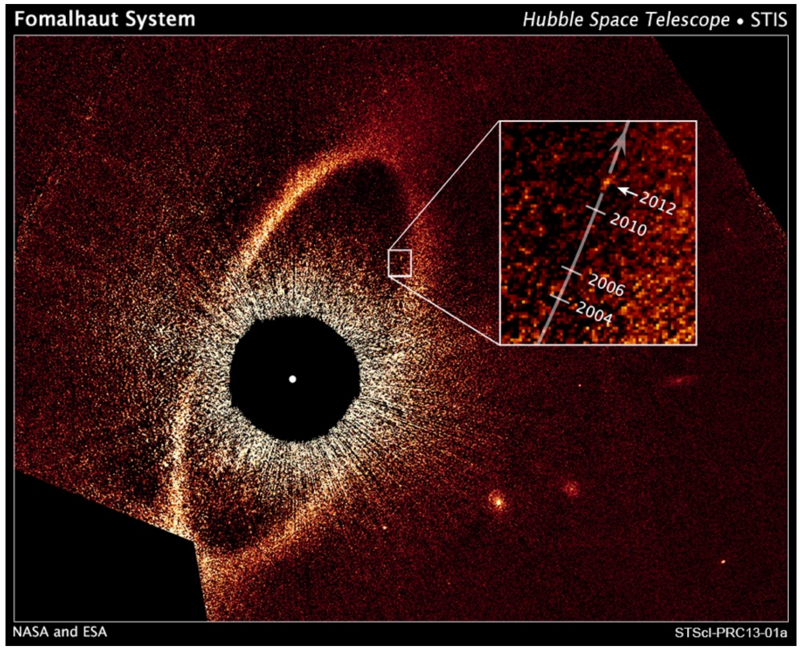
Activity 12: Planet Hunting



Are there planets in orbit around other stars besides the Sun? Today we will see that yes, planets do orbit around other stars! And, we will look at the two most common methods that astronomers have used to confirm that.

Planets around other stars are called "**extrasolar planets**" because they exist outside our solar system.

Extrasolar planets are far too small (compared to stars) and too dim (they do not produce their own light; instead they just reflect their star's light) and much too far away for us to take a direct photograph of one (with extremely rare exceptions, such as the photograph above).

So, if planets are invisible to us because they are small, dim, and far away, how can we know that planets exist around other stars? That's what we'll investigate in today's Activity.

Part 1: The Doppler Effect and Light

In the Pre-Lab you learned about the Doppler Effect and saw that the Doppler Effect can happen with various kinds of waves, such as water waves or sound waves.

SQ1: Let's summarize the Doppler Effect below.

As a wave source moves (toward / away from) a detector, the frequency of the detected wave (increases / decreases).

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Recall from the homework about Light that there exists a *wave model for light* in which light is modeled as an electromagnetic wave. Therefore, does light also experience the Doppler Effect? Yes, it does! Let's investigate that now.

Astronomers don't observe sound waves coming from space, but they do observe light waves coming from space. Everything we did in the Pre-Lab with sound and water waves also applies to light waves.

For instance, in the Pre-Lab we could've just as easily done the Doppler Effect simulation with the wave source being a light bulb instead of a sound speaker, the detector being an eye instead of a microphone, and the speeds could've been in fractions of the speed of light instead of the speed of sound.

STEP 1: As we discussed above, for the Doppler effect to be noticeable, a wave source must be moving at a significant fraction of the wave speed. Electromagnetic waves move at the speed of light, which is roughly *670 million miles per hour*. Complete the following statement by filling in the blanks.

> For the Doppler effect of a *light source* to be noticeable, the wave source must
>
> be moving at a significant fraction of ________________________________.

Is the Doppler effect of light going to be noticeable in our everyday lives? Why or why not?

STEP 2: If a light source is moving toward you, what happens to the *frequency* of the light that you observe? Apply what you know about the Doppler Effect (see SQ1).

Remember, when dealing with electromagnetic radiation, the frequency determines *where on the electromagnetic spectrum* we are. In this case, the Doppler effect causes a wave to shift its location on the spectrum.

Color	Wavelength	Frequency
Red	620 – 750 nm	400 – 484 THz
Orange	590 – 620 nm	484 – 508 THz
Yellow	570 – 590 nm	508 – 526 THz
Green	495 – 570 nm	526 – 606 THz
Blue	450 – 495 nm	606 – 668 THz
Violet	380 – 450 nm	668 – 789 THz

If a light source that emits *yellow visible light* is moving *toward* you, which direction will it shift on the visible spectrum as a result of the frequency change (toward red or toward blue)? Consult the frequencies of the visible spectrum given in the table above.

If a light source that emits *yellow visible light* is moving *away from* you, which direction will it shift on the spectrum as a result of the frequency change (toward red or toward blue)?

SQ2: We call the above two effects **redshift** and **blueshift**. They are both consequences of the Doppler Effect when applied to light (electromagnetic waves). Let's summarize this below.

When a light source is moving (toward / away from) a detector, that detector will

detect a (blueshift / redshift) because of the Doppler effect.

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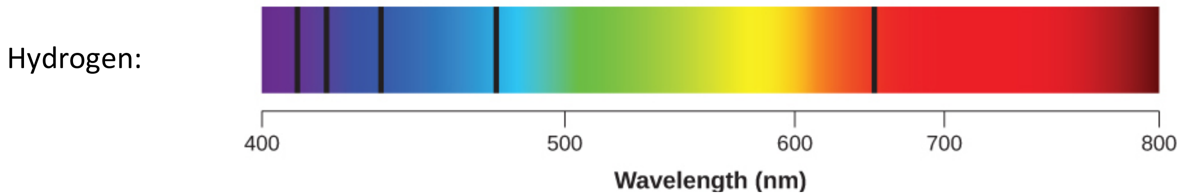
detect a (blueshift / redshift) because of the Doppler effect.

Aside: You may be wondering, if everything so far has an analog with light waves, then does that mean there's a "sonic boom for light" as well? The surprising answer is: yes! The speed of light through a medium (say underwater) is lower than the speed of light in vacuum, and therefore in some rare cases an object can move through a medium with a speed that *exceeds the speed of light in that medium* (although it still can never exceed the speed of light in vacuum). In those cases, we get the light equivalent of a sonic boom, which is called **Cherenkov Radiation** (named for the Soviet scientist that first detected it and for which he was awarded the Nobel Prize in 1958). Cherenkov Radiation has since been used in experiments as a means of detecting neutrinos passing through the Earth, among other things.

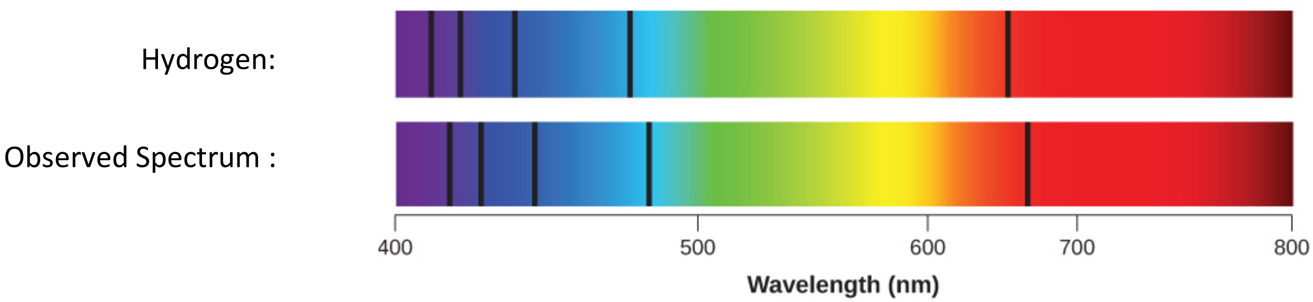
Now let's apply what we know about the Doppler Effect and look at spectral lines.

Below is the absorption spectrum for hydrogen that we've seen before.



Remember, this spectrum is like a “fingerprint” for hydrogen, meaning it is a pattern that is unique to hydrogen. The vertical lines are the precise wavelengths of light absorbed (or emitted) by the electrons in energy levels around a hydrogen atom.

Suppose you pointed your telescope and spectrometer at an astronomical object and recorded another spectrum. For ease of comparison, the hydrogen spectrum has been reproduced below with your observation directly below it.



STEP 3: Look carefully at the two spectra. How does the second compare to the first? What are the similarities and what are the differences?

Similarities:

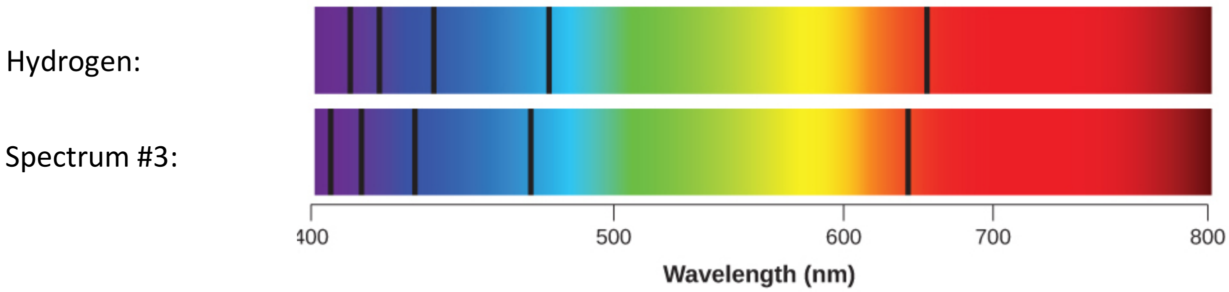
Differences:

a) What evidence do you see that supports the possibility that the second spectrum may have been produced by hydrogen?

b) If you were to start with the spectrum of hydrogen and alter until it looks like the second spectrum, how would you have to alter it?

c) If the second spectrum is indeed from hydrogen, then what would this imply about the motion of the object that produced the second spectrum?

STEP 4: Suppose you made another observation that produced a third spectrum. Below is your observation alongside the original hydrogen spectrum.



What might you conclude about the motion of the object that created this latest spectrum? Why?

SQ3: We've now seen yet another way in which astronomers extract clues from the light that we receive from astronomical objects. Summarize it below by completing the blanks.

If a spectrum is observed that has the same ________________________________ as the spectrum of a known element but the spectral lines appear shifted, this can be explained by the ______________________ Effect. If the spectral lines are shifted toward the color ______________ then the source is moving ________________________ us. And if the spectral lines are shifted toward the color _________________ then the source is moving _____________________ us.

Part 2: Gravity and Orbits

Now let's move on to discussing planetary systems (we will come back to the Doppler Effect shortly). To begin with, we need to review a couple of things from our very first Activity, which was on the force of gravity.

STEP 1: Answer this summarizing question from our first Activity:

With two (and only two) objects present and interacting via gravity, … (choose one)

one object *can* experience a different gravitational pull than the other object.

each object *always* experiences the same gravitational pull as the other object.

The above behavior is seen over and over in nature and is called *Newton's Third Law.*

> **Newton's Third Law** states that, for every force-at-a-distance (like gravity), there is always an equal but opposite force-at-a-distance.

STEP 2: Now let's apply this idea. Suppose you are holding a textbook out at arm's length. The force of gravity is pulling downwards on the book with 5 pounds. With what force (in pounds) is the *book pulling upward* on the Earth?

When you release the book, the book falls to the Earth. Why doesn't the Earth "fall to the book"? To answer this, let's break it down into the following steps:

1) Does the Earth pull on the book with the force of gravity? YES NO

2) Does the book move noticeably after you release it? YES NO

3) Compared to the Earth, is the book difficult to move (i.e., does it have a lot of inertia)? Recall that *mass* is the measure of an object's *inertia*. YES NO

Now let's apply the same reasoning to the Earth…

4) Does the book pull on the Earth with the force of gravity? YES NO

5) Does the Earth move noticeably after you release the book? YES NO

6) Compared to the book, is the Earth difficult to move (i.e., does it have a lot of inertia)? YES NO

In summary, the Earth and book both pull on each other with the *same force* of gravity, but the book falls to the Earth when you let go of it, and the Earth doesn't "fall to the book". Why?

STEP 3: Now let's apply these concepts to the case of the Earth and the Moon.

The Earth has 81 times the mass of the Moon. That's a big difference, but *nowhere near* the mass difference between the Earth and a textbook!

If the Earth pulls on the Moon with a gravitational force of X, with what force does the Moon pull on the Earth? What rule/law supports your answer?

Does the Earth cause the Moon to move in an orbit due to its gravitational influence (remember from our Orbits Homework: an orbit is just "gravitational free-falling forever")?

Based on your above answers, would you expect the *Earth* to move in an orbit due to the *Moon's* gravitational influence? If so, would the Moon's gravity have a big effect on the Earth's motion, or a small effect?

STEP 4: Open the following URL to see an animation (not to scale) of the motion of the Earth and Moon.

https://en.wikipedia.org/wiki/File:Orbit3.gif

How would you describe the Moon's motion? Is it moving in a circle?

How would you describe the Earth's motion? Is it moving in a circle? If so, roughly where is the center of that circle -- is it inside or outside the Earth?

If they're both moving in a circle, which one is moving in a bigger circle and which one in a smaller circle?

Why is this the case (you can use the same reasoning we used with the Earth and textbook)?

STEP 5: If we wanted the Earth to move in a bigger circle, what could we change about the Earth-Moon system? Try to come up with two changes that could produce a bigger effect on the Earth.

Pluto and its moon Charon are much closer in size than the Earth and its moon.

Pluto has only eight times the mass of Charon. And the distance between them is only 10% the distance between the Earth and its moon.

Would you expect Pluto's motion would be affected by the gravitational pull of Charon? If so, would you expect it to be a greater (i.e., more noticeable) or lesser effect than the effect of the Moon's gravity on Earth's motion? Why?

STEP 6: Open the following animation of Pluto and its moon Charon:

https://en.wikipedia.org/wiki/File:Pluto-Charon_system-new.gif

If Pluto is moving in a circle, roughly where is the center of that circle with respect to Pluto itself?

Does this agree with your prediction from Step 5 regarding how noticeable the effect is compared to the Earth-Moon system?

STEP 7: Now let's discuss planets going around stars, starting with the Earth and Sun.

Does the gravitational pull of the Sun affect the Earth's motion? What is Earth's motion?

Do you expect the gravitational pull of the Earth would affect the Sun's motion? If so, would it be more noticeable or less noticeable than the effect of Charon on Plato?

Open the following URL for an animation (not to scale) of the Earth going around the Sun.

https://en.wikipedia.org/wiki/File:Orbit4.gif

Does the Earth affect the Sun's motion? If so, what is the shape of the Sun's path?

SQ4:

a) Does the Sun's gravity affect the Earth's motion? What shape is the Earth's motion?

b) Does the Earth's gravity affect the Sun's motion? What shape is the Sun's motion?

c) Comparing the effects you've described in (a) and (b), which one is a bigger effect? *Why* is this the case?

Part 3: Radial Velocity Method

In Part 2, we established that the Earth's gravitational force can influence the Sun and make the Sun move in a small circle.

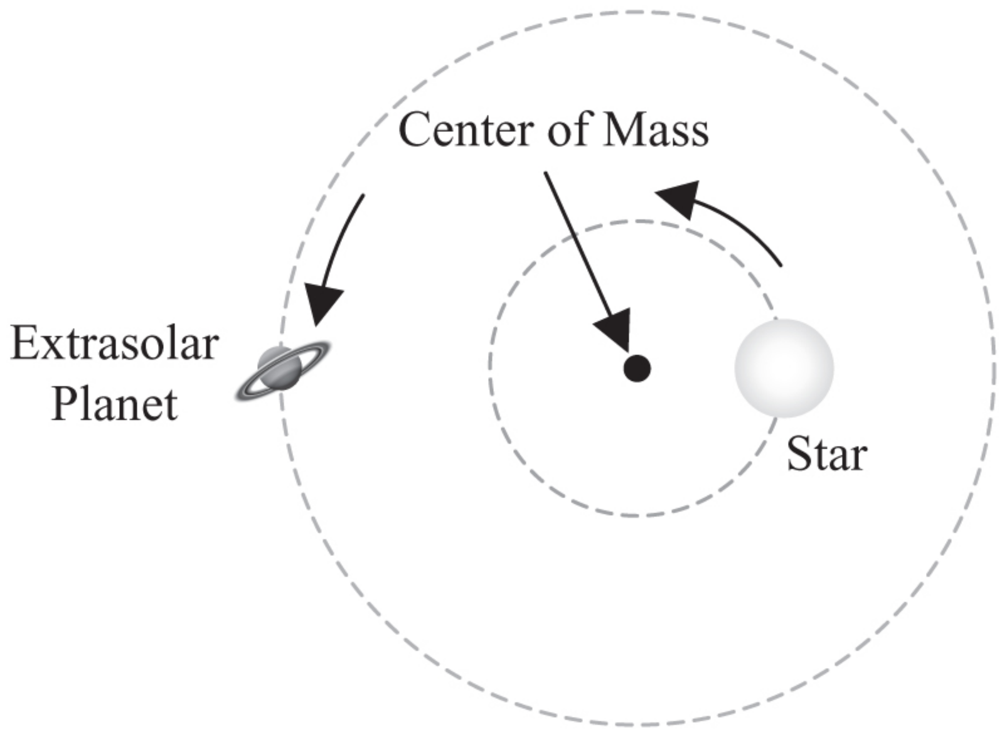
> Note: The other planets also affect the Sun's motion, and so the Sun's actual motion is much more complicated than a simple circle. But for our purposes today, let's focus on just the Earth and Sun and their mutual influence.

SQ5: It was mentioned in the introduction of today's Activity that (with rare exception) it is impossible to directly photograph extrasolar planets. Why? Give three reasons.

So how can we know extrasolar planets exist? In a nutshell, we can look for an extrasolar planet's influence on the star it orbits! Based on what you learned in Part 2, describe the effect of an extrasolar planet's influence on the star it orbits. And, will it be a big effect or small effect?

The slight effect on the star by an orbiting planet is nicknamed "wobble" because it makes the star move in a circle, but not very much. So, how can we observe a star's wobble even though it is a small effect? We will use the Doppler Effect!

STEP 1: Consider the following exaggerated drawing of an extrasolar planet's influence on the star it orbits:

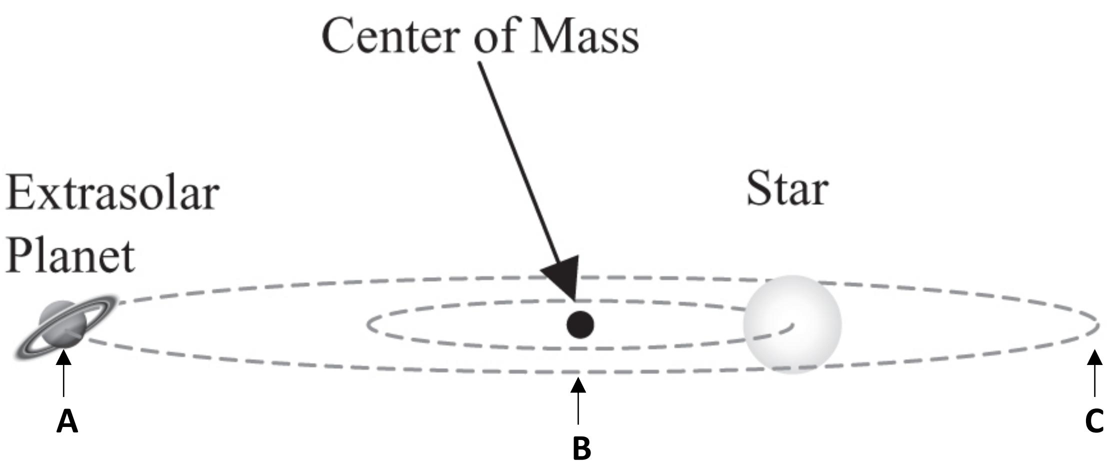


In what direction (clockwise or counter-clockwise) is the *planet* orbiting when viewed from this angle?

> Note: This orbital direction is not always the same for every extrasolar planetary system because it depends on the orientation of the extrasolar system with respect to us, which is random.

In what direction (clockwise or counter-clockwise) is the *star* orbiting when viewed from this angle?

STEP 2: Now let's suppose we do not see this solar system from "above" the plane of the orbit but instead are looking it at "edge-on" to the plane of the orbit. This is depicted below using a perspective drawing (i.e., the orbits are still circles, but from this angle they appear squashed into ovals).



Both the planet and the star are orbiting counterclockwise when viewed from above, as before, but now our perspective has changed.

At point A, in which direction does the extrasolar planet appear to be moving (from our perspective)?

Left to Right Right to Left Towards Us Away from Us

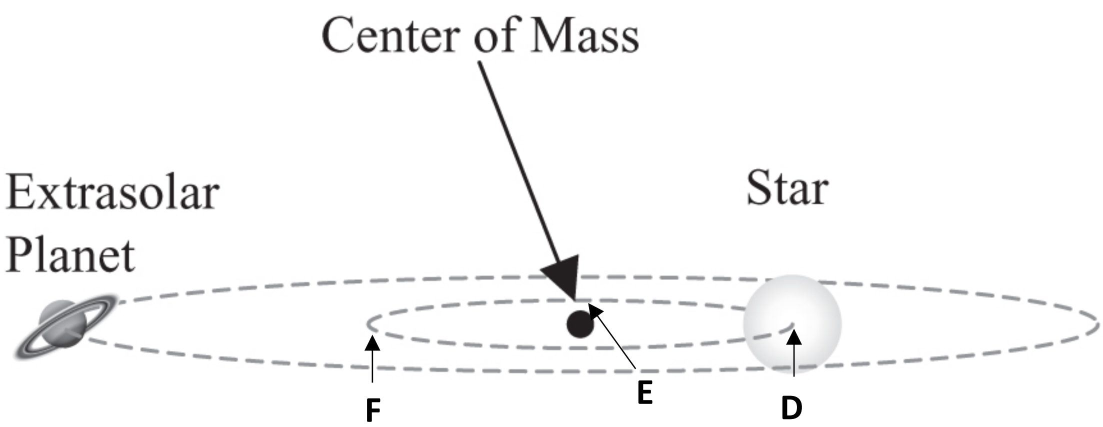
At point B, in which direction does the extrasolar planet appear to be moving (from our perspective)?

Left to Right Right to Left Towards Us Away from Us

At point C, in which direction does the extrasolar planet appear to be moving (from our perspective)?

Left to Right Right to Left Towards Us Away from Us

STEP 3: Let's repeat Step 2, but this time focusing on the *motion of the star* instead of the planet.



At point D, in which direction does the star appear to be moving (from our perspective)?

Left to Right Right to Left Towards Us Away from Us

At point E, in which direction does the star appear to be moving (from our perspective)?

Left to Right Right to Left Towards Us Away from Us

At point F, in which direction does the star appear to be moving (from our perspective)?

Left to Right Right to Left Towards Us Away from Us

STEP 4: Based on what you've learned about the Doppler Effect, do you expect the star's light would ever be redshifted or blueshifted, from our perspective?

SQ6:

a) At what point(s) (D, E, F, or none) would you expect the star's light to be redshifted? Why?

b) At what point(s) (D, E, F, or none) would you expect the star's light to be blueshifted? Why?

c) At what point(s) (D, E, F, or none) would you expect the star's light to *not* be Doppler shifted? Why?

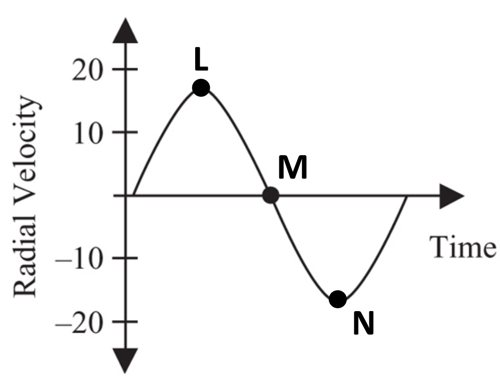
d) When the star is moving towards us in its orbit, where is the planet (location A, B, or C) and in what direction is the planet moving?

e) When the star is moving away from us in its orbit, where is the planet (location A, B, or C) and in what direction is the planet moving?

STEP 5: Using the Doppler Effect, what we can ascertain is whether the star is moving away from us or toward us, and how fast. Let's plot this toward and away motion, which we call the **radial velocity** of the star.

Let's adopt the convention that when the star is moving away from us it has *positive* radial velocity and when the star is moving toward us it has *negative* radial velocity.

Consider the radial velocity graph below. Radial velocity is plotted on the vertical axis. Time is plotted on the horizontal axis.



There are three points on the graph which are labeled L, M, and N.

SQ7: Correlate the points L, M, and N on the graph to the position of the star from the previous Step (D, E, and F).

L correlates to… D E F

M correlates to… D E F

N correlates to… D E F

Below is a summary of what we saw in this part:

Radial Velocity Method

Planets can be detected around other stars because their gravitational influence on the star causes the star to "wobble". We measure this wobble by looking at the redshift and blueshift of the star's spectrum. This method of finding extrasolar planets is called the **radial velocity method**.

Part 4: Transit Method

STEP 1: We saw the term *transit* once before when we discussed the transit of Venus across the Sun during our Virtual Planetarium Homework. **Transit** describes the scenario in which one object passes between us (observers on Earth) and another distant object. Eclipses are examples of transits.

During a solar eclipse (in which the Moon passes between Earth and the Sun), the

________________ is ***transiting*** across the ______________.

For observers on Earth, what happens to the brightness of the Sun during a solar eclipse? Why?

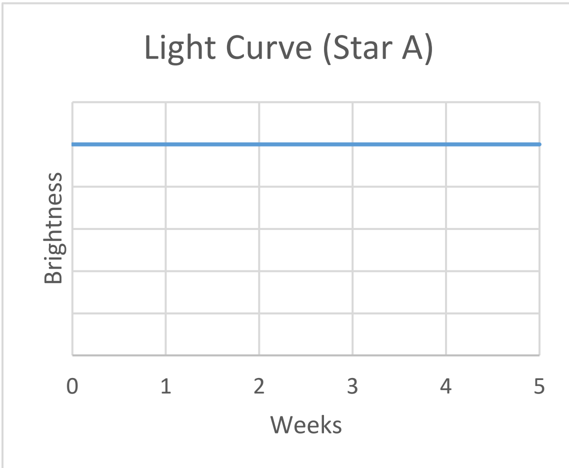
Now let's think about extrasolar planets. In which scenario would the extrasolar planet transit across the star, as seen from Earth? Answer by completing the sentence below.

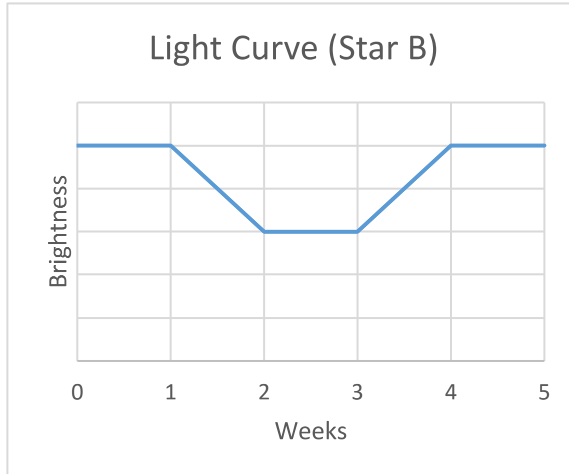
To see a planet transiting across a star, we need to find planetary systems that we are looking at…. (circle one)

…from "above" the plane of the orbit …from "edge-on" to the plane of the orbit

For observers on Earth, what do you expect will happen to the brightness of the star when a planet transits in front of the star? Why?

STEP 2: Let's watch the brightness of various stars over a period of a few weeks and plot the star's brightness (vertical axis) versus time (horizontal axis). This is called a **light curve**.





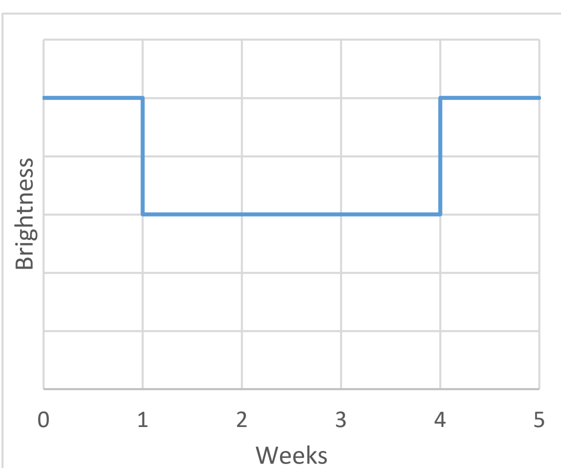
Over what length of time were these observations made?

Which star above (A or B) experiences no planetary transit during the period of observation? And which star experiences a planetary transit during the period of observation? How can you tell?

For the star that experiences a planetary transit, when does the transit begin? When does it end?

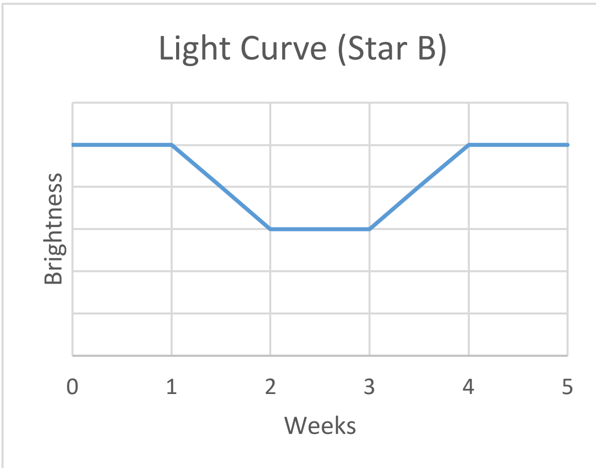
Starts:

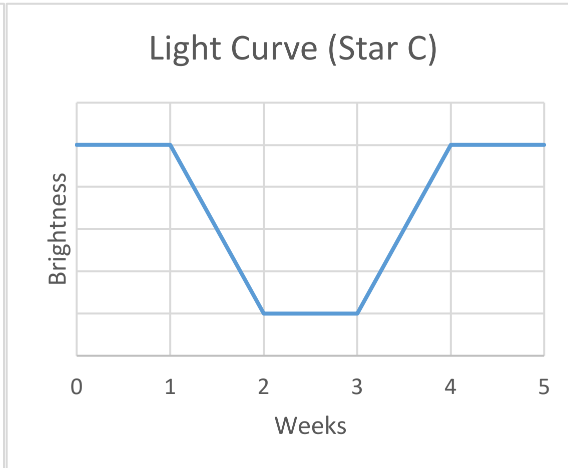
Ends:



STEP 3: Why does the brightness of the star being transited decrease gradually instead of suddenly? In other words, why doesn't a star that's being transited exhibit the light curve at the left?

STEP 4: Consider the two light curves below.



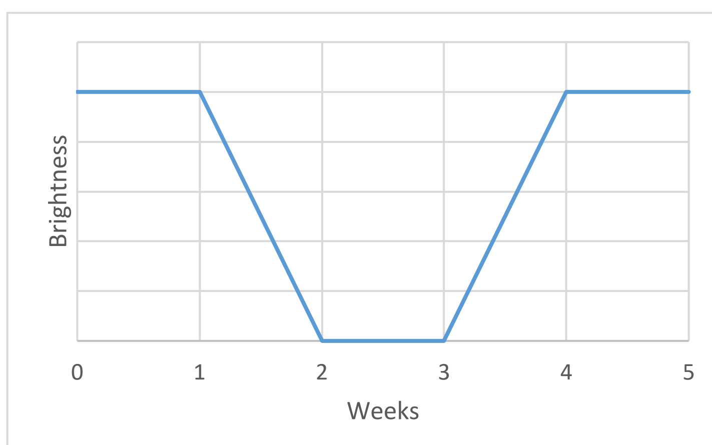


SQ8: In which scenario (B or C) does the transiting planet have a larger apparent size (i.e., a larger cross-sectional area as seen from Earth)? How can you tell?

To see an animation that encapsulates all of these transit ideas so far, open the following URL:

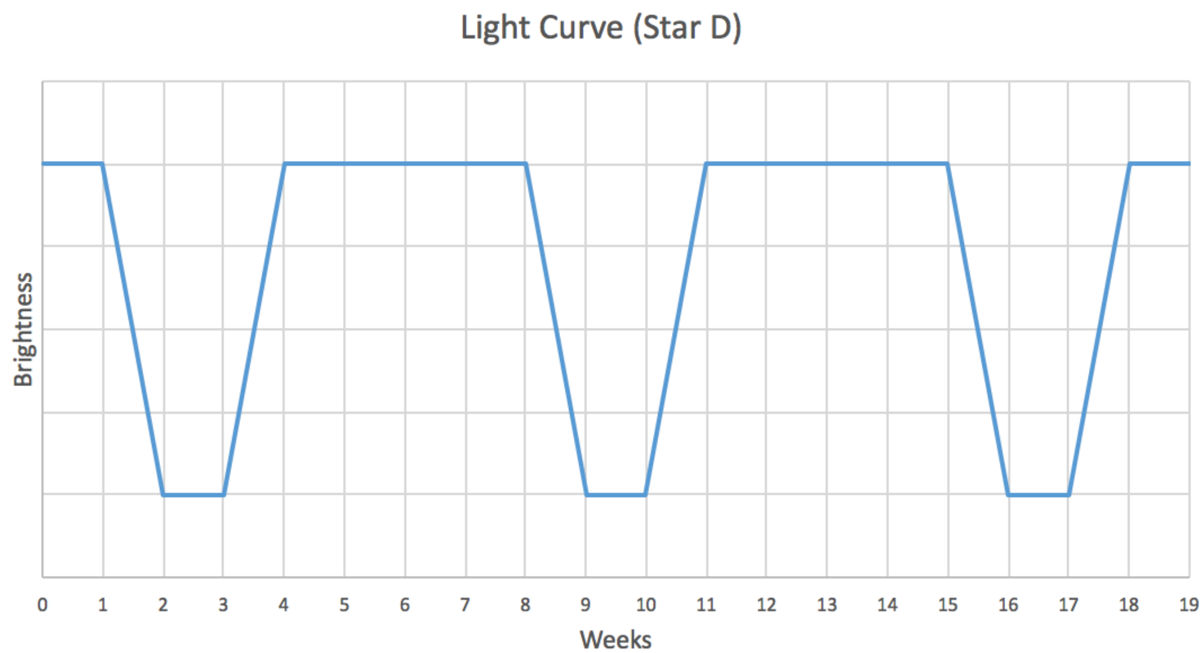
https://tinyurl.com/y82555hw

STEP 5: Notice in the light curves we've seen so far, the brightness of the star decreases but does not decrease all the way to zero. In which case *would* you have a light curve that looks like the one on the right?



What is the phenomenon that we observe from Earth that would have a light curve like this?

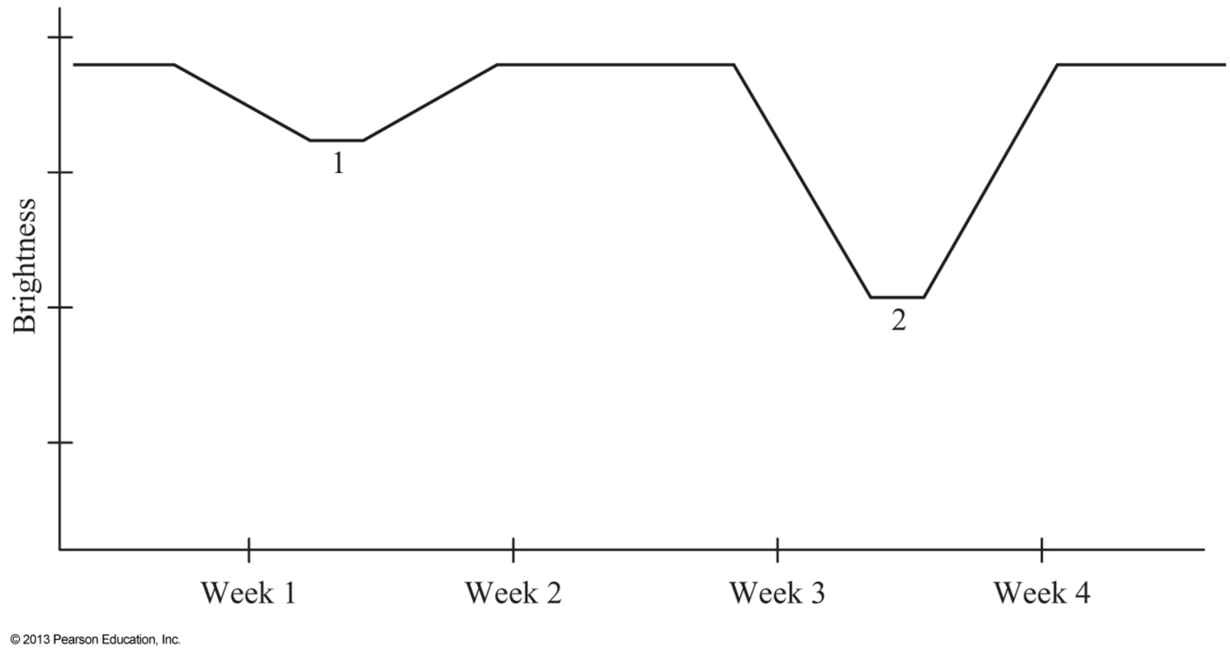
STEP 6: Consider the light curve below.



Assuming there is just one planet orbiting Star D, how much time does it take for the planet to complete a single orbit around its star?

Based on your previous answer, do you think this planet is *close* (relative to an AU) to the star it is orbiting (i.e., making a small orbit) or *far* (relative to an AU) from the star it is orbiting (i.e., making a large orbit)?

STEP 7: What if there are multiple planets orbiting a star? Consider the light curve below.



SQ9:

a) Based on this data, at least how many planets are orbiting this star? How can you tell (for instance, how do you know it's not the same planet transiting multiple times)?

b) How do the apparent sizes of the planets compare? How can you tell?

Part 5: Extrasolar Planets

Let's talk about what types of planets astronomers have found, and how many, using the detection methods we've briefly outlined above.

The first confirmed detection of an extrasolar planet occurred in 1992. Relatively speaking, planet hunting is a very young scientific field!

As of 2022, there are *over 5,000 confirmed extrasolar planets*!

Here are some interesting facts about these extrasolar planets:

> The least massive planet detected is called Draugr. It has twice the mass of our Moon.
>
> The most massive planet detected is HR 2562b. It has 30x the mass of Jupiter. There are some debates as to whether this object is actually a planet or a brown dwarf star.
>
> The nearest extrasolar planet to us was found in the nearest star system to us: Alpha Centauri.
>
> Based on our observations so far, it has been estimated that about 1 in 5 Sun-like stars has an Earth-like planet that may be habitable (based on its temperature). This would imply at least 11 billion potentially habitable worlds in our Milky Way galaxy.
>
> It was previously thought that other planetary systems might look like our own solar system, with rocky planets in close to the star and gas giants out farther from the star. We now know this is not always the case.

A whole class of planets has been discovered that have been nicknamed ***Hot Jupiters***, because they are gas giants (like Jupiter) that are orbiting extremely close to their host star. In some cases, a Jupiter-size planet makes a complete orbit around its star in less than 10 Earth days!

Hot Jupiters were some of the first extrasolar planets detected because they are readily detectable.

Why do you think a Hot Jupiter is readily detectable when using the radial velocity method?

Why do you think a Hot Jupiter is readily detectable when using the transit method?

For a while, because of the abundance of Hot Jupiters that astronomers were finding, it was thought that perhaps most solar systems have gas giants in close, and solar systems with rocky planets like ours are very rare. But, this turned out just to be a detection bias. As the sensitivity of our instruments improved, we were able to detect smaller and smaller motions of stars and use that to detect smaller, Earth-size planets too.

Other extreme planets have been discovered. Take, for example, ***Fomalhaut b*** (also known as *Dagon*). This planet is on a highly elliptical orbit that takes it as far as 300 AU away from its host star. The orbital period of Fomalhaut b is about *555,000 Earth days*.

Another interesting fact about Fomalhaut b is that it is one of the few extrasolar planets that has actually been directly imaged. This was done by the Hubble Space Telescope in 2010 and 2012. It is pictured on page 1 of this Activity

The nearest known Hot Jupiter to our solar system is **HD 189733b**, which is about 65 light years away and about 13% larger than Jupiter. Because of its relative nearness, this Hot Jupiter has been studied more than any other. It has been detected using both of the methods we learned about today. Some very interesting discoveries have been made about this planet, such as:

- It orbits its star 12x closer than Mercury does our Sun and it completes an orbit every 2.2 Earth days
- The surface temperature is about 1150 K (1610°F)
- Its atmosphere is blue and it contains silicate particles (i.e., glass) (found by spectroscopy)
- It has extreme weather: winds blow up to 5400 mph and it rains molten glass
- Occasional solar flares from the star cause the planet's atmosphere to evaporate at a rate of a billion grams per second

Perhaps the most violent weather system ever discovered is on **HD 80606b**, another Hot Jupiter with 400% the mass of Jupiter, which was discovered using the radial velocity method. It has a very eccentric orbit, ranging from about 1 AU down to a mere 0.03 AU from its star. At its closest approach (which happens every 111 days), computer simulations predict the surface temperature rises 1000°F in just 6 hours, producing supersonic wind speeds that reach 11,000 mph.

SQ10: What are two most common methods for detecting extrasolar planets? In your own words, briefly describe how each detection method works.