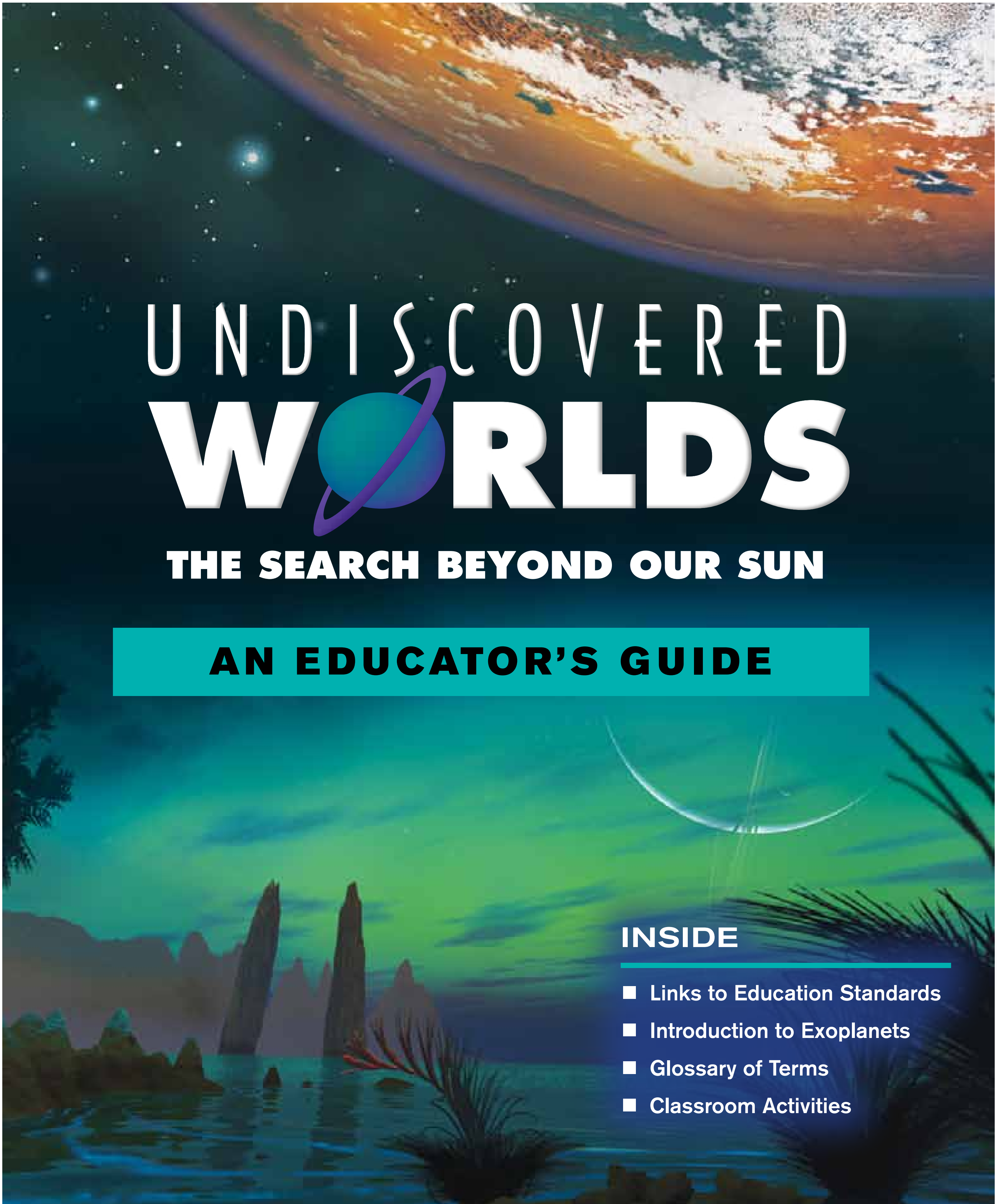

UNDISCOVERED WORLDS

THE SEARCH BEYOND OUR SUN

AN EDUCATOR'S GUIDE

INSIDE

- Links to Education Standards
- Introduction to Exoplanets
- Glossary of Terms
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About This Guide

UNDISCOVERED WORLDS

How to Use This Guide

This guide is meant to be a supplement for teachers bringing their students to the Planetarium show *Undiscovered Worlds: The Search Beyond Our Sun* at the Museum of Science, Boston.

- The suggested age groups for this show are grades 3 – 12.
- Suggested activities and follow-up questions are included in this guide.
- **Bolded words** are defined further in the glossary (pages 24 – 25).

Contact Information

- For questions regarding *Undiscovered Worlds: The Search Beyond Our Sun,* email schoolplanetarium@mos.org.
- For general field trip planning resources, visit mos.org/educators.
- For school group reservations, call Science Central, open daily 9:00 a.m. – 5:00 p.m.: 617-723-2500, 617-589-0417 (TTY).

Credits

Undiscovered Worlds: The Search Beyond Our Sun was produced by the Museum of Science, Boston (mos.org). This guide was developed by the Charles Hayden Planetarium staff.

ABOUT THE CHARLES HAYDEN PLANETARIUM

THE EXPERIENCE

The newly renovated Charles Hayden Planetarium at the Museum of Science offers visitors of all ages an immersive space exploration experience. Detailed and accurate star maps and digital video are projected onto the 57-foot-wide dome overhead, allowing students to appreciate the vastness of space in three dimensions.

ACCESSIBILITY

The Charles Hayden Planetarium is wheelchair accessible. Show scripts for *Undiscovered Worlds* are available upon request. Please contact *schoolplanetarium@mos.org* with questions about further accessibility needs, including assistive-listening devices, closed-captioning for the hearing impaired, and Braille materials for the visually impaired.

Connections to Education Standards

The general education standards that are explored in this show are listed below. Find more detailed standards online at mos.org/educators.

National Science Education Standards

GRADE LEVEL	CONTENT STANDARDS
All	Abilities necessary to do scientific inquiry
	Understanding about science and technology
	Science as a human endeavor
K – 4	Position and motion of objects
	Light, heat, electricity, and magnetism
	Objects in the sky
5 – 8	Motions and forces
	Transfer of energy
	Earth in the solar system
9 – 12	Motions and forces
	Origin and evolution of the Earth system

Massachusetts Science and Technology/Engineering Frameworks

GRADE LEVEL	CONTENT STANDARDS
3 – 5	The Earth in the solar system
6 – 8	The Earth in the solar system
	Properties of matter
	Motion of objects
9 – 12	The origin and evolution of the universe

Exotic and intriguing worlds beyond our solar system have long been the stuff of our imaginations. However, in recent years, science fiction has become science fact! Equipped with constantly improving telescopes and detection techniques, astronomers have discovered hundreds of planets orbiting other stars in our galaxy and beyond. Now that we know that they are indeed out there, we wonder: are Earth-like planets common or unique in the universe?

Our journey begins on a starlit beach, but the coming dawn reveals that this is no ordinary world. We see a world with unfamiliar plant life, mysterious landscapes, and an alien sky.

From there, we travel to a star very similar to our Sun, 51 Pegasi, to see a giant exoplanet in orbit. It is extremely close to its star and is more than a hundred times as massive as the Earth—a combination unlike any planet in our solar system.

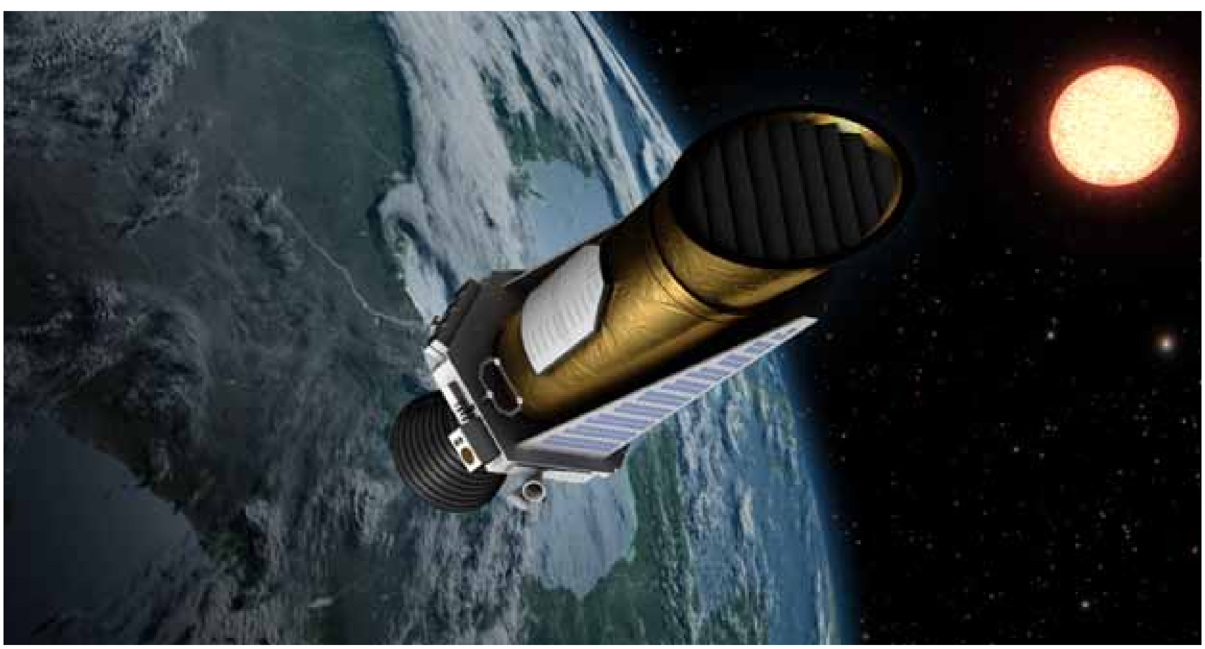
To better appreciate how unexpected this discovery is, we look at our own solar system. 4.5 billion years ago, our Sun and planets were born from a giant spinning disk of gas and dust. Closer to the Sun, planets became small and rocky. Farther away from the Sun, planets became large and made of gas. Since astronomers are now finding exoplanets that do not follow this same pattern, they are re-thinking the currently held views of planetary mechanics.

These exoplanets are very far away, so how do we actually "see" them? Exoplanets are nearly impossible to photograph in the traditional sense, so we have to find them by observing the effects they have on their parent stars. These effects, driven by gravity and line-of-sight, are visible to us as either periodic dimming (called "transits") or shifting wavelengths within the electromagnetic spectrum (referred to as a "wobble").

To find a world capable of supporting life, scientists target rocky, terrestrial worlds, but they are not always hospitable. Take the exoplanet CoRoT-7b, for example. This planet is so close to its star that rock melts on the surface! Scientists must therefore also look in the habitable zones of stars, where temperatures allow liquid water to exist. One planet in the system of Gliese 581 may be just inside the habitable zone. We visit this exoplanet to see that it could possibly sustain standing water and vegetation on its surface, much like Earth.

There are several current missions dedicated to finding these habitable worlds. Launched in 2009, the Kepler telescope is watching over 100,000 stars in the hopes of observing Earth-like exoplanets transiting their stars. The results of Kepler will help us decide how common or rare planets like Earth may be in the universe.

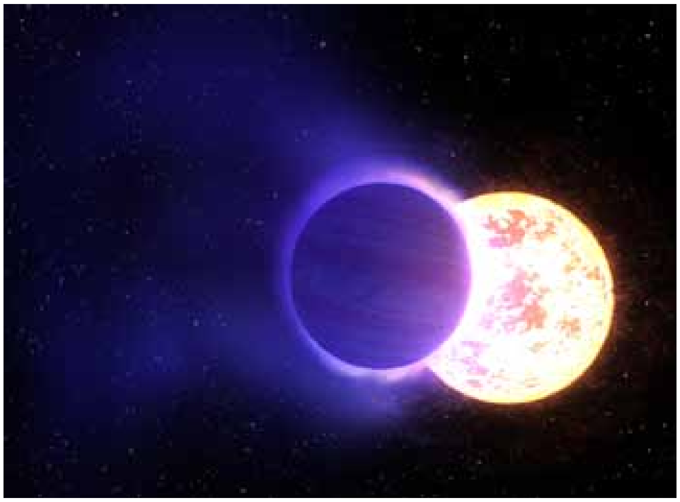
As the show comes to a close, we ponder the idea that, whatever we find, our human existence is just one tiny grain on the beach of the cosmic sea. Humans have only been around for a very short time, but during that time, we have made extraordinary discoveries, with many more on the nearby horizon.



CoRoT-7b

- Discovered in February 2009
- 480 light years away
- 20-hour orbit
- **Super-Earth:** 9 times the mass of Earth
- CoRoT-7 (star): Yellow dwarf

HD 209458b



- Discovered in November 1999
- 150 light years away
- 3.5-day orbit
- **Hot Jupiter:** 220 times the mass of Earth
- First observed transit
- Atmosphere determined by transit: sodium, hydrogen, methane, water vapor, and carbon dioxide
- HD 209458 (star): Yellow dwarf

Gliese 581d

- Discovered in April 2007
- 20 light years away
- 67-day orbit
- Super-Earth: 5.5 times the mass of Earth
- Part of a system of 4-6 planets
- Orbits on outer edge of habitable zone
- Gliese 581 (star): Red dwarf

We suggest reviewing the following information with your students before your visit to the Museum. That way, your students will come equipped with a basic knowledge of exoplanets so they will be ready to better understand the concepts discussed in the show.

Why do astronomers search for exoplanets?

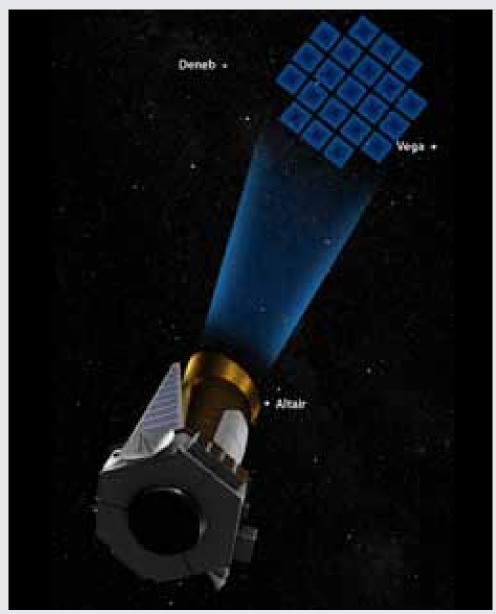
One of the most important goals of the search for exoplanets is finding another world capable of supporting life. We want to know how unique, or common, planets like Earth really are in the universe. The conditions to support life, at least as we currently know it, require a fine balance of variables like temperature, a stable atmosphere, access to liquid water, and the presence of carbon molecules.

THE KEPLER MISSION

Kepler is a telescope launched by NASA in 2009, designed specifically to look for transiting exoplanets. To verify a planet, Kepler must observe at least three transits, measuring a consistent periodic dip in the starlight to reflect orbital motion. Because these transits may take anywhere from hours to years, Kepler must continue staring at the same part of the sky in order not to miss anything.

To maximize on the need for a stationary view, the telescope has been aimed at a section of sky in the constellations of Lyra and Cygnus (part of the Summer Triangle of constellations). Here, the star population is especially dense because of the proximity of these constellations to the plane of the Milky Way.

While in orbit, Kepler will be trained on 100,000 stars for a minimum of 3.5 years with a field of view about 15 degrees across, which is the equivalent of about 30 Moons lined up in a row. If planets turn out to be common in just this limited piece of sky, just imagine how many planets there must be throughout the universe!



The Kepler telescope is staring at over 100,000 stars in the same section of sky, between Vega and Deneb. The waffle-shaped grid represents the field of view of the telescope. Over the three years of its mission, Kepler's goal is to identify Earth-sized exoplanets in this region of space. *Image © Museum of Science*

Naming an exoplanet

An exoplanet is named after the star it orbits, followed by a lowercase letter (starting with "b"). Progressive lowercase letters are used (c, d, e…) when more than one planet is found in a system, with the letters assigned in order of discovery, not distance from the star.

Let's use the Kepler telescope as an example. When a star targeted by Kepler shows characteristics consistent with a transiting planet, this planet is categorized as a **candidate.** Ground-based observations are then used to confirm or reject the candidate. **Confirmed** exoplanets are listed separately with a name like "Kepler-10b," which signifies that it is in orbit around the tenth star confirmed by Kepler to have planets (this star is called "Kepler-10"), and it is the first (or only) planet associated with that particular star. If another planet is found around the same star, the prefix will still be "Kepler-10," but the lowercase letter will change.

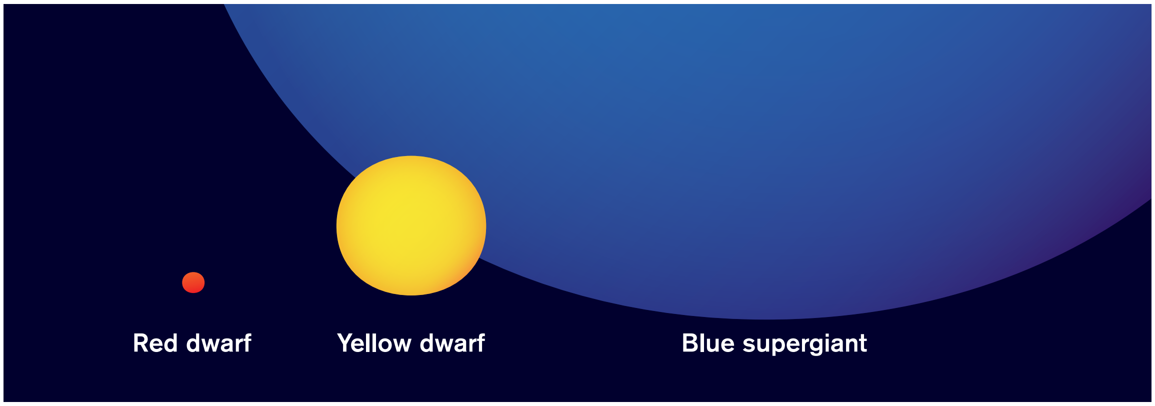
Orbital speed

To determine the speed of a planet's orbit, we need to know how close the planet is to its star. More specifically, the angular momentum of an orbiting object is determined by its mass, speed, and distance from the center of mass it is orbiting. Since angular momentum remains constant and planetary masses do not typically change, then the velocity and distance of the planet are inversely proportional to each other. In other words, $L = mvr$, where L is the angular momentum, "m" is the mass of the planet, "v" is the velocity of the planet's orbit, and "r" is the distance between the planet and the star. Planets close to their stars, like Mercury in our solar system, orbit very quickly. Planets farther away take longer to complete a full orbit.

TEACHER TIP

DOWNLOAD FIELD TRIP GUIDES!

Use these handy activity sheets for chaperones and students to make the most of their day at the Museum. Download them before your visit: mos.org/educators.



Types of stars and their relative size differences.

Where to look

If we want to look at the stars with the most potential for habitable planets, we need to narrow our search to stars that supply planets with the right amount of energy needed for life to exist. Not all stars are the same; they have widely different temperatures, sizes, and life expectancies. Here are the characteristics of different types of stars:

- **Blue supergiants** are among the hottest stars. Color can tell you a lot about temperature; just think about the difference in flame color between a blow torch and a birthday candle, for instance. Blue supergiants are also some of the most massive stars. Because they are so massive, they burn through their hydrogen fuel at a much faster rate than a star the size of our Sun, so they are also relatively short-lived. Any life on a planet around one of these stars would not have much time to develop. Also, once the star has completely run out of fuel, it could explode.
- **Yellow dwarfs,** like our Sun, are of moderate temperature and size. They also have reasonably long lifetimes. Our Sun, for instance, was born with enough fuel to burn for at least 10 billion years. As our own existence proves, that is plenty of time for life to develop, so this category of stars makes an excellent choice to search for exoplanets.

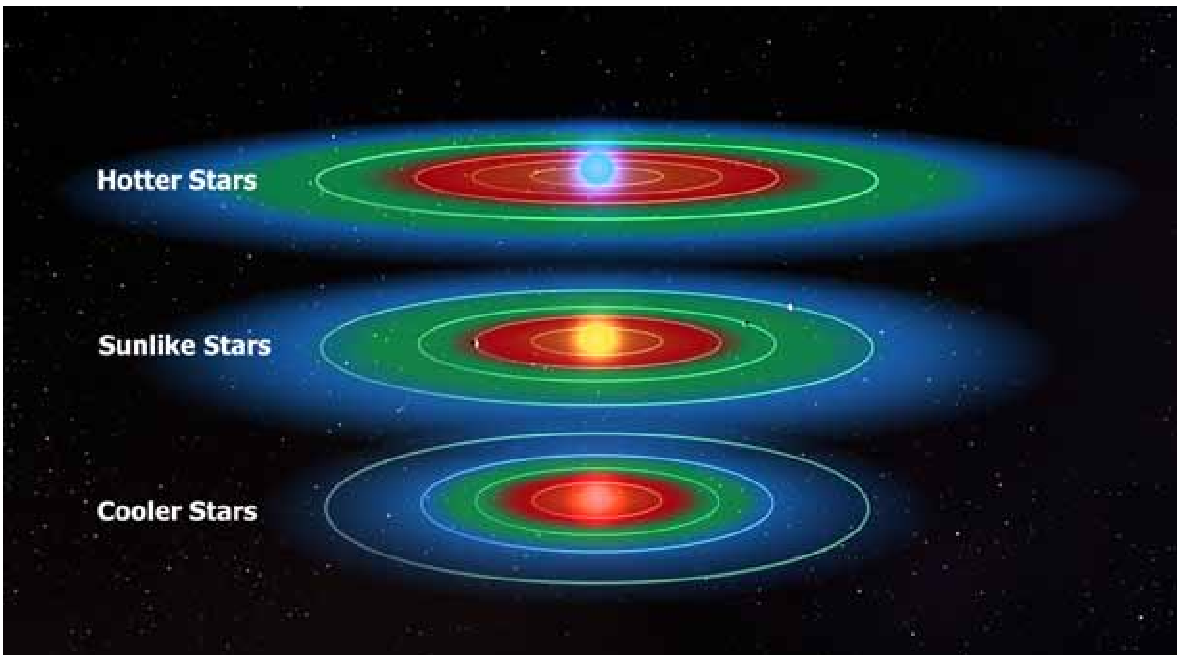
DID YOU KNOW?

Our own Sun is classified as a yellow dwarf star. It has enough fuel to burn for at least another 5 billion years.

- **Red dwarfs,** much smaller and cooler than our Sun, outnumber yellow dwarfs ten to one. Because of their smaller mass, they can exist much longer than stars like our Sun. That means any planets would have ample time to develop and support life. As a result, these stars are also excellent contenders. In fact, many currently confirmed exoplanets are known to orbit red dwarfs.

Why temperature matters

A star's temperature is one of the most important factors in determining the habitable zone of a particular system. The habitable zone is the distance within which a planet must orbit its star to support liquid water (neither too close/hot nor too far/cold). Thus, blue supergiants will have a habitable zone much farther from the star than a red dwarf. This specific criteria exists because of the necessity for liquid water to support life as we currently know it.



Representation of the temperature distribution and its effect on the stability of liquid water around different types of stars. Red indicates temperatures are too hot, blue indicates temperatures are too cold, and green indicates temperatures are just right for liquid water to survive on a planet. *Image credit: NASA.*

Finding life as we know it

No life has been found on any exoplanet so far. Scientists think our best chance for finding life exists on Earth-sized planets or rocky moons orbiting planets in the habitable zones of stars. With telescopes like Kepler searching for evidence of these worlds, we may be on the verge of finding out just how unique or common Earth really is in the universe.

Interested in learning more about exoplanets? The information provided below covers the latest in exoplanet research. Use it to personalize your lesson plan by connecting the show's main themes to your curriculum.

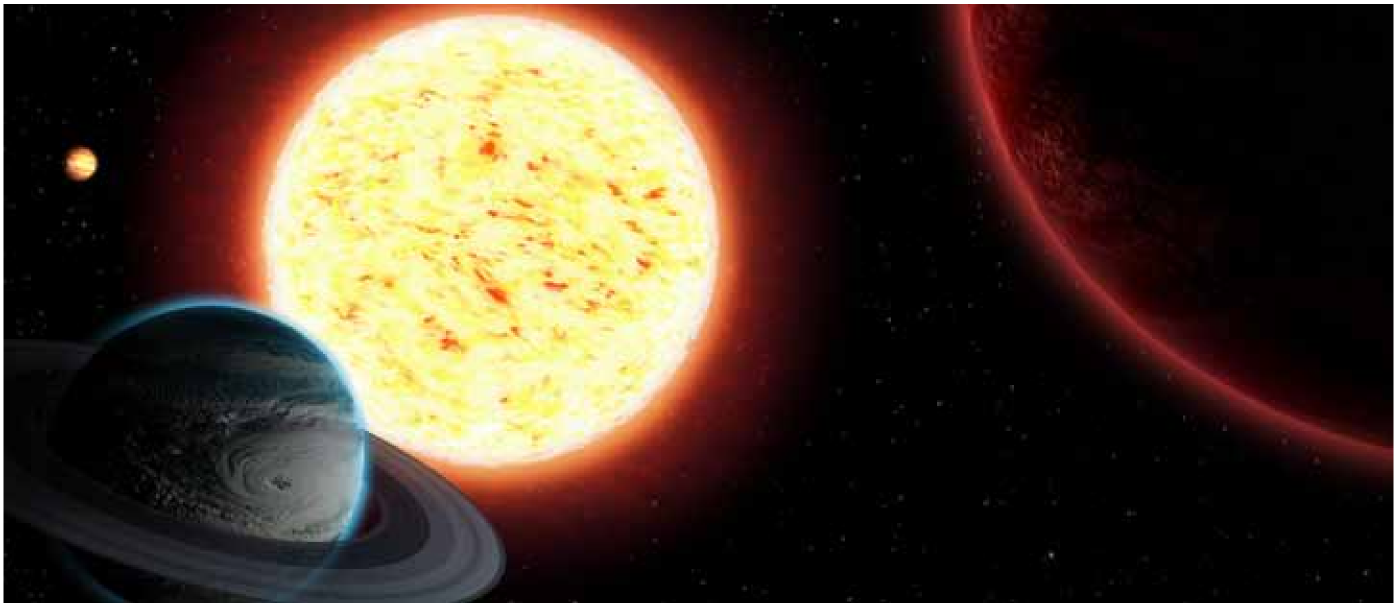
THEME 1: INTRODUCTION TO EXOPLANETS

When did astronomers find proof of exoplanets?

Until very recently, planets outside our own **solar system** existed only in our imaginations. Scientists had been hypothesizing about their existence for centuries, but they did not have the technology required for definitive proof. It was not until 1992 that astronomers Aleksander Wolszczan and Dale Frail confirmed the first **exoplanets,** found in orbit around the **pulsar** PSR B1257+12.

Pulsars emit too much radiation to allow the existence of organic life, so scientists continued looking for proof of other planets orbiting stars like our own, where life might have a chance to form and survive. Astronomers Michel Mayor and Didier Queloz found the first such planet in 1995: 51 Pegasi b.

51 Pegasi b (at right) was the first exoplanet to be found orbiting a star like our Sun. *Image © Museum of Science.*



Hot Jupiters are planets that are much more massive than Earth and that have orbits extremely close to their stars. *Image © Museum of Science.*

The discovery of 51 Pegasi b showed us that planets are not a phenomenon unique to our solar system, although it is unlike any planet we had ever known. It is more than 100 times as massive as the Earth, with an orbit so close to its star that it completes a full revolution in only four Earth days. Compared to the 88 days of the orbit of Mercury, the planet closest to the Sun in our solar system, this is blisteringly fast! 51 Pegasi b's proximity to its star also leads to surface temperatures of over 1,000°F. We call exoplanets like 51 Pegasi b "hot Jupiters"—"hot" because they orbit extremely close to their star and "Jupiters" because they have roughly the same mass as Jupiter (or larger).

Why was the discovery of 51 Pegasi b so important?

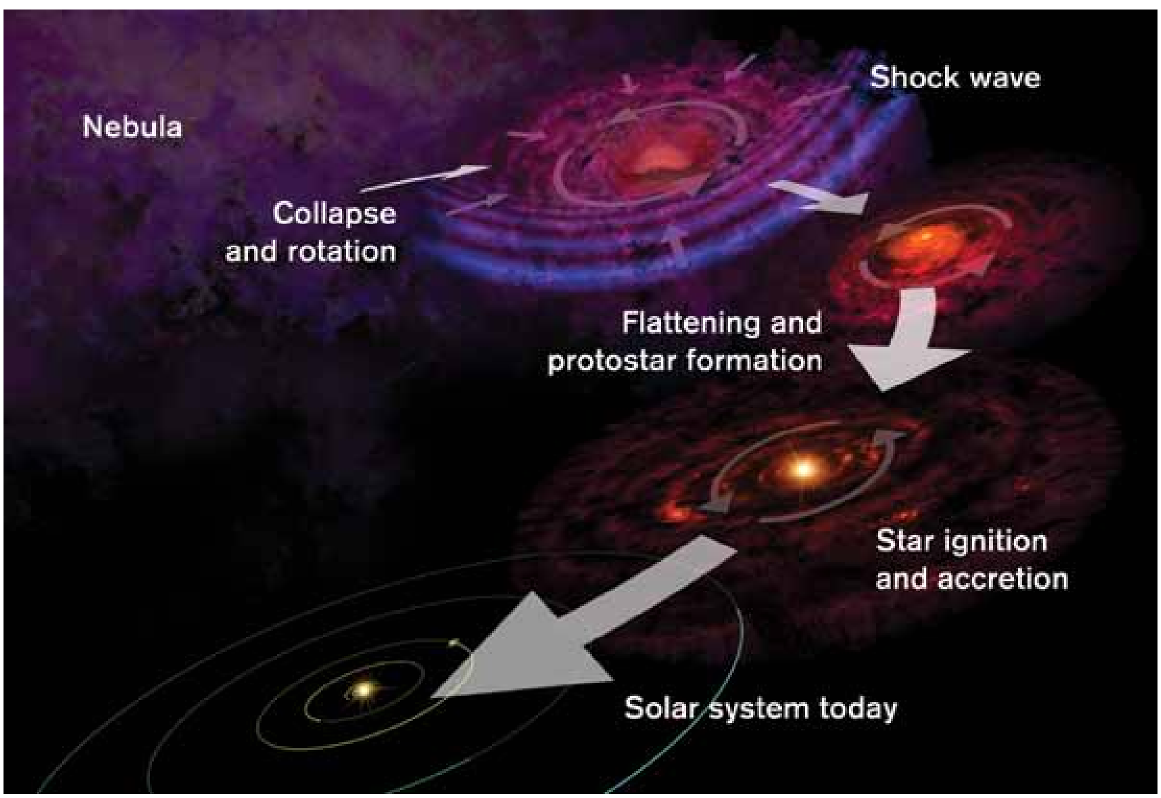
The discovery of 51 Pegasi b challenged the universality of our tidy solar system model, with regular orbits and an orderly and predictable distribution of planets. Now we know that not all planetary systems follow the same evolutionary path. However, the mechanics of planet formation should remain the same, so we can get an idea about how exoplanets first formed by looking at our own solar system.

THEME 2: SOLAR SYSTEM FORMATION

How did it all begin?

Approximately 4.5 billion years ago, our solar system existed only as a clump of dust and gas, in what is called a **nebula.** Then, a cosmic disturbance, like a shock wave from a nearby supernova, disturbed this clump, causing it to begin to collapse in on itself. As it collapsed, it also began to spin. Much like spinning pizza dough, the nebula began to flatten into a circular plane, revolving around a center of mass. For millions of years, this center continued to accumulate more mass, increasing in density, temperature, and pressure, and eventually forming a **protostar.** When the outward pressure at the center of the mass became strong enough, the nebula stopped collapsing and the proto-Sun ignited, beginning nuclear fusion.

The leftover dust and gas continued to revolve, and gravity caused pieces to crash into each other and stick together, in a process known as **accretion**. Bigger clumps attracted smaller ones, resulting in growing **planetesimals.** Eventually these planetesimals swept up and accumulated most of the material in their orbital path, growing into the larger objects of our solar system, such as asteroids, comets, moons, and even planets.



This diagram shows the typical progression of solar system formation.
Image © Museum of Science.

How did the Sun determine the distribution of planets?

The temperature and size of this new Sun determined the distribution of the planets. For example, the planets closest to our Sun are small and rocky. Their smaller size is due primarily to the location of the **ice line** (also called the frost or snow line), which is the distance from the star beyond which the temperature finally becomes cool enough to allow the condensation of ice. The ice line in our solar system is in the middle of the asteroid belt, between the orbits of Mars and Jupiter. Since the inner planets are within this limit, there was no ice for them to accrete, and so the amount of material for growing planets was limited. The gas giants, on the far side of the ice line, had access to ample amounts of ice, explaining their noticeably higher masses. In turn, the higher mass made it possible for these planets to attract and hold on to their characteristic gas-rich atmospheres, accumulated from the surrounding nebula.

Planets finally stopped growing when the strong solar winds of the new Sun pushed the remaining gas and dust out of the solar system, far into space.

Do exoplanets form in a similar way?

Astronomers believe that exoplanets form in a similar way as planets in our own solar system. As such, observing other planetary systems in a variety of stages of evolution has given us some valuable insight into the past and future of our own system. However, for a giant planet like 51 Pegasi b to be so close to its star, some other mechanics must be involved. One hypothesis is that 51 Pegasi b formed at a more typical distance, farther from its star, where it had access to ice and could thus grow to a larger size. It then, over time, "migrated" inward to its current position. The exact method and timing of the migration has not yet been completely explained.

It is important to note that, despite the discovery of a significant number of hot Jupiters, it is still possible that Earth-sized planets *do* orbit their stars at more typical distances. We just haven't found them yet, and much of that has to do with the location of these planets in space. For example, one of the closest known exoplanets (Epsilon Eridani b) is still almost 63 trillion miles away. We could never see it with the naked eye, or even with some of our most powerful telescopes. Not only would the light from the parent star block out the planet, but it would also be too small for us to see across such a vast distance. It would be like standing in Boston, trying to see a firefly in San Francisco! But before we discuss how exoplanets are detected, let's take a look at how we calculate distance in space.

THEME 3: DISTANCE IN SPACE

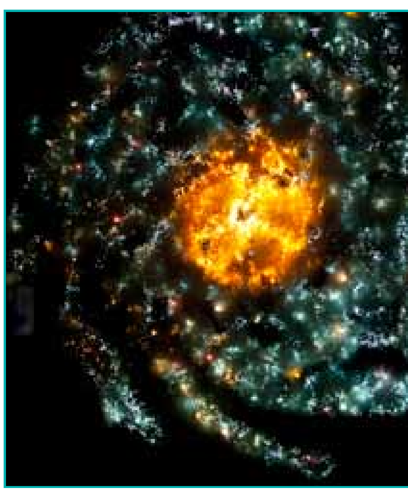
What is an astronomical unit?

Since the universe is so large—some say infinite—it is difficult to measure physical distances with units like miles or kilometers. The numbers also work out to be quite unwieldy using these conventional terms. For example, the distance from the Earth to the Sun is 92,955,807 miles. That's a lot of numbers, and the farther out you get in space, the more difficult it is for scientists to record these numbers accurately. As a result, scientists have created new measurement systems to quantify distances in space. Instead of 92,955,807 miles, the distance from the Earth to the Sun is referred to as one **astronomical unit,** or AU.

What is a light year?

Beyond our solar system, even astronomical units aren't large enough to use as a tool to calculate the great distances between stars. Instead, we must rely on the properties of light to measure astronomical distances. We use the known speed of light (approximately 186,000 miles per second) to calculate how far light can travel in a vacuum in one Earth year. This works out to be approximately 5,865,696,000,000 miles. For simplicity, we refer to this distance as one **light year.**

Light years are also a useful measuring tool because they allow us to measure how far back we are looking in time. For example, if we are looking at a star 20 light years away, we know that the light left the star 20 Earth years ago, traveling at the speed of light. That means that the light we are seeing today is 20 years old. Anything that happened to that star 15 years ago will be hidden from us for another 5 years.



FAR OUT! How long does it take light to reach the Earth from…?

our Moon:	1.3 seconds
our Sun:	8 minutes
our nearest star (Proxima Centauri):	4.2 years
the Andromeda Galaxy:	2.5 million years

So, with these concepts of distance in mind, how do we find exoplanets in this giant universal haystack?

THEME 4: METHODS OF DISCOVERING EXOPLANETS

Since it is exceptionally difficult to visually detect exoplanets, we must instead find them by observing the effects they have on the stars they orbit. The following are some of the most common and effective methods of detection:

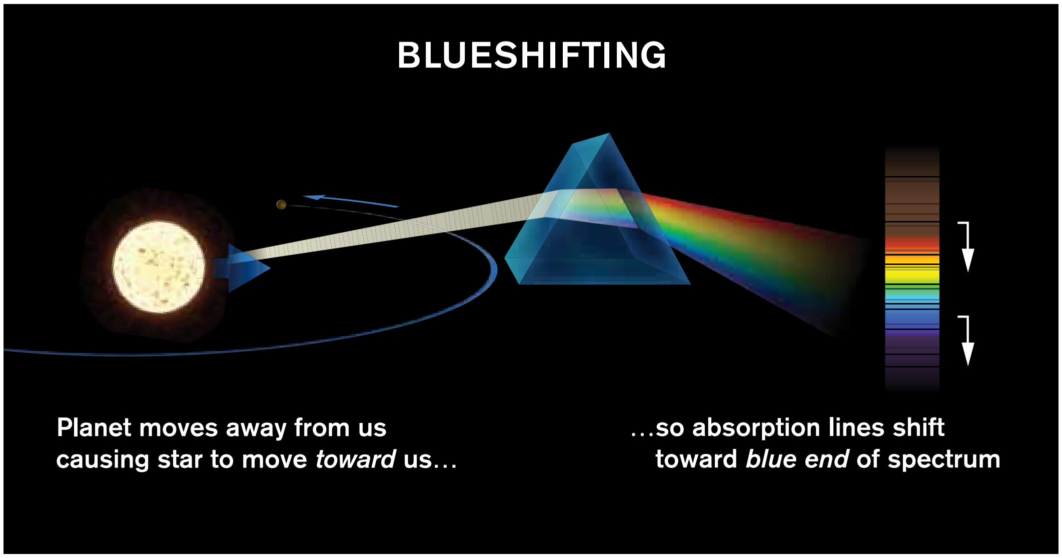
METHOD 1: RADIAL VELOCITY (a.k.a. The "wobble" method)

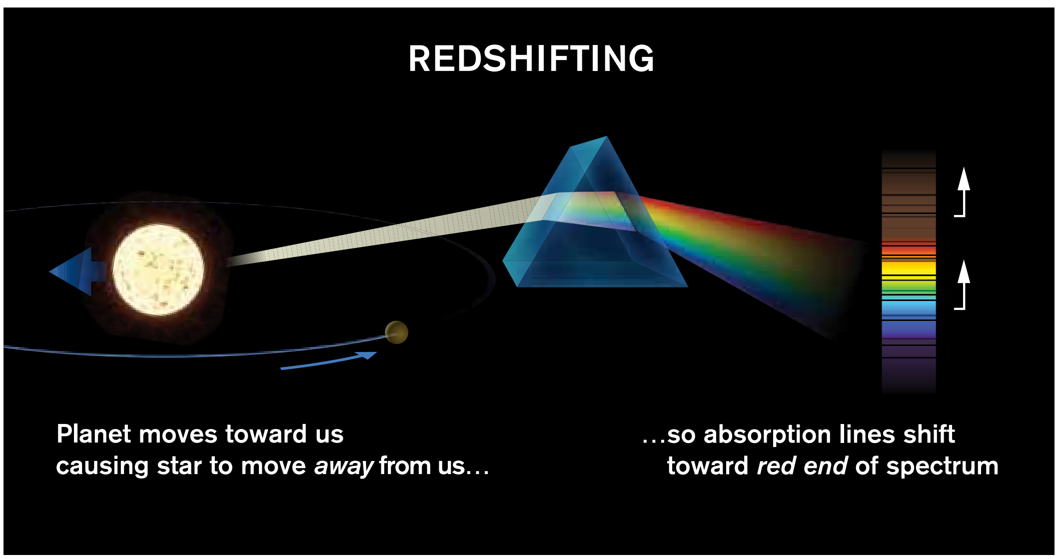
One important concept in exoplanet detection is that stars emit light, and each star's light gives off a distinctive signature. We can see this signature by passing the starlight through a spectrograph, which breaks the light up into its constituent colors, like a prism. The identifying markers of the particular star are visible as dark **absorption lines** cutting through the different colors. Each line corresponds to a different element, and no two stars have the same exact pattern of absorption lines.

How does gravity play a role?

Equally important is the concept that all bodies have mass, and when two masses encounter each other, gravity pulls them together. In the case of a planetary system, planets are kept in orbit around a star as a result of this attraction. Even though the star is significantly more massive than any of its planets, it is not immune to the gravitational effects of something in its orbit. In other words, just as the star is pulling on the planet, the planet is pulling on the star. As a result, stars with orbiting planets do not appear stationary, but instead move in a tiny orbit around a shared center of mass.

This orbit results in a "wobble" in the absorption lines of the star's spectrum. When the star is orbiting toward the observer (in our case, Earth), the wavelengths of the light appear to be shortened, shifting the signature lines in the direction of the bluer wavelengths. This is called "**blueshifting**." As the star moves slightly away from the observer, the wavelengths of light are elongated, shifting the signature lines in the direction of the redder wavelengths. This is called "**redshifting**." This concept is similar to the Doppler effect of an ambulance siren (higher-pitched as it comes closer, lower-pitched as it moves away).





The orbit of a planet and its star around a shared center of mass leads to changes in the star's light spectrum.

As the star swings around to orbit toward the observer, the wavelengths of light are compressed and shift toward the blue end of the spectrum.

As the star orbits away from the observer, the same wavelengths are now elongated, shifting them toward the red end of the spectrum.

Image © Museum of Science

What can the wobble tell us?

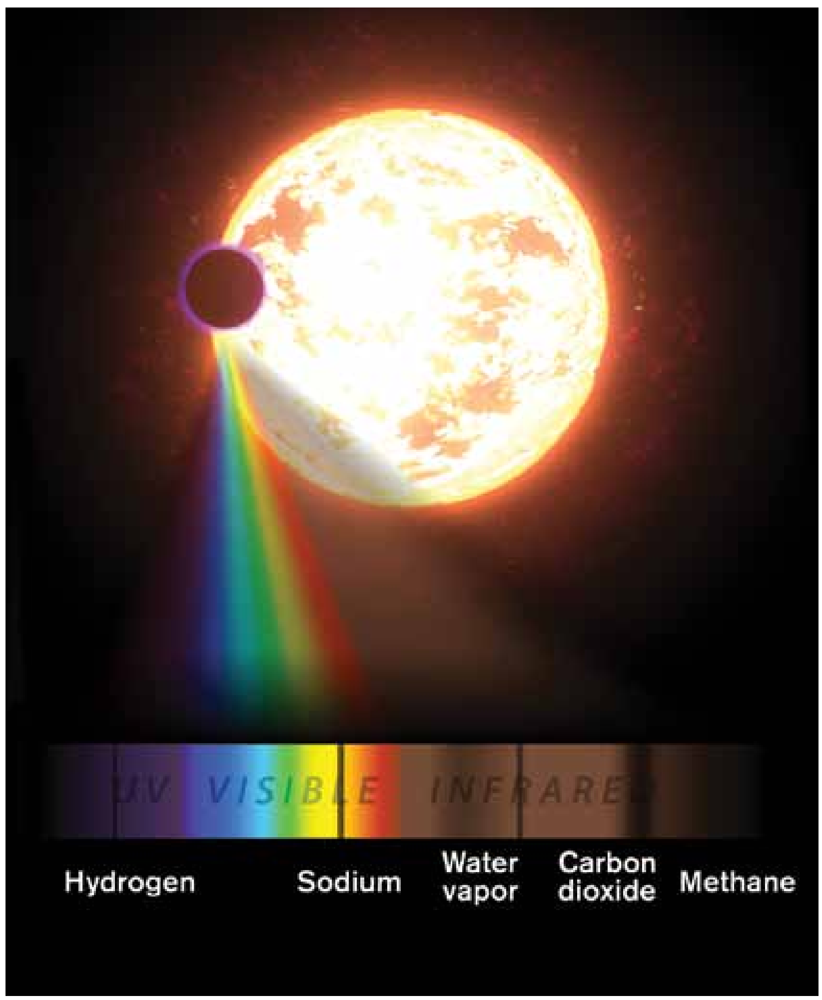
Astronomers can measure the degree and duration of this shift in the spectrographic lines to determine the mass and orbit of a planet. This method is more effective for discovering very massive planets and those closer to their parent stars because these variables lead to more noticeable wavelength shifts.

METHOD 2: TRANSIT

In some cases, if the orientation is just right, we can observe a planet periodically passing in front of its parent star. This passage is called a **"transit."** During the transit, the planet blocks out some of the light normally emitted by the star. If we observe this dip in measured light repeatedly, it indicates an orbiting planet. We can measure the time between dips to calculate the planet's **orbital period.** Transits can also be used to measure an exoplanet's relative size, since bigger planets block more light.

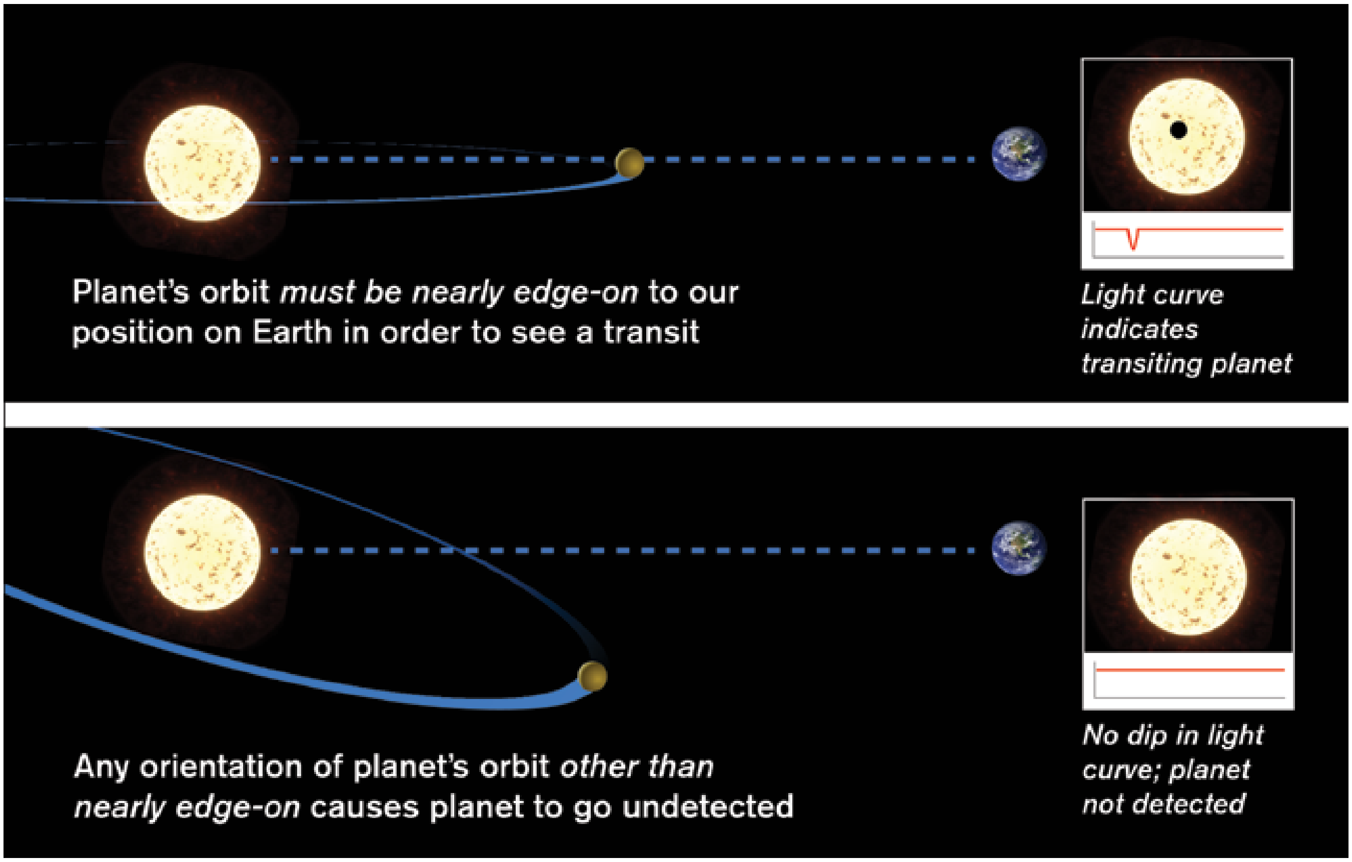
What else can astronomers study using the transit method?

The transit method also gives us a chance to study a planet's atmosphere—if it has one. As light from the star filters through a transiting planet's atmosphere, the spectrographic signature of the light will change briefly, adding more absorption lines to represent the additional elements through which it must now pass. This technique is particularly exciting as it applies to the search for life. The presence of gases like carbon dioxide, water vapor, and ozone can indicate, though not confirm, biological processes.



As planet HD209458b passes in front of its star, its atmosphere absorbs certain colors of starlight which reveal chemical elements in the planet's atmosphere.

Image © Museum of Science



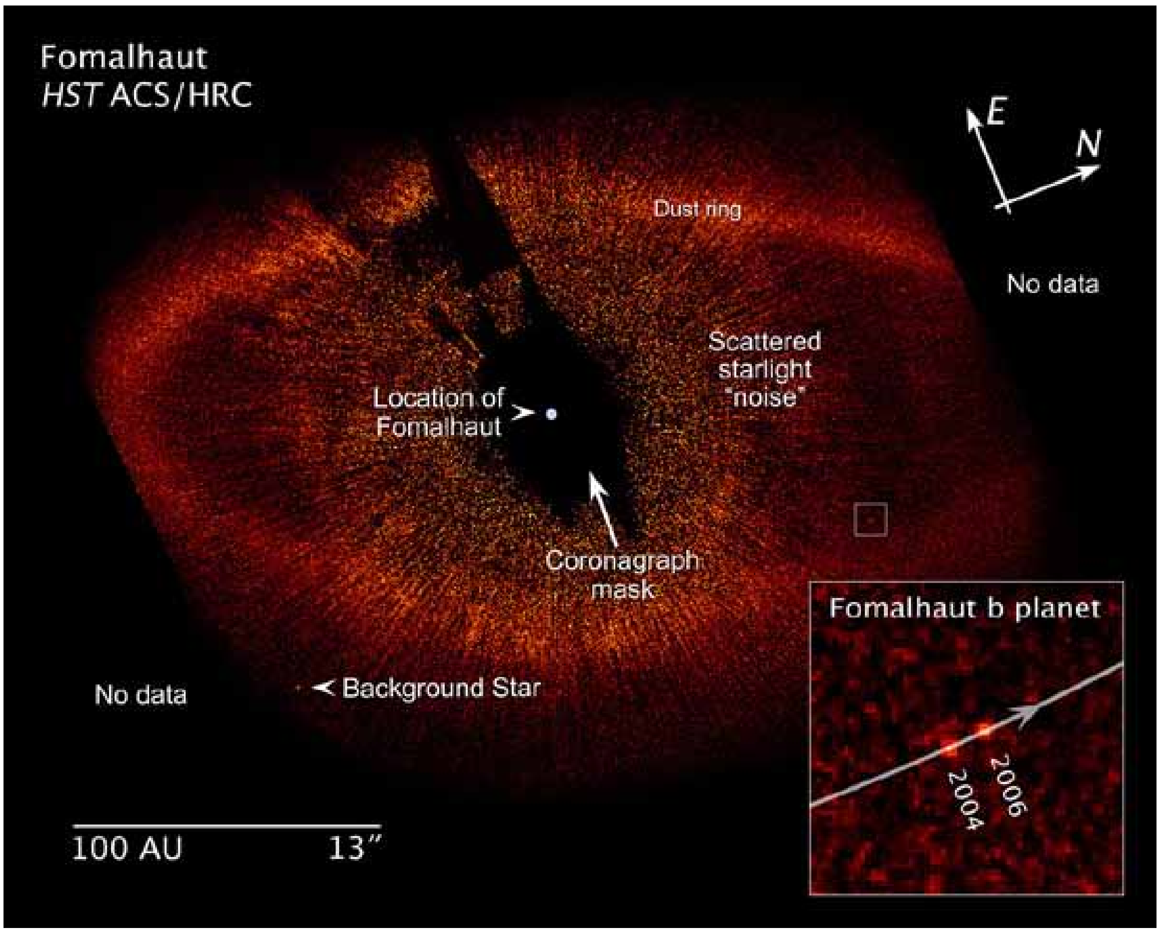
Note the importance of orientation in using the transit method to find exoplanets. Image © Museum of Science

What role does perspective play?

An important note about transits: they are dependent on the perspective of the viewer. Think of the rings of Saturn—sometimes, they appear to be knife-edge thin, or even invisible from Earth; at other times, they appear as wide bands. The rings themselves are not changing, but our perspective is. This is a result of our orbital position in relation to the tilt and position of Saturn in its own orbit. If an exoplanet's orbit crosses in front of its star from our perspective, then we will see it. However, if that exoplanet orbits in a plane at a high enough angle to our point of view, we will never see a transit. If a star does not show evidence of a transit, this does not mean that there are no planets orbiting that star.

METHOD 3: DIRECT IMAGING

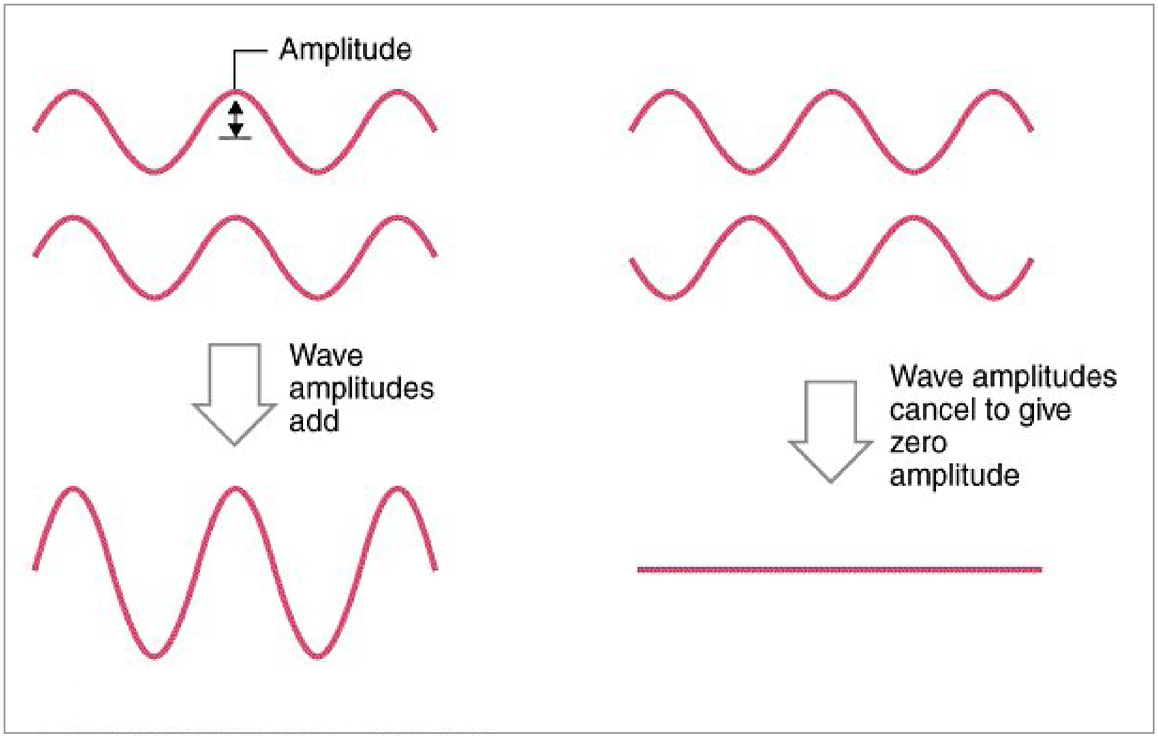
As mentioned before, it is exceptionally difficult to directly image (essentially "photograph" in either the visible or infrared wavelengths) an exoplanet. Until very recently, exoplanets could only be "seen" when the planet was hugely massive, at a great distance from its star, or still hot enough from accretion that it emitted significant infrared radiation. Even then, these planets still appear to us as only a dot of light.



Fomalhaut b is one of the few exoplanets to be directly imaged. It was discovered in 2008 using photographs from the Hubble Space Telescope. Image Credit: NASA, ESA, P. Kalas, J. Graham, E. Chiang, E. Kite (Univ. California, Berkeley), M. Clampin (NASA/Goddard), M. Fitzgerald (Lawrence Livermore NL), K. Stapelfeldt, J. Krist (NASA/JPL)

How can we take pictures of exoplanets?

Over the past several years, astronomers have had some success detecting planets using new tools and techniques. One such improvement is the use of **coronagraphs,** which are disc-shaped telescope attachments designed to block out the light of the star. Think of a total solar eclipse—when our Sun's light is blocked out by our Moon, startling solar surface features like prominences suddenly become visible at the edges of the Sun's disk. Another new technique called **interferometry** involves cancelling out the wavelengths of light from the star using destructive interference, leaving dimmer light sources surrounding the star visible.



Representation of constructive and destructive interference. Interferometry uses the concept of destructive interference to cancel out the light emitted by a star in the hopes of revealing a planet in orbit.

TEACHER TIP

ASK YOUR STUDENTS: What methods and tools do you think will be used for future discoveries of exoplanets? To find out, visit planetquest.jpl.nasa.gov and click on "exoplanet missions."

Glossary of Terms

UNDISCOVERED WORLDS

Absorption lines Indicators of an atom's change in energy state. They are visible as dark lines in a spectrograph, and each line is like the unique fingerprint of a particular element within the object being observed.

Accretion The process of accumulating dust and gas, usually through collision, into larger objects within a protoplanetary disk.

Astronomical unit (AU) A unit of measurement for distances in space. This unit is based on the distance from the Earth to the Sun, which is equal to 1 AU.
1 AU = 92,955,807 miles.

Blueshift The shortening of the wavelength of light coming from an object. Detection of this shortening, often by the shift of expected wavelengths toward the blue end of the spectrum of visible light, can indicate a star orbiting toward the observer. This is useful in the "wobble" method of exoplanet detection.

Candidate exoplanet This type of planet has been detected to exhibit the characteristics of a transiting exoplanet but has not been confirmed by ground-based observations.

Confirmed exoplanet This type of planet has been detected to exhibit the characteristics of a transiting exoplanet and has been confirmed by ground-based observations.

Coronagraph A disc-shaped telescope attachment designed to block out the light of a star. This attachment could be useful for directly imaging planets.

Dwarf planet An object that (a) orbits the Sun and (b) has sufficient mass to assume a nearly round shape, but (c) may orbit in a zone that has other objects in it. There are currently five accepted dwarf planets: Ceres, Pluto, Eris, Makemake, and Haumea.

Exoplanet A planet found orbiting a star outside our solar system. In some cases, more than one exoplanet is discovered orbiting the same star, making it part of a multiple planetary system.

Habitable zone The distances within which a planet must orbit its star to support liquid water (neither too close/hot nor too far/cold).

Hot Jupiter Exoplanets that are roughly the same mass as Jupiter (or larger), but which orbit extremely close to their star.

Ice line The distance from a star beyond which temperatures are low enough to allow water to freeze into ice.

Interferometry A technique used to directly image exoplanets that involves applying destructive interference to star light in order to effectively cancel it out.

Light year The distance that light can travel in a vacuum in one Earth year (equivalent to approximately 6 trillion miles). This unit can be used to measure both distance and time.

Nebula An interstellar cloud of dust and gas (predominantly hydrogen and helium) from which stars and planets are often formed.

Orbital period The time it takes an object to complete a full orbit of another object.

Planet A celestial body that (a) orbits a star, (b) has sufficient mass to assume a nearly round shape, and (c) has cleared the neighborhood around its orbit, which means it is free of other large objects because the forming planet has accreted most of the nearby available material.

Planetesimals Celestial bodies formed by accretion within a protoplanetary disk. These are the beginnings of larger bodies like asteroids, moons, or planets.

Protostar A large mass in a nebula that represents the early stages of star formation. It is still accreting matter from the nebula because it has not yet initiated nuclear fusion.

Pulsar Rotating neutron stars that emit pulses of electromagnetic radiation.

Redshift The lengthening of the wavelength of light coming from an object. Detection of this lengthening, often by the shift of expected wavelengths toward the red end of the spectrum of visible light, can indicate a star orbiting away from the observer. This is useful in the "wobble" method of exoplanet detection.

Solar system A collection of objects, such as planets, dwarf planets, moons, asteroids, and comets that orbit a star. "Solar system" also refers to our own planetary system, orbiting the Sun.

Super-Earth An exoplanet that is 2 – 10 times the mass of Earth. This term only applies to mass and is not meant to imply any similarity to other Earth-like characteristics, such as temperature or habitability. In fact, many Super-Earths are too close to their stars and, thus, too hot to support life.

Transit The observed passage of an exoplanet in front of its parent star, viewed as a dip in the amount of light normally emitted by a star.

Online Learning Tools

UNDISCOVERED WORLDS

These websites are intended to provide access to further information about exoplanets for teachers and middle and high school students. They largely provide information regarding the history, methods, and technology behind the search for exoplanets.

HubbleSite: Discovering Planets Beyond

Provides videos and information on planet formation and planet hunting strategies.

hubblesite.org
and click on "Extrasolar Planets."

Kepler: A Search for Habitable Planets

The homepage for the Kepler mission. Contains information on the transit method and updated discoveries.

kepler.nasa.gov

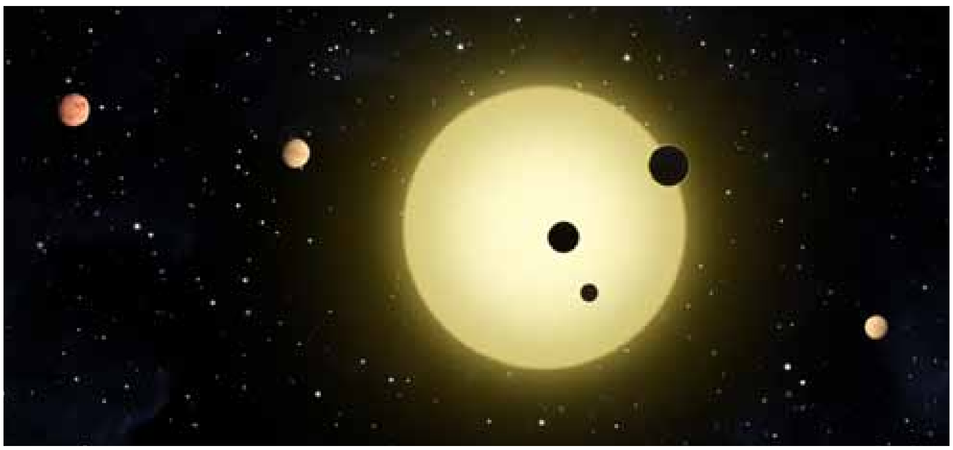
PlanetQuest: Exoplanet Exploration

Provides a comprehensive overview of the history, methods, and technology of finding exoplanets.

planetquest.jpl.nasa.gov

Exoplanets in the News

Because new telescopes and planet-finding techniques are now constantly in development, exoplanets are being identified faster than ever before. This section summarizes some of the latest discoveries in the search for exoplanets and will be updated regularly. Check back for more news!



Kepler-11 is a Sun-like star around which six exoplanets orbit. At times, two or more planets pass in front of the star at once, as shown in this artist's conception of a simultaneous transit of three planets observed by NASA's Kepler spacecraft on August 26, 2010.

Image credit: NASA/Tim Pyle

Kepler-11 System *Announced February 2, 2011*

Kepler-11 is a yellow dwarf star, quite similar to our Sun. Located in the constellation Cygnus, this star is about 2,000 light years away. This means that the light we are seeing right now was originally sent out into space around AD 11 (in Earth years). This star is especially exciting because it has been confirmed to host a system of six exoplanets—the largest group of planets yet discovered outside our own solar system.

These planets, lettered "b" through "g," all occupy orbits very close to their star, making the system very compact. Five of the planets orbit closer to Kepler-11 than Mercury does to our Sun. The sixth planet occupies an orbit closer to Kepler-11 than the orbit of Venus around our Sun.

Kepler Discovery Bonanza *Announced February 2, 2011*

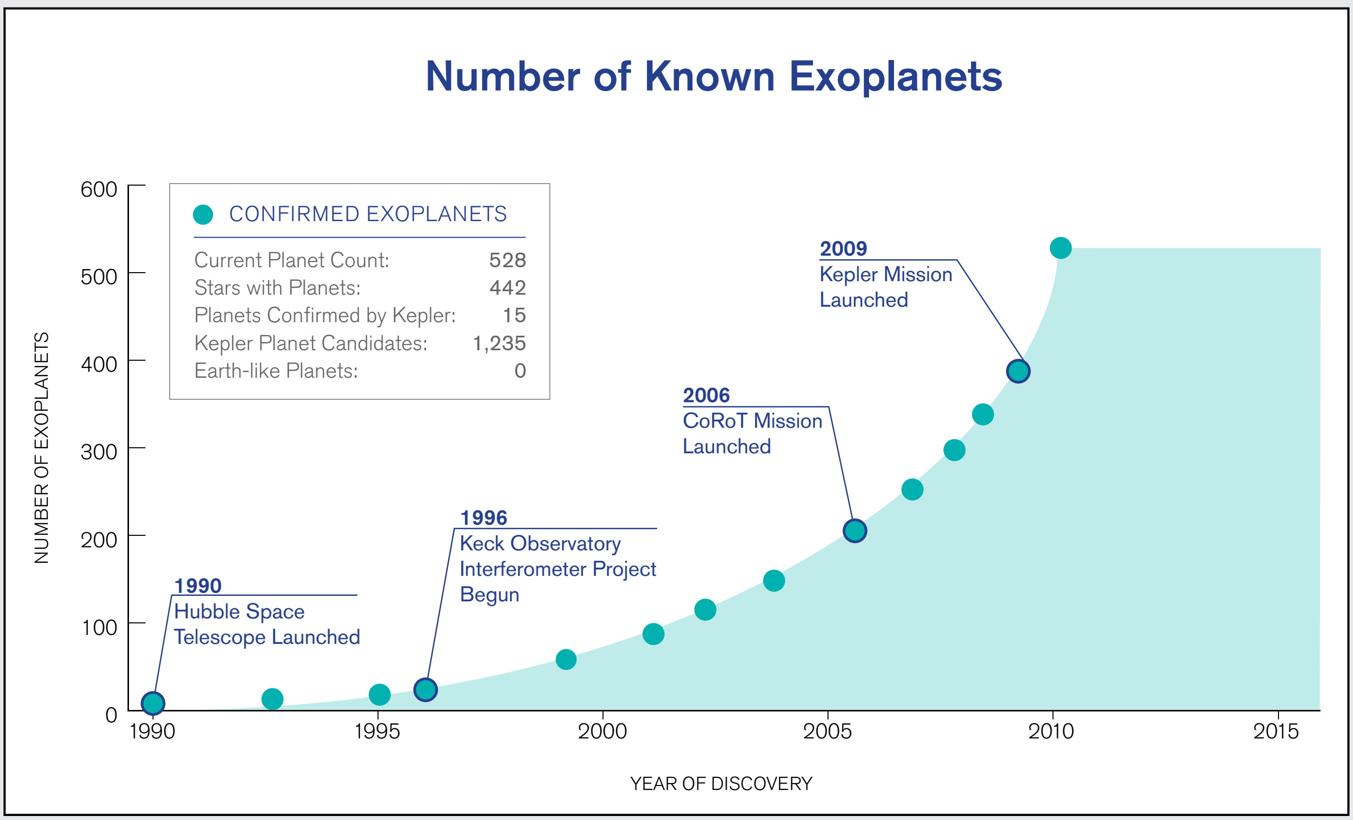
The number of planet candidates identified by Kepler recently increased to 1,235. Approximately 68 of those candidates are Earth-sized, and 54 of those 1,235 candidates orbit within their star's habitable zone. Perhaps most excitingly, five of the Earth-sized candidates are located in habitable zones. These discoveries, though not yet officially confirmed, could actually bring us closer to finding Earth-like planets capable of supporting life!

Facts and Figures

Space-based missions provide some of the clearest measurements of exoplanets because they are free of the interference of the Earth's atmosphere. Ground-based observatories also continue to provide valuable services both as support to these missions and as independent discoverers of exoplanets. With the rapid pace of improving technology, new missions and telescopes are being designed and constructed almost constantly.

CURRENTLY DISCOVERED EXOPLANETS (AS OF FEBRUARY 2011)

Since 1995, exoplanet discoveries have increased almost exponentially. This is an exciting modern example of the constant improvements in scientific technologies and scientific methods that lead to new discoveries.



DURING YOUR VISIT

Related Museum Programming ▪ Live Planetarium Shows

CLASSROOM ACTIVITIES

Grades 3 – 5 ▪ Grades 6 – 8 ▪ Grades 9 – 12

Classroom Activities (Grades 3 – 5)

The following activities are designed to help you introduce your students to the concept of exoplanets. Use them before your Museum visit to maximize your field trip experience.

BEFORE YOUR VISIT

ACTIVITY 1

OUR PLACE IN SPACE

Our own solar system may seem incredibly large (and it is!), but it is only a very small piece of our galaxy, and our galaxy is only a tiny piece of the entire universe. Here on Earth, it can be hard to visualize how tiny we really are in the grand scheme of things.

- Print the graphic of a star with planets provided on page 37 and hold up the sheet of paper in the front of the classroom.
- Ask students what they see from their desks, then take the sheet across the room. Ask them what they can still see.
- Ask your students why they can't see some of the objects anymore. Continue taking the paper farther and farther away until the students can only see the star. Explain that this is how our solar system might appear from another star with its own planets.

ACTIVITY 2

EXOPLANET SCOOP!

- Ask students to research a recent exoplanet discovery and write a short news article about it. They can choose a specific planet or a whole planetary system.
- Compile these articles into a newsletter to distribute to the entire class. The latest news can be found in several places, including the Kepler mission website (kepler.nasa.gov), the PlanetQuest website (planetquest.jpl.nasa.gov), and the European Space Agency's CoRoT mission website (esa.int/esaMI/COROT/index.html).

ACTIVITY 3

EXTREME PLANET MAKEOVER

planetquest.jpl.nasa.gov (click on "Extreme Planet Makeover")

This interactive program allows students to create their own exoplanetary system by adjusting variables such as distance from star, planet size, star type, and planet age.

National Standards

- Abilities necessary to do scientific inquiry
- Understanding about science and technology
- Science as a human endeavor
- Position and motion of objects
- Light, heat, electricity, and magnetism
- Objects in the sky

Massachusetts Frameworks

- The Earth in the solar system

Classroom Activites (Grades 3 – 5)

BACK IN THE CLASSROOM *(Instructions for activity on page 39)*

Student activity sheets are largely intended for use after your field trip, building on information provided during the show. An answer key is provided on page 40.

STUDENT ACTIVITY SHEET

DESIGN AN EXOPLANET

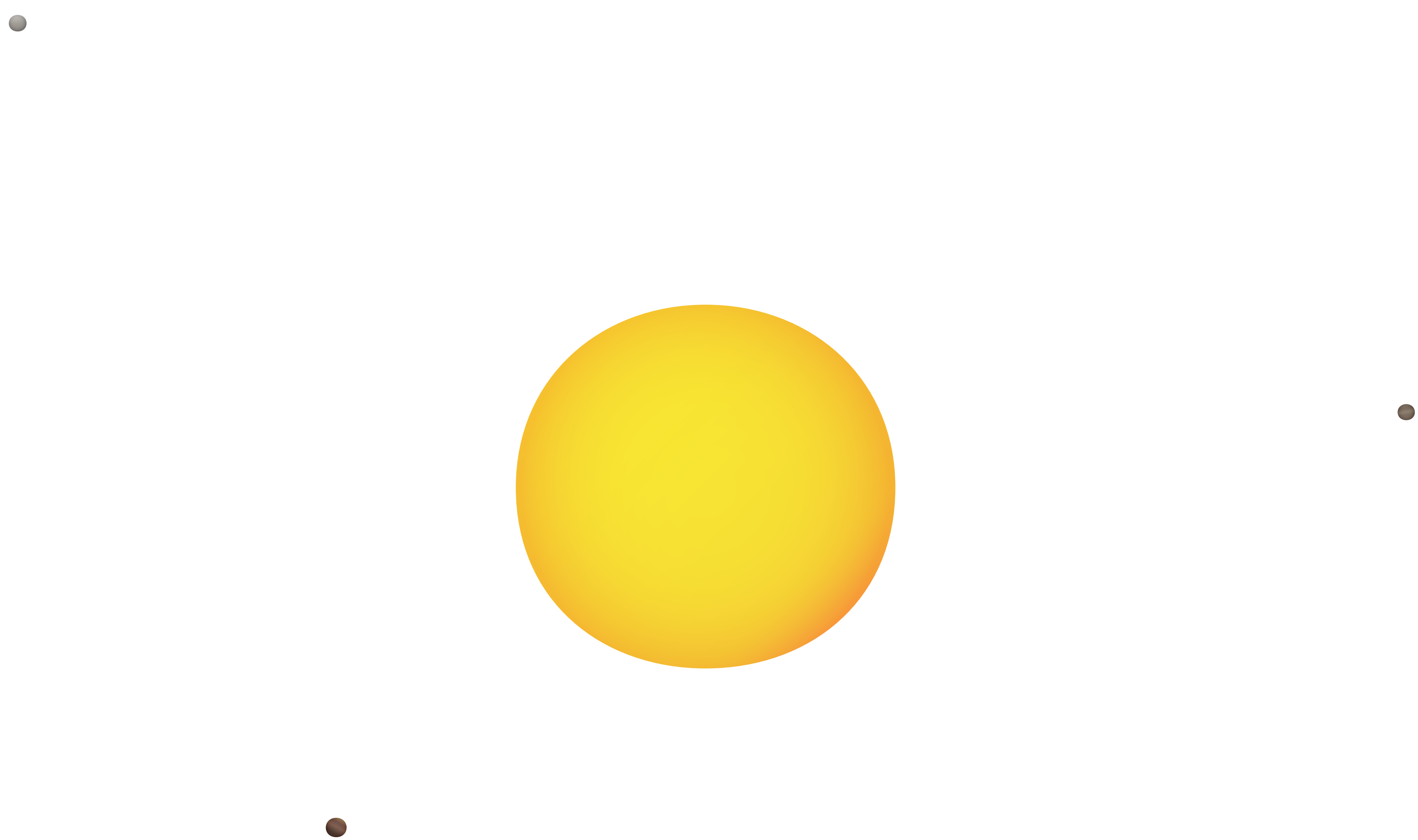
Photocopy the student activity sheet on page 39 for your students. Instruct your students to choose the characteristics of their own alien world, then draw what they imagine it would look like.

To gauge what the students observed on their field trip, you could have them do this exercise both before and after your field trip. Has their planet changed based on the new information they learned?

TEACHER TIP

ASK YOUR STUDENTS THESE GUIDED QUESTIONS RELATED TO EDUCATION STANDARDS:

- How do you define a planet's "year"?
- What does it mean if a planet is part of a "solar system"?
- If a star looks like it is dimming regularly, what might this tell us? (Hint: Is something blocking the light?)
- Why is Mercury hotter than Earth?
- Could life survive on Mercury? Why or why not?
- What makes Earth special compared to any other planet?



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Student Activity (Grades 3 – 5)

Design an Exoplanet!

Name: ______________________________

Imagine you are standing on the surface of a planet in another solar system. Look around: what do you see? Are there trees? Water? Is it mountainous or flat? Is the sky blue? Maybe it's red, or maybe there's no sky at all and you can see the stars during the day. How big does the Sun look? So far we have not found any planets like our Earth, and the view from any planet would look different from what we normally expect.

Fill in the blanks below to decide what characteristics your planet will have, then draw the surface of your planet in the box.

Name of planet: ______________________________

Size of the star (big, small, etc.): ______________________________

Color of the sky: ______________________________

Water? (yes or no): ______________________________

Surface type (hilly or flat?): ______________________________

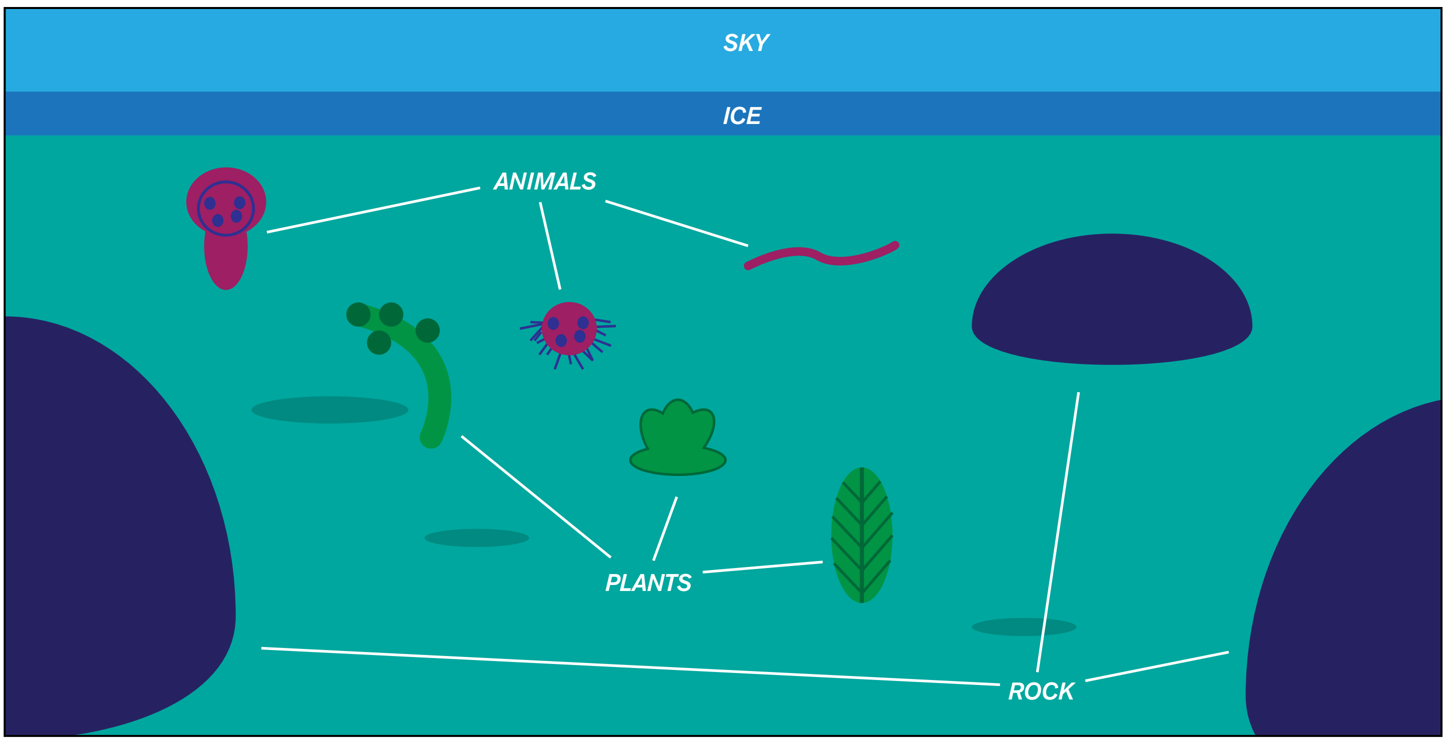
Life? (yes or no): ______________________________

Design an Exoplanet!

EXAMPLE/ANSWER KEY

Imagine you are standing on the surface of a planet in another solar system. Look around: what do you see? Are there trees? Water? Is it mountainous or flat? Is the sky blue? Maybe it's red, or maybe there's no sky at all and you can see the stars during the day. How big does the Sun look? So far we have not found any planets like our Earth, and the view from any planet would look different from what we normally expect.

Fill in the blanks below to decide what characteristics your planet will have, then draw the surface of your planet in the box.



Name of planet: *CORO*

Size of the star (big, small, etc.): *MEDIUM*

Color of the sky: *GREENISH-BLUEISH*

Water? (yes or no): *YES, REGULAR AND ICY*

Surface type (hilly or flat?): *ICY AND COLD*

Life? (yes or no): *YES*

Classroom Activities (Grades 6 – 8)

The following activities are designed to help you introduce your students to the concept of exoplanets. Use them before your Museum visit to maximize your field trip experience.

BEFORE YOUR VISIT

ACTIVITY 1

EXOPLANET SCOOP!

- Ask students to research a recent exoplanet discovery and write a short news article about it. They can choose a specific planet or a whole planetary system.
- Compile these articles into a newsletter to distribute to the entire class. The latest news can be found in several places, including the Kepler mission website (kepler.nasa.gov), the PlanetQuest website (planetquest.jpl.nasa.gov), and the European Space Agency's CoRoT mission website (esa.int/esaMI/COROT/index.html).

ACTIVITY 2

EXTREME PLANET MAKEOVER

planetquest.jpl.nasa.gov (click on "Extreme Planet Makeover")

This interactive program allows students to create their own exoplanetary system by adjusting variables such as distance from star, planet size, star type, and planet age.

ACTIVITY 3

THE HISTORY OF EXOPLANETS

nasa.gov/externalflash/PQTimeline

Follow an interactive timeline chronicling scientists and discoveries related to the search for exoplanets.

ACTIVITY 4

WE COME IN PEACE!

Your class has been asked to help design a probe to send to the nearest known exoplanet (Epsilon Eridani b, 10.5 light years away). Have your students work together to make a list of the items that should be included with the probe. Things to keep in mind: What would you like to measure (temperature, distance from star, atmosphere, etc.)? What type of fuel should you use? Will it return to Earth? Should you include a message with the probe, in case intelligent life finds it? What language will you use? Explain to students that we cannot send astronauts on this mission because the trip will take much longer than a human lifespan (about 70 – 80 years).

National Standards

- Abilities necessary to do scientific inquiry
- Understanding about science and technology
- Science as a human endeavor
- Motions and forces
- Transfer of energy
- Earth in the solar system

Massachusetts Frameworks

- The Earth in the solar system
- Properties of matter
- Motion of objects

Classroom Activities (Grades 6 – 8)

BACK IN THE CLASSROOM *(Instructions for activities on pages 43, 44, and 47)*

Student activity sheets are largely intended for use after your field trip, building on information provided during the show. Answer keys are provided on pages 45 – 46 and 48.

STUDENT ACTIVITY SHEET 1

SOLAR SYSTEM MOTIONS: PART 1

Photocopy the student activity on page 43 for your students. Students will determine the characteristics that might be expected in an exoplanet system, using our own solar system as a model.

SOLAR SYSTEM MOTIONS: PART 2

Photocopy the student activity on page 44 for your students. Building on the activity from part 1, they will also design their own exoplanet system and explain the mechanics behind their design.

STUDENT ACTIVITY SHEET 2

ROAD TRIP!

Photocopy the student activity on page 47 for your students. Students will determine the resources needed to sustain life during a long trip through space. This journey will be an analog for understanding and identifying what resources are necessary for supporting the existence of life.

TEACHER TIP

ASK YOUR STUDENTS THESE GUIDED QUESTIONS RELATED TO EDUCATION STANDARDS:

- What is an exoplanet?
- A planet is transiting its star. What will we see? How can we turn what we see into a graph? What will that graph tell us?
- What keeps planets in motion around their stars?
- What kind of force do both stars and planets exert on each other?
- The exoplanets we have found so far are within our own galaxy. Do you think other galaxies might also have planets?
- What makes Earth special compared to any other planet?

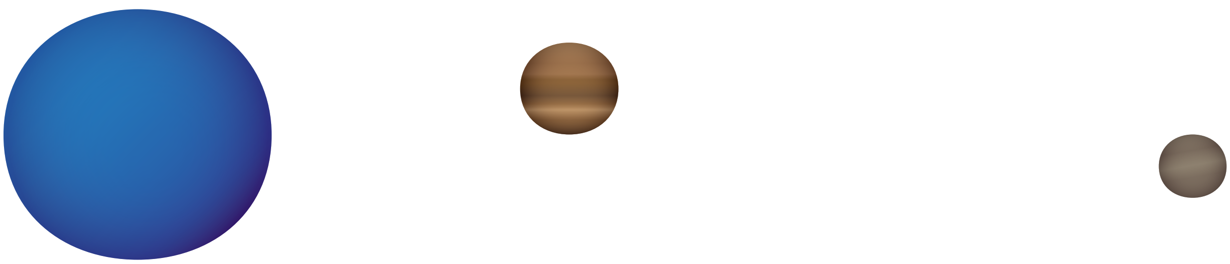
Student Activity (Grades 6 – 8)

Solar System Motions: Part 1

Name: ____

Even though exoplanets orbit distant stars, they follow many of the same trends as our own solar system. In fact, looking for exoplanets has taught scientists about what our solar system might have been like in the past and might be like in the future. Think about our own solar system—how long does it take Mercury to orbit the Sun once? What about Jupiter? Would the warmest planets be located closer to or farther from the Sun?

Look at the exoplanet systems drawn below and make some assumptions about what they are like.

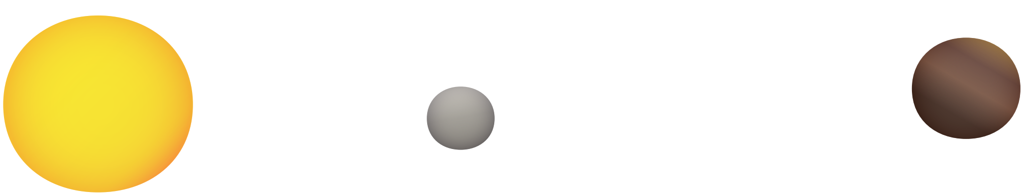


Star A   Planet A1   Planet A2

Star A is a blue supergiant. Stars like this can be 5 times hotter than our Sun and 16 times as big.

Which planet orbits Star A faster? ____

Which planet is hotter? ____



Star B   Planet B1   Planet B2

Star B is a yellow dwarf, very similar in size and temperature to our own Sun.

Which planet orbits Star B more slowly? Why? ____

Which planet is hotter? ____

Student Activity (Grades 6 – 8)

Solar System Motions: Part 2

Name: ____________________

Thinking about what you now know about exoplanet systems, design your own!

1) Choose your star. You can choose whatever kind of star you want. Remember that bluer stars are hotter, while redder stars are cooler.

2) Draw your planets. Your system must have 6 planets, but you can choose whether they are gas giants (like Jupiter, or even bigger), terrestrial planets (like Earth), or a mix or both.

3) Which planet supports life? At least one planet must be able to support life. Draw an arrow labeling which of your planets could have life and explain why you drew it/them where you did.

4) How long is a year? Label each planet with the amount of time it takes to go around its star once (its "year"). Your answers can range from a couple of hours to hundreds of years.

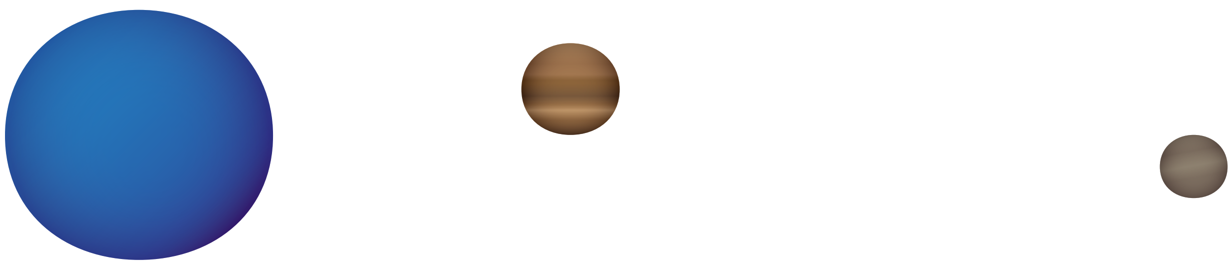
Describe your exoplanet system:

Solar System Motions: Part 1

EXAMPLE/ANSWER KEY

Even though exoplanets orbit distant stars, they follow many of the same trends as our own solar system. In fact, looking for exoplanets has taught scientists about what our solar system might have been like in the past and might be like in the future. Think about our own solar system—how long does it take Mercury to orbit the Sun once? What about Jupiter? Would the warmest planets be located closer to or farther from the Sun?

Look at the exoplanet systems drawn below and make some assumptions about what they are like.

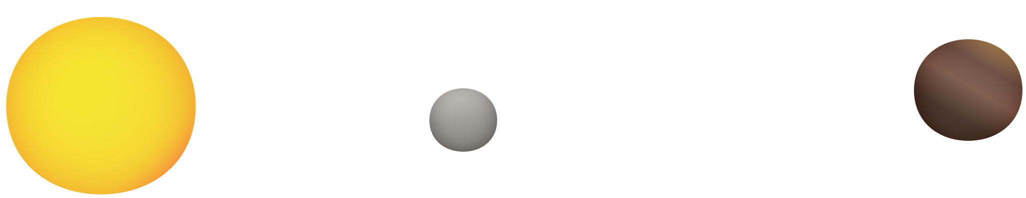


Star A — Planet A1 — Planet A2

Star A is a blue supergiant. Stars like this can be 5 times hotter than our Sun and 16 times as big.

Which planet orbits Star A faster? *PLANET A1.*

Which planet is hotter? *PLANET A1.*



Star B — Planet B1 — Planet B2

Star B is a yellow dwarf, very similar in size and temperature to our own Sun.

Which planet orbits Star B more slowly? Why? *PLANET B2. IT IS FARTHER AWAY FROM STAR B.*

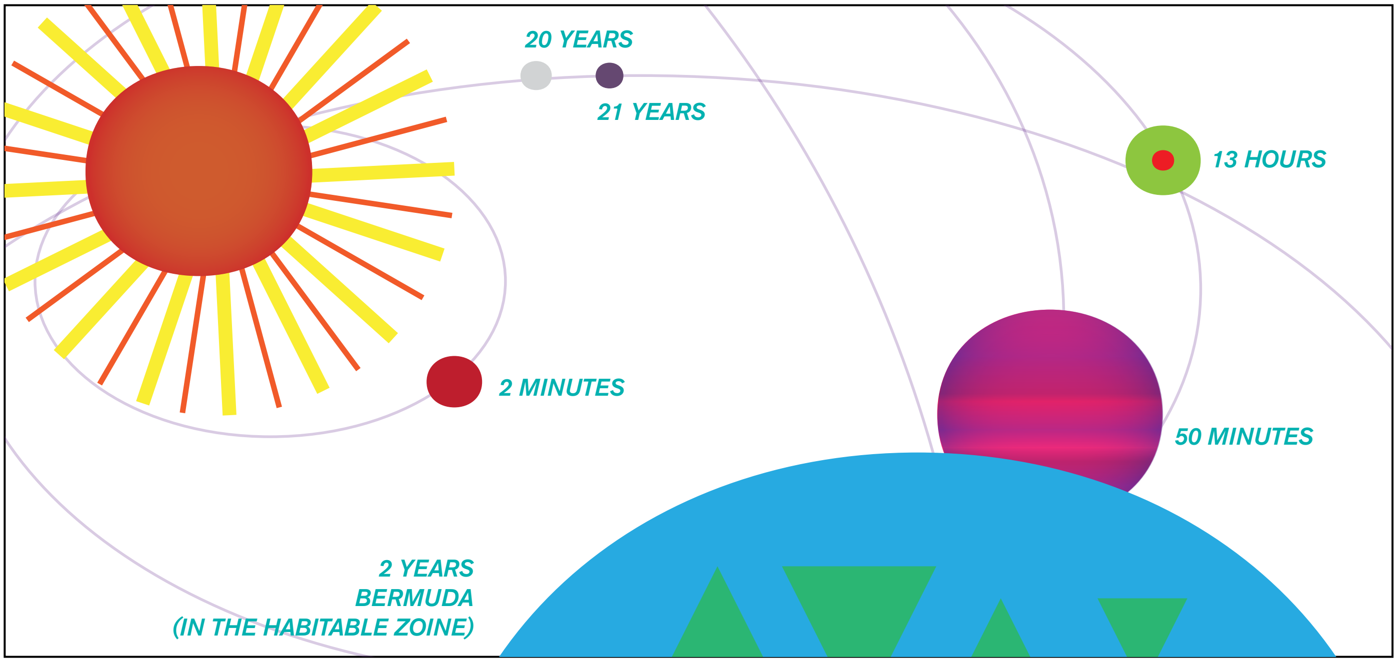
Which planet is hotter? *PLANET B1.*

Solar System Motions: Part 2

UNDISCOVERED WORLDS

EXAMPLE/ANSWER KEY

Thinking about what you now know about exoplanet systems, design your own!



1) Choose your star. You can choose whatever kind of star you want. Remember that bluer stars are hotter, while redder stars are cooler.

2) Draw your planets. Your system must have 6 planets, but you can choose whether they are gas giants (like Jupiter, or even bigger), terrestrial planets (like Earth), or a mix or both.

3) Which planet supports life? At least one planet must be able to support life. Draw an arrow labeling which of your planets could have life and explain why you drew it/them where you did.

THE PLANET(S) SUPPORTING LIFE SHOULD NOT BE RIGHT NEXT TO THEIR STAR, NOR SHOULD THEY BE VERY FAR AWAY. YOU'RE LOOKING FOR A PLANET A "MODERATE" DISTANCE FROM ITS STAR.

4) How long is a year? Label each planet with the amount of time it takes to go around its star once (its "year"). Your answers can range from a couple of hours to hundreds of years.

THE YEARS MUST GET LONGER THE FARTHER THE PLANET IS FROM ITS STAR.

Describe your exoplanet system:

THIS IS A VERY HOT EXOPLANET SYSTEM. THE EARTH-LIKE PLANET IS AT THE VERY EDGE OF THE HABITIABLE ZONE. THE LAND FORMED INTO GREEN TRIANGLES BECAUSE THE LIFE FORMS ARE ABLE TO TERRA FORM. THE ALIENS ARE COOL.

Student Activity (Grades 6 – 8)

Road Trip!

Name: ______________________________

You are leaving Earth to visit our nearest known exoplanet, Epsilon Eridani b, 10.5 light years away. Even though that may sound close, it is actually more than 60,000,000,000,000 miles, which means that you need to pack for a long trip. There is nowhere to stop for supplies along the way, so you have to make sure that you can survive on whatever you bring. Space is limited, so you can only pack the absolute necessities (think carefully before you pack that iPod!).

List five things you think YOU WILL NEED TO SURVIVE and why you are packing them:

ITEM	REASON FOR PACKING THE ITEM
1)	
2)	
3)	
4)	
5)	

If aliens were to look at Earth, what do you think they would see to tell them that life exists on our planet?

____

____

____

____

____

Road Trip!

EXAMPLE/ANSWER KEY

You are leaving Earth to visit our nearest known exoplanet, Epsilon Eridani b, 10.5 light years away. Even though that may sound close, it is actually more than 60,000,000,000,000 miles, which means that you need to pack for a long trip. There is nowhere to stop for supplies along the way, so you have to make sure that you can survive on whatever you bring. Space is limited, so you can only pack the absolute necessities (think carefully before you pack that iPod!).

List five things you think YOU WILL NEED TO SURVIVE and why you are packing them:

	ITEM	REASON FOR PACKING THE ITEM
1)	*WATER*	*YOU NEED WATER TO DRINK TO SURVIVE.*
2)	*AIR*	*YOU NEED AIR TO BREATHE TO SURVIVE.*
3)	*FOOD*	*YOU NEED FOOD TO EAT FOR ENERGY.*
4)	*HEAT*	*SPACE IS COLD! YOU WILL NEED HEAT (AND, TO SOME EXTENT, COOLING SO YOU DON'T OVERHEAT) TO KEEP CRITICAL BODILY FUNCTIONS WORKING.*
5)	*ELECTRICITY*	*ELECTRICITY WILL PROVIDE ENERGY/ POWER FOR PROPULSION, LIGHTS, HEAT, ETC.*

If aliens were to look at Earth, what do you think they would see to tell them that life exists on our planet?

TREES.

AN ATMOSPHERE (WITH OXYGEN AND CARBON DIOXIDE).

LIQUID WATER.

OBJECTS NOT FOUND IN NATURE, SUCH AS BUILDINGS, SATELLITES.

Classroom Activites (Grades 9 – 12)

The following activities are designed to help you introduce your students to the concept of exoplanets. Use them before your Museum visit to maximize your field trip experience.

BEFORE YOUR VISIT

ACTIVITY 1

THE HISTORY OF EXOPLANETS

nasa.gov/externalflash/PQTimeline

Follow an interactive timeline chronicling scientists and discoveries related to the search for exoplanets. A running tally shows how the number of exoplanets has grown rapidly since the discovery of 51 Pegasi b in 1995. In fact, we have discovered more than 150 new planets in just the last two years!

ACTIVITY 2

KEPLER EXOPLANET TRANSIT HUNT

kepler.nasa.gov (Click on "Multimedia," then "Interactives")

Kepler uses the information provided by the transit of an exoplanet to determine a number of variables regarding its size and mass. This interactive program allows students to collect and input data on different stars in order to determine these variables for themselves.

National Standards

- Abilities necessary to do scientific inquiry
- Understanding about science and technology
- Science as a human endeavor
- Motions and forces
- Origin and evolution of the Earth system

Massachusetts Frameworks

- The origin and evolution of the universe

Classroom Activites (Grades 9 – 12)

BACK IN THE CLASSROOM *(Instructions for activity sheet on page 51)*

Student activity sheets are largely intended for use after your field trip, building on information provided during the show. An answer key is provided on page 52.

STUDENT ACTIVITY SHEET

USING THE TRANSIT METHOD

Photocopy the student activity on page 51 for your students. Students will determine what a transit graph should look like in comparison to a graph of other astronomical phenomena. They will also use the transit method to determine the orbital period of an exoplanet.

TEACHER TIP

ASK YOUR STUDENTS THESE GUIDED QUESTIONS RELATED TO EDUCATION STANDARDS:

- What is a light year?
- Could we travel to another exoplanet within our lifetime?
- We have discovered some exoplanets that are still forming from a nebula. How might those planets change over time?
- Why are many of the exoplanets we have discovered very large and very close to their stars? Does this mean that other types of planets are unlikely to exist?
- What kinds of factors should we consider when looking for an exoplanet that might have life?
- Why is the number of discovered exoplanets constantly increasing?

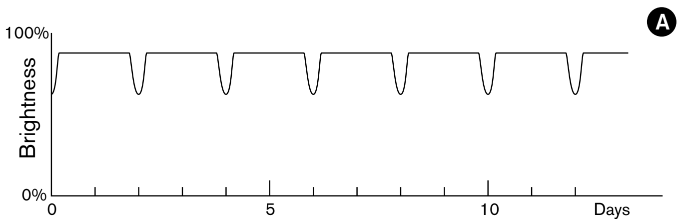
Student Activity (Grades 9 – 12)

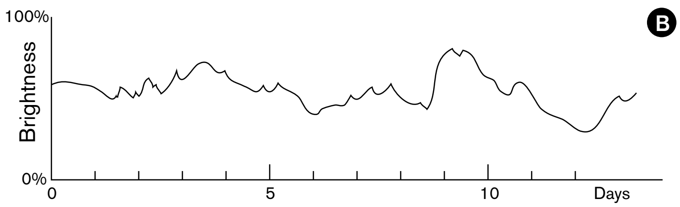
Using the Transit Method

Name: ____________________

Astronomers can use the transit method to tell them many things about a planet. First, they can count the time between dips in brightness to tell them how long it takes the planet to travel around the star. The first measured dip represents when the planet is between the observer and the star; the next dip would represent when the planet has orbited all the way around the star to return to the same place (its "orbital period").

Look at the graphs below. Which one might represent a transit, and which one might represent "noise"?





Real transit graph: ____________________

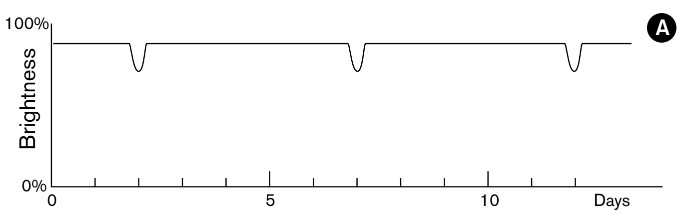
"Noise" transit graph: ____________________

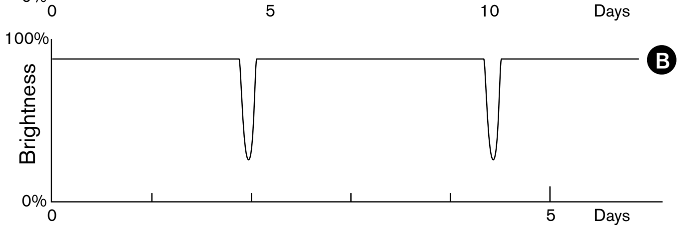
How long does it take the planet in the real transit graph to complete one orbit?

____________________**days**

Transits can also indicate the relative size of an exoplanet. For example, the bigger the planet, the more light it will block out as it transits its star. Look at the graphs below.

Which graph represents a bigger planet? How long is the orbital period for both graphs?





Bigger planet ____________________

Graph A period ____________________**days**

Graph B period ____________________**days**

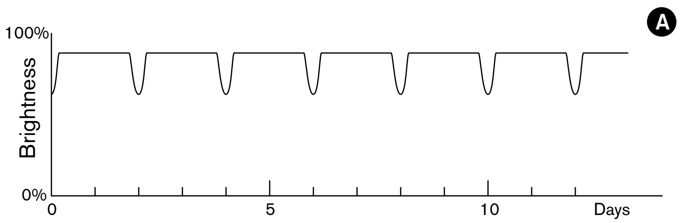
Student Activity (Grades 9 – 12)

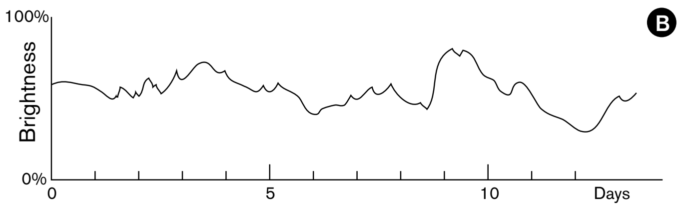
Using the Transit Method

EXAMPLE/ANSWER KEY

Astronomers can use the transit method to tell them many things about a planet. First, they can count the time between dips in brightness to tell them how long it takes the planet to travel around the star. The first measured dip represents when the planet is between the observer and the star; the next dip would represent when the planet has orbited all the way around the star to return to the same place (its "orbital period").

Look at the graphs below. Which one might represent a transit, and which one might represent "noise"?





Real transit graph: GRAPH A

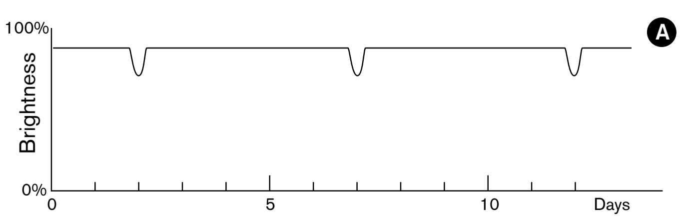
"Noise" transit graph: GRAPH B

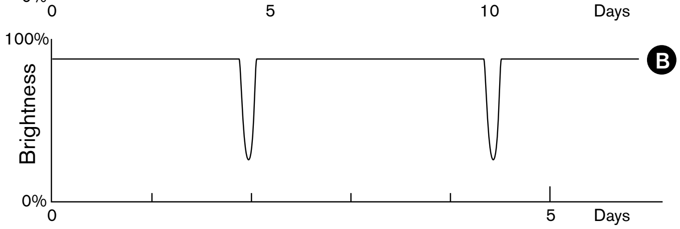
How long does it take the planet in the real transit graph to complete one orbit?

2 **days**

Transits can also indicate the relative size of an exoplanet. For example, the bigger the planet, the more light it will block out as it transits its star. Look at the graphs below.

Which graph represents a bigger planet? How long is the orbital period for both graphs?





Bigger planet GRAPH B

Graph A period 5 **days**

Graph B period 2.5 **days**