs with a higher color temperature (~4000K and above) are said to emit **"cool" light**, and are often labeled "cool white" or "daylight." These bulbs emit lots of light in the blue region of the visible spectrum. From a dark-sky friendly lighting perspective, warm light is almost always preferable to cool light. Why?

- Molecules in our atmosphere preferentially scatter blue light, a process known as Rayleigh **scattering**. This is why the sky is blue during the day and is also the primary cause of skyglow at night. A bulb that emits lots of blue light will cause more visible skyglow than a warmer bulb of equal brightness.[5]

- Humans use **scotopic vision** at night and our dark-adapted eyes are more sensitive to blue light than they are during the day. Using blue-rich light outdoors at night exacerbates glare and compromises vision.
- Blue light tends to be more detrimental to nocturnal wildlife and interferes more strongly with our **circadian rhythm** and **melatonin** production.[6] The American Medical Association recommends that outdoor lighting be 3000K or lower.[7]

For most of human history, our methods of lighting up the night have emitted warm light. Fires, candles, gas lamps, and **incandescent** light bulbs all have a low color temperature and emit very little blue light. Only recently have blue-rich bulbs, like many **compact fluorescents (CFLs)** and **LEDs**, become common. The effects of blue light are discussed further in *Chapter 3.2*.

High intensity light bulbs

High intensity bulbs, such as those used in streetlights, parking lot lights, and other industrial applications, are major sources of artificial light at night. These **high-intensity discharge (HID) lamps** generate light by creating an electric arc inside a glass tube filled with metal vapor. Their color temperature depends on the combination of metals and gasses used. Common varieties of HID lighting include **low-pressure sodium (LPS)**, **high-pressure sodium (HPS)**, **metal halide (MH)**, and **mercury vapor (MV)** (Fig 9). HID lamps are generally very energy efficient (often comparable to LEDs) and have historically been used to illuminate large areas.

From a light pollution standpoint, **low-pressure sodium** is the least intrusive type of outdoor lighting available.[8] LPS lamps emit a nearly **monochromatic** yellow-orange light and almost no blue light (Fig 9). As a result, LPS causes the least amount of skyglow and minimal disruption to nocturnal organisms and our own circadian rhythm. The main disadvantage of LPS lamps is their poor color rendition, making them inappropriate for situations where being able to accurately discern colors is important. LPS streetlights are used in many communities, especially those

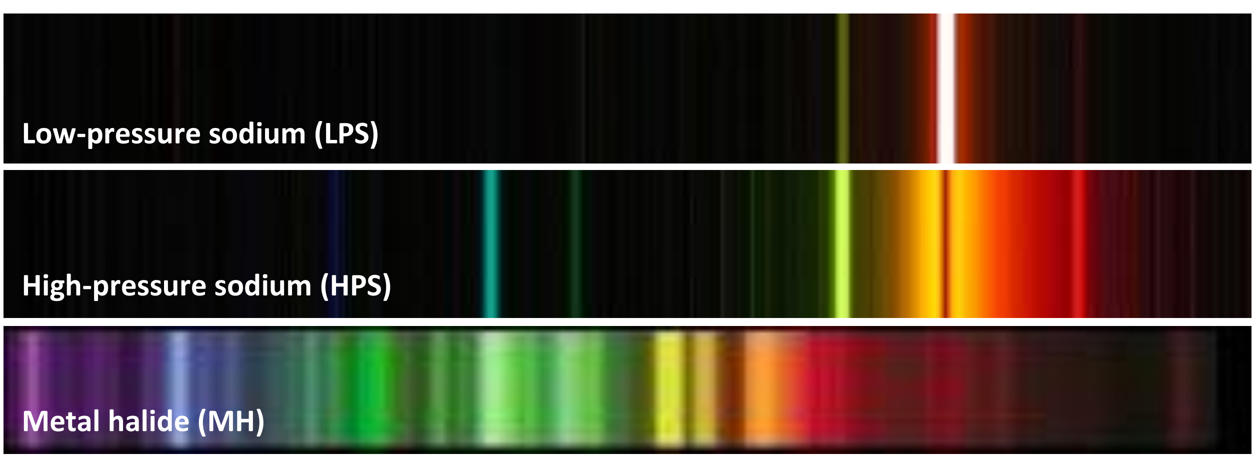


Figure 9-Spectra of commonly used high-intensity discharge lamps. (LPS and HPS: Flagstaff Dark Skies Coalition, MH: Illinois Coalition for Responsible Outdoor Lighting)

near major observatories such as Flagstaff, Tucson, and the island of Hawai'i (Fig 10). However, the sole remaining manufacturer of LPS lighting is slated to discontinue production in 2019 or 2020, forcing these cities to search for new dark-sky friendly alternatives.[9]

Figure 10-A parking lot in Flagstaff, AZ illuminated by low-pressure sodium lamps with a color temperature of ~1800K. (Zach Schierl)

High-pressure sodium (HPS) lamps, which also have a warm color and emit relatively little blue light, have long been the most common type of streetlight (Fig 9).[10] HPS lamps emit a slightly broader spectrum of light compared to LPS, and thus have better color rendition though at the expense of slightly greater skyglow impact. In conjunction with fully shielded fixtures, HPS lamps are a solid choice for dark-sky friendly municipal or industrial lighting. However, like LPS, HPS lamps are rapidly being replaced by LEDs, a transition discussed in detail below.

In contrast to LPS and HPS, **metal halide** and **mercury vapor** lamps emit lots of blue light and are poor choices for high-intensity outdoor lighting (Fig 9). Mercury vapor bulbs are no longer common in the U.S. because of their low energy efficiency, but are still widespread in countries where newer, more efficient lighting technology is not yet available.

The LED Revolution

Across the globe, incandescent, fluorescent, and HID lamps are being replaced en masse by **light-emitting diodes**, or **LEDs**. As of 2016, LEDs had been installed in nearly 30% of all outdoor lighting fixtures in the U.S.[11] From 2010 to 2016, the percentage of street and roadway lights using LEDs jumped from 0.3% to 28.3% (Fig 11).[12]

The topic of LEDs sparks many passionate conversations among dark sky advocates. Like any technology, LEDs have pros and cons. If done correctly, the mass conversion to LED lighting offers the possibility of vast energy savings and darker skies. Unfortunately, LEDs are still poorly understood by many users. Consequently, flawed implementations of this technology can have devastating consequences for dark skies and cause potential energy savings to vanish.

LEDs are fundamentally different than light bulbs of yesteryear. Instead of using electricity to heat a metal filament or excite sodium vapor, LEDs are a form of *solid-state lighting*. This means that they use semiconductors to convert electricity directly into light.[13] The fine details of the

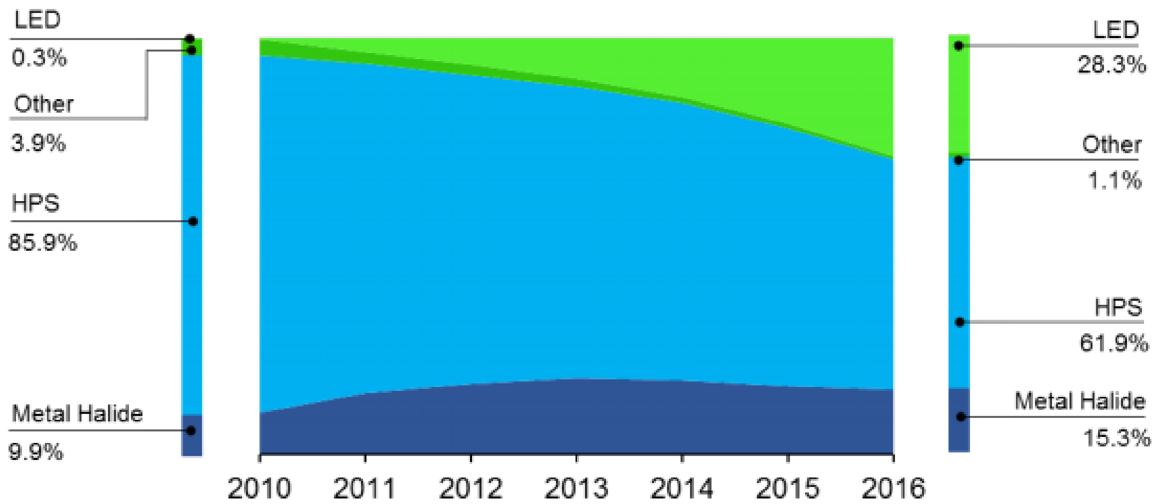


Figure 11-Graph showing the percentage of different lamp types installed in U.S. street and roadway lights. Note the rapid increase in LED and decrease in high-pressure sodium beginning in 2010. (Navigant, 2017)

technology behind most commercial LEDs involves quantum physics, garnered its inventors a Nobel Prize in 2014, and is beyond the scope of this handbook. In a nutshell though, beneath most white LEDs is a *bright blue LED*. Phosphors on or near the blue LED convert some of the blue light into other colors, producing the wide range of white LED bulbs on the market today.[14]

LEDs offer many potential benefits for dark-sky friendly lighting. The highly directional nature of LED light makes it easier to control where the light is going, thus minimizing glare and light trespass. Unlike many older lighting technologies, LEDs can be easily and cheaply integrated with dimmers, timers, and motion sensors, making it easier to put the right amount of light in the right place at the right time.

The most cited advantages of LEDs are their high energy efficiency and long lifetime. LED lamps are expected to last much longer than other types of light bulbs, theoretically lowering total cost over time. LEDs are much more energy efficient than the incandescent and fluorescent bulbs prevalent in *indoor* lighting, offering great potential energy savings in this realm.[15] However, for *outdoor* applications like roadway and industrial lighting, LED efficiencies are often only marginally better than the low and high-pressure sodium lamps they are replacing.[16]

Potential energy savings associated with the switch to LEDs can also be offset by another factor. Satellite measurements tell us that Earth as a whole continues to get brighter at night.[17] Some researchers attribute this to a "rebound effect." When a commodity such as light gets cheaper, we tend to use more of it rather than bank the savings.[18-19] With the advent of cheap light from LEDs, we are seeing artificial light used in an array of new applications, such as the electronic billboards and marquees that now line many highways. Sadly, this phenomenon often leads to an increase in light pollution in addition to cancelling out potential energy savings.

But perhaps the greatest concern with LED lighting is the significant proportion of blue light emitted by many white LEDs. Remember that inside most white LEDs lives a bright blue LED. A typical LED converts some of this blue light to other colors, but it can be difficult to convert it all without sacrificing efficiency. Consequently, many of the most energy efficient LED bulbs, those at the forefront of the LED revolution, emit lots of blue light relative to other colors (Figs 12-13). This is often true even with warmer, low color temperature LEDs. Because LEDs are so different than traditional lamps, color temperature is not always a good indicator of how much blue light a LED emits.

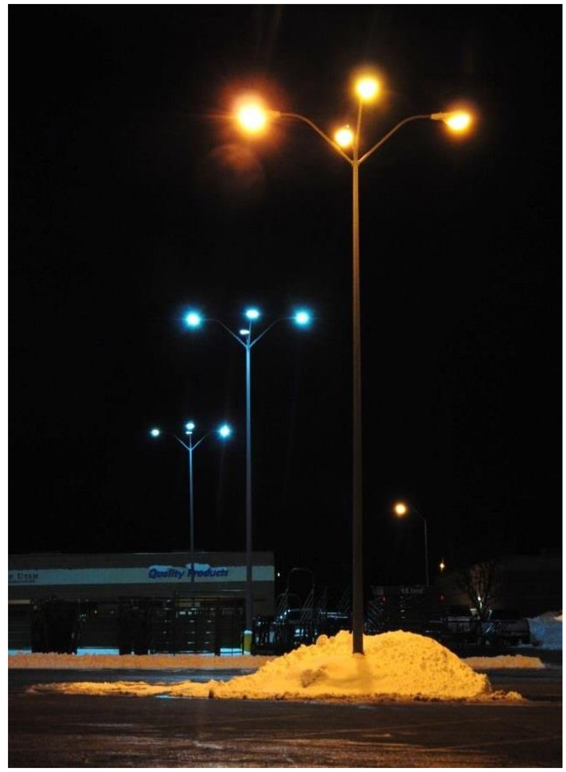


Figure 12-Parking lot lit by a combination of warm high-pressure sodium lamps (foreground) and cool LED lamps (background). (NPS/Zach Schierl)

As we've seen, blue light has a greater impact on nocturnal ecosystems, human health, and skyglow. Switching from warm high-pressure sodium streetlights to blue-rich 4100K LED streetlights can greatly exacerbate skyglow above a city (Fig 14). Because blue light scatters more in the atmosphere and the human eye is more sensitive to blue light at night, blue-rich LEDs can produce 6-8 times as much skyglow compared to LPS lamps of equal brightness, and 3 times as much skyglow as HPS lamps.[20] In addition, ecologists have found that LEDs increase the ecological impact of light pollution, regardless of color temperature.[21] In 2016 the American Medical Association issued a statement discouraging the use of LEDs with a CCT greater than 3000K, yet blue-rich LEDs remain a common choice for cities converting to LEDs.[22]

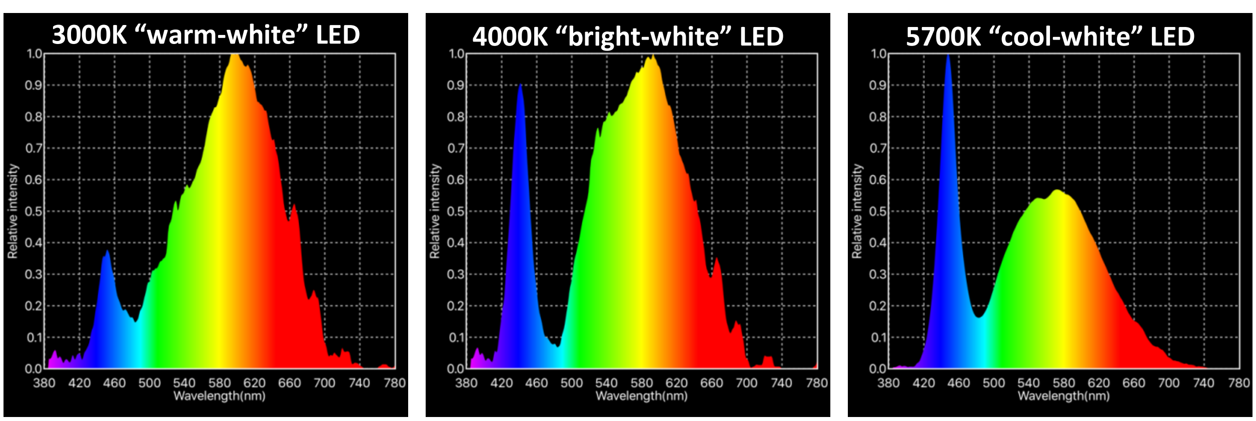


Figure 13-Spectra of several different LED streetlights in Cedar City, UT. Note how even the "warm-white" LED still emits a "spike" of blue light. (NPS/Zach Schierl)

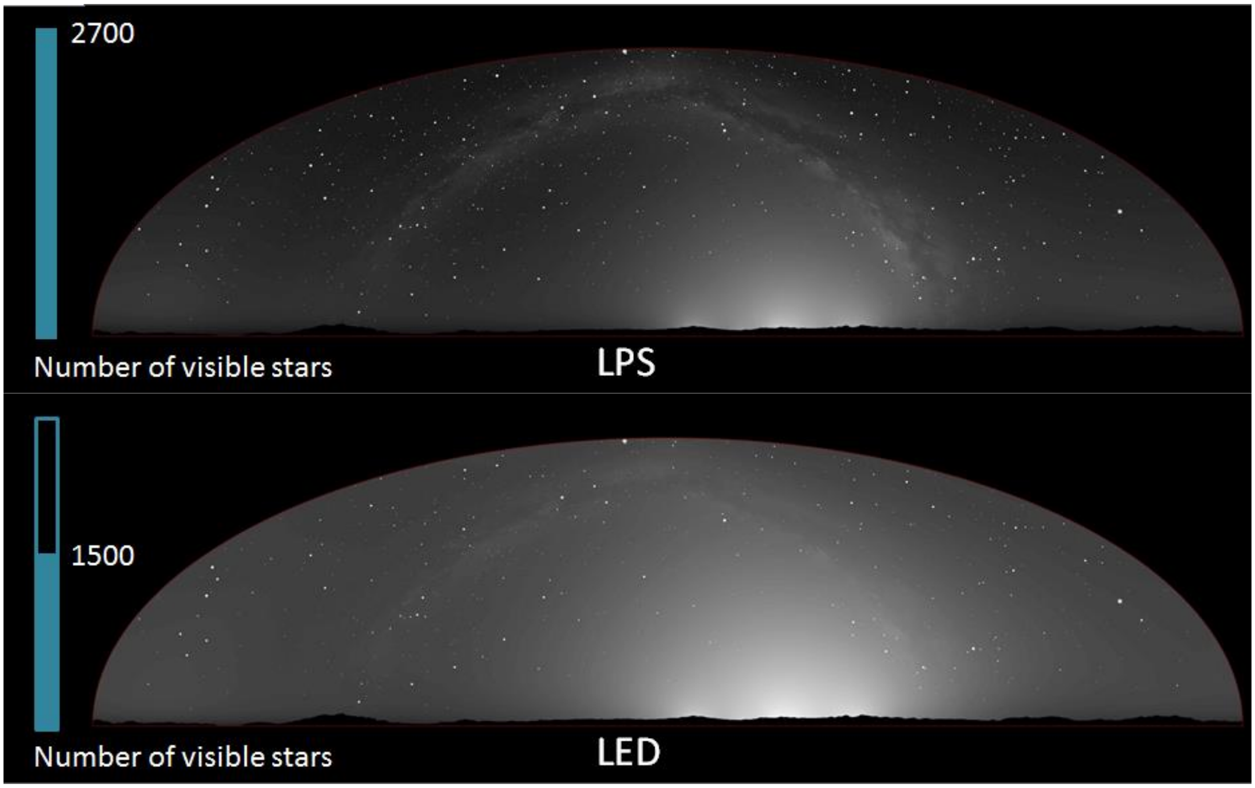


Figure 14-Simulated views of the night sky from Sunset Crater National Monument (near Flagstaff, AZ) showing the predicted effect of a switch from low-pressure sodium (LPS) streetlights (top) to 4100K LED streetlights (bottom). Narrow-band amber LEDs have a minimal skyglow impact that is roughly the same as low pressure sodium. (Flagstaff Dark Skies Coalition)

While this might make it seem like LEDs and dark skies are incompatible, there are dark-sky friendly LED products on the market. Energy efficient LEDs engineered to minimize blue light emissions are becoming more common. **Narrow-band amber LEDs (NBA LED)** emit a warm amber light that is very similar to low-pressure sodium lamps (Fig 15). The spectrum of other dark-sky friendly LED options are shown in Figure 16, all of which have a skyglow impact lower than that of 3000K white LEDs, while some even approach that of LPS and HPS.[23-24] Many cities concerned about protecting dark skies and/or minimizing human and wildlife exposure to blue light are

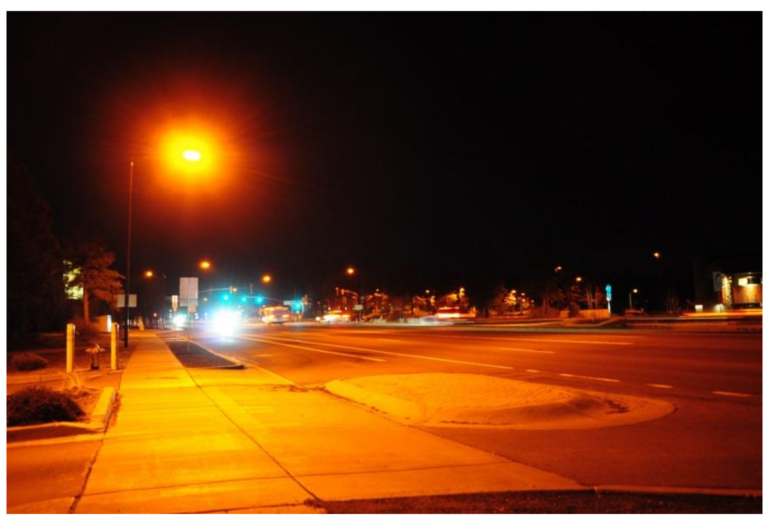


Figure 15-An arterial street in Flagstaff, AZ illuminated by narrow-band amber LED (NBA LED) streetlights. (Zach Schierl)

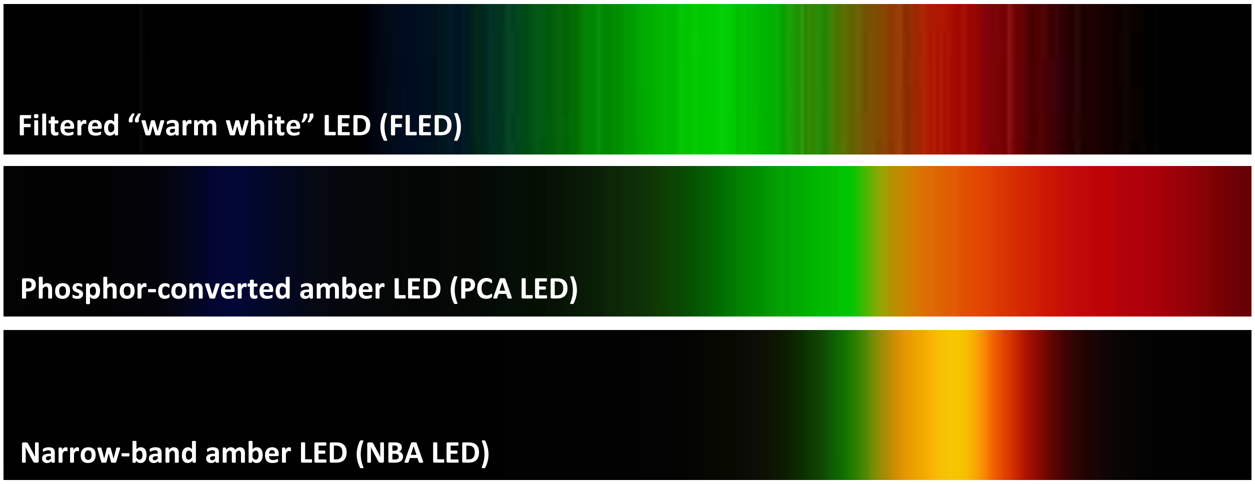


Figure 16-Spectra of various dark-sky friendly LED light sources. (Flagstaff Dark Skies Coalition)

choosing these dark-sky friendly LED technologies. Examples include Flagstaff, AZ (mixture of NBA LED and 2700K LED)[25], the County of Hawaii (FLED)[26], and several municipalities within the Mont-Megantic International Dark Sky Reserve in Quebec, Canada (PCA LED).[27]

Even cities converting to traditional white LEDs can do so without sacrificing the night sky. From 2014 to 2017, Tucson, AZ, home to one of the world's first dark-sky lighting ordinances, converted ~18,000 LPS and HPS streetlights to fully shielded 3000K white LEDs while simultaneously decreasing the total amount of light emitted by each streetlight. Following the retrofit, researchers found no evidence of a significant increase in skyglow over the city, while satellite data suggests that light emissions from Tucson may have decreased by ~7%.[28]

LEDs are not inherently good or bad; they have advantages and disadvantages. LED lighting can be dark-sky friendly so long as it adheres to these six principles.

5: Use the right amount of light

Even when using fully shielded fixtures and warm-colored bulbs, excessively bright lights can still contribute to light pollution. As we saw in Principle #2, every light should have a concrete purpose or task. When installing a light, it is important to think about how much light is needed for that task. Using the right amount of light and avoiding over-illumination can save energy, money, and reduce light pollution.

The total amount of visible light emitted by bulb is measured in **lumens (lm)**. However, lumens aren't particularly helpful for determining the right amount of light for a task. What we actually care about is how much light makes it to the intended target. Therefore, a more useful metric is **illuminance**, which is the amount of light striking a surface such as a sidewalk or roadway. Illuminance is easily measured using a light meter and is commonly expressed in units of **lux** (Table 1)**.** Sufficient illuminance is what determines whether we step over a curb, or trip over it.

The full moon produces an illuminance of about 0.1 lux, enough for most of us to walk around without tripping over anything. Yet many outdoor light installations produce illuminances of several hundred lux. This is as bright as many indoor spaces, and far more light than we need to see well at night. Over-illumination and bright glare can actually inhibit visibility and safety by compromising our night vision.

In general, illuminances of just a few lux are sufficient for lighting building entrances, sidewalks, roadways, and other public areas at night. The recommended light levels shown in Table 1 provide enough light to navigate safely, but not so bright as to completely ruin our night vision.

Table 1: Common Illuminance Levels[29-30]

Source	Illuminance (lux)
Full sunlight	103,000
Partly sunny	50,000
Operating table	18,000
Cloudy day	1,000-10,000
Bright office	400-600
Most homes	100-300
Twilight	6.4
Clear night with full moon	0.1-0.3
Clear night with quarter moon	0.01-0.03
Clear starry sky with no moon	0.001
Overcast night sky	0.00003-0.0001
Recommended lux levels:	
Active building entrance	20
Building approach	2
Sidewalks	2
Parking lots	2-8
Freeways	5

6: Consider overall energy efficiency, lifecycle cost, and disposal

As of 2006, 8% of electricity used worldwide on lighting was consumed by outdoor lighting.[31] In the United States alone, an estimated 30% of all outdoor lighting is wasted by poorly-designed, unshielded light fixtures, at an estimated cost of $3.3 billion per year.[32] By using dark-sky friendly lighting, we can eliminate wasted light, preserve dark skies, and save money.

Most of us are familiar with the idea of a **watt (W)**, a measure of how much energy a light bulb uses. Back when most light bulbs contained a glowing filament, more watts generally meant more **lumens** (more energy=more light). Thanks to major advances in lighting technology, this isn’t always true today. For example, a 10W LED bulb emits more lumens than a 40W **incandescent** or **halogen** bulb. The energy efficiency of a light bulb can be expressed in **lumens per watt (lm/W).**

Until recently, the most common type of light bulb was the incandescent bulb, which accounted for 79% of global light bulb sales as recently as 2006.[33] Using a design more or less unchanged since first commercialized by Joseph Swan and Thomas Edison more than 130 years ago, a typical incandescent light bulb emits just 12 lumens of visible light per watt of electricity used (Fig 17). Expressed another way, only about 5% of the energy that enters an incandescent bulb is converted into visible light; the remaining 95% is emitted as heat.

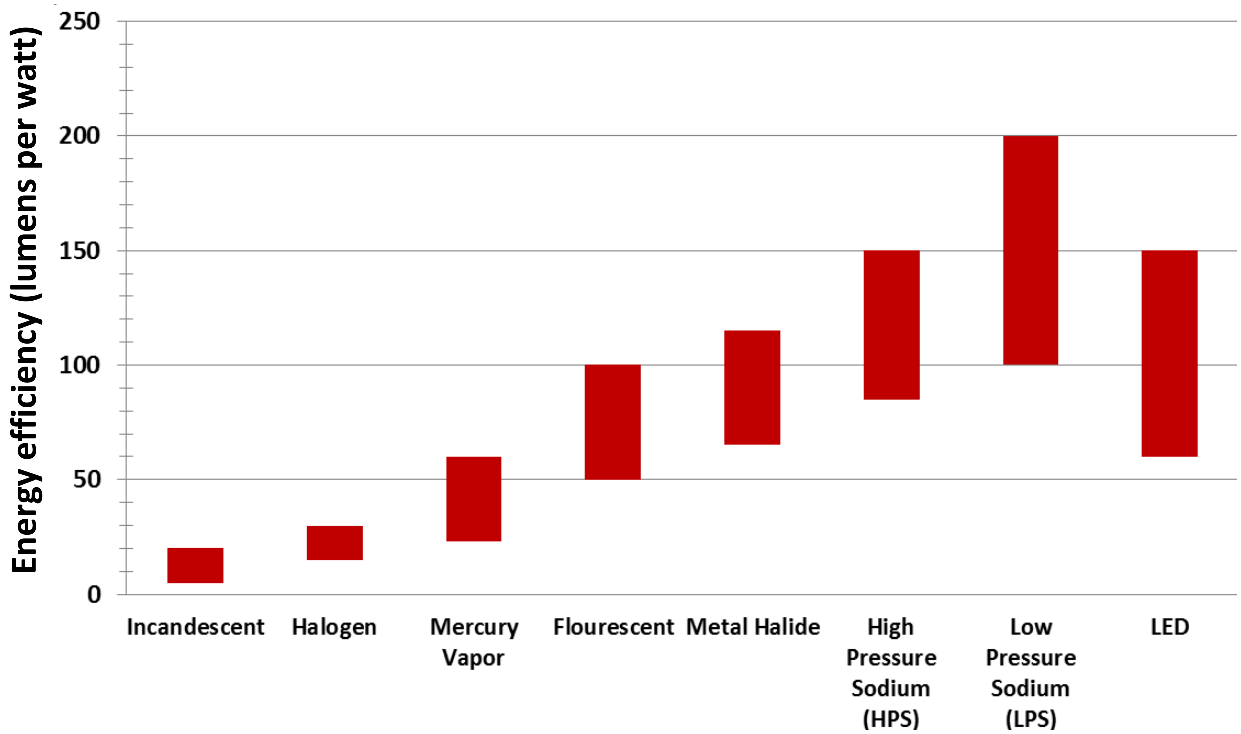


Figure 17-Energy efficiency of different light sources discussed in this chapter. Because efficiency varies depending on the exact bulb used, a range is shown. All values are approximate and reflect lighting technology circa 2018. (NPS/Zach Schierl)

Many newer forms of lighting technology, such as LEDs, emit well over 100 lumens per watt, a nearly ten-fold increase in efficiency compared to incandescent bulbs (Fig 17). While these newer bulbs can have a higher sticker price than an incandescent or halogen bulb, the energy savings can quickly offset the initial investment and lead to dramatic savings over the lifetime of the bulb. For example, an incandescent bulb typically lasts for just a few thousand hours, while newer LEDs are expected to last 25,000 hours or more because they don't have a filament to burn-out.

Finally, when choosing a light bulb, consider any potential disposal concerns. Some light bulbs, such as those that contain mercury (like CFLs) or sodium, should not be thrown away in household trash.

What about cost?

Now that we're familiar with the six principles of dark-sky friendly lighting, let's examine a few final myths. One of these is the idea that dark-sky lighting is too expensive. While retrofitting lights to be dark-sky friendly may incur an up-front cost, in many cases the resulting energy savings quickly recoup the expense. After all, dark-sky friendly lighting is all about eliminating wasted light. Light costs money, whether it is wasted or not. Let's look at an example:

Consider a front door being lit by a 72W **halogen** light bulb in an unshielded light fixture (Fig 18). Halogen bulbs are a slightly more energy-efficient variety of incandescent bulbs, and currently the cheapest available light bulbs at most hardware stores. Using a light meter, we find that this scenario produces an illuminance of 8.5 lux on the ground in front of the door, more than enough light for this task. This 72W bulb would cost us approximately $34/year in electricity to operate from dusk to dawn every night.

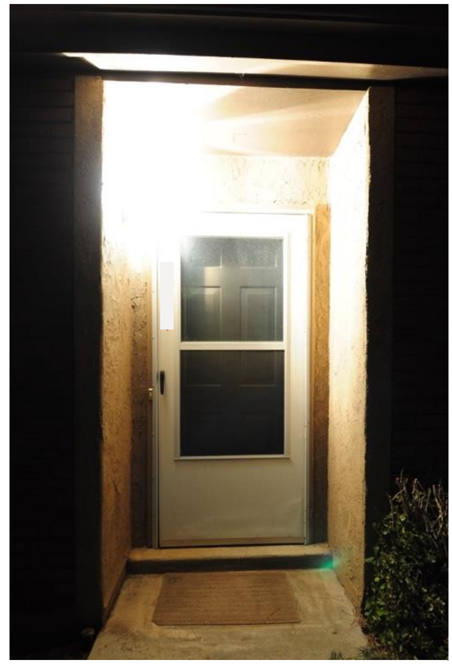


Figure 18-A 72W halogen light bulb in unshielded fixture. (NPS/Zach Schierl)

However, as you can see in Figure 18, there is significant glare from unshielded fixture and the most brightly lit area is actually *above* the door. This is not an efficient use of light; most of our $34 is being wasted on light going up and sideways rather than onto the door and ground where we need it. Can we do better?

Let’s start by replacing the unshielded fixture with a fully shielded fixture. Such a fixture might cost $20-$50 at a local hardware store. We’ll use the same light bulb (a 72W halogen) and place the new fixture right next to the old one. Figure 19 shows the result.

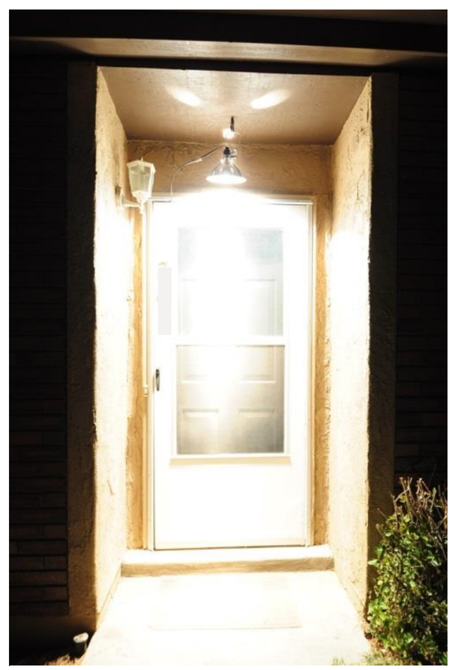


Figure 19-A 72W halogen bulb in a fully shielded light fixture. (NPS/Zach Schierl)

Our front door is now lit up like the Las Vegas Strip! *(Note that all photos were taken with the same camera, lens, and exposure settings.)* The fully shielded fixture directs all of the light from the bulb onto the front door, producing an illuminance of 330 lux. That’s almost as bright as a typical office. We now have way more light than we need, but are still paying $34/year on electricity to power the bulb. Plus we are out the ~$50 we spent on the new light fixture.

This is where the energy saving potential of dark-sky friendly lighting comes into play. Because we are now using a fixture that utilizes all of the light from the bulb, we can substitute a lower wattage bulb. Let’s insert a 5W warm white LED into the fully shielded fixture and see what happens. Figure 20 on the next page shows the result.

Figure 20-A 5W LED bulb in a fully shielded fixture. (NPS/Zach Schierl)

Much better! The 5W LED combined with the fully shielded fixture gives us 67 lux at the front door, more light than we had using the 72W bulb and the unshielded fixture (and still more than we really need for this task). The big difference is that we are now using just 5W of electricity. Each year the light is operated, we will save $31 on electricity compared to the old 72W bulb, which pays for the new LED bulb (~$5) and fully shielded fixture ($20-$50) in just one to two years. We have installed a dark-sky friendly light fixture and will quickly recoup our investment via energy savings.

In 2011, Cedar Breaks National Monument partnered with the International Dark Sky Association to retrofit the 34 outdoor lighting fixtures within the monument. Like the previous experiment, the result was a 90% decrease in energy usage (and money spent on outdoor lighting) while maintaining a sufficient level of light for staff and visitors.[34] As a result of this retrofit, Cedar Breaks now has dark-sky friendly lights throughout the monument. These lights not only permit visitors an unimpaired view of the night sky, they also save the monument money. These examples demonstrate how dark-sky friendly lighting is not inherently more expensive than traditional lighting, especially if installed from day one.

What about safety?

Another common myth associated with dark-sky friendly lighting is that using it makes us less safe. This is a natural and understandable reaction. After all, humans are inherently scared of the dark and we have, with some exceptions, been conditioned to believe that more light equals a safer environment. Any talk of reducing light emissions often causes people to jump to the conclusion that safety would be impaired. There are several ways to address this myth.

First, we need to remember that the goal of dark-sky friendly lighting is not to get rid of useful light on the ground, but rather to eliminate wasted light that escapes into the sky and into the surrounding landscape. It is difficult to argue that this wasted light is beneficial or making anyone safer. As we saw in the previous section, switching to fully shielded fixtures often results in *more* light on the ground, not less. Simply reiterating that a dark sky does not require a dark ground can often alleviate these concerns.

Secondly, there is little research to support the idea that simply adding more light to an area makes us safer. While average nighttime lighting levels have increased over time, this is largely because lights have become more energy efficient and can produce more illumination at a lower cost, not because evidence strongly indicates that more light is better.[35] Research on the effects of roadway lighting generally shows that fewer accidents occur on lit streets compared to unlit streets, but that the safety benefits of lighting plateau or diminish beyond a certain illumination level.[36] In other words, lighting makes roads safer, but only up to a certain point. A comprehensive study of towns in England and Wales that decided to dim their streetlights at night to save money and reduce emissions found no evidence of an increase in traffic accidents or crime.[37] In 1998, the city of Chicago began increasing alley lighting levels in an attempt to increase feelings of safety and decrease crime. The project included control areas and the resulting study reported an *increase* in crime in the more brightly lit alleyways.[38] More light might make us *feel* safer, but there is no conclusive evidence that it *actually* makes us safer.

What does make us safer is *good* lighting. Glare from overly bright unshielded light fixtures actually inhibits visibility, decreasing our ability to see both celestial *and* terrestrial objects at night (Figs 21-22).[39] Poorly-designed unshielded lights such as those in the left half of Figure 21 create uneven illumination and dark shadows that can mask threats. Contrast this with the fully shielded lights shown in the right half of Figure 21. These dark-sky friendly lights evenly illuminate the ground and avoid glare and light trespass, resulting in better nighttime visibility.

Because dark-sky friendly lighting promotes *good* lighting, as opposed to simply *brighter* lighting, it often leads to improved visibility, enhanced safety, money saved, and a better view of the night sky — a win-win-win-win combination!

Figure 21-Photographs of four streetlights at night, two unshielded (left), and two fully shielded (right). There is a person standing beneath each light, but the combination of glare and dark shadows created by the unshielded streetlights renders them nearly invisible. (Illinois Coalition for Responsbile Outdoor Lighting)

Figure 22-More light isn't always the answer! In the left image, a bright unshielded "security" light creates shadows that mask an "intruder" in the gate. Only when the light itself is shielded does the person in the gate become visible. These images were taken using camera settings that approximate what the human eye would see in the same conditions. (George Fleenor)

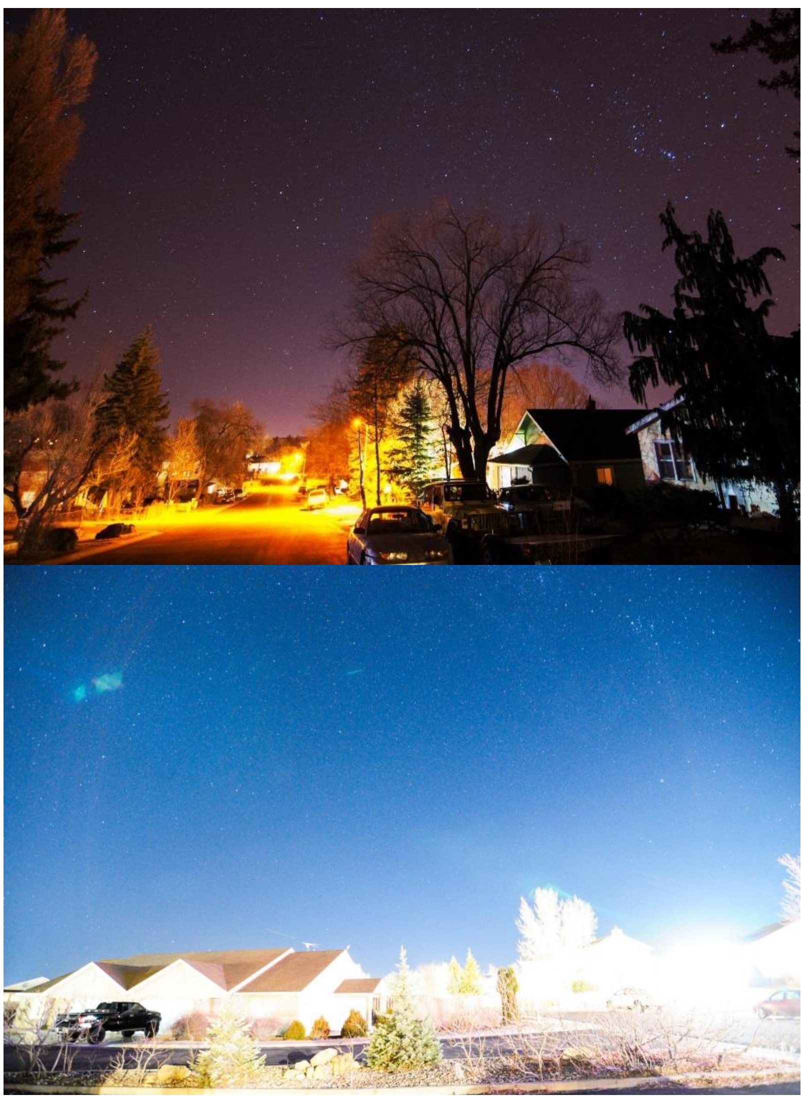


Figure 23-Municipal lighting in Flagstaff, AZ, the world's first International Dark Sky City (top) and Cedar City, UT (bottom). Images were taken using the same camera, lens, and exposure settings.

Note how in Flagstaff, the ground and street are well illuminated by the fully shielded, amber-colored, low pressure sodium streetlights, but the tree tops and sky remain dark. Orion is clearly visible in the sky at right.

In striking contrast, the Cedar City neighborhood is over-illuminated, few stars are visible, and glare from municipal and residential light fixtures overwhelms the scene, inhibiting visibility. (Zach Schierl)

Does it make a difference?

The ultimate question remains: "If we follow these principles, can we save or bring back the night sky in our cities, towns, and parks?" The short answer is "yes!"

Unlike other types of environmental degradation, light pollution is 100% reversible. Unlike a polluted lake or stream, the night sky hasn't been damaged per se, it is simply masked by our fog of wasted artificial light. Simple actions, like those discussed in this chapter, can go a long ways toward bringing it back.

In remote areas with little skyglow, installing dark-sky friendly lighting on even a handful of buildings can greatly improve night sky visibility and decrease light trespass. See the images on the cover of this chapter for an example from Big Bend National Park in Texas.

When used on a larger scale, dark-sky friendly lighting can have an extraordinary impact. Below are two measurements of **sky luminance** from the National Park Service Natural Sounds & Night Skies Division. (For an explanation of these images, see *Chapter 3.3*.) Figure 24 shows the night sky from Brian Head Peak (just outside Cedar Breaks NM), 21 kilometers (13 miles) from downtown Cedar City, UT. Cedar City is a typical mid-sized town with an area population of ~40,000. The night sky, while dark overall, is noticeably degraded by the skyglow of Cedar City.

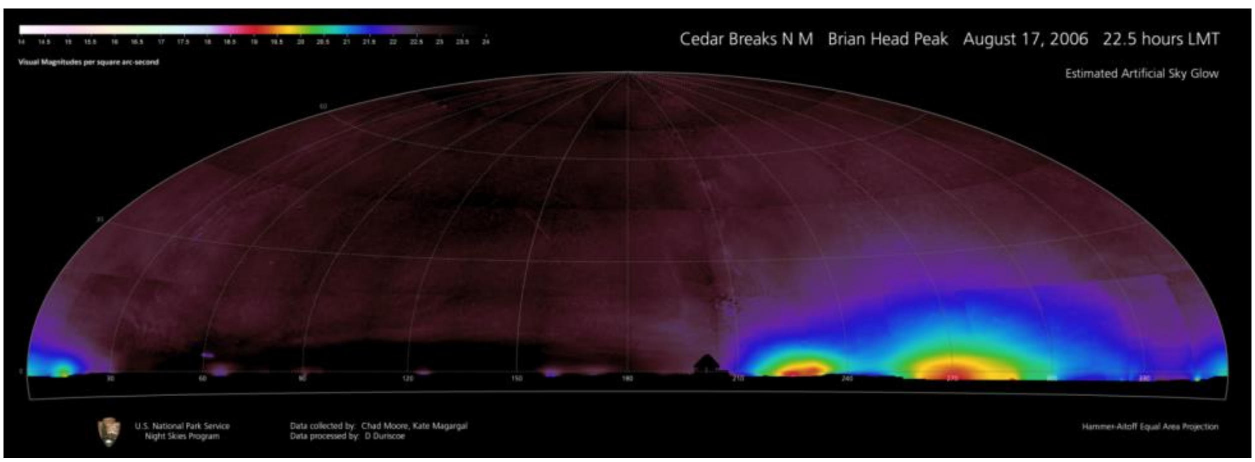


Figure 24-Measurement of artificial sky luminance from Brian Head Peak, just outside Cedar Breaks National Monument, Utah. Primary sources of skyglow are Cedar City (right) and St. George, UT (left). (Natural Sounds & Night Skies Division/NPS)

In contrast, Figure 25 shows the night sky from Sunset Crater National Monument, 21 kilometers (13 miles) from downtown Flagstaff, AZ. Flagstaff is home to about two and a half times as many people as Cedar City, with an area population of ~100,000 people. Surprisingly, the sky from Sunset Crater is as dark at the same distance, if not darker, despite Flagstaff being more than twice as populous. How is this possible?

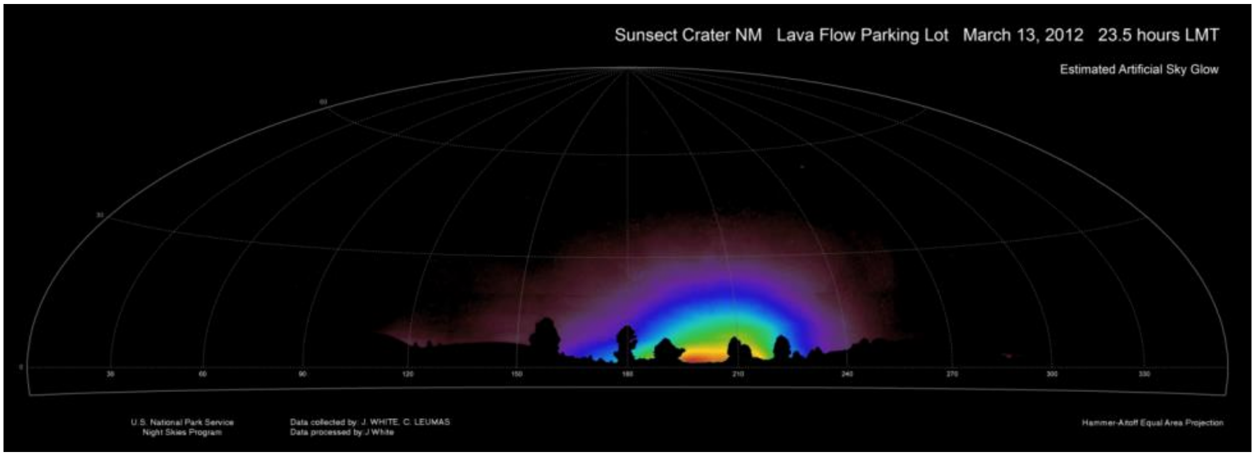


Figure 25-Measurement of artificial sky luminance from Sunset Crater National Monument, Arizona. Source of skyglow is Flagstaff, Arizona. (Natural Sounds & Night Skies Division/NPS)

The scene described at the beginning of this chapter takes place nightly at Lowell Observatory in Flagstaff. Home to multiple observatories, Flagstaff has been looking up at the sky since 1894, when Boston astronomer and mathematician Percival Lowell established the observatory that now bears his name on a mesa just one mile from the city center. After Pluto was discovered using one of its telescopes in 1930, Lowell Observatory grew into a leading institution for astronomical research and was responsible for mapping much of the lunar surface prior to the Apollo missions in the 1960s.

In the 1950s, with Flagstaff growing rapidly, Lowell Observatory realized they would soon need to seek darker skies in order to continue operations. Recognizing the economic, scientific, and cultural benefits of having the observatory in town, in 1958 Flagstaff became the first known municipality to enact a **lighting ordinance** aimed at protecting the city's view of the night sky.[40] The 1958 ordinance prohibited the "advertising searchlights" that were becoming widespread at the time, and which were very detrimental to astronomical observations.[41] In 1973, the ordinance was expanded to require that lights be directed downward, making Flagstaff the second city (after Tucson, AZ in 1972) to combat light pollution in this manner.[42] Flagstaff's outdoor lighting ordinance was amended again in 1989 to cap the number of **lumens** emitted per acre of property. As a result of these actions, between 1989 and 2009, the population of Flagstaff grew by 25% while skyglow increased by just 17%, as opposed to a predicted 43% without the 1989 lighting ordinance amendments.[43]

Because of Flagstaff's dark sky stewardship, Lowell Observatory remains an integral part of the community to this day. Several other observatories have also been drawn to the Flagstaff area, which is now home to the Northern Arizona University Atmospheric Research Observatory and the U.S. Naval Observatory. The Milky Way can be seen throughout the city and the local astronomical society frequently hosts stargazing events on the public square downtown. Flagstaff has become a hub for **astro-tourism** and shows us that, when light is used wisely, a safe, thriving city and a dark night sky can exist in perfect harmony. In 2001, Flagstaff was designated as the world's first "International Dark Sky City" by the International Dark Sky Association. Today, Flagstaff's SLEDS Project (Street Lighting for Enhancing Dark Skies) is a leader in the effort to identify dark-sky friendly LED roadway lighting.[44]

While Flagstaff may be the model example of dark-sky friendly lighting, many other towns and cities are following suit. Here in Southern Utah, several municipalities have enacted lighting codes with dark sky stewardship in mind, including Kanab, Torrey, Springdale, and Toquerville. In 2018, the Utah Legislature passed a resolution encouraging the use of dark-sky friendly lighting throughout the state.[45] The International Dark Sky Association provides assistance and resources for communities interested in protecting their view of the night sky, including a Model Lighting Ordinance developed in partnership with the Illuminating Engineering Society of America. See the links at the end of the chapter for more information.

Many national parks and monuments are also working to make their lighting dark-sky friendly, both to improve the view of the night sky for visitors and for the benefit of nocturnal wildlife. This is one of the requirements for a park to be certified as an International Dark Sky Park by the IDA. Even historical parks like Mount Rushmore and the Washington Monument have worked with manufacturers to design lighting solutions that minimize impacts on the night sky while still illuminating the memorials and monuments at night. However, the biggest threat to dark skies at most national parks is still skyglow from cities and towns outside park boundaries. Therefore, collaborations between parks and local communities will be necessary to promote good lighting and keep skies dark for future generations.

Review

Common misconceptions

Below is a list of commonly encountered misconceptions about dark-sky friendly lighting. As a way to review content from this chapter, see if you can explain why each misconception is inaccurate:

- Saving the night sky or bringing back the stars requires that we turn all our lights off and go back to the dark ages.
- Switching to dark-sky friendly lighting is expensive and a waste of money.
- More light at night means more safety/less crime.
- More light improves visibility at night.
- LEDs are great for dark-sky friendly lighting.
- LEDS are bad for dark-sky friendly lighting.
- The more people there are in a city, the fewer stars you will be able to see.
- Light pollution is an unavoidable byproduct of progress and prosperity.

Questions for thought

- What are some ways that a homeowner, business, or city could minimize the cost of switching to dark-sky friendly lighting?

- If someone asked you to recommend a dark-sky friendly light for their front porch, how would you respond? In which direction would you point them?

- Flagstaff is often cited as a model example of a dark-sky friendly city. Would Flagstaff's approach to dark sky stewardship work everywhere? Why or why not?

- Take a walk around your neighborhood at night and take a close look at the lights. What percentage of the lights are dark-sky friendly? How could they be improved?

For More Information

- Flagstaff, AZ Outdoor Lighting Standards: http://www.flagstaff.az.gov/DocumentCenter/Home/View/14707
- "Dark Sky Residential Lighting Products" (Flagstaff Dark Skies Coalition): http://www.flagstaffdarkskies.org/dark-sky-residential-lighting-products/
- International Dark Sky Association *Fixture Seal of Approval* Program (dark-sky friendly lighting fixtures): http://darksky.org/fsa/
- IDA/IES Model Lighting Ordinance: https://www.darksky.org/our-work/lighting/public-policy/mlo/
- "Lamp Spectrum and Light Pollution" (Flagstaff Dark Skies Coalition): http://www.flagstaffdarkskies.org/for-wonks/lamp-spectrum-light-pollution/
- "LED Practical Guide" (International Dark Sky Association): https://www.darksky.org/our-work/lighting/lighting-for-citizens/led-guide/
- "LED: Why 3000K or Less" (International Dark Sky Association): http://www.darksky.org/lighting/3k/#list
- Outdoor Lighting Codes (Flagstaff Dark Skies Coalition): http://www.flagstaffdarkskies.org/dark-sky-solutions/dark-sky-solutions-2/outdoor-lighting-codes/
- "Overexposed" (Architect Magazine): http://www.architectmagazine.com/technology/overexposed_o
- "Visibility, Environmental, and Astronomical Issues Associated with Blue-Rich White Outdoor Lighting" (International Dark Sky Association): http://darksky.org/wp-content/uploads/bsk-pdf-manager/8_IDA-BLUE-RICH-LIGHT-WHITE-PAPER.PDF

SECTION 4: **SHARING THE NIGHT SKY**

CHAPTER 4.1-USING A TELESCOPE

Amateur telescopes come in all shapes and sizes. Here, a 20” Dobsonian telescope is set up in preparation for a star party at Cedar Breaks National Monument. (NPS Photo)

Chapter 4.1 Goals

After reading this chapter and participating in the corresponding workshop activities, you should be able to:

- Independently set up and operate a backyard telescope and be able to locate objects both manually and using a GoTo system.

Meet the Telescopes

While cutting-edge astronomical research has replaced the human eye with digital cameras, there remains something special about seeing Saturn, a galaxy, or a star cluster with your own eyes. Seeing a picture of a celestial object in a magazine or on a phone screen just isn't the same as seeing it yourself under a dark, starry sky. Backyard telescopes, those that can be purchased commercially and are portable enough to be carried around in a regular vehicle, offer us a "live" portal into the wonders of the universe. They are also a fantastic way to share the night sky with others. The ability to operate a backyard telescope is one of the most important skills you can possess as an astronomy educator.

This chapter is a guide to using two of the most common types of backyard telescopes on the market today: a **Dobsonian reflector** and a computerized **Schmidt-Cassegrain** (pictured on following pages). While the telescopes you learn to use in your Master Astronomer Workshop may not be identical to those shown here, they will likely be similar. The general principles described here translate to nearly any type of telescope. Learning how to use a Dobsonian and a Schmidt-Cassegrain will give you the basic skills to operate any telescope you might encounter.

A Dobsonian telescope is operated entirely by hand, and is arguably the easiest type of telescope to operate. We recommend learning to use a Dobsonian first. The learning curve of a computerized Schmidt-Cassegrain is considerably steeper. Computerized telescopes must be initialized before they can be used, a process that is much easier if you are already familiar with the basics of telescope operation from using a Dobsonian.

If you encounter any unfamiliar terminology in this chapter, refer back to *Chapter 2.4: Telescopes & Observatories* for a refresher on the different types of telescopes and mounts, how they work, and the advantages and disadvantages of each. For now though, let's meet the telescopes!

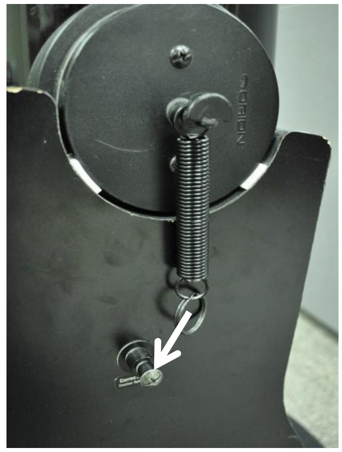
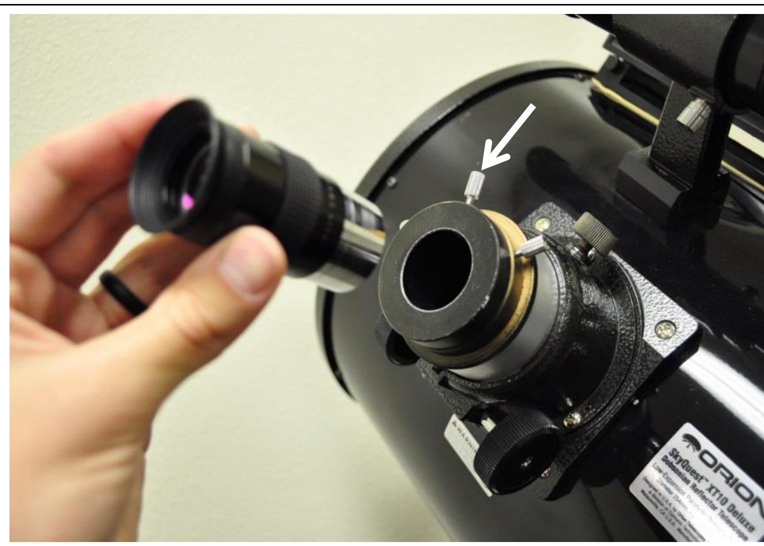
Dobsonian reflector:

Computerized Schmidt-Cassegrain:

Step 1: Setting up the telescope

Dobsonian reflector:

1. Place the base on a level surface. It doesn't need to be perfectly level, but should be close. Ensure that all feet are in contact with the ground and that the base does not rock back and forth.	
2. Pick up the optical tube, and gently rest the altitude bearings (the round discs on the side of the optical tube) in the cradle on the base.	

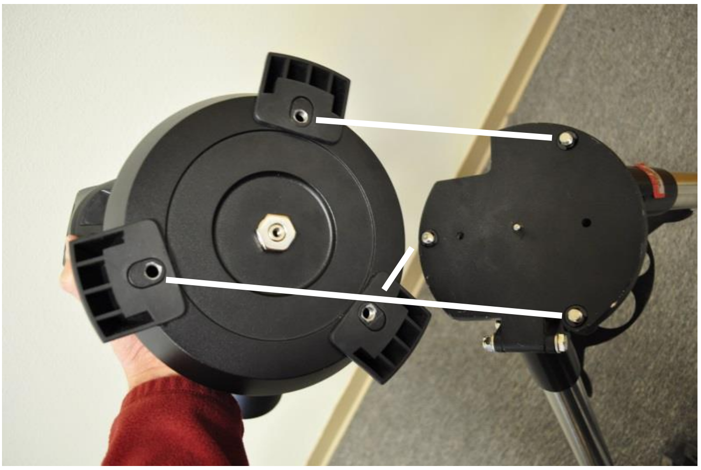
3. If applicable, connect the spring hanging from the altitude bearing to the base as shown in the photos. This increases friction between the tube and base, preventing the telescope from moving when you don't want it to. Different models have different systems for achieving this.	 
4. Remove the optical tube dust cover. Secure in a safe location. **From this point on, be very careful not to point the telescope in the direction of the Sun!**	
5. Remove the eyepiece cap and secure it in a safe location. Insert an eyepiece into the telescope focuser and tighten the small set-screw (arrow) until the eyepiece is secure.	

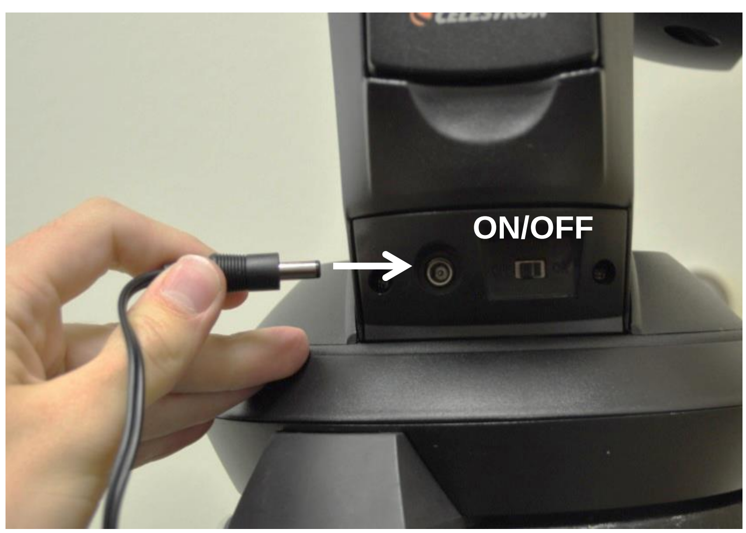
6. Congratulations! You are now ready to use the telescope. A Dobsonian telescope can be moved manually by grabbing the end of the optical tube and pushing or pulling the telescope in any direction.	

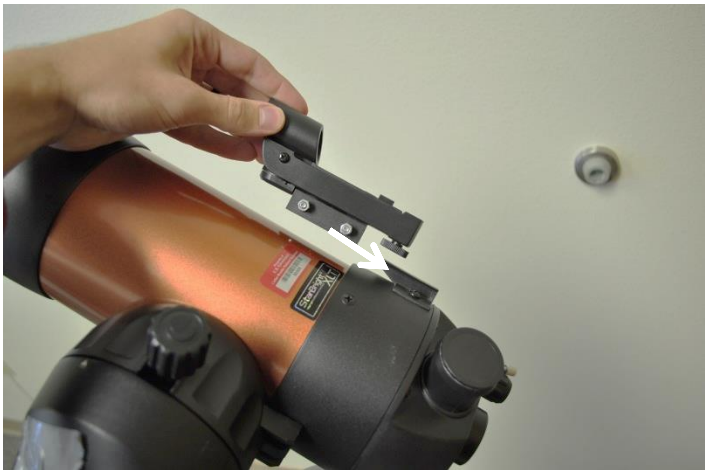
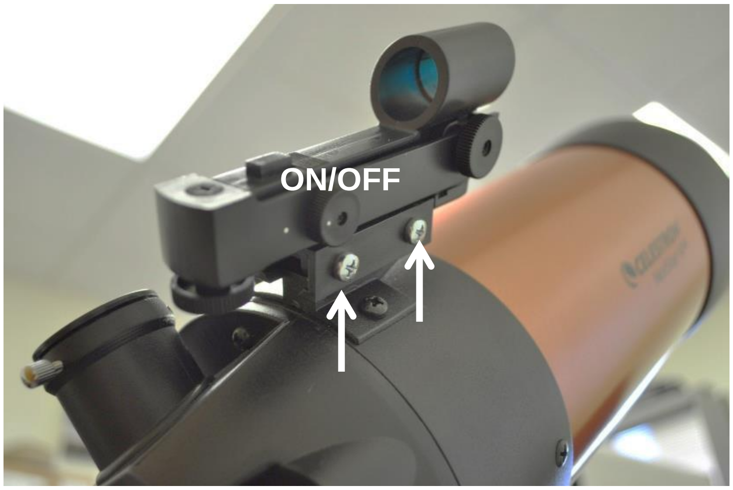
Celestron NexStar Schmidt-Cassegrain:

1. Begin by gathering the tripod, tripod stabilizer, and a bubble level.	
2. Set up the tripod on a level surface.	

3. Unscrew the knob from the metal rod in the center of the tripod. Place the metal stabilizer plate on the rod, aligning the three arms with the tripod legs. Re-attach the knob, tightening until the tripod is steady and the legs do not move.	 
4. Loosen the set screws at the bottom of the tripod legs and extend the legs until the top of the tripod is near waist or chest height. Re-tighten the set screws.	 
5. Adjust the tripod legs as necessary to level the metal plate on top of the tripod. Use the bubble level to ensure that the plate is level. Be sure to move the level around to ensure that the plate is flat in all directions.	

6. Next you will need the telescope mount itself.	
7. Line up the screws on the tripod plate with the holes on the underside of the telescope mount.	
8. Place the mount on top of the tripod with the tripod set screws aligned with these holes. Tighten the three black plastic set screws on the tripod to secure the mount to the tripod.	

9. Your telescope should now look like this.	
10. Next you'll need a battery pack and a 12V power adaptor. Insert the large end of the adaptor into the 12V port on the battery pack.	
11. Insert the other end of the adaptor into the power port on the telescope mount. Turn the battery ON, and then turn the mount ON using the small switch to the right of the power port. The keypad should illuminate. If not, you did something wrong in steps 10-11, or your battery is dead.	

12. Remove the optical tube dust cover. Secure in a safe location. **From this point on, be very careful not to point the telescope in the direction of the Sun!**	
13. Slide the red dot finder telescope onto the dovetail bracket on the top of the telescope tube. Do not let go until Step 14 is complete!	
14. Secure it by tightening the two Philips-head screws (arrows) on the side of the red-dot finder. Turn the red-dot finder on by turning the power knob.	

15. Remove the eyepiece cap and secure it in a safe location. Insert an eyepiece into the telescope focuser and tighten the small set-screw (arrow) until the eyepiece is secure.	
16. Congratulations! You are now ready to use the telescope. The telescope can be moved by using the arrow buttons on the keypad. **Do not attempt to move the telescope manually or you may damage the gears!**	

Step 2: Aligning Finder Telescopes

After you have set-up the telescope, the next step is to align any **finder telescopes**. Recall that the purpose of a finder telescope is to help you locate objects in the night sky. For this to work, any finder telescopes must be pointed in precisely the same direction as the primary telescope.

Aligning a finder telescope is best done in daylight by aiming the main telescope at a distant tree or other stationary terrestrial object, and then adjusting the finder telescopes so that they are pointed at the same reference object. Alignment can also be performed after dark using a bright naked eye star or planet as a reference point, but in this case the entire process must be done very quickly because the star will be moving across the sky.

To align a finder telescope:

1. Point the telescope in the general direction of a distant tree top or distinct terrestrial object (or a bright star if aligning at night) either manually (Dobsonian) or by using the arrow keys on the controller (Schmidt-Cassegrain). This will be your alignment object.

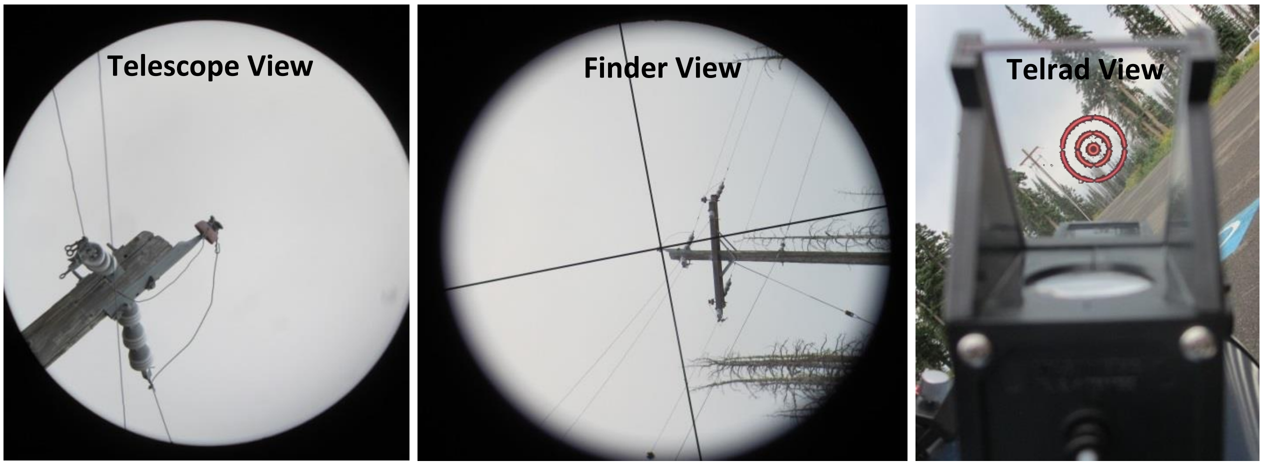


Figure 1-Aligning a finder telescope and Telrad using the top of a utility pole as an alignment object. The top of the pole is first centered in the telescope eyepiece (left), then the finder telescope crosshairs (center), and finally the Telrad bullseye (right). (NPS/Zach Schierl)

2. Look through the main telescope eyepiece and center the chosen alignment object in the field of view (Fig 1, left).

3. Next, without bumping the telescope, look through the finder telescope and adjust the alignment knobs (Fig 2, top) until the alignment object is centered in the crosshairs (Fig 1, center).

4. Look along the telescope tube through the Telrad or red dot finder until the red dot or bullseye is visible. Adjust the alignment knobs (Fig 2, bottom) until the red-dot or bullseye is centered on the alignment object (Fig 1, right).

5. Finally, check your work by returning the main eyepiece and ensuring that the alignment object is still centered in the field of view. If it is, you are good to go. If it is not, you bumped the telescope somewhere during the process and may need to start over.

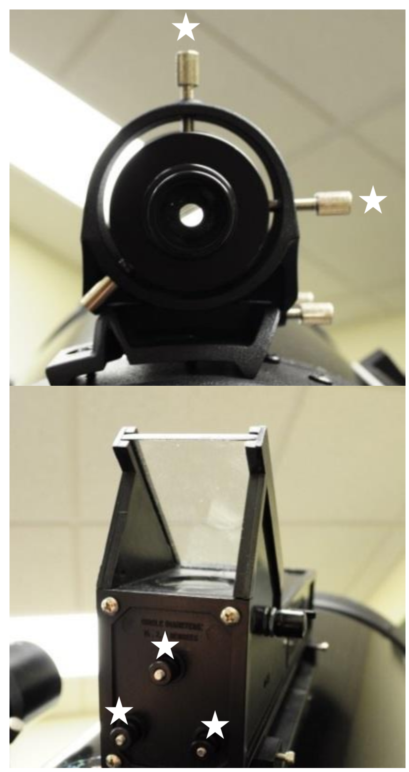


Figure 2-Alignment knobs on a traditional finder telescope (left) and a Telrad finder (right). (NPS/Zach Schierl)

Step 3: Initializing a Computerized Telescope

Note: this step applies to computer-controlled telescopes only. The procedures described here are for Celestron NexStar models (what we use at Cedar Breaks) but the process is very similar for other models of GoTo telescopes. Refer to your telescope's instruction manual for details. If you are using a Dobsonian telescope, skip directly to Step 4: Locating Objects.

With the telescope set-up and any finder-scopes aligned, you are now ready to initialize the computer controller. This process is also usually known as "alignment," but should not be confused with the finder telescope alignment process described in the previous section. The purpose of alignment here is to tell the telescope computer where it is on Earth, what time it is, and which direction it is looking. Once this is accomplished, the internal computer will be able to both track and locate celestial objects automatically.

There are several possible alignment methods. We will discuss two of them here: **SkyAlign** and **Two Star Align.** Before starting either alignment procedure, use the arrow keys on the keypad (Fig 3) to lower the telescope tube to horizontal by lining up the index markers on the telescope tube and arm. You should also point the telescope tube north (roughly).

Figure 3-A Celestron hand controller. (NPS/Zach Schierl)

SkyAlign

1. Press ENTER to begin the SkyAlign alignment process.
2. On the following menu, select "SkyAlign" (Use UP and DOWN to scroll through the menus, as opposed to the arrow keys which will move the telescope) and then press ENTER.
3. The keypad will ask you to confirm the date, time zone, location, etc.
    a. Local Time: enter the current time in 24 hour format. This needs to be precise!
    b. Date: Enter the current date
    c. Time Zone: Mountain Time Zone
    d. DST: On or Off depending on date
    e. Location: Cedar City, UT (or choose custom site if observing from somewhere else)
        i. *If you choose a custom site,*

you will need to enter the latitude and longitude of your location. The latitude of Cedar Breaks is 37° 36’ 47”, and the longitude is -112° 50’ 17”

4. After confirming this information, press ENTER to continue.
5. Use the arrow keys on the keypad to center a bright object (such as a star or planet) in the telescope’s field of view. Once the object is centered, press ENTER, and then ALIGN.
6. Center a second bright object in the field of view using the keypad. Press ENTER, and then ALIGN.
7. Center a third bright object in the field of view using the keypad. Press ENTER, and then ALIGN.
8. After the third object, the screen will indicate whether or not the alignment was successful. If successful, the screen will say “Match Confirmed” in which case the telescope is now ready to use. If the alignment failed, you must try again, starting with pointing the telescope back to north and re-entering the date and time information.

Two Star Alignment

1. Press ENTER to begin the Two Star Alignment process.
2. Select “Two Star Alignment” from the menu (Use UP and DOWN to scroll through the menus, as opposed to the arrow keys which will move the telescope) and hit ENTER.
3. Choose a bright star that is currently above the horizon and select its name from the provided menu. Press ENTER.
4. Use the arrow keys to slew the telescope to that star. Hit ENTER. Now look through the eyepiece and precisely center the star in the field of view (the motors will move more slowly once you hit ENTER). Once the star is exactly centered, press ALIGN.
5. Repeat Steps 3 & 4 for a second star, preferably one that is in a very different area of the sky.
6. After pressing ALIGN for the second star, the screen will indicate whether or not the alignment was successful. If successful, the screen will say “Match Confirmed” in which case the telescope is now ready to use. If the alignment failed, you must try again, starting with pointing the telescope back to north and re-entering the date and time information.

Alignment tips

- Hitting “RATE” and then a number will adjust the speed of motion: 9 is the fastest, 1 is the slowest.
- The power cables for the batteries are long enough to account for the telescope swiveling in a complete circle, as long as they have enough slack and aren’t caught on anything.
- Once alignment is complete, **ALWAYS** use the arrows or keypad buttons to move the telescope. **NEVER** physically grab the telescope and move it like a Dobsonian, because this will cause it to become misaligned.

Step 4: Locating objects

Locating objects with a computer controller

After successfully aligning the telescope, you can use the keypad to find objects automatically:

1. Begin by pressing the button corresponding to the type of object you wish to find. For example, if you want the telescope to locate Saturn, press PLANET. If you want to locate a Messier Object, press M.
2. Once you have selected an object type, you will do one of two things
   a. If you selected PLANET or STAR, use the UP and DOWN buttons (not the arrow keys, which will move the telescope) to scroll through the list of objects. Once you find the one you want, press ENTER. The telescope should slew to the object you selected.
   b. If you selected a catalog such as M or NGC, you will need to use the keypad to enter the catalog number of the object you wish to observe. For example, if you want to look at the Globular Cluster M22, after pressing M, you will need to enter "0022." Once the catalog number is entered, press ENTER and the telescope should slew to the selected object.

Depending on how precise your initial alignment was, your chosen object might be slightly off center in the field of view. You may need to use the arrow keys on the keypad to center it. If your alignment was poor, the object may not be in the field of view at all and you may have to search the surrounding area a little bit using the keypad arrow buttons. **Remember to never move the telescope manually after alignment is complete!**

Locating objects manually

GoTo telescopes can make locating objects fast and easy, assuming that you perform a good quality alignment at the start of the evening. That being said, there is no better way to learn your way around the night sky than learning how to locate objects manually with a Dobsonian telescope. After all, you won't always have a computerized telescope at your disposal, and you never know when a battery might die rendering a GoTo system unusable.

Amateur astronomers are often asked how they can hone in on faint galaxies and nebulae with such ease. The answer is "practice!" Finding your way around the night sky can seem daunting at first, but quickly gets easier as you become familiar with important landmarks. With even a few nights of practice with a Dobsonian telescope, you will begin to develop a mental map of the night sky and where important objects are located.

1. To begin, you need to select an object and figure out where in the sky it is located. If your target is a naked eye object, such as a planet or bright star, this is easy. If your target is **not** visible with the naked eye (most deep-sky objects), you will need to use a star chart,

planisphere, or night sky app to create a mental map of its location relative to naked eye stars and constellations. Look for patterns or shapes that will help you remember where the object is (Fig 4).

Figure 4-The galaxy M81 (small oval) is not visible to the naked eye, but a line drawn diagonally across the bowl of the Big Dipper points almost directly to it. Recognizing geometric relationships like this is the key to locating deep-sky objects without the aid of a computer. (NPS/Stellarium)

2. Insert a low power eyepiece (focal length of 25mm or more) into the telescope. This will give you a wide field of view and increase your odds of locating the object. You can always insert a higher powered eyepiece later once you have found it.
3. Grab the telescope tube (or use the arrow keys if using an unaligned computerized telescope) and move it until it is pointing in the general direction of your chosen object.
4. If your telescope has one, look through the red dot finder (or Telrad) until you can see the red dot (or bullseye) projected onto the sky. With your eyes on the red dot or bullseye and your hands on the telescope, position the red dot as close as possible to the location of your object as identified in step 1.
5. If your telescope is equipped with a regular finder telescope, look through it and see if your object is visible. Extremely dim deep-sky objects may not be visible in the finder scopes, but brighter ones (such as Messier Objects) should be. If your target is visible, gently adjust the position of the telescope until it is centered in the finder cross hairs.

6. Once your object is centered in the finder, or if the object is not visible in the finder, next look through the main telescope eyepiece. If your finder telescope(s) are well-aligned, your target should be visible. If not, or if your target was too faint to be seen in the finder, you may have to hunt around. Try moving the telescope in small circles to see if it is nearby.
7. If your object is still not visible, go back to your star chart or finder telescope and try again.
8. Remember that without a tracking drive, your object will move. (Actually, we are rotating, but the result is that your object appears to move.) You will need to periodically check the eyepiece and move the telescope slightly to follow the object so that it doesn't disappear.

Like learning any new skill, locating objects manually with a telescope can be frustrating at first. It can take years to become truly proficient, but the reward of being able to find planets, star clusters, and galaxies with ease is worth the effort.

All About Eyepieces

Interchangeable **eyepieces** allow you to change the **magnification** and **field of view** of the telescope depending on what you are looking at. A high-quality eyepiece can be as important as the quality of the telescope mirror or lens. Many amateur astronomers will spend as much money (or more) on a single eyepiece than a telescope itself.

To swap an eyepiece, simply loosen the one or two small setscrews holding it in place. Remove the eyepiece, insert a new eyepiece barrel into the telescope, and re-tighten the setscrew.

Figure 5-The two standard eyepiece barrel sizes: 2" (left) and 1.25" (right). The 28mm eyepiece will provide a low magnification view, which the 9mm eyepiece will provide a higher magnification view. (NPS/Zach Schierl)

Eyepieces come in two common barrel diameters: 1.25" and 2" (Fig 5). Most telescopes have an adaptor that allows either size to be used.

Calculating Magnification

The **focal length** of an eyepiece in millimeters (Fig 5) gives you an idea of the magnification and field of view that will result from using that eyepiece. The shorter the eyepiece focal length, the higher the magnification and the smaller the field of view will be (Fig 6). Eyepiece focal lengths generally range from about 3mm (extremely high power) to 55mm or more (very low power). Some eyepieces are "zoom eyepieces" which allow you to change the focal length (and thus the magnification and field of view) without physically changing eyepieces. When you are trying to locate an object, always start with a low power eyepiece. The larger field of view will make it easier to hone in on your target.

Magnification depends on both the focal length of the telescope (which is fixed for any given telescope) and the focal length of the eyepiece you are using. This is why reputable telescope manufacturers do not advertise their equipment based on magnification: the magnification depends on the combination of telescope and eyepiece. To calculate the magnification of a particular eyepiece/telescope combination, use the following formula:

$$magnification = \frac{focal\ length\ of\ telescope\ (mm)}{focal\ length\ of\ eyepiece\ (mm)}$$

The maximum magnification of a telescope is effectively limited by atmospheric turbulence and the telescope's aperture. As a general rule of thumb, the maximum useful magnification is 50x the aperture of the telescope in inches (Table 1). Larger telescope handle higher magnification better because they collect more light *to* magnify. In theory, a 3" telescope *could* magnify an object 600x, but a 3" telescope collects so little light to begin with that such a view would be a dim, blurry mess.

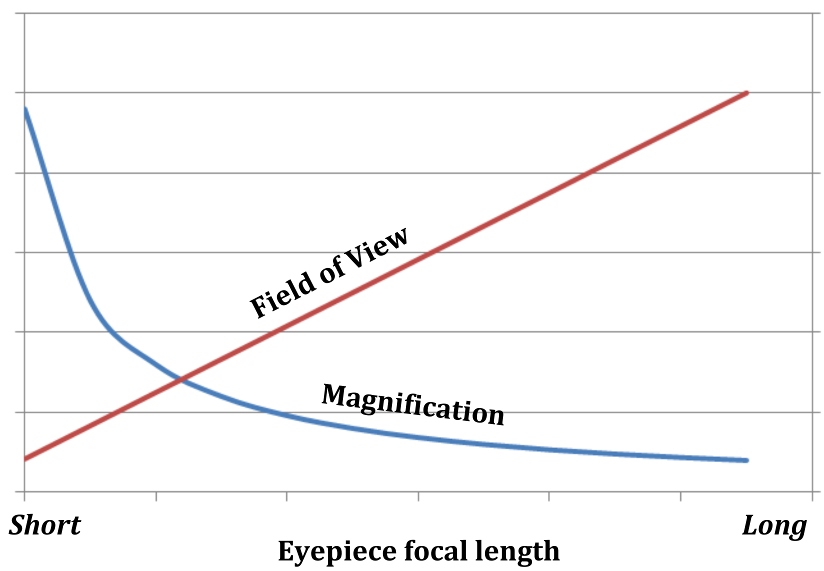


Figure 6-Graph showing how the focal length of an eyepiece controls the magnification and field of view of a telescope. (NPS/Zach Schierl)

Some celestial objects respond better to increased magnification (typically small, bright objects) while others (large, dim objects) do not. Remember that as an object is magnified, the same amount of light is spread out over a larger area, meaning that it will appear larger, but progressively dimmer.

Table 1: Maximum Magnification for Backyard Telescopes

Telescope Aperture	Maximum Useful Magnification
3"	150x
4.5"	225x
6"	300x
8"	400x
10"	500x
12"	600x

Another important property of eyepieces is **eye relief**. Eye relief is also measured in millimeters, and tells you how close your eye must be to the glass to see the entire field of view. Low quality short focal length (high magnification) eyepieces will often have very little eye relief, making them difficult to look though, especially for those who wear glasses. High powered eyepieces with longer eye relief are generally expensive. Eyepieces with less than 15mm of eye relief can be difficult to look through, and 10mm or less is almost impossible.

Figure 7- A variety of eyepiece filters. (NPS/Zach Schierl)

Eyepiece filters

Most eyepieces have threads on the bottom of the barrel in order to accept a wide variety of astronomical filters (Fig 7). Filters can enhance the view of certain objects by transmitting only select wavelengths of light and blocking out others. Since any filter will, by definition, block some of the light collected by the telescope, they are generally more useful on larger telescopes with greater light-gathering capability. If you do use a filter, be sure to unscrew it before moving to another object. Table 2 summarizes some commonly used filters.

Table 2: Common Filters for Backyard Astronomy

Filter:	What it does:	Good for:
Moon filter/neutral density filter	Reduces the amount of light entering the observer's eye when the Moon is bright. Essentially a piece of dark glass (neutral density filter).	Observing the Moon anytime that it is brighter than a crescent (full, gibbous, quarter phases)
Planetary filters (variety of different colors)	Colored pieces of glass that can subtly accentuate surface features on the planets. Different colors enhance different features.	Moon, Mars, Jupiter, Saturn. Be careful: these filters give the planets an unnatural color and can confuse the public if you do not clearly explain that a filter is being used.
Oxygen III and UHC (Ultra High Contrast) filters	Isolates specific wavelengths of light produced by atoms common in certain types of nebulae.	Emission nebulae, planetary nebula, supernovae remnants
Deep-sky, skyglow, & light pollution filters	Block certain wavelengths of light associated with light pollution to improve contrast between deep-sky objects and the background sky.	Modestly improving views of deep-sky objects in light polluted areas. BUT, they are a poor substitute for dark skies.

Observing Tips & Tricks

Averted Vision

Averted vision is a technique to help you see faint objects in a telescope. The idea is simple, but counterintuitive: if you are struggling to spot a faint object, or a subtle detail in a bright object, it often helps to not look directly at it. Instead, avert your gaze to the side slightly, placing the thing you want to see at the periphery of your vision, and the object will often pop into view.

Averted vision works because our **rods**, the photoreceptor cells that we use to see faint things at night, are more densely clustered around the perimeter of our retina. By letting faint starlight fall on the edges of our eyes, we can often see things that we can't when looking directly at them.

Focusing

Focusing is an often overlooked element of using a telescope. Depending on the eyepiece you are using (or the eyesight of the person that looked before you) the focus may need to be adjusted to produce a sharp image. Every backyard telescope has a focusing knob, usually located near the eyepiece.

If the focus is off, you will likely see a blob of light like the one in Figure 8. If the focus is extremely off, you may not see anything at all. In either event, begin adjusting the focus knob. If the blob gets smaller, you are headed in the right direction. If the blob gets larger, turn the focusing knob the other way. Keep turning until the stars are as small and point-like as possible.

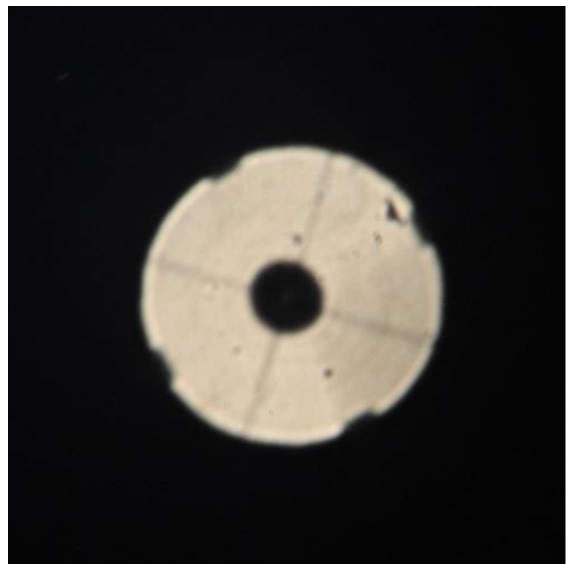


Figure 8-View of an out-of-focus star through a Newtonian reflector. If you see something similar to this when looking through your telescope, it likely needs to be focused. (NPS/Zach Schierl)

If you are still not able to get stars to focus properly, there are a few possibilities:

- The **seeing** might be very poor. A turbulent atmosphere can make it very difficult to bring an image into perfect focus.
- The optical elements of the telescope may be out of alignment. See below for information on how to **collimate** your telescope.
- The problem might lie with your eyes or your prescription. If you wear glasses, try focusing without them (or vice-versa). Contact lens wearers or those with astigmatism sometimes have difficulty getting a telescope to focus properly.

Telescope Care & Maintenance

Most modern telescopes require very little maintenance. Simple precautions are generally all that is needed to keep telescopes in good working order.

When not using a telescope, keep all openings covered with dust caps to prevent dust and debris from accumulating on the mirrors and/or lenses. A little bit of dust will not harm the image quality. Beginners are often surprised by just how much dust can accumulate on a telescope mirror before there is a noticeable drop in image quality.

If a mirror or lens becomes extremely dusty (so dusty you are having a hard time seeing your reflection), it probably needs to be cleaned. In this event, it is best to seek the assistance of a knowledgeable amateur astronomer or someone who has cleaned mirrors before. Because of the extremely delicate optical coatings on most mirrors and some lenses, cleaning them is a very delicate process that needs to be done properly. One scratch on the optical coating can do more harm than quite a bit of dust, so only clean mirrors when absolutely necessary!

Cleaning eyepieces is a simpler matter. Eyepieces generally do not have the delicate reflective coatings like telescope mirrors, so they can be cleaned in much the same way that you might clean eyeglasses or a camera lens. Dust can be removed using a soft brush or “lens-pen,” or blown off using a bulb blower. Grease or grime from people’s eyelashes will accumulate on eyepiece lenses over time, and can be cleaned off using lens-cleaning fluid and a soft wipe or cloth. Always moisten the wipe or cloth with fluid first; never pour fluid directly onto the eyepiece lens! It can leak around the edges of the lens and get trapped inside the eyepiece barrel.

The other common maintenance issue is **collimation**. Collimation refers to the proper alignment of the optical components in a reflecting or Schmidt-Cassegrain telescope. Frequent or rough transport can cause the mirrors to shift out of alignment, decreasing the sharpness of the image. Reflecting telescopes in particular need to be routinely collimated in order to get the best views. Schmidt-Cassegrain telescopes should rarely need to be collimated unless they are handled very poorly. Instructions for collimating a telescope can be found in telescope instruction manuals or online.

For More Information

- *The Backyard Astronomer’s Guide*, Third Edition, 2008, Terence Dickinson & Alan Dyer
- *Star Ware: The Amateur Astronomer's Guide to Choosing, Buying, and Using Telescopes and Accessories*, by Philip S. Harrington, Fourth Edition, 2007
- *Stellarium (*free open source planetarium software for your computer): http://www.stellarium.org/

CHAPTER 4.2: COMMUNICATING ASTRONOMY & THE IMPORTANCE OF DARK SKIES TO THE PUBLIC

Participants in the Master Astronomer Program learn about celestial motions using kinesthetic astronomy. (NPS/Leesa Ricci)

Chapter 4.2 Goals

After reading this chapter and participating in the corresponding workshop activities, you should be able to:

- Use your knowledge of astronomy to promote dark sky stewardship by facilitating meaningful connections between individuals and the night sky.
- Effectively address common misconceptions about astronomy, the night sky, and light pollution.

Why is Communication Important?

The movement to protect dark night skies and natural darkness is growing rapidly, both in the United States and abroad. Organizations such as the International Dark-Sky Association have more members than ever before. More than 100 parks and communities worldwide have been certified as International Dark Sky Places. Night sky programs are now commonplace at national parks and monuments. Research into the effects of artificial light at night has exploded in the past decade and become truly interdisciplinary. While light pollution was once a niche concern of astronomers, you can now find economists, architects, urban planners, physicists, ecologists and many others collaborating on research and potential solutions. Cities large and small are thinking more carefully about how they use artificial light at night.

These statements are true because of education. Only a few decades ago, mentioning the term "light pollution" in the company of anyone but astronomers would usually net a blank stare. This is no longer the case. Awareness of light pollution has skyrocketed and the education and public outreach efforts of the International Dark Sky Association, National Park Service, astronomy clubs, and many other groups are a major reason why. Becoming an effective astronomy and dark sky communicator is the most consequential thing you can do to promote the protection of dark night skies for future generations. That's what this chapter is all about.

Sharing the Joy of the Night

By the end of your Master Astronomer workshop, you'll have spent many hours learning about the night sky and light pollution. While the learning process is never over, you now have a solid foundation and likely know more about astronomy than 99.9% of your friends, family, and neighbors. Stored away in your brain, this knowledge serves only one individual: you!

The ultimate goal of the Master Astronomer Program is not simply to teach astronomy, but to enable and empower you to share your knowledge and passion for the night sky with others. We hope that you will help us spread the joy and inspiration of a naturally dark night sky. Why? Senegalese conservationist Baba Dioum famously said: "In the end, we will conserve only what we love, we will love only what we understand, and we will understand only what we are taught."

Our night sky is rapidly disappearing, completely unbeknownst to many of those around us. Dioum's remark illustrates how education is the first step toward combating the loss of the night. Our actions today will determine whether our children and grandchildren will still be able to see the Milky Way 50 years from now. To save the night sky, we must effectively communicate what the night sky and natural darkness have to offer our society, and what we lose when we lose the night. Only then will enough people act to preserve the night sky for future generations. As a Master Astronomer, your knowledge gives you the power to connect people to the night sky and promote stewardship of our dark night skies.

There are many different ways to educate the public about astronomy and the importance of dark night skies. For example, at Cedar Breaks National Monument, we:

- Host public **star parties** throughout the summer to promote enjoyment of our dark night skies and educate park visitors about dark-sky friendly lighting.
- Offer guided full moon hikes where visitors can explore the nighttime side of their national parks while learning about the importance of natural darkness for wildlife.
- Educate local communities about the importance of dark skies by visiting K-12 classrooms and science festivals, helping scout troops earn astronomy merit badges, offering Master Astronomer workshops, and giving public talks on astronomy and light pollution for local astronomy clubs, service groups, and libraries.

Connecting people to the night sky can even be as simple as pointing out constellations with a green laser pointer and telling star stories next time you go camping with friends or family. The opportunities for outreach and education are nearly endless.

Informal Education

As a Master Astronomer, your communication efforts will typically take the form of **informal education**: learning that occurs outside of a structured classroom. Informal education audiences will often have little prior knowledge of astronomy or dark skies, and informal education opportunities are generally very short. Rarely will you have the time to explain the details of stellar astrophysics or other complex topics. At most, you might have 30 minutes to an hour with an audience. More often, you'll have just seconds or minutes while showing off a view of Saturn or a galaxy at a star party. These two facts have important ramifications for how we present information to the public.

As an informal educator, your goal should *not* be to make someone an expert or share everything you know about galaxies, but rather to provide an engaging, enlightening, and inspiring experience. Good astronomy and dark sky outreach often has little to do with science or depth of content, and everything to do with presentation and style. In other words, *how* we communicate is just as crucial as *what* we communicate.

Remember that our ultimate goal is dark sky stewardship. Talking about astronomy can help us achieve that, but if our approach to education strictly involves bombarding people with cool space facts, we are unlikely to deepen anyone's appreciation for the night sky or spur them to help steward dark skies. Instead, our job is to help make the night sky come alive! Anyone can learn to point a telescope at Saturn. Turning this into a meaningful and relevant experience that gets someone to care about the night sky takes some extra thought and preparation. The purpose of this chapter is to help you take the first steps down that path.

Making the Sky Come Alive

To facilitate deeper connections with the night sky, we must do more than simply present information about astronomy. After all, most people don't encounter astronomy on a regular basis. Unless we can help someone draw connections between the night sky and their everyday lives, they won't care about helping protect it.

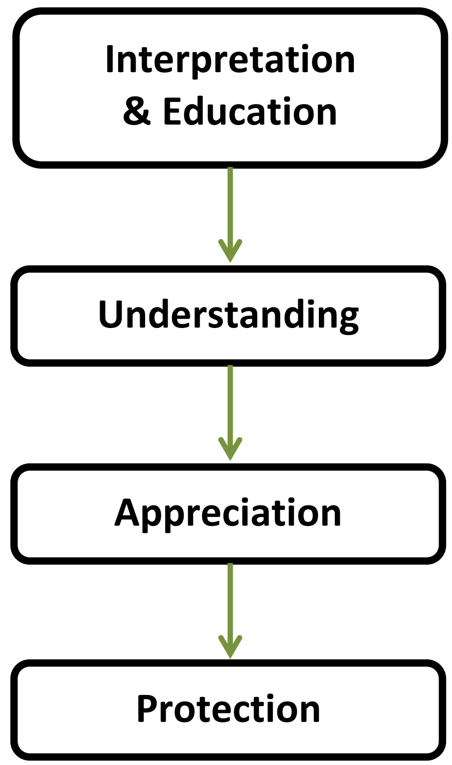


Figure 1-The path to protection of dark night skies begins with good interpretation! (NPS)

Forging emotional and intellectual connections between an audience and a resource (such as the night sky) is the goal of a distinct style of communication known as **interpretation**. Practiced by park rangers, museum educators, naturalists, zoo guides, and other informal educators, interpretation has a very distinct end goal compared to traditional education.

While an instructor or professor might teach to increase someone else's knowledge of a subject, an interpreter's ultimate goal is simply to reveal and inspire. In other words, an interpreter helps answer the question: "Why should I care?" As Master Astronomers, we want to answer the question: "Why should I care about the night sky?", so interpretation is a natural technique for us to use.

For an astronomy interpreter, content knowledge is secondary to helping people discover personal meaning and significance in astronomy and the night sky. Rather than drowning people in a deluge of information, an interpreter chooses facts selectively to create a story that appeals to the intellect and the emotions. An interpreter might not care if someone learns exactly how far away the Orion Nebula is, or the spectral type of the star Betelgeuse, but they do want to communicate the significance of these objects and why they are worth being able to see. Interpreters are ultimately storytellers; our job is to find and craft the most compelling stories the night sky has to tell and share them with others.

Fortunately, the sky does a lot of this work for us. People naturally gravitate towards the night sky and astronomy. We've never met anyone who didn't like looking at the stars and for many the night sky is inherently inspiring. This pull offers us a natural starting point we can use as a springboard to help connect people to the night sky. Let's now look at an example that illustrates the importance of good interpretation.

A Tale of Two Nebulae

Imagine you are attending a star party at Cedar Breaks on a clear, brisk, late-summer evening. The Milky Way stretches across the sky nearly from horizon to horizon, disappearing only where it meets the **skyglow** of St. George and Cedar City in the southwest. You walk up to the first telescope you see and look through the eyepiece. The operator, with nary a "Hello," begins to explain what they are looking at:

Astronomer #1: *"This is M57, a planetary nebula about 2,300 light-years away in Lyra. It is several light-years in diameter and expanding into space at more than 20 kilometers per second. The different ionized gasses in the nebula emit lots of different colors. Planetary nebulae form when small stars die and expel the outer layers of their atmosphere to reveal a white dwarf."*

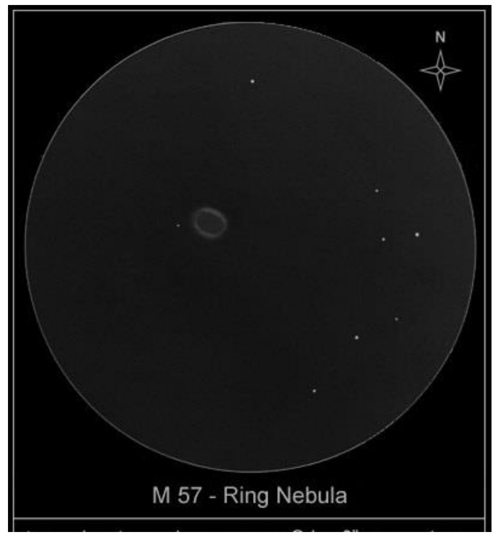


Figure 2-The Ring Nebula (M57), as seen through a backyard telescope. Views of faint fuzzies like this require good interpretation to be meaningful. (Michael Vlasov)

You thank them for their time and move on to the next telescope. Take a moment to think about this description from the perspective of someone who has never looked through a telescope before. What would you take away from it?

While Astronomer #1's description was technically accurate, it failed on several fronts. They neglected to explain what to look for in the eyepiece. The operator alluded to a colorful object, but all you saw was a fuzzy grey blob. Many of the terms they used—light-year, ionized, white dwarf, and nebula—are familiar friends to most amateur astronomers, but might as well be a foreign language to the general public. They failed to explain why the object is important or relevant. This person clearly knows their nebulae, but could they do better?

A few minutes later, you discover another telescope that appears to be aimed in the same direction. The operator is wearing a shirt that reads "Master Astronomer." They greet you with a friendly "Good evening!" and use their red flashlight to guide you to the eyepiece. Once your eye is at the telescope, they begin by explaining what to look for:

Astronomer #2: *"You're looking for a fuzzy smoke ring. Do you see it? It's sort of faint and gray. In fact I can't even see it from my backyard in town because of the light pollution, but it looks pretty good here under dark skies."*

Once they confirm that you're seeing the correct celestial cheerio, they proceed:

This object is called the Ring Nebula and it lets us look into the past and the future at the same time. This is what our Sun will look like in about four billion years. When Sun-like stars die, they eject the outer layers of their atmosphere into a bubble of gas like you see here.

The Ring Nebula is so far away that its light takes about 2,300 years to reach us here on Earth. We are seeing it not as it is today, but as it was just before construction began on the Great Wall of China. In fact, it is expanding so fast that it would probably look noticeably different if we could see it as it is today!

Once again, you thank the operator and step aside so the next person in line can have a look. You appreciate how Astronomer #2 began by helping you look through the telescope and confirming that you saw the object before telling you more about it. You note that Astronomer #2 used many of the same facts as Astronomer #1, but used them to tell a more cohesive story about the object. You learned why this fuzz ball is relevant: it reveals the ultimate fate of our own life-giving star, the Sun. Astronomer #2 also took care to avoid jargon. Instead of telling you the object is "2,300 light-years away," they provided context for this distance in more relatable terms. They avoided catalog numbers and the term "planetary nebula" entirely, yet you came away with a better understanding of what you were looking at. They even got in a brief light pollution message when they mentioned the Ring Nebula was invisible from their home in town.

Ultimately, Astronomer #2 attempted to *interpret* the Ring Nebula rather than simply rattle off facts. Did you leave knowing everything there is to know about the Ring Nebula? Certainly not, but remember that's not the point of interpretation. What are some things Astronomer #2 could do to make their interpretation of the Ring Nebula even more compelling?

Now imagine yourself in this situation. Pick an object, any object. You have one minute to show it to a visitor though your telescope. What would you say? How would you say it? How do you make the view meaningful? What is the most important thing they should know? Remember, many astronomical objects are fuzzy grey blobs, and, with a few notable exceptions such as Saturn and the Moon, telescope views need good interpretation to make the sky come alive.

Communication Tips & Techniques

In this section, we'll introduce some specific techniques and strategies that will help you better connect audiences to the night sky. Most of these techniques are universal; they can help you improve your astronomy communication whether you are spending 30 seconds interpreting the view through a telescope or presenting a 30 minute talk on light pollution at the local library.

Make it Tangible

A core concept in interpretation is the idea of *tangibles* and *intangibles*. A tangible is something people can see, hear, smell, or otherwise directly experience. In our case, the tangible will usually be the night sky or something in it, such as a planet, star cluster, or perhaps skyglow. By itself, a tangible is sterile. Only by connecting a tangible resource to some sort of *in*tangible meaning does it achieve relevance.

Intangibles are the meanings associated with tangible objects. For example, an intangible meaning associated with the Sun might be “life”; after all, we wouldn’t be here without it. In the case of the night sky, an intangible might be “survival”; humans throughout history have used the stars to navigate dangerous seas and many animals still depend on natural darkness to survive today.

Interpretation is most powerful when it links tangible things with intangible meanings. For example, black holes are interesting, but they are not very tangible. A star party visitor can’t see one or experience one like they can Jupiter or a meteor shower. The best interpreters try to avoid talking about things the audience can’t see or experience themselves. A view of a globular star cluster is more tangible, but without context or meaning, it’s pretty…boring! Combining tangibles and intangibles allows for the most meaningful interpretation of the night sky.

Make it Personal

The most powerful intangibles are known as **universal concepts**. Universal concepts are aspects of the human experience everyone can relate to, such as passion, confusion, anger, hope, and love, albeit in our own unique ways. Relating astronomy to universal concepts makes it personal and relatable.

Table 1: Examples of Universal Concepts:				
Anger	Dreams	Grief	Morals	Survival
Beauty	Emptiness	Growth	Nature	Trust
Birth	Eternity	Guilt	Pain	Violence
Change	Failure	Happiness Hate	Peace	War
Community	Faith	Health	Play Power	Work
Conflict	Family	Home	Progress	
Courage	Fate	Justice	Relationships	
Darkness	Fear	Life	Silence	
Death	Freedom	Light	Strength	
Desire	Friendship	Love	Struggle	
Destruction	Greed	Money	Success	

Sadly, we often shy away from these concepts when talking about space and science. Too often, astronomers (even amateurs) and scientists default to sterile facts instead of appealing to emotions, when it is emotions that prompt people to actually care about something like the night sky. The more we can relate astronomical topics back to people's lives, the more successful we will be in our attempt to steward dark night skies.

How do I collimate my alt/az Schmidt-Cassegrain?

It's actually not that difficult, but you wouldn't know it given all that jargon. Astronomy is rich in big words and as you become familiar with them, it is easy to forget how utterly foreign they sound to others. Most people you encounter doing astronomy outreach will not know the meaning of terms like "Schmidt-Cassegrain," "magnitude," or even "light-year." As a general rule, assume no prior knowledge unless someone has explicitly indicated they have it.

It can be tempting to assume that people will simply ask you to clarify any unfamiliar terminology. In reality, most people won't bother because they either don't want to interrupt or they don't want to sound uneducated. Even if they are inclined to ask for clarification, once someone has a question in their head, they stop paying full attention to you and start thinking about when they can ask their question. Consequently, the use of jargon does nothing but erect a barrier between you and your audience.

"Jargon" isn't limited to terms that people have never heard before: common words can be jargon as well. For example, almost everyone has heard the words "solar system," "galaxy," and "universe." However, a member of the general public may have a very different idea of what those words mean than an astronomer. If you discuss the "solar system" with a star party visitor, but they are operating with a different definition of the word than you, (perhaps they hold the common misconception that everything we see in the night sky is part of our Solar System), they are unlikely to understand you and even worse, you could be inadvertently sowing misconceptions.

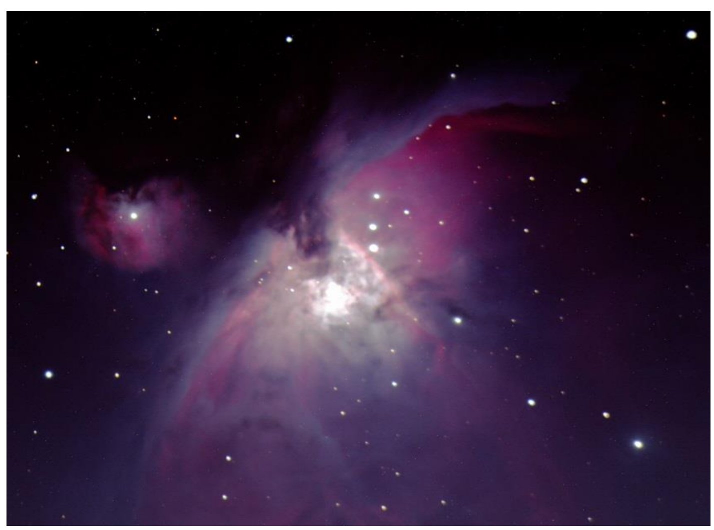


Figure 3-Imagine you are seeing the Orion Nebula for the first time. Which term, "emission nebula" or "stellar nursery" is more effective at communicating what this cloud actually is? (Zach Schierl)

Jargon has its place, and scientists use it for a reason, to avoid confusion. Sometimes we simply must use terms that most people are not familiar with. At a minimum, always take the time to clarify unfamiliar terminology. Better yet, consider not using it at all! When showing a group the Orion Nebula through a telescope, does using the term "**emission nebula**" enhance their connection to the night sky? Or would sticking with "stellar nursery" be more evocative and give them a better sense of what they are looking at?

To be clear: avoiding jargon isn't the same as "dumbing it down." It is simply about making astronomy accessible and speaking a language that will resonate with anyone, regardless of prior experience or knowledge. The Master Astronomer Program is based in community outreach, and unlike a traditional classroom we rarely have a captive audience. Something as simple as a talk loaded with unfamiliar terminology can be enough to drive people away.

Less is More

If you are as enthusiastic about astronomy as we are, it can be hard to stop once you start talking to someone about the night sky. Exercise caution though. Remember that the other person is probably not as fanatical about astronomy as you are…at least not yet!

Much like the careless use of jargon, inundating an audience with too much information, no matter how exquisitely it is presented, can be extremely alienating and cause people to tune-out. Sometimes referred to as the *firehose approach,* this should be avoided at all costs. Just because you know the name, distance, and spectral class of every star in the Big Dipper doesn't mean your audience cares. You might find such info interesting, but unless you can convince others that it matters, save these facts for when someone explicitly requests them.

Instead, try adopting the *iceberg approach.* Most of an iceberg's mass lies below water, and so should your astronomy knowledge. As a general guideline, aim to present the most significant and relevant 10% of what you know on a subject. Keep the other 90% in reserve. If your audience expresses an interest, reveal more information in small increments.

Get to Know Your Audience

People from diverse walks of life and backgrounds are drawn to astronomy and the night sky. This is a blessing but can also be a challenge because different audiences will respond to identical information in drastically different ways.

Knowledge of your audience is extremely valuable in interpretation, and every other form of astronomy education. Kids are going to respond to information differently than adults. A star party for an elementary school science night needs to be different from one attended primarily by tourists at a national park. A talk on light pollution for a city planning commission needs to be different than one for a local Rotary Club, which in turn needs to be very different than one for a group of tourists from Las Vegas or China who might never have even seen the Milky Way before. If you approach each potential audience the same way, you will miss a golden opportunity to engage in effective interpretation.

Before speaking to a group, take some time to think about your audience. What do you already know about them? What should you try to find out? What are they seeking? What are some characteristics of your audience that will affect the lens through which they view the information you give them? Tailoring your information to your audience can easily make the difference between a great talk and a flop. It can determine whether someone decides to attend the next star party, or stay home and watch TV next time.

Figure 4-People from all nationalities and backgrounds attend astronomy events in Utah. Being conscious of your audience and the assumptions you are making about them can help your outreach efforts resonate with the greatest number of people. (NPS/Zach Schierl)

Consider the astronomy interpretation offered in the national parks and monuments of Southern Utah. Many of the visitors to these parks are international tourists. Astronomy texts, like virtually all fields of study, are largely written by the people who are in power in a given geographic location. This is just human nature; people want to write about themselves. The problem is, when you're dealing with large groups of diverse people, you will lose people if you don't step outside the bubble. How much do you know or care about Gan De or Aryabhata or Valentina Tereshkova? Visitors from outside the U.S. probably care about Clyde Tombaugh, John Glenn, and Buzz Aldrin about as much. For the U.S. there is a particularly nationalistic streak in our astronomy history because of the Space Race. In many ways, we've tied American pride to our accomplishments in outer space. But you cannot sell an international audience on American exceptionalism. You can't. We've tried. It doesn't work. A program about the United States' accomplishments in outer space might very well fall flat in an audience filled with foreigners. Fortunately, astronomy has been practiced by virtually everyone at some point, so it's not hard to be inclusive, it just takes a little extra research.

Communicating Astronomy to Kids

Kids are naturally curious about most things, including space. Some adults find communicating with kids about astronomy to be challenging. Oftentimes, this is because they use more or less the same approach as they do with adults, and then become frustrated when it doesn't work. Others are guilty of the opposite and have a tendency to simply "dumb down" information presented to children. Instead, according to Freeman Tilden, a pioneering figure of interpretation, "Interpretation addressed to children should not be a dilution of the presentation to adults but should follow a fundamentally different approach."[1]

When working with an audience that contains children, it helps to keep in mind some of the ways in which kids are different than adults. In general, children have much shorter attention spans than adults and can get bored very quickly. Kids also have a very different frame of reference for interpreting astronomical information. "13.8 billion years" is a hard concept for *adults* to comprehend, much less kids. Adults at least have some context for understanding deep time. Children don't. "Million," "trillion," and "zillion" all pretty much mean the same thing. It's the same with distance. While adults might struggle to comprehend the meaning of a light-year, younger children face the same obstacle even when talking about yards or miles.

So how can we better engage children when doing astronomy outreach? Here are a few tried-and-true techniques (all of which apply to adults as well!):

- **Smile:** A positive attitude goes a long way with children. If you are surly, or dreading talking to kids, you're doomed before you even start. Instead, go out of your way to exhibit a warm, welcoming, and enthusiastic attitude.
- **Make them move:** Involve children in activities rather than just talking at them. Asking them to help demonstrate something, like distances in the Solar System, will go a long way toward holding their attention because they're moving around and active.
- **Engage their senses and intellect:** Children, especially younger children, learn primarily through sensory exploration. Activities that require kids to make observations using their sense of sight, smell, touch, or hearing are often very successful. Most kids are enthusiastic about sharing their experiences, so asking questions can be a great way to engage a group.
- **Engage their imagination and sense of wonder:** Focus on provoking a sense of wonder and exploration, as opposed to reciting complex facts. Say you're observing Titan, one of Saturn's moons. You could talk about its lakes of methane and how it is the only moon in our Solar System with a significant atmosphere, but kids probably won't be impressed. Instead, try getting them to imagine what being on Titan would be like: *"You'd weigh almost nothing and the air is so thick you could strap kite wings to your arms and fly!"*
- **Make connections to what they care about:** Connect astronomy to something kids have already seen. For example, in the movie *Moana*, Maui's Fishhook is the same constellation as Scorpius, which we can see in the summer. Disney didn't make the constellation up. In

Hawaiian astronomy, it really is Maui's Fishhook. Adults might not care about this, but most kids will connect because they've all seen *Moana*.

Remember that the goal of the Master Astronomer Program is to encourage stewardship of our night skies. Children are the next generation of night sky stewards so we have a responsibility to be prepared to educate both kids and adults. Plus, their parents will appreciate the effort.

Active Learning

Tell me, I forget. Show me, I remember. Involve me, I understand.

—Proverb

In 2009, a comprehensive study tracked more than 4,000 students taking introductory college astronomy courses at a variety of different institutions across the United States. The authors found that the most important variable predicting the amount of student learning was the *level of interactivity* employed by the instructor.[2]

Research shows that students fare better when educators use **active (or interactive) learning** strategies.[3] "Active learning" has been defined as "instructional activities involving students in doing things and thinking about what they are doing."[4] In contrast to "traditional" learning where students passively receive information from an expert, active learning can include problem solving, group discussions, role-playing activities, and peer teaching. In short, we learn best not by listening to lectures, watching videos, or reading textbooks, but by *doing things.*

Figure 5-Master Astronomer participants engage in an active learning activity about the Solar System. Few things help facilitate an understanding of the scale of our Solar System better than actually acting it out. (NPS/Shannon Eberhard)

While much of the research on active learning comes from the classroom environment, it is important to think about how we can make our astronomy and dark sky outreach more active. Simply taking a group outside to look at the stars isn't necessarily active learning. An outdoor talk to kick off a star party can be just as passive and ineffective as a classroom lecture if the audience isn't involved. The key to active learning is engaging your audience instead of only talking *at* them.

What does this look like in practice? Let's say you're giving a talk on a bright comet currently visible in the night sky. Instead of verbally describing what comets are made of, perhaps you help your audience make their own "comet" out of common household ingredients. Want to teach a group about the motions of the Sun, Moon, and planets? Have them act out these motions themselves instead of using a slide presentation or videos. Trying to get your city council to take action on light pollution? Offer to take them on a walking tour of downtown where you'll teach them how to identify dark-sky friendly lighting. Active learning can take many forms—all it takes is a little extra time and creativity on your part. Additional examples of active learning techniques can be found in the links at the end of this chapter.

The Importance of Experience

It is impossible to learn how to throw a pot, drive a car, or teach a class of kindergarteners simply by reading a book or listening to a podcast. Hands-on experience and practice is required to master these skills. Similarly, it is hard to learn about astronomy, the night sky, and light pollution without spending time outside experiencing these things for yourself.

"Experiential learning" is an especially powerful form of active learning in which an immersive experience and subsequent reflection forms the basis for learning about a particular topic. The "reflection" part is critical: a fun and exciting experience doesn't automatically result in learning. Experiential learning occurs only when immersive experiences are combined with opportunities for reflection, analysis, and synthesis.

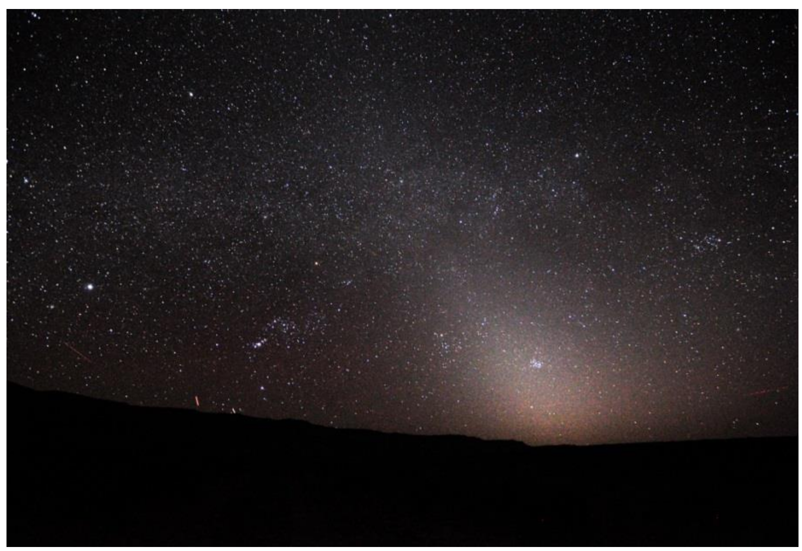


Figure 6-A truly dark night sky, with no skyglow and the zodiacal light towering above the horizon, is something that most people have never seen. Facilitating such an experience is a great way to connect people to the magic of the night sky. (Zach Schierl)

This is important to keep in mind when engaging in astronomy and dark sky outreach. Consider a standard "star party." For a star party to be effective at teaching participants about dark skies and promoting dark sky stewardship, the immersive experience (usually stargazing, telescope viewing, constellation tours, etc.) must be combined with opportunities for participants to reflect on what made their experience possible, and perhaps even what actions they might need to take to ensure that their children can still have the same experience decades from now.

This could be an interactive ranger talk on dark skies, a demonstration of dark-sky friendly lighting, or a night hike through the forest to learn about natural darkness. As educators and interpreters, our role is to make the experience transformative by helping participants make the intellectual connection between their experience and the importance of dark skies.

At a minimum, whenever possible we should try to share our dark sky message outside beneath the actual sky, as opposed to in a classroom, lecture hall, or even a planetarium. While this is not always feasible, especially for those of us who live in light polluted cities, the sight of a truly dark night sky often makes a more compelling case for taking action against light pollution than any argument that can be made indoors.

Take a moment to think about how active and experiential learning strategies have been used throughout the Master Astronomer Program. How have they affected your experience?

Asking Good Questions

Asking questions is a great way to facilitate a two-way dialogue between you and your audience. Well-crafted questions break down the traditional teacher/student dynamic and can help you better engage audiences of all ages and backgrounds.

Good questions for astronomy interpretation are inviting, open-ended, non-judgmental, and inclusive. Questions such as "What does this nebula look like to you?", "Do you think there is other life somewhere in the universe?", or "What is your favorite memory involving the night sky?" are queries *anyone* can answer regardless of their background because there is no "right answer." These are known as *dialogic questions* because they open up communication between you and your audience and help people feel more involved. Furthermore, responses will help you learn more about your audience, allowing you to more effectively help them make connections to the night sky.

Dialogic Question Checklist

• Is the question inviting? Does it allow people to respond with feelings or thoughts?	YES	NO
• Is the question open-ended? Does it require more than a "yes or no" answer?	YES	NO
• Is the question non-judgmental; that is, free of cultural, political, or ideological assumptions?	YES	NO
• Is the question inclusive? Could anyone, regardless of their astronomy knowledge, contribute an answer?	YES	NO
• Does the question lack a "right" answer?	YES	NO

Not all questions are good though: certain types put up barriers rather than take them down. Bad questions are those that make people feel like they are being quizzed. Most people don't attend star parties to feel like they're having their astronomy knowledge tested. Questions like "Does anyone know how many light-years away this nebula is?" are more likely to intimidate people and might make them feel dumb and unwelcome if they don't know the answer. Most astronomers don't even have such figures memorized and the majority of a typical star party audience may not even know what a light-year *is*. By asking content-specific questions, you are catering solely to the astronomy nerds in your audience and creating a crevasse of communication between you and everyone else.

Addressing Misconceptions

One of the most fundamental concepts in education is that individuals without formal training in a subject, astronomy for example, are not "empty vessels" or "blank slates" waiting to be filled with new information.[5] Teaching would be much easier if this was true, but *everyone* brings an existing belief system and model of how the world works to the table. All information that an educator provides will naturally be processed through that lens.

For many people, this existing belief system includes misconceptions about astronomy. For example, a biennial survey of scientific literacy conducted by the National Science Foundation *consistently* finds that 24-29% of Americans think the Sun goes around the Earth and that 42-45% are unaware of how long it takes the Earth to go around the Sun.[6]

Why are misconceptions important?

The prevalence of astronomy misconceptions poses a significant challenge for educators, whether in the classroom or at a star party. Research into how people learn shows that misconceptions are not easily replaced, even when accurate information is presented clearly by a skilled educator.[7] Instead, misconceptions often create an almost impenetrable barrier to learning unless they are explicitly addressed and corrected. In other words, an individual often has to *unlearn* an incorrect idea before they can learn something new.[8]

Therefore, effective educators must not simply present new information, but do so in a way that explicitly, yet kindly, addresses pre-existing inaccurate beliefs so they do not persist.[9,10] Obviously, this is easier said than done, especially in informal education. After all, how do we know if someone we're talking to at a star party holds a particular misconception?

In most cases, we don't. This is why we've included lists of common misconceptions at the end of each chapter in this handbook. The misconceptions listed are not the fallacies we've run into once or twice, but rather ones that we and other astronomy educators come across *regularly*. Many have been documented and explored more deeply in an enlightening book by University of Maine astronomer Neil Comins: *Heavenly Errors: Misconceptions about the Real Nature of the Universe.* Becoming familiar with the most prevalent misconceptions and addressing them proactively when talking about a particular subject will help you become a better educator.

Care must be taken when combating misconceptions. Many people are firmly attached to certain beliefs, even those that they have developed entirely unconsciously over time. An effective strategy can be to share a story about an astronomy misconception you once held. We *all* have had, and still have, misconceptions about how the world works. Authors of astronomy handbooks probably have just as many misconceptions about biology, law, cybersecurity, and other topics that are outside our area of expertise. Emphasize that holding a misconception is not a badge of shame, but rather an opportunity to learn something new.

Sources of Astronomy Misinformation & Misconceptions

Where do astronomy misconceptions come from? Compared to other sciences, such as chemistry, biology, or physics, relatively few people take an astronomy class in high school or college. As a result, most of what the public "knows" about astronomy has been absorbed not from science teachers, but from a variety of different sources, many of which vividly portray fallacies and misinformation about how the universe works.

In other cases, the fact that science is complex and often counterintuitive can lead to misconceptions. In many instances, our senses simply deceive us or we lack sufficient information to fully understand something. For example, most people would say that the Sun is a yellow star because it *appears* yellow to our eyes. This seems logical, but ignores the effect our atmosphere has on the color of the Sun. It also seems reasonable to assume that summer is warmer because we are closer to the Sun. Yet, as we learned in *Chapter 2.2*, the real cause of the seasons is more complex and involves factors that are difficult to discern from Earth.

Humans are also very good at finding patterns that don't actually exist. This is why so many people believe the Full Moon makes people crazy, even though controlled studies show no correlation between moon phases and modern human behavior. (Prior to the advent of electric lighting, the full moon probably did control human behavior to some extent, because its light permitted activity into the otherwise dark evening hours.[11])

Finally, an increasing number of astronomy misconceptions can be attributed to misinformation spread—both innocently and deliberately—via the internet, or through more traditional media channels such as TV and newspapers. We'll take a closer look at how to avoid falling prey to these misconceptions, and how to combat them if you meet someone who already has.

The Internet & Social Media

The internet has become the first place most of us turn for information about astronomy, and just about everything else. In many ways, the internet has revolutionized astronomy education; never before have so many people had such easy access to a plethora of great resources. Unfortunately, the Internet can also be a hive of scum and villainy – as well as astronomical misinformation.

Memes are a common source of astronomical nonsense because many social media sites give precedence to images over text. Perhaps you've seen a meme like the one in Figure 7. It's catchy and memorable, but also inaccurate.

Name a star — any star — and there's a good chance it's close to us astronomically speaking. Even "distant" stars like Deneb are only a few thousand light-years away, meaning their light takes no more than a few thousand years to reach Earth. If a naked eye star had been dead for a few million years, we wouldn't still be able to see it. This may be a witty meme, but it isn't grounded in reality and its prevalence has actually created a common misconception about how the universe works. Spreading misinformation just for laughs is bad astronomy.

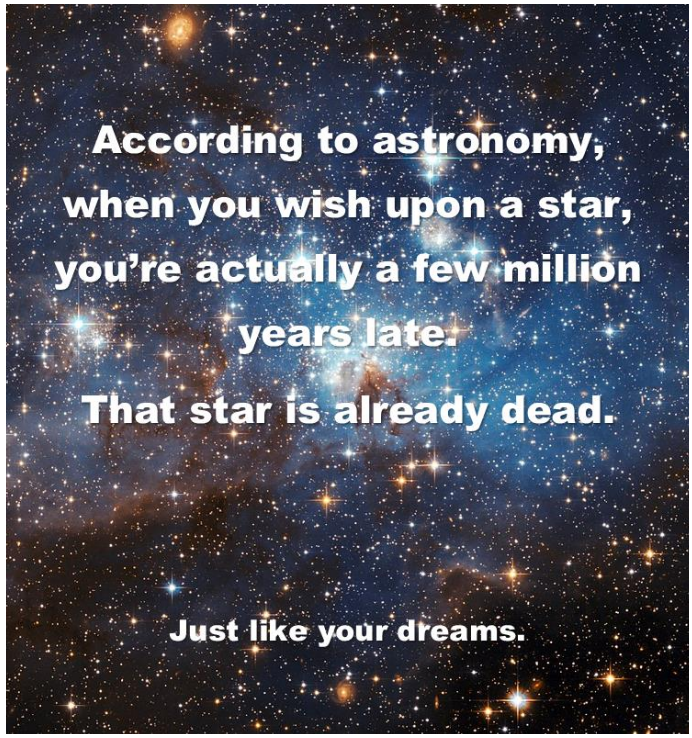


Figure 7-The underlying premise of this meme is true: when we see a star, we see it as it was in the past. However, most stars we see with the naked eye are less than 10,000 light-years away and stars change very little in such a short period of time. (NPS/Leesa Ricci)

While social media has opened up a Pandora's Box of misinformation, it can still be spread the old-fashioned way: via email. For example, the infamous "Mars Spectacular" email hoax, which claims that Mars will soon appear as large as the full moon, has been circulating for more than a decade. Every few years it resurfaces and, to make matters worse, is often picked up by careless media outlets. Although the planet Mars is physically larger than our Moon, it's almost a thousand times farther away and will never appear as large as the full moon, even when it is at **opposition**. If it ever does, we have a major problem on our hands!

While misinformation is dishearteningly common, it can give you an opportunity to engage people in critical thinking. When people mistakenly claim that all the stars we see are dead, you have a golden opportunity to talk about the concept of a light-year and stellar evolution. When people ask why Mars doesn't look as big as the full moon, you have a chance to impress upon them the true scale of the Solar System. Always be careful not to make people feel stupid, but try to engage people in a way that will make them more likely to ask "Is that true? How do we know?" in the future.

The internet is also home to lots of good information, so the challenge is to distinguish between memes and other internet phenomena that are bogus and the many that actually contain sound astronomy. As a general rule, be especially wary of anything on social media. Tweets and Facebook posts can be easily fabricated to appear as though from a legitimate source (Fig 8). So prevalent is online astronomy nonsense that several sites exist almost solely to debunk it, such as Phil Plait's Bad Astronomy (http://www.badastronomy.com/index.html) and a Twitter account devoted to exposing fake astrophotography (https://twitter.com/fakeastropix).

Instead, seek out or verify information directly from a primary source such as NASA, university astronomy departments and research centers, peer-reviewed science journals, or reputable science-journalism outlets. It may be easy to fake a tweet, but it's a lot harder to get a fake article posted on the NASA website. Links throughout this handbook will direct you to good starting points.

Figure 8-A tweet proclaiming to be from NASAs official Twitter account. Such tweets can be fabricated in a matter of seconds and easily used to spread astronomy misinformation far and wide. (Zach Schierl)

Misinformation from the Media

Another common source of astronomy misinformation is the media. In contrast to the blatant misinformation often found on social media and online, issues with astronomy stories in the news tend to be more subtle. Many otherwise reputable outlets tend to excessively hype mundane celestial events, or use unwarranted hyperbole in stories about new discoveries.

In recent years, the textbook example of media hype has been the spike in breathless articles about upcoming "supermoons." A term rarely used by astronomers, "supermoon" refers to a full moon that appears slightly larger and brighter than an average full moon. The Moon's orbit around the Earth is an ellipse, which means its distance from us is variable. When a full moon coincides with the Moon's closest approach to Earth, we get a supermoon. The difference is hardly "super" though: a supermoon is about 14% larger and 30% brighter than a full moon occurring when the Moon is furthest from us. The fact that this small difference is not easily noticed with the naked eye often goes unmentioned in these articles. On one hand, it's hard to complain when astronomy makes the news, but in this case, the hyperbole often sets people up with unrealistic expectations and ultimate disappointment with their experience.

News articles are often guilty of misinterpreting or exaggerating the results of scientific studies. Even reliable media sources, like the BBC or the New York Times, can—and often do—make mistakes when it comes to science journalism. If you see a discovery getting a lot of press, try to look up the primary source, such as the original paper that made the claim or a press release from NASA or the scientist's university. Good science journalism outlets will include a link to this information. If the article *doesn't* include the original source, you should be even more wary of the information and diligent in seeking it out. Oftentimes what you find there will be markedly different from the news article.

Misinformation from Television, Hollywood, and Science Fiction

Many television shows and movies involve elements of astronomy, especially those in the science fiction genre. While a lot of sci-fi is based in some amount of reality, it is called science *fiction* for a reason: inaccurate portrayals of how the universe works are commonplace. Kids in particular are susceptible to misconceptions from TV and movies, as they are often exposed to them at an early age before they are taught anything resembling astronomy in school. Furthermore, most of us suspend our critical thinking when watching movies or TV, meaning that we are more susceptible to absorbing inaccurate ideas while we are being entertained.

Amazingly, some of the most ubiquitous astronomy misconceptions can be traced back to a single movie or TV show. For example, the common (but inaccurate) belief that the asteroid belt is jam packed with flying boulders (and that the odds of successfully navigating one are 3,720 to 1) dates from 1980, when the *Star Wars* film *The Empire Strikes Back* was released.[12] Many other concepts, such as faster than light travel (FTL), wormholes, antimatter weapons or drives, and of course, those massive prima donnas of misinformation themselves, black holes, have all been portrayed inaccurately on screen enough times that there is now often a mainstream belief in highly unscientific scenarios.

Due to the popularity of sci-fi, this class of misconceptions can be an excellent opportunity to educate people if approached tactfully. Instead of saying "no, faster than light travel is just not possible," you can do a little bit of research and say "actually, physicists in the 1960s did propose faster than light particles called tachyons. They appear in Star Trek – which is kind of cool. But the tachyon hypothesis, though once a legitimate idea, has now been relegated to the world of sci-fi. There just hasn't been any evidence for their existence." Finding physicists and real theories to direct people towards can be very helpful. It takes people out of the realm of fiction, and directs them toward real people.

To be fair, sometimes people just want to talk about fiction. That's okay, but as a Master Astronomer, you have the responsibility to make a clear distinction between what is known and what is speculation.

Handling Difficult Questions and Situations

Most astronomy misinformation is harmless and straightforward to combat. If someone comes to a star party expecting to see Mars as big as the full moon, a quick look at tiny orange Mars through a telescope will likely be enough to convince them they were duped.

Spend enough time doing astronomy education though and you will inevitably encounter people with questions or comments that go beyond simple misinformation and down into the rabbit hole of pseudoscience and conspiracy theories. Naturally, these situations are more difficult to deal with and so they are worth taking a closer look at.

Before we dive in, remember that Master Astronomer is a science-based program**.** While we are not trying to force any particular belief on anyone, sticking to established science is your responsibility anytime you are officially representing the Master Astronomer Program.

I Don't Know!

The easiest "difficult" questions are those where you simply don't know the answer. Everyone gravitates towards different aspects of astronomy. Maybe you love the weird chemistry in the outer Solar System, planetary geology, the history of space exploration, or learning about the older instruments used by pre-telescopic astronomers. No one knows everything, and the public is great at coming up with strange or esoteric questions out of the blue. It is perfectly acceptable to say something like "I'm new, and really don't know much about that yet" or "I'm not that interested in aliens" when faced with a difficult question. Not knowing the answer doesn't make you a bad Master Astronomer, but trying to fake it when you don't know – that's bad astronomy. Never guess, avoid speculation, and be honest if a question is outside your knowledge base. "I don't know" is *always* an acceptable answer. Never be afraid to say it.

If you can't answer a legitimate question, try to direct them to someone who might in order to acknowledge and stimulate their interest. Or perhaps you know of a website or book that could help them. When stumped, the best educators try to set the questioner on a path to resolving their question.

Another tricky situation is when you *do* know the answer to a question but don't have time to explain. Perhaps you have a line of 50 people waiting to look through your telescope. You don't want to sacrifice their experience for the benefit of one person with a time-consuming question. Although questions are a welcome sign that you are engaging your audience, you have to be careful to not let them get in the way of what you planned in the first place. For example, if you are giving a talk titled *A History of Deep Time* and you get to a point where you're just answering questions about life on Mars, that's not fair to the rest of your audience who came to learn about deep time.

Things Astronomers Don't Know… Yet

More challenging are questions that deal with things astronomers don't know, can't know, or questions that don't make sense scientifically. The study of **dark matter**, **dark energy**, antimatter, gamma rays, and subatomic physics are all relatively new. Every step we take is a step forward, but sometimes we are still millions of steps away from truly understanding something. It can be hard for people to accept that basic questions like "What is dark matter?" don't have good, conclusive answers yet. While astronomers and physicists certainly have ideas, it is important to delineate what is merely an idea (a hypothesis) from what is commonly accepted science (a theory).

Other questions are not only currently unanswerable, they may *never* be answerable. Hearing "we may never know" can be even more unsavory, but it is still important for us as educators to resist the temptation to dive into pure speculation. Questions such as "What came before the Big Bang?" or "What's inside a black hole?" are intriguing, but practically devoid of science-based inquiry. By their very nature, we just don't have the ability to test them.

The Outskirts of Science

The most challenging and potentially contentious questions are those that deal with pseudoscience or that are outside the realm of astronomy or science entirely. Often, a personal worldview or belief system lives behind these questions, which can make them especially delicate or uncomfortable to discuss. Some common examples include questions about:

- Astrology & Horoscopes
- Aliens & UFOs
- Apollo Moon landing conspiracies
- Apocalyptic/end-of-the-world scenarios
- Young-Earth Creationism

We all have our own views about the universe, what's in it, and how it was created or formed. We are not here to force a worldview on anyone. Doing so would be disrespectful to our audience and runs counter to our mission. However, our job *is* to promote dark sky stewardship by communicating the best currently available science about astronomy and the night sky. If someone's worldview conflicts with that science, it is not your job to change their mind. If they chose to disagree with you, that is their prerogative and right.

The topics listed above are all related to astronomy in some way, yet outside the realm of science. It is important to remember that the public doesn't always realize this. For example, there are many people who genuinely believe that astronomers develop the horoscopes they see in the paper and will ask questions to that effect at a star party. They're not necessarily trying to start an argument about astrology, they just don't understand the difference between astrology and astronomy. In this sort of situation, you have an opportunity to talk to people about what science is, how the two disciplines were indeed intertwined centuries ago, and the difference between astronomy and astrology today.

Unfortunately, in other cases, questions involving these topics aren't really "questions" at all, but rather statements meant to agitate or provoke. How you respond to such a scenario will depend on your experience, personality, and confidence handling uncomfortable situations.

It is crucial to be able to size up the person and determine what they are seeking; are they curious or confrontational? Perhaps they genuinely seek your expertise and want to have a discussion. Others have no interest in a productive dialogue. They may just be looking for you to legitimize their ideas or might want to cause a scene. In the latter case, it is best to avoid direct confrontation. Try to find a point of common ground and make the best of it. For example, regardless of how someone believes the universe was created, most people would agree that a dark night sky is incredibly beautiful, which is the ultimate message we are trying to communicate through our education in the first place.

If you determine that someone is not interested in a serious scientific conversation, keep in mind the following rules:

#1: Prioritize Your Safety

We have an advantage in astronomy. Unlike other subjects such as medicine or public policy, misconceptions and fringe theories in our field are unlikely to hurt anyone. Believing that stars have physical control over people's lives, that aliens are routinely visiting us, or even that the world is flat, is unlikely to result in immediate harm. While there are exceptions, in general, false ideas concerning astronomy are not on the same level as false ideas concerning medicine, vaccines, or climate change.

As such, if someone is becoming belligerent, getting angry, or if you have reason to believe they may become dangerous, let it go. Never argue with such a person or put yourself in harm's way. Always prioritize your own personal safety.

#2: Seize control… nicely

If you determine that a question is meant to agitate or provoke, but are not concerned for your safety, you must act quickly to seize control of the situation. The key is to remain calm and pleasant. This person probably knows that you don't agree with them, and may just be trying to get a rise out of you. Don't indulge them. Never argue with someone who has deeply held beliefs. You're unlikely to change their mind even if you're the best educator in the world.

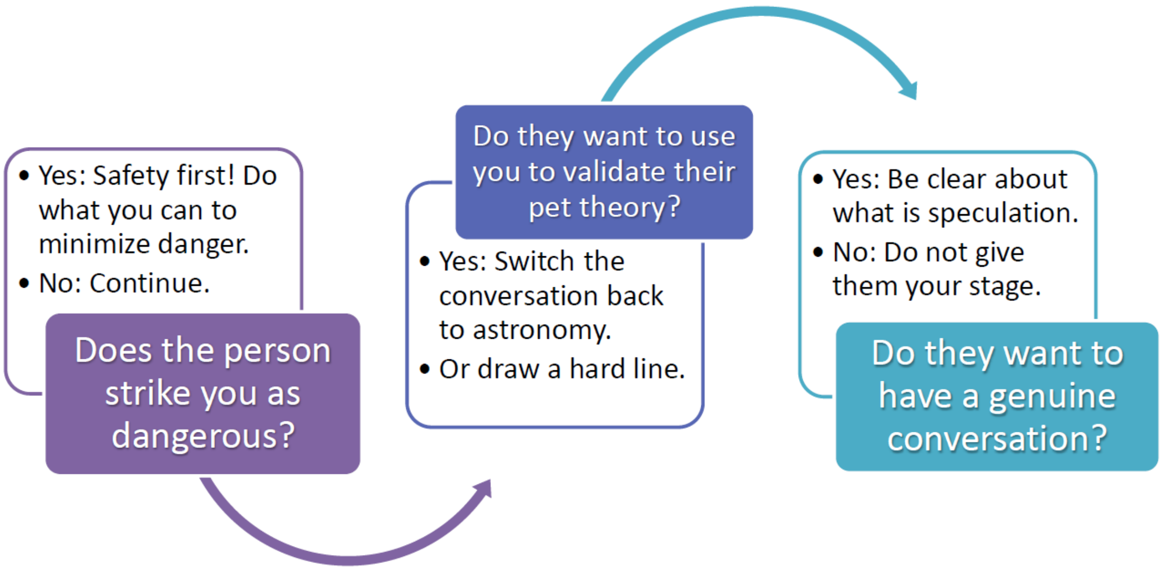


Figure 9-A pictorial guide to handling difficult questions or situations. (NPS/Leesa Ricci)

#3: Get back on topic

When talking to a group, changing the conversation and getting back on topic is often the best way out of a difficult situation. For example, if someone says "I heard there is a comet that's going to hit us in 2031 and it was foretold by [insert old book here]," you can say: "You know, I haven't heard that, but has anyone ever seen a comet?" If someone in the audience has, ask them about it. Ask them if they took pictures, talk about what it looked like, etc. If you're looking at Saturn and someone asks a completely unrelated question, steer the conversation back to Saturn: "We're looking at Saturn right now. Let me get back to the telescope and perhaps we can talk more about your question later."

It's important to remember there's a variable here you can't control: the other person. Being good at conflict resolution doesn't mean you will always succeed. You can't force someone to stop talking about deadly comets or UFOs, and you can't predict exactly how someone will react. Changing the topic tends to work better in larger groups. Someone is less likely to insist on talking about their topic if there are a lot of other people around who want to listen to what else you have to say.

#4: Avoid Needless Speculation

If you determine that a difficult question is the result of genuine curiosity, you may want to discuss the topic further. In this event, it is important to remember that, as a Master Astronomer, your job to represent the Program professionally and factually. Sometimes people just want to shoot the breeze, and if you start to find yourself in the realm of pure speculation or pseudoscience, try to steer the conversation back to facts as best you can (See Rule #3). If all else fails, you can also take a hard line approach using one the following:

- "There is no evidence for that."
- "That is not accurate."
- "That is not within the field of astronomy."

Talking about Light Pollution

Astronomy and night sky education can be an effective tool for promoting dark sky stewardship. We hope the techniques discussed in this chapter will help you become a more effective and engaging astronomy communicator. Often times though, protecting dark night skies requires a more direct approach. Talking to the public about light pollution and dark-sky friendly lighting can seem more intimidating than talking about astronomy, but it doesn't have to be. When having direct conversations with the public about light pollution, here are some additional communication tips to keep in mind:

We are all affected by light pollution: Light trespass might be making it more difficult for your neighbor to get a good night's sleep or use the new telescope they just bought. Glare from a new, poorly shielded streetlight might be affecting motorists on your street. A local business might be interested in hearing how they could lower their electricity bill by using dark-sky friendly lighting. The bottom line is that light pollution isn't just an issue for astronomers, so don't present it as such. When people are exposed to the wide-ranging benefits of using light more wisely, it tends to be a relatively non-controversial topic.

Keep your message positive: It can be easy to get bogged down in a "woe is me" rut when talking about light pollution. Instead, summarize the negative effects that are most relevant to your specific audience quickly and succinctly, and then move on to a positive message. Focus on identifying simple, low-cost solutions that benefit everyone, emphasizing that light pollution is one of the easiest environmental problems to fix.

Be aware of, and combat, common misconceptions: Three of the most common light pollution myths are:

- Light pollution is just astronomers whining; it doesn't affect the rest of us
- Reducing light pollution means sacrificing safety
- Reducing light pollution is expensive

Addressing and debunking these myths in a non-confrontational manner is crucial to being able to inspire an audience to take action. Try making the following points part of your message:

- Light pollution affects all of us (see *Chapter 3.2*)
- Outdoor lighting can be night-sky friendly and enhance safety (see *Chapter 3.4*)
- Night-sky friendly lighting saves money over the long run by reducing wasted light (see *Chapter 3.4*)

Accept that you cannot and will not change everyone's mind: Regardless of how much research you do and your skill as an educator, there will always be people opposed to any change, no matter how small or smart it might be. Try not to let this bother you. Change can be slow and the path littered with obstacles and delays.

Build Community Pride in Dark Skies: The communities most successful at combating light pollution are those with a collective pride in their dark skies. While a few dedicated individuals can often enact positive change in the short-term, maintaining dark skies over the long-term requires broad based support from many segments of the community. Emphasizing how dark skies benefit the community as a whole will go a long way toward stewarding dark skies in your area.

Promoting Dark Sky Stewardship

Depending on where you live, there may already be organizations in your area working to protect dark skies. Many regions have local chapters of the International Dark Sky Association that are active on dark sky issues. Many astronomy clubs are passionate about preserving dark skies, as are many national and state parks. A great way to get started is to check with these groups in your area and see if you can use your Master Astronomer knowledge to help them.

Table 2: Ideas for spreading the dark sky message

Who?	What?
• Homeowners associations (HOAs) • Wildlife or conservation groups • Civic groups (Rotary, Elks Club, etc.) • Utility companies • City Council or County Commission • Chamber of Commerce • City Planning/Zoning Commission • City Engineers • Schools & Universities (both K-12 & higher education) • Science Centers & Museums • Astronomy Clubs/Societies • Public Libraries • Local businesses (such as hardware stores that sell lighting) • Outdoor guide companies & outfitters	• Star parties • Sidewalk astronomy • Constellation tours • Night sky photography workshops • Astronomy movie night • Astronomy talks and workshops • Booths or demonstration tables at science fairs or STEM festivals • Classroom visits • Astronomy themed-tours • Dark sky lighting workshops • Regular column in a newspaper or a radio station segment • Meteor observing • Night hikes • Astronomy-themed art events • Nocturnal wildlife watching • Posts on a blog or social media network.

Striking out on your Own

If you can't find an existing group dedicated to dark sky stewardship, you could always start your own! A good way to begin is by organizing a star party or other astronomy-themed event in your community. If you don't have access to a telescope, even a simple constellation tour can open eyes to the wonders of the night sky. Enlist the help of other Master Astronomers, a local astronomy club, or do it yourself if you're feeling brave. Schools, libraries, and scout groups are examples of places or groups that are often eager to have astronomically-inclined folks speak or bring a telescope.

Working with public officials

In order to change how lighting is used in your community, at some point you may have to work directly with public officials. A great first step is to explore the "Dark Sky Assessment Guide" created by the Utah Office of Community Development (https://www.darksky.org/wp-content/uploads/bsk-pdf-manager/2019/01/Dark-Sky-Assessment-Guide-Update-12_20_18.pdf). This guide helps you assess the current state of lighting in your community, and identify possible areas for improvement.

Examples of dark-sky lighting ordinances are available from the International Dark Sky Association and other dark sky groups. Many dark-sky lighting codes are the result of passionate citizens who want to see the night sky protected in their communities. Regularly reviewing city council or planning commission minutes and agendas can help you find out if your city has any plans to change or retrofit lighting in the near future. If so, this can be a good time to talk to them about dark-sky friendly lighting. Arming yourself with knowledge from the Dark Sky Assessment Guide and then attending a community meeting is a good way to get dark skies on the radar of decision makers in your area. Better yet, go with a group. Such meetings are often poorly attended so even a half dozen people showing up in support of protecting dark skies can make a big impression.

Another group to reach out to is city engineers. Engineers are often the ones who make decisions on what kind of streetlights to purchase and what kind of fixtures to use. Having a city engineer that is well versed in the principles of dark-sky friendly lighting is a major asset when it comes to improving lighting in your community.

For More Information

Interpretation

- *Environmental Interpretation*, by Sam H. Ham, 1992
- Free online classes in interpretation from the Eppley Institute: http://provalenslearning.com/courses?course_topic=47
- *Interpretation for the 21st Century*, by Larry Beck & Ted Cable, 2002

- *Interpretation: Making a Difference on Purpose,* by Sam H. Ham, 2013
- *Interpreting Our Heritage,* by Freeman Tilden, *4th edition*, 2008
- National Association for Interpretation: http://www.interpnet.com/

Astronomy Education, Outreach, and Interpretation

- "Interactive Teaching Techniques": http://www.fctl.ucf.edu/TeachingAndLearningResources/CourseDesign/Assessment/content/101_Tips.pdf
- Peer-Reviewed Astronomy Education Activities (International Astronomical Union): http://astroedu.iau.org/en/
- *Communicating Astronomy With the Public* (peer-reviewed journal from the International Astronomical Union): http://www.capjournal.org/
- European Space Agency Education Site: http://www.esa.int/Education
- Las Cumbres Observatory Education Portal: https://lco.global/education/
- NASA Education Site: https://www.nasa.gov/stem
- NASA Night Sky Network Outreach Resources: https://nightsky.jpl.nasa.gov/download-search.cfm
- National Park Service *Junior Ranger Night Explorers* Program: https://www.nps.gov/subjects/nightskies/juniorrangernight.htm

Astronomy Misconceptions

- *Bad Astronomy: Misconceptions and Misuses Revealed, from Astrology to the Moon Landing "Hoax"*, by Phil Plait, 2002
- "Handling Difficult Questions (and Difficult People)" (Astronomical Society of the Pacific): https://astrosociety.org/SharingTheUniverse/questions.html
- *Heavenly Errors: Misconceptions About the Real Nature of the Universe*, by Neil F. Comins, 2001

Dark Sky Stewardship

- "Dark Sky Assessment Guide" (Utah Community Development Office): https://www.darksky.org/wp-content/uploads/bsk-pdf-manager/2019/01/Dark-Sky-Assessment-Guide-Update-12_20_18.pdf
- "How to Start a Local Dark Sky Group" (International Dark Sky Association): http://darksky.org/how-to-start-a-local-dark-skies-group/
- Local Chapters of the International Dark Sky Association: http://darksky.org/about/chapters/

Appendix A: Glossary of Terms

A

absorption line: wavelengths of light missing from a **continuous spectrum** due to their absorption by certain atoms and/or molecules.

accretion: the clumping together of small dust grains to form larger bodies

accretion disk: a disk of material rotating around a massive body such as a star.

adaptive optics: a technology that allows telescopes to correct for the distortion of starlight caused by turbulence in the Earth's atmosphere.

airglow: naturally occurring light emitted by gases (predominantly oxygen) in Earth's upper atmosphere as a result of being excited by **ultraviolet** radiation from the Sun during daytime hours. Not usually obvious to the naked eye, but a major contributor to the natural brightness of the night sky.

altazimuth (alt/az) mount: a simple type of telescope mount where the telescope can be moved in either altitude (up/down), or azimuth (left/right).

altitude: the height of a celestial object above the horizon in **degrees.** The **zenith** is 90° above the horizon.

annual motions: changes in the sky due to Earth's orbit around the Sun. For example, the movement of the Sun through the **zodiac** constellations.

aperture: the diameter of a telescope's primary mirror or lens. Aperture determines the light gathering capability of a telescope.

aphelion: the point in the orbit of a planet (or other object, such as asteroid or comet) where it is furthest from its parent star. For Earth, aphelion occurs in July. Compare to: **perihelion.**

apparent magnitude (or magnitude): the perceived brightness of an astronomical object as seen from Earth in visible light. Lower and negative numbers indicate brighter objects.

archaeoastronomy: a combination of archeology and astronomy; the study of the astronomical knowledge of ancient or prehistoric cultures.

arcminute (or **minute of arc):** angular measurement equal to 1/60th of 1 degree, or 60 arcseconds. With the sky divided up into 360 degrees, 1 arcminute is also equal to 1/21,600th of the sky.

arcsecond (or **second of arc):** angular measurement equal to 1/60th of an arcminute. If we take the whole sky and divide it up into 360 degrees, 1/60th of 1 degree is an arcminute, and 1/60th of an arcminute is an arcsecond. An arcsecond is thus 1/3600th of 1 degree, or 1/1,296,000th of the whole sky.

artificial light at night (ALAN): visible light emitted or reflected at night by a man-made source.

artificial satellite: an artificial object or spacecraft placed into orbit around a solar system body, such as the Earth or Mars. Examples include the International Space Station, Hubble Space Telescope, and Mars Reconnaissance Orbiter.

asterism: a well-known pattern of stars that are not officially a **constellation** (such as the Big Dipper (part of Ursa Major) or the Teapot (part of Sagittarius)).

asteroid: a relatively small, predominantly rocky body orbiting around the Sun.

asteroid belt: region of the Solar System between Mars and Jupiter, home to the vast majority of asteroids in our Solar System.

astronomical unit (AU): the average distance between the Earth and the Sun. In concrete terms, 1 AU equals 150 million km (93 million mi).

astro-tourism: visiting places with a pristine or near-pristine view of the night sky in order to observe celestial phenomenon or astronomical objects.

AU: see **astronomical unit**

aurora borealis/australis (northern/southern lights): phenomenon observed when charged particles from the Sun interact with our **magnetic field**, causing atmospheric gases to glow. Most commonly seen in a belt surrounding the north and south magnetic poles, but can be seen at lower latitudes during periods of intense solar activity.

average all-sky luminance: an average of many **sky luminance** measurements taken across the entire sky. More indicative of night sky quality than **zenith sky luminance** because it encapsulates light domes along the horizon.

averted vision: a technique for viewing faint celestial objects in which the observer looks slighting off to the side of the target objects, allowing the light to strike the edge of the retina, where light sensitive **rods** are more numerous.

axial tilt: the tilt of a planet’s rotational axis relative to the plane of the Solar System. Earth’s is 23.5 degrees.

azimuth: the compass direction of a celestial object in the night sky measured in **degrees**. North is 0/360°, east is 90°, south is 180° and west is 270°

B

Bayer System: a system for naming stars that assigns a letter of the Greek alphabet to each star in a given constellation. The brightest star is “Alpha” (with some exceptions), the 2nd brightest is “Beta,” etc.

Big Bang: the origin of our universe, the Big Bang is what we call the hot, dense, and extremely energetic point from which the universe came. It is the currently accepted theory on the origins of the universe.

binary star: two stars in orbit around a common center of mass.

black hole: a region of spacetime where an object has collapsed to the point where the escape velocity from its surface is greater than the speed of light. A black hole contains a "singularity" or extreme mass which causes its immense gravity, and is surrounded by an event horizon, a region of space around the singularity from which nothing can escape.

bolide: a large, bright meteor that explodes in Earth's atmosphere. Often used interchangeably with **fireball.**

Bortle Dark Sky Scale/Bortle Class: a nine-class scale devised by astronomer John Bortle for characterizing the quality of the night sky using a series of naked eye observations. A pristine dark sky is Bortle Scale 1, while an inner-city sky is Bortle Class 9.

C

cardinal point: north, east, south, and west.

catadioptric: a type of telescope that uses a combination of both lenses and mirrors. Examples include **Schmidt-Cassegrain** and **Maksutov-Cassegrain**.

CCD (charge-coupled device) Camera: a type of electronic detector used to take digital images of astronomical objects. CCD cameras have essentially replaced film to due to their greatly increased sensitivity to faint light.

Cepheid variable: a type of pulsating **variable star** that can be used to determine the distance to other galaxies.

CFL: see **compact fluorescent**

chondrite: a class of primitive **meteorite** that provides a good method to date the formation of the Solar System.

chromatic aberration: a phenomenon that occurs in **refracting telescopes** because lenses focus different colors of light at difference distances. It causes fringes of color to appear around bright objects such as the Moon.

circadian rhythm: the 24-hour cycle that governs physiological and biological processes in living things.

circumpolar stars/constellations: stars and constellations that lie near the **north or south celestial pole** and do not appear to rise and set from high northern or southern latitudes, but rather remain visible throughout the night.

collimation: the alignment of optical elements within a telescope for optimal viewing.

color temperature (or Correlated Color Temperature CCT): an indicator of the hue and overall appearance of light emitted by a light bulb.

comet: a relatively small rocky, dusty, and icy object in orbit around the Sun.

compact fluorescent (CFL): a type of light bulb that produces light via the excitation of mercury atoms, which then emit **ultraviolet light** that causes a fluorescent powder inside the bulb to glow in visible light. CFLs are much more energy efficient that **incandescent** or **halogen** bulbs.

continuous spectrum: a spectrum of light without **absorption lines** or **emission lines**, such as that emitted by an incandescent light bulb.

cool light: light rich in blue wavelengths that cause more **skyglow** and impacts to wildlife and humans.

cones: one of two types of photoreceptors in the human eye (along with rods). Cones are sensitive to color but do not function well in low light conditions. They are responsible for **photopic** (or "daytime") vision. Compare to: **rods.**

constellation: 1. Historically, a pattern of stars in the night sky. 2. In modern astronomy, a region of the sky delineated by well-defined boundaries, akin to country borders on a world map. 88 official constellations encompass every part of the sky.

coronal mass ejection (CME): A burst of charged particles from the Sun's atmosphere that travels outward into the Solar System. CMEs can trigger **auroral** displays and blackouts if directed at Earth.

cosmic microwave background (CMB): the leftover radiation from the **Big Bang** that permeates the entire universe, detectable using **radio** telescopes.

D

dark adaptation: the process of allowing the **rods** in our eyes to achieve maximum sensitivity. This process takes 20-30 minutes on average and is reset by even very brief exposure to bright light.

dark energy: a poorly understood form of energy responsible for accelerating the expansion of the universe.

dark matter: matter whose existence can be inferred due to its gravitational influence on other objects, but that not does emit any **electromagnetic radiation** (that we have detected so far). Dark matter dominates the total mass of the universe.

dark nebula: a dense cloud of non-luminous dust and gas, visible only because it obscures the light from more distant stars.

dark-sky friendly lighting: outdoor lighting that follows a set of six principles that collectively minimize impacts to the night sky and the nighttime environment.

deep-sky (or deep-space) object (DSO): astronomical objects other than the stars and Solar System bodies. Examples include **nebulae**, **star clusters**, and **galaxies**.

degree: an unit of measurement equal to 1/360th of a circle. That is, if we take any circle and divide it into 360 equal parts, one of those parts is a degree. A degree can be further subdivided into **arcminutes** and **arcseconds**.

diurnal motion: the rising and setting of celestial objects due to Earth's rotation.

dobsonian: a modified version of an Alt/Az mount where the telescope optical tube sits on a wooden box-like mount. The cheapest and simplest type of telescope mount.

double star: two stars that appear very close to each other in the sky. Double stars can either be **binary stars**, or **optical doubles** in which the proximity of the stars is an illusion.

dwarf galaxy: relatively small galaxies that contain less than ~10 billion stars.

dwarf planet: an object that orbits the Sun and is large enough to be spherical, but that has not cleared its orbital neighborhood of other small Solar System objects. Examples include Ceres, Pluto, and Eris.

dwarf star: a relatively small, low **luminosity** star. Most stars are dwarfs, including our Sun.

E

east: the direction of the sunrise, and goes back at least as far as the Greek e*os/heos* meaning "dawn."

eccentricity: a measure of how circular or elliptical a planet's **orbit** is, where 0 is a perfect circle and 1 is a parabola. Mercury has the highest orbital eccentricity of any planet, at 0.2. Earth has an orbital eccentricity of 0.016.

eclipse: see **solar eclipse** or **lunar eclipse**.

ecliptic: the apparent annual path of the Sun in the sky. The ecliptic represents the plane of the Earth's orbit around the Sun.

ecosystem services: beneficial services that humans receive from ecosystems, such as nutrient recycling, water purification, and pollination provided by various species, many of which are adversely affected by excessive artificial light at night.

electromagnetic radiation/spectrum: another name for **light** of all types. The electromagnetic spectrum encompasses all the different types of light from **radio waves** to **gamma rays**.

elliptical galaxy: galaxies that appear round in shape (as opposed to the disk-like shape of **spiral galaxies**) and that contain old stars, few or no star forming regions, and little gas or dust.

emission lines: discrete bands of color in a **spectrum**, formed when hot gas emits light only at very specific wavelengths, as opposed to a **continuous spectrum**. See also: **absorption line**.

emission nebula: a cloud of hydrogen gas ionized by **ultraviolet light** from nearby stars, causing it to glow in **visible light**.

equatorial mount: a type of telescope mount where one axis is aligned with the **north celestial pole**. Equatorial mounts allow tracking of celestial objects and astrophotography.

equinox: the times when neither of Earth's hemispheres are tilted towards the Sun and day and night are of approximately equal length.

extrasolar planet: an extrasolar planet is a **planet** that goes around a star other than our Sun. The closest extrasolar planet is around our nearest stellar neighbor: Proxima Centauri. Also known as an **exoplanet.**

eyepiece: a magnifying lens inserted into a telescope focuser used to view the image produced by a telescope. Eyepieces determine the **magnification** and **field of view** of a telescope.

eye relief: the distance that an observer's eye must be from a telescope **eyepiece** to see the full **field of view.**

F

false-color: a type of astronomical image where the colors do not represent what the human eye would see in **visible light**. Usually, the colors in a false-color image represent varying intensities of some other wavelength of light, like **x-rays** or **infrared**.

field of view (FOV): the portion of the sky that can be seen at one time through a telescope or pair of binoculars.

finder telescope (or **finder scope):** a small telescope attached to larger one, often with a larger **field of view**, used to aim a telescope at a desired object.

fireball: A abnormally bright **meteor**, often one that disintegrates or explodes during passage through Earth's atmosphere. Often used interchangeably with **bolide**.

focal length: in a telescope, the distance that light must travel from the **objective** mirror or lens to the focal point or **eyepiece**. In an eyepiece, an indication of the relative **magnification** that eyepiece will produce.

fully shielded: an outdoor light fixture that emits no light above the horizontal. In other words, a fixture that directs all of its light downward onto the ground.

G

galactic disk: the flattened component of a **spiral galaxy** (such as the **Milky Way**) that contains most of the stars, gas, and dust within the galaxy.

galactic halo: the spherical region surrounding the nucleus of a **galaxy**. Home to **globular clusters**.

galactic light: light from the Milky Way Galaxy, its stars, gas, and dust, in our night sky.

galaxy: a large collection of stars bound together by gravity. Galaxies are larger than **globular clusters**.

galaxy cluster/supercluster: a grouping of several dozen or more galaxies, which are in turn arranged into groupings of galaxy clusters known as **superclusters**.

Galilean moons: The four largest satellites (moons) of Jupiter: Io, Europa, Ganymede, and Callisto.

gamma rays: the shortest wavelength, highest energy form of light. Emitted only by very energetic objects in space. Very dangerous.

gas giant: a large gaseous planet, with gas clouds of (usually) molecular hydrogen. It is not a place you could stand on, or land on. Jupiter and Saturn are gas giants. Compare to: **terrestrial planet** and **ice giant**.

glare: excessive or bright light that causes visual discomfort or disability. One of the three types of **light pollution.**

globular cluster: a spherical shaped star cluster of up to several million very old stars. Generally found in the **galactic halo**.

GoTo: a computerized telescope that can automatically locate and track celestial objects after an initial alignment.

H

habitable zone: the region around a given star in which temperatures *could* allow liquid water to exist on the surface of a planet located in the zone. Also known as the "**Goldilocks" Zone**.

halogen: a modified type of **incandescent** light bulb where the filament is surrounded with halogen gas to make the bulb more energy-efficient and last longer. Less energy-efficient than CFLs and LEDs.

highlands: the older, mountainous, and more heavily cratered of the two major terrain types on our Moon (contrast with **maria**).

high-pressure sodium (HPS): One of the most common types of light bulbs used in streetlights and other commercial applications. Emits a warm light with very little blue.

I

ice giant: a planet that is mostly gaseous, with some ices. For this reason, they are very cold planets and typically occur far from stars. Neptune and Uranus are ice giants. Compare to **gas giant** and **terrestrial planet**.

illuminance: The amount of light striking a given area or surface. Expressed in units of lux. Can be used as a metric of night sky quality, and quantify the extent to which **light pollution** affects a given landscape.

incandescent: a type of light bulb in which electric current is run through a metal filament, causing it to glow and emit visible light. The least energy-efficient of commonly available light bulb types; most energy is emitted as heat rather than light.

inferior planet: any planet with an orbit closer to the Sun than that of the Earth.

informal education: education that occurs outside of a classroom environment. Includes most types of astronomy communication.

infrared: light with a longer wavelength than **visible light**, but shorter than **radio waves**. Infrared light is given off by objects such as planets, humans, and stars.

International Dark Sky Association (IDA): a non-profit group based in Tucson, AZ that works to help stop **light pollution** and protect the night sky for present and future generations.

International Dark Sky Park (IDSP): a park or other protected area that possess a dark night sky (relative to surrounding areas), a dark sky education and monitoring program, and that has taken steps to mitigate its lighting to be **dark-sky friendly**. IDSPs are certified by the **International Dark Sky Association**.

interpretation: a style of communication that focuses on helping people make personal connections to the topic being discussed. Interpretation focuses on meanings as opposed to simply facts.

inverse square law: the law stating that the apparent brightness of an object decreases with the square of its distance. For example, if the distance to an object doubles, its apparent brightness will decrease by a factor of four.

ionized: when an atom has lost all of its electrons, usually occurs at very high temperatures.

iridium flare: a bright, short lived flash of light seen when sunlight reflects off the large reflective surfaces of an iridium satellite.

irregular galaxy: galaxies that have no cohesive shape or structure, and that are clearly not spiral or elliptical.

K

Kepler: a space observatory designed to look for **extrasolar planets** using the **transit method.** To date, Kepler has discovered more exoplanets than all other search programs combined. Named for astronomer Johannes Kepler.

Kuiper Belt: region of the Solar System extending from 30-100 AU from the Sun, home to **dwarf planets**, **comets**, and other small Solar System bodies. Objects within the Kuiper Belt are known as **Kuiper Belt Objects**, or **KBOs**.

L

LED: see **light emitting diode**

light: electromagnetic radiation. The term "light" is most often used to refer to visible light, the portion of the **electromagnetic spectrum** that our eyes can see. However it can also be used to refer to electromagnetic radiation of any wavelength, such as **infrared, radio, or ultraviolet**.

light dome: visible **skyglow** over a populated area, as seen from a distance.

light emitting diode (LED): type of light bulb that uses a semiconductor to generate light very efficiently.

light pollution: the alteration of natural light levels in the outdoor environment by man-made sources that degrade the aesthetics or function of the natural environment. Also defined as unnecessary, unwanted, and/or excess light created by humans. Light pollution can take many forms, including **glare**, **skyglow**, and **light trespass.**

light trespass: light that is cast or shone into an area where it is unwanted or undesired. Light trespass is one of the three types of **light pollution.**

light-year: The distance that **light** travels in a vacuum in one year: roughly 9.46 trillion km, or 6 trillion miles (6,000,000,000,000 miles).

lighting ordinance/code: a set of policies in a city, county, or state code that pertain to the use of outdoor lighting, often in an attempt to minimize wasted light and preserve the night sky and/or natural darkness.

Local Group: the group of about 40 galaxies of which the **Milky Way** is a member.

low-Earth orbit: the region extending between 160 and 2000 km (99 and 1200 mi) above Earth's surface that is home to many **artificial satellites**, such as the International Space Station and the Hubble Space Telescope.

low-pressure sodium (LPS): type of light bulb used in streetlights and other commercial applications. Highly regarded by astronomers for its monochromatic orange light that has the lowest impact on **skyglow** than any other commonly available bulb.

lumens (lm): a measure of luminous flux, or the total amount of light emitted by a light source, such as a light bulb. Not to be confused with **illuminance**, which is the amount of light striking a surface.

lumens per watt (lm/W): common indicator of the efficiency of a light bulb.

luminance: the brightness of a surface, such as the night sky. See: **sky luminance**.

luminosity: the total energy output of an astronomical object, such as a star. Measured in **watts (W)**. In contrast to **apparent magnitude**, luminosity is a measure of the intrinsic brightness of an object.

lunar eclipse: an event that occurs when the Earth passes between the Sun and Moon, casting its shadow on the lunar surface.

lux: unit of **illuminance**. Used to express how much light is striking a given area or surface. Measured with a lux meter or illuminance meter.

M

magnetic field: the region surrounding a magnet (or a planet with a magnetic field) where other magnetic particles would be affected.

magnitude: see **apparent magnitude**

magnification: how many times an image seen through a telescope is enlarged. Magnification is calculated by dividing the **focal length** of the telescope by the focal length of the **eyepiece** being used.

main sequence: A main sequence star is a star that is stable, and fusing hydrogen into helium in its core.

mare (plural: **maria):** a large volcanic plain on the Moon, consisting largely of the volcanic rock basalt. Known as "seas" because early astronomers believe they were oceans of water on the surface of the Moon.

megalith: A megalith is any large stone or group of stones erected by humans. Stonehenge, the Moai of Rapa Nui, the Inuksuk of Greenland, and Saqsaywaman in Peru are all examples of megalithic structures. Some megaliths seem to indicate knowledge of celestial motions.

melatonin: A hormone secreted in the human brain that plays a large role in the sleep-wake cycle, and whose production is inhibited by exposure to small amounts of blue-rich light at night.

Messier Catalog: a catalog of 110 deep-sky objects compiled by French astronomer Charles Messier in the 18th century. Often regarded as the "greatest hits" of **deep-sky objects**; nearly all are visible in a small backyard telescope.

metal halide: commonly used high intensity discharge lamp that emits a bright white/blue light. Compared to low and high pressure sodium, metal halide bulbs cause increased **skyglow** because of the abundance of blue light they emit.

metallic hydrogen: hydrogen that is under enough pressure that it becomes a metallic liquid capable of conducting electricity, just like metal. It is found within both Jupiter and Saturn.

metals: in astronomy, all elements other than hydrogen and helium, that is, elements that are created by **nucleosynthesis** inside stars.

meteor: a small piece of space rock disintegrating in Earth's atmosphere. A **meteor shower** occurs when Earth passes through an especially rich region of space debris.

meteoroid: a small piece of rock in outer space that is smaller than an **asteroid**. Meteoroids become **meteors** when they enter Earth's atmosphere, and m**eteorites** if they hit the ground.

meteorite: a piece of rock or iron from outer space that impacts the Earth's surface. **Meteors** that do not completely disintegrate while passing through Earth's atmosphere become meteorites upon hitting the ground.

Milky Way: 1. Our home galaxy, a barred **spiral galaxy** ~100,000 light-years wide containing several hundred billion stars. 2. The fuzzy band of light visible from dark locations in the night sky, corresponding to the disk of our galaxy.

molecular cloud: large, cool, dense clouds of hydrogen gas that can collapse to form new stars and Solar Systems.

Moon: 1. Our Moon, as in the Earth's natural satellite. 2. Any natural satellite of another planet, dwarf planet, or asteroid.

multiple star: three or more stars in orbit around a common center of mass.

N

Naked eye limiting magnitude (NELM): the **apparent magnitude** of the faintest star visible to the naked eye from a given location. Used as a metric of night sky quality.

National Park Service: federal agency that manages all 59 national parks in the United States, as well as many national monuments, national historic sites, and other cultural and recreational sites.

near-Earth object/asteroid (NEO/NEA): Solar System objects that pass within or come near Earth's orbit. By definition any Solar System object with a **perihelion** distance of <1.3 **AU** is a NEO.

Nebula (plural=**nebulae):** from the latin word for cloud, a cloud of interstellar gas and/or dust in space. There are many different types, including **emission nebulae, dark nebulae**, and **planetary nebula**e.

neutron star: the extremely dense leftover core of a high-mass star that has exploded in a **supernova.**

NGC (New General Catalog): large catalog of 7,840 deep-sky objects compiled in 1888. Along with the Messier Catalog, the NGC catalog contains nearly every **deep-sky object** of interest to the backyard astronomer.

nocturnal: an animal that is active primarily at night and sleeps primarily during the day. The opposite is **diurnal**, while animals most active at dusk/dawn are known as **crepuscular.**

north: the left perpendicular direction of where the Sun rises.

north celestial pole (NCP): the point in the sky directly above the Earth's north pole. Bright stars located near this point are generally known as the **north star**. The position of the NCP relative to the stars changes over time as Earth's axis wobbles.

north star: a star that lies close enough to the **north celestial pole** to be reasonably used as a navigational aid.

nuclear fusion: the process by which two atoms merge together to create a larger, more massive atom. Fusion is the process occurring in stellar interiors that generates the energy emitted by all stars.

nucleosynthesis: the process by which stars create new nuclei (protons and neutrons) inside their cores.

O

objective: another term for the primary mirror or lens of a telescope.

Oort Cloud: a cloud of **comets** surrounding our Sun. The Oort Cloud extends from 2,000-50,000 **AU** (and may even extend as far as 200,000 AU) from the Sun.

open cluster: a grouping of up to several thousand young stars, found primarily in the disk **of spiral galaxies.**

opposition: the point at which a planet appears directly opposite the Sun in the sky, and is thus highest in the night sky at midnight. Planets generally appear brightest and largest when at opposition.

optical double: a double star in which the two stars appear close merely because they lie along the same line of sight, but actually lie at very different distances.

optical tube: the metal, plastic, or composite tube containing the lenses, mirrors, and/or optical elements of a telescope.

orbit: the path followed by a celestial body as the result of the gravitational pull of another object.

Organic Act of 1916: the act of Congress which established the National Park Service and directed it to "conserve the scenery and the natural and historic objects and the wildlife therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations."

P

perihelion: the point in the orbit of a planet (or other object, such as asteroid or comet) where it is closest to its parent star. For Earth, perihelion occurs in January. Compare to: **aphelion**.

phase: the appearance of a celestial object, such as the Moon or Venus, based on how much of the sun-illuminated portion is visible from Earth.

photon: an individual particle of light.

photopic vision: vision of the eye in well-lit conditions, such as during the daytime.

planet: an object in orbit around a star that is large enough to be round and that has gravitationally cleared its orbit of smaller bodies. **Extrasolar planet** refers to a planet in orbit around a star other than our Sun.

planetary nebula: a glowing shell of gas ejected from a small star near the end of its lifetime.

plasma: a gas that has been entirely **ionized**, and thus consists of ions and electrons.

plutoid: any object that is both a **dwarf planet** and a **trans-Neptunian object** (out past Neptune). Pluto, Eris, Haumea, and Makemake are the current known Plutoids.

Polaris: the proper name of our current **north star**.

precession (or **axial precession):** the wobble of the Earth's axis over time, leading to the movement of the **north celestial pole** in the sky and different **north stars**.

prograde orbit: where a body (such as a moon) orbits in the same direction as the parent body. For example, as seen from above the North Pole, Earth is travelling around the Sun in a counterclockwise motion. Our Moon is also orbiting us in a counterclockwise motion, so it is in a prograde orbit.

proper motion: the apparent movement of a star, relative to more distant stars, over time. Barnard's Star, the star with the fastest proper motion, is moving relative to the background stars at 10.3 **arcseconds** across the sky per year.

protoplanetary disk: a flattened, rotating disk of gas and dust surrounding a young star in which planets and other solar system objects form.

Q

quadrant: a device used to measure the altitude of stars, the quadrant is a quarter of a circle, with marks for degrees and/or **arcminutes** on the curved portion.

R

radial velocity method: a method for detecting objects orbiting around other stars, particularly **extrasolar planets**. Sometimes called the "wobble method"; as a planet goes around a star it exerts a gravitational pull on the star, causing the star to wobble. Using the **Doppler effect**, astronomers can discover planets by looking for those wobbling stars.

radiant: the point in the night sky where all **meteors** appear to originate during a meteor shower.

radio waves: light with a very long wavelength (>1mm). Used by astronomers to study cool, low density objects in space.

red dwarf: small M-type stars still on the **main sequence**.

red giant: a giant star with a low surface temperature, typically an evolved Sun-like star that has left the **main sequence** and is nearing the end of its lifetime.

reflection: the process by which light bounces off of matter and changes direction.

reflection nebula: a cloud of gas and/or dust that is visible to us only because it reflects visible light from some nearby source, such as a star.

reflector: a telescope that utilizes mirrors to collect and focus light.

refractor: a telescope that utilizes lenses to collect and focus light.

resolving power: the ability of a telescope to distinguish between two small, closely spaced objects. Along with **aperture**, resolving power is a primary yardstick by which the capabilities of a telescope are measured.

retrograde orbit: a satellite that orbits in the opposite direction as its planet's rotation. No **regular satellites** have retrograde orbits.

rods: one of two types of photoreceptors in the human eye (along with cones). Rods are more sensitive to low light conditions, and are not sensitive to color. They are responsible for **scotopic** (or "night") vision. Compare to: **cones.**

rotation: the spinning of a celestial body (such as a planet or star) around its axis.

S

scattering: the interaction of light with particles of matter smaller than the **wavelength** of the light. Causes the sky to be blue and contributes to **skyglow**.

Schmidt-Cassegrain: the most common type of **catadioptric** telescope.

scotobiology: the study of the biological need for darkness, and how darkness affects different organisms.

scotopic vision: Vision of the eye under low-light conditions, such as at night. Requires an adaptation period (**dark adaptation**) in order for the eye to reach maximum light sensitivity.

seasons: periods of the year characterized by distinct weather patterns and varying hours of daylight. Seasons are caused by the changing orientation of the Northern and Southern Hemispheres relative to the Sun as the Earth moves in its orbit.nta

seeing: an astronomer's measure of the stability of the atmospheric conditions on a given night. "Good seeing" represents stable conditions that lead to clear, sharp views of celestial objects, whereas "bad seeing" indicates a turbulent atmosphere leading to blurry telescopic views.

shifting baseline syndrome: a gradual change in the accepted norms for the condition of the environment. With regard to light pollution, shifting baseline syndrome is the reason that light polluted skies are now viewed by many as "dark."

sidereal day: the time it takes for the stars to return to the same spot in the sky, as seen from a celestial body. Earth's sidereal day is 23 hours and 56 minutes long. Sidereal day is effectively the rotational period of a planet or other body.

sidereal year: the orbital period of the Earth (or another planet) with respect to the stars. Earth's sidereal year is 365.25 days.

skyglow: brightening of the night sky caused by artificial light scattered and reflected off of air molecules and particles in Earth's atmosphere. Skyglow is one of the three types of **light pollution**.

sky luminance: quantitative measurement of the brightness of the night sky at a single point, expressed using mag/arcsec^2. Used as a metric for night sky quality. A pristine dark night sky is generally defined as 22.0 mag/arcsec^2 but there is great natural variability. Values significant lower than this usually indicate that light pollution is degrading the sky to some extent.

sky quality meter (SQM): a device used to determine **sky luminance**.

solar day: the time it takes for the Sun to return to the same spot in the sky as seen from a planet or other celestial body. The Earth's solar day is 24 hours long, 4 minutes longer than its sidereal day. Compare to **sidereal day.**

solar eclipse: an event that occurs when the Moon passes between the Earth and Sun, temporarily blocking part or all of the Sun's disk as seen from Earth's surface. A **total solar eclipse** occurs when the Moon completely blocks the Sun's disk, while a **partial solar eclipse** occurs when only a portion of the Sun is blocked.

solar system: a solar system includes all of the objects going around a parent star. In the case of our own Solar System, the **planets**, **dwarf planets**, **asteroid belt**, **Kuiper Belt**, and cloud of **comets** within the gravitational pull of our Sun, are all part of the Solar System.

solar wind: the stream of charged particles constantly being ejected from the Sun.

solstice: the two points in Earth's orbit where the Earth's rotational axis is tilted most directly toward/away from the Sun.

space telescope: a telescope located in outer space, either to gain clearer views uninhibited by Earth's atmosphere, or to observe **wavelengths** of light partially or completely blocked by our atmosphere.

spectrograph: a device attached to a telescope used to record the **spectrum** of astronomical objects.

spectroscopy: the study of obtaining and studying **spectra** from astronomical objects in order to determine their composition, velocity, distance, and other properties.

spectrum (plural: spectra): the range of colors/wavelengths emitted by a particular light source (e.g., a light bulb or the Sun).

spectral type: a method for classifying stars based on the **absorption lines** that appear in its **spectrum**. The primary spectral types are O,B,A,F,G,K, and M. O-type stars are the hottest and are very blue, while M-type stars are the coolest and very red.

speed of light: The speed at which **light** (electromagnetic radiation) travels in a vacuum: 300,000 km/sec (186,000 mi/sec).

spiral galaxy: galaxies consisting of a flat disk of stars, gas, and dust in a spiral pattern, along with a central bulge.

south: the right perpendicular direction of where the Sun rises.

star: a large ball of mostly hydrogen gas that generates energy via nuclear **fusion** in its core.

star count: a method to determine the darkness of the night sky by counting all the visible stars in a defined section of the night sky.

star party: a gathering of astronomy enthusiasts for the purpose of looking at the night sky, usually with telescopes.

sun: 1. the star at the center of our Solar System (capitalized) or 2. Another star.

superior planet: a planet further from the Sun than the Earth.

supernova/supernova remnant (SNR): the explosion of a star, usually a high-mass star at the end of its lifetime. A **supernova remnant** is the glowing remains of such an explosion, often visible for tens of thousands of years following the event itself.

synchronous rotation: when a celestial body orbits on its axis in the same amount of time as it orbits another celestial body. The moon is in synchronous rotation with the Earth.

synodic period: the time it takes for a planet to appear at the same point in the sky in relation to other objects (background stars). For example, the synodic period of Mars (the time between oppositions) is just over two years.

T

terminator: the dividing line between the day and night side of the Moon, and an area where great detail can be seen on the Moon with a telescope.

terrestrial planet: a planet that is made primarily out of rocky materials (with some metals), like Earth. A planet with a solid surface that you could (theoretically) land on. Mercury, Venus, Earth, and Mars are all terrestrial planets.

tidal heating: a source of heat that causes the interior of some outer Solar System moons (such as Io and Europa) to be liquid.

tidally locked: a body that has the same rotational period as its orbital period around its host planet or star.

torquetum: like the quadrant, a torquetum is an instrument used to measure the altitude of a celestial object. However, it has more planes and moving parts and can measure coordinates of objects for altitude, azimuth, and the object's distance from the ecliptic plane.

tracking drive: a motorized telescope mount that compensates for the rotation of Earth.

transit: the passage of any celestial body in front of another body. For example, a transit of Venus is when Venus passes in front of the Sun from our vantage point.

transit method: a method for detecting **extrasolar planets** that watches for the dip in brightness of the host star's light when a planet crosses in front of it.

trans-Neptunian object (TNO): any object in our Solar System that is past Neptune. Pluto, Eris, Haumea, Makemake, Sedna, Quaoar, and most comets are all TNOs.

Type I Error: a Type I Error, or false positive, is when a hypothesis is not true but we believe it is. If I believe I take a test that shows that I have cancer, but it turns out that I actually never had cancer, this would be an example of a Type I Error.

Type II Error: a Type II Error is when a hypothesis is true, but we don't accept it. It's missing the truth. Many historical hypotheses are subject to this type of error because time wears away concrete evidence.

U

ultraviolet (UV): a type of **l**ight with a **wavelength** slightly shorter than **visible light**, but shorter than **x-rays**. UV light emitted by the Sun causes sunburn.

universal concepts: aspects of the human experience that are understood by everyone, such as love, power, anger, beauty, etc.

unshielded fixture: outdoor light fixtures that allow light to escape sideways and upwards, wasting light and causing **light pollution.**

upward radiance: light from Earth's surface that escapes directly up into the night sky where it can be imaged by satellites.

V

variable star: a star whose **apparent magnitude** varies over time, either because of eclipses by a companion star, or intrinsic changes in the brightness of the star itself.

visible light: light that our eyes can see. Includes all light with a wavelength between 400-700 nanometers (nm).

W

warm light: light rich in yellow and orange wavelengths. Causes less **skyglow** and less impacts to wildlife and humans.

watt (W): A unit of power that can be used to express: 1. The energy output, or **luminosity**, of an astronomical object such as the Sun or 2. The energy usage of a light bulb or other appliance.

wavelength: the distance between adjacent peaks or troughs of a light wave. An indication of how energetic the light is; shorter wavelength light waves are more energetic (e.g., **gamma rays**) while longer wavelengths are less energetic (e.g., **radio waves**).

west: the opposite direction of east and etymologically goes back to the Greek Hesperus, or Roman Vesper, god of the evening star.

white dwarf: the hot, compressed corpse of a low-mass star that has reached the end of its lifetime. It is the leftover core of the star.

X

x-rays: high energy, short **wavelength** form of light emitted by energetic objects such as **accretion disks**, pulsars, and **supernovae**.

Z

zenith: the imaginary point in the sky directly above an observer.

zenith sky luminance: the night **sky luminance** directly overhead. Usually the darkest portion of the night sky and a measurement of zenith sky luminance will often not capture **skyglow** near the horizon.

zero-power finder: a finder telescope that does not magnify the night sky, but rather projects a bulls eye or red dot indicating where the telescope is pointed. A Telrad is an example of a zero-power finder.

zodiac: the set of **constellations** lying along the **ecliptic** that the Sun passes through on its annual trip around the sky.

zodiacal light: an elliptical band of light in the night sky caused by sunlight scattering off of interplanetary dust particles in the plane of the Solar System. Visible to the naked eye from dark locations, but always a significant contributor to the natural brightness of the night sky.

APPENDIX B: GENERAL ASTRONOMY RESOURCES

Books

- *365 Starry Nights: An Introduction to Astronomy for Every Night of the Year*, by Chet Raymo, 1990
- *The Backyard Astronomer's Guide*, by Terence Dickinson & Alan Dyer, Third Edition, 2008
- *Night Sky with the Naked Eye: How to Find Planets, Constellations, Satellites, and Other Night Sky Wonders Without a Telescope*, by Bob King, 2016

Documentaries

- *Cosmos: A Personal Voyage,* 1980
    - The classic astronomy series written and hosted by Carl Sagan. While some of the information here is out-date, Sagan's gift for communicating astronomy to the public makes this worth watching even several decades years later.
- *Cosmos: A Spacetime Odyssey,* 2014
    - The 2014 remake of Carl Sagan's Cosmos, hosted by Neil DeGrasse Tyson, produced by Seth McFarlane

Podcasts

- *Astronomy Cast:* A weekly podcast on all things astronomy and space: http://www.astronomycast.com/
- *Crash Course Astronomy:* a 46-part video series introducing you to all aspects of astronomy, hosted by Phil Plait: https://thecrashcourse.com/courses/astronomy

Southern Utah Dark Sky/Astronomy Groups and Events

- Ashcroft Observatory (Southern Utah University): https://www.suu.edu/cose/physci/physics/observatory.html
- Cedar Breaks National Monument Dark Sky Program: https://www.nps.gov/cebr/star-parties.htm
- Cedar Breaks National Monument Library Telescope Program: https://www.nps.gov/cebr/learn/education/cedar-breaks-library-telescope-program.htm
- Cedar Breaks National Monument Master Astronomer Program: https://www.nps.gov/cebr/learn/education/cedar-breaks-master-astronomer-program.htm
- Colorado Plateau Dark Sky Cooperative: https://cpdarkskies.org/
- Great Basin Observatory: http://www.greatbasinobservatory.org/
- St. George Astronomy Group: https://sgag.club/
- Southern Utah Space Foundation (Cedar City): https://susf.org/
- Southwest Astronomy Festival: https://www.nps.gov/cebr/planyourvisit/southwest-astronomy-festival.htm

Websites

- Ask an Astronomer (Cornell University): http://curious.astro.cornell.edu/
- Astrobites (summaries of astronomy research papers): https://astrobites.org/
- The Astronomical League: https://www.astroleague.org/
- Astronomical Society of the Pacific: https://www.astrosociety.org/
- Astronomy Picture of the Day (APOD): https://apod.nasa.gov/apod/astropix.html
- *Bad Astronomy* (blog by astronomer Phil Plait): http://www.syfy.com/tags/bad-astronomy
- Calendar of Celestial Events: http://www.seasky.org/astronomy/astronomy-calendar-current.html
- NASA Homepage: https://www.nasa.gov/
- Sky & Telescope Magazine: http://www.skyandtelescope.com/online-resources/
- Universe Today: https://www.universetoday.com/

APPENDIX C: ACKNOWLEDGEMENTS

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- **Zach Schierl,** Education Specialist and Master Astronomer Program Lead
- **Leesa Ricci**, Dark Sky Ranger and curriculum co-author
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Image Sources

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About the Authors

Zach Schierl grew up in the world's first International Dark Sky City (Flagstaff, Arizona) and has been an astronomy nerd since receiving a 4.5" telescope for his 10th birthday. Since then, he has earned a B.S. in geology and astronomy from Whitman College, and a M.S. in geology with an emphasis in earth science education from Western Washington University. Zach has taught high school and community college geology and astronomy courses and worked as an astronomy educator and dark skies advocate at Lowell Observatory, Bryce Canyon National Park, and Black Canyon of the Gunnison National Park. He is now the Education Specialist and Dark Skies Coordinator at Cedar Breaks NM.

Leesa Ricci started out in astronomy by attending the Stansbury Park Observing Complex (SPOC) meetings when she was a teenager. Later, as a student at Southern Utah University, she started taking astronomy and physics classes and was hired as a lab tech at the Ashcroft Observatory in Cedar City where she worked for 6 years. In 2015, she became the president of the Southern Utah Space Foundation (SUSF) whose primary purpose is astronomy outreach and education. In March 2016, she joined the dark skies team at Cedar Breaks National Monument to help develop and launch the Master Astronomer Program.

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