

Meet the Neighbors: Planets Around Nearby Stars

An AstroCappella Lesson Plan by Padi Boyd to accompany the song Dance of the Planets

Grade Level: 11th and 12th grade physics and mathematics classes.

Objectives

1. Students will be able to explain why a transiting planet causes a periodic dimming in the light from its parent star.
2. Students will determine the radius of a planet, and its orbital distance, by analyzing data and manipulating equations.
3. Students will compare the results obtained for the extrasolar planetary system to our own solar system, and be able to discuss the major differences.

Prerequisites

Math: Students should have learned some pre-algebraic concepts such as pattern recognition, ratios, proportions and percents. Students should also be familiar with manipulating algebraic equations.

Science: Students should have learned about Kepler's Laws of Planetary Motion, specifically the third law. They should be familiar with the Doppler shift and its relationship to the velocity of the source and observer. Helpful, but not essential, is an understanding of light flux and how space detectors work. Students should know that stars give off light, but planets do not.

Time Requirements: For each class, you'll probably need at least 2 periods/mods.

Curriculum Connection: Several concepts in physics are used and reinforced, including: the Doppler shift, Kepler's Laws of Planetary Motion, and spectroscopy. In order to complete the activity, students express their observations in mathematical form, and use algebra to ultimately measure the radius and orbital distance of an extrasolar planet. Since this exercise uses quite current data applied to a cutting edge problem, it is also an excellent (and accurate!) way to introduce upper level students to the processes of science.

Introduction/Engagement

In 1995, Michel Mayor and Didier Queloz made the truly revolutionary discovery of a planet in orbit around a star other than the Sun. They found a telltale “wobble” in the Doppler shifted spectral lines of the star **51 Pegasi**. Even though the planet was far too small to see even with today’s powerful telescopes, the repeated wobbling of the star, backward and forward as it and the planet orbit about their common center of gravity, provides evidence beyond doubt that 51 Pegasi does not wander through the galaxy alone. Like our Sun, it is attended by at least one planet, and possibly more. Suddenly, Earth was no longer a planet in the only solar system we know—we’d taken our first look at a neighbor!

Today (November of 2001) we know of about 80 neighbors (or **extrasolar planets**), and the numbers grow all the time. Now, astronomers wait until they have found six or eight new planets before announcing their discoveries. Think about it: in a way, over the last six years the known universe has expanded to include the sure existence of numerous planetary bodies! But what are some of the ways these discoveries are made?

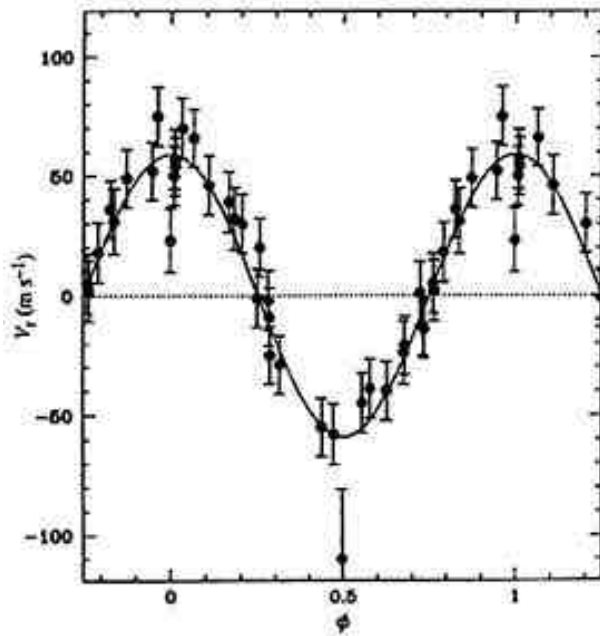


Figure 1. Doppler velocity versus orbital phase for 51 Pegasi (Mayor and Queloz, 1995). The y-axis is in meters per second. Only very recently has the technology (CCDs, fast computers, better optics) converged in such a way that such small velocities can be measured from distant stars. The vertical lines represent the observational error. The sinusoidal line through the points is the best fitting orbital solution.

Astronomers send starlight through a spectrometer to disperse the light into its component colors. They learn what stars are made of from the appearance and strength of lines in the spectrum from hydrogen, helium, and heavier elements. In stars, the spectral lines are typically not found at their rest (laboratory) wavelengths. Instead they are *Doppler-shifted* due to their relative motion with respect to the observer. Mayor and

Queloz found a small, repeating, nearly sinusoidal signal in the Doppler shift from 51 Peg. From this signal they could measure the period (a zippy 5 days!), and predict what the Doppler shift should be for future times as well. Several groups went back to take a closer look at the same type of data on this star and others. The wobble was confirmed independently, and more were found. Extrasolar planetary astronomy was born!

An Extrasolar Dimming!

As the number of planets detected with the Doppler shift grew, it was only a matter of time before one would be found to be aligned in such a way that the planet would pass in front of the star, as seen from Earth.



Figure 2 Artist's impression of an extrasolar planet transiting its parent star (credit: NASA).

In 1999, astronomers Tim Brown and David Charbonneau detected a characteristic decrease in the light from one of the stars with planets, HD 209458. They saw the same decrease again, at precisely the time that the Doppler-determined period predicted. A transiting planet had been found!

Lots of Physics from a Little Bit of Light!

Did you know the ancient Greeks were able to accurately determine such hard to measure quantities as the relative diameters of the Earth and Moon? They were observers, and one of the events they observed—eclipses of the Sun and Moon— could be coupled with simple geometry to give important clues about the sizes of objects in our immediate neighborhood.

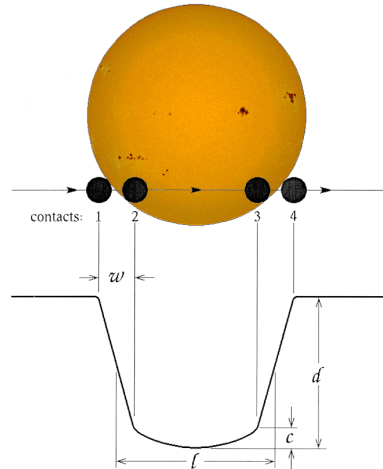


Figure 3 The transit of a planet across the face of a star produces a characteristic dip in the light curve (intensity of the star versus time). The numbers 1,2,3,4 refer to the contacts—planet just crossing the star, entire planet disk obscuring part of the star, and the reverse on the other side. Other measurable quantities of the eclipse (it's length, depth, curvature, steepness) are shown.

The same is true for astronomers today. Eclipses, particularly in binary star systems, provide unique information about the masses and radii of stars. Because the Doppler shift only tells us about the component of velocity coming directly toward or away from us, it underestimates the true velocity in the case where two objects orbit in a plane not aligned with our line of sight. But in systems where the alignment is just right, the Doppler velocity is essentially the true velocity, and we can accurately determine the masses. In addition, the shape of the eclipse (its duration, depth, and steepness) hold a wealth of information about the relative sizes of the two objects. When a planet passes in front of the Sun, the dimming of the light is much less dramatic than during an eclipse. These events are called transits. The planet Venus transits the Sun occasionally. The next transit of Venus will occur on June 8, 2004. The last time it occurred was in 1882!

During the transit of Venus in 1761

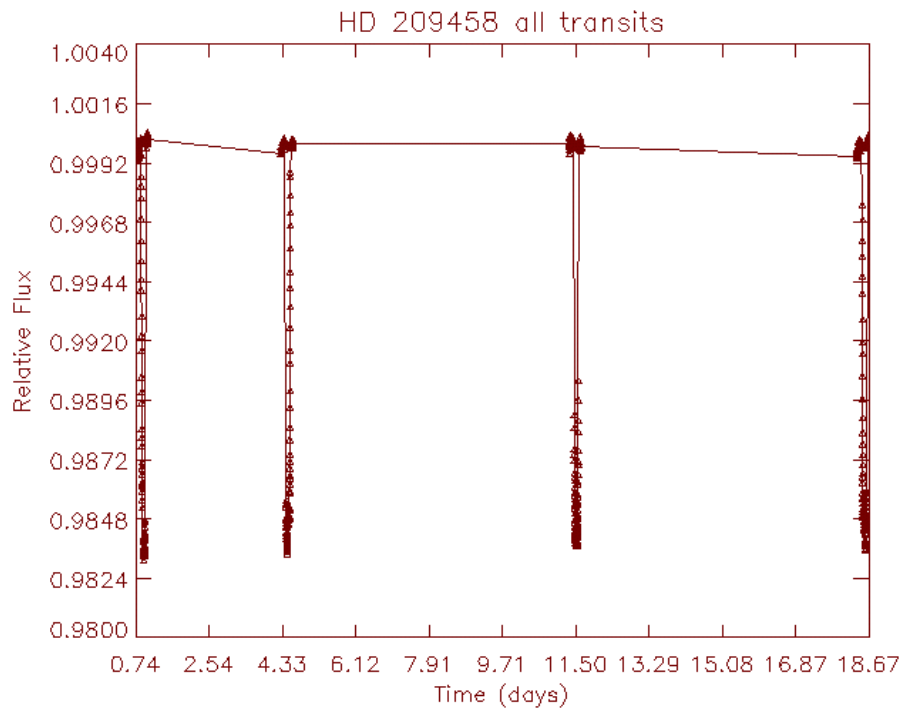
Hubble Views “Eclipse” of Planet

The transiting extrasolar planet was detected with fairly low power, small, ground-based telescopes, but its repeated slight dimming was proof enough that a planet was regularly transiting its parent star. The importance of this discovery, and the desire for very high resolution data of this event led Brown and Charbonneau to request immediate observations with the Hubble Space Telescope’s Imaging Spectrograph (STIS).

STIS measures spectra in the visible and ultraviolet portions of the spectrum. It can also be used as a *photometer*—an instrument that gives an accurate measurement of the brightness of an object as a function of time. Brown and Charbonneau used STIS to record four transits of HD 209458 in April and May of 2000. Realizing that this observation would have broad appeal, the scientists have made their data set available to the public through the World Wide Web.

Procedure

You will use actual data from the Hubble Space Telescope to determine the period of a planet around the star HD 209458. Once its period is determined, you will use the same data to estimate the size of the planet's projected area on the face of the star during the transit. Using your measurements, and assuming the star has nearly the same mass and radius as our Sun, you'll determine the distance at which the planet orbits using Kepler's Laws, and, using simple geometry, determine the radius of the planet. Finally, you'll be asked to compare this planetary system to our own.



STEP 1: Estimate and measure the period

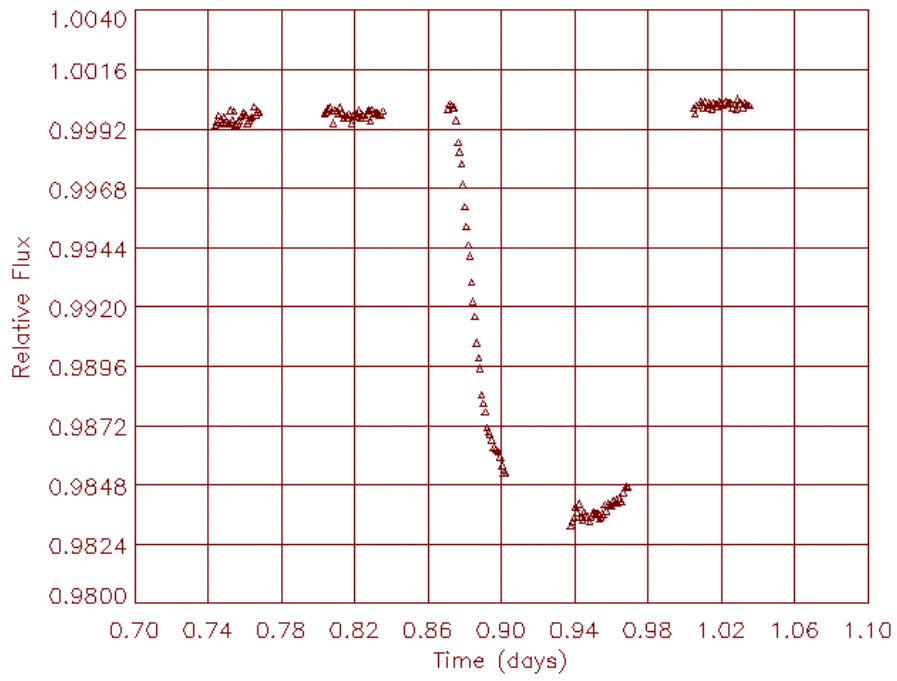
Look at the figure above. This is a plot of the STIS data. On the x-axis, time from the beginning of the observations is measured in days. On the y-axis, the brightness is measured in relative flux. The value 1.0 corresponds to the brightness of the un-eclipsed star. Triangles are actual data points. Lines connecting the points are used only to guide the eye.

Question 1: Estimate the period of this planet around the star. Did the observers get data for each and every transit over the 18.67 days of the observing campaign? What reasons can you think of that might have made it impossible to observe every transit? [Possible answers: gaps caused by the Earth getting in the way of the source during

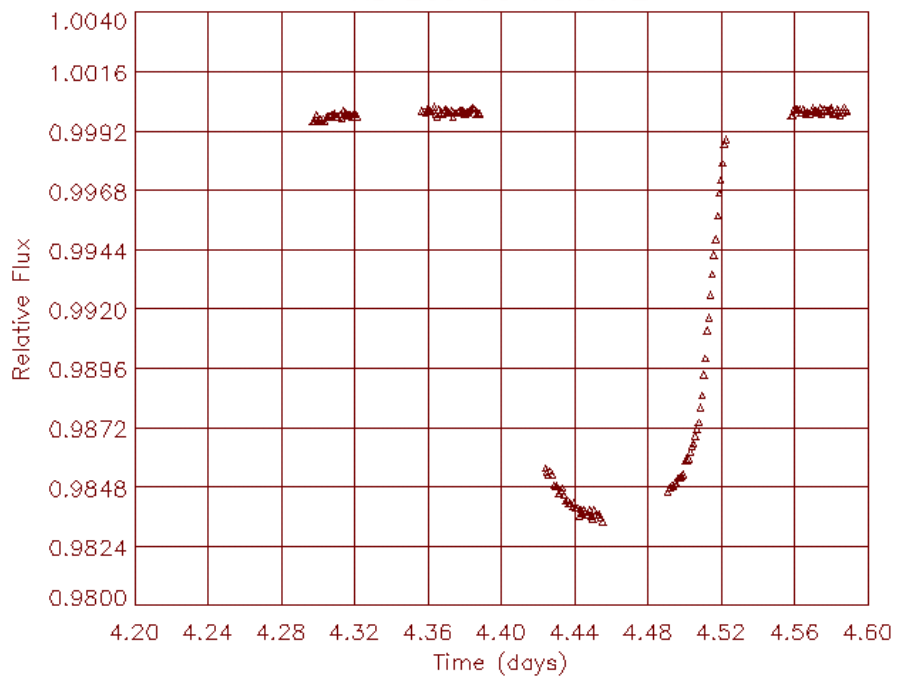
HST's orbit; the need to share telescope resources with other teams and other instruments; attempts to line up the gaps with the portions of the transit needed to get complete coverage.]

Measurement 1: The four graphs below are enlargements of the four transits shown in the previous plot. In each case, the entire transit is not observed. In each case, there is enough data to make a measurement of the time of the middle of the transit. Do this for each of the four transits, and record your data on the table provided.

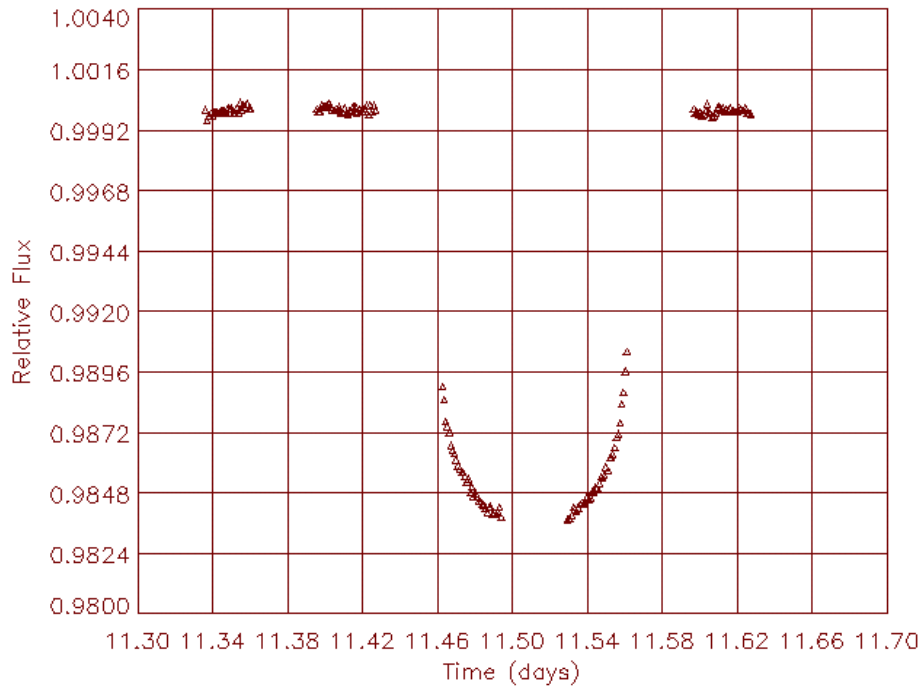
HD 209458 transit 1



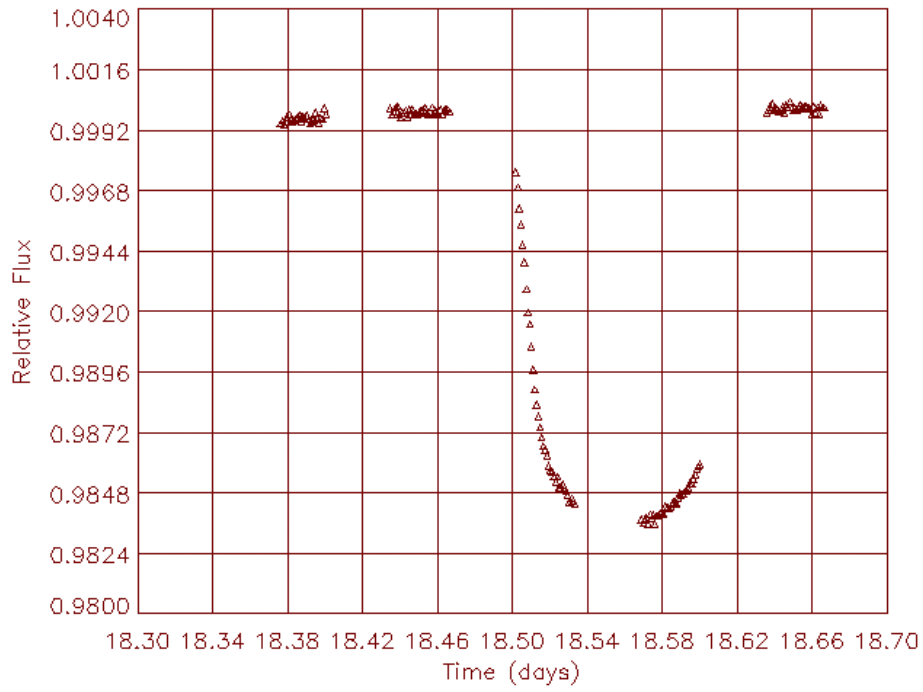
HD 209458 transit 2



HD 209458 transit 3



HD 209458 transit 4



Data Table 1: For each of the four transits, estimate the time of minimum from the graphs provided. You may wish to draw a curve through the points, or to fold the graph along the vertical so the left side of the transit lines up with the right side. For transits 2, 3, and 4, compute the time elapsed between transits, T . Use these values, and your answers to question 1 above, to estimate a value for the period of the orbit from each transit.

<i>Transit Number</i> N	<i>Time of mid-transit</i> T_n (days)	<i>T (days)</i> $T_n - T_{n-1}$	<i>Period</i> (days)
1		—	—
2			
3			
4			

Average period: _____ (days).

Question 2: Give an estimate of your measurement error. What are the sources of error? Brown and Charbonneau found a period of $P=3.52474 \pm 0.00007$ days. Does your value of the period match theirs, within measurement errors?

STEP 2: How Dim Does the Star Get During Transit?

When the planet transits the star, some of the light from the star is blocked because the planet is in the way. The larger the planet with respect to the star, the more dim the middle of the transit will appear. Look at the transit shown in Figure 2 above. From this image, it is clear that the larger the area of the star obscured by the planet, the dimmer the star will appear. We can turn this around to get the size of the planet—if we measure the reduction in the brightness of the star during the planetary transit, then we can calculate the percentage area of the star obscured by the planet. Since both the planet and the star have the projected area of a circle, we will then know the radius of the planet in terms of the radius of the star.

Look at the two cases illustrated in the next Figure. In each case, the star is represented by the big, white circle, with radius R . The planet is the small, dark circle,

with radius r . When the planet is far from the star (left), the bright area is R^2 . When the planet transits the star, (right) the bright area is $R^2 - r^2$.



The STIS flux is given in relative brightness—all brightness readings are normalized (or divided) by the brightness of the star outside of transit (F_0). So, using the two pictures, and equations for area above, the relative flux at mid-transit (F_1/F_0) can be written as:

$$F_1/F_0 = (R^2 - r^2) / (R^2).$$

Question 3: show that this leads to $r = \sqrt{(1 - F_1/F_0)} \times R$.

We will use this expression and measure the average value of F_1/F_0 to estimate the radius of the planet.

Measurement 2: Using the same four transit plots, estimate the relative flux of the star when the planet is at mid-transit. Record your results in the table below. Calculate the average value of the depth of the transit.

Data Table 2: For each of the four transits, estimate the relative flux at the minimum from the graphs provided. Use the times you measured for mid-transit, and measure the corresponding y-values on the graphs. Use these values to calculate an average value for the relative flux of mid-transit.

<i>Transit Number</i>	<i>Relative flux at mid-transit (no units)</i>
1	
2	
3	
4	

Average relative flux at mid-transit (F_1/F_0): _____ .

Wrapping it Up: Physics from Light

Now we'll use our measurements to learn about this mysterious planet in orbit around another star. First, let's estimate its size (radius). Using the value of relative flux above and your answer to question three, calculate the radius of the planet r in terms of the radius of the star, R .

$$r = \text{_____} R.$$

HD 209458 is nearly the same size as the Sun, so use the Sun's radius in kilometers ($R = 6.96 \times 10^5$ km) to get an estimate of the radius of the planet in kilometers.

$$r = \text{_____} \text{ km.}$$

The radius of the Earth is 6.38×10^3 km, and Jupiter's radius is 10.8 times the Earth's radius. How large is this planet compared to Earth? To Jupiter?

Finally, from your measurement of the period of the orbit of the planet, estimate the orbital distance from its star. Since the masses of the star is so similar to the Sun, assume that Kepler's Laws of Planetary Motion are valid in this extrasolar planetary system as well, and $P^2(\text{years}) = a^3(\text{Astronomical Units})$.

$$a = \text{_____} (\text{AU}).$$

Question 4: How does this planet compare to planets in our own solar system, in terms of its radius, and its distance from the star? Do you think life as we know it could exist on this planet? Why or why not?

Closure

Ask the students to write a letter to a friend or relative, explaining the existence of extrasolar planets, and why the discovery of a transiting planet is important. Have them emphasize the process of obtaining results on the size of the planet and its orbit from data.

**Solar System Data Table: Radii, Orbital Distance
from Sun, Orbital Period**

Name	Radius (km)	Distance from Sun (AU)	Orbital Period (years)
Mercury	2440	0.39	0.241
Venus	6052	0.72	0.615
Earth	6378	1.00	1.000
Mars	3397	1.52	1.880
Jupiter	71492	5.20	11.862
Saturn	60268	9.54	29.475
Uranus	25559	19.19	84.017
Neptune	24766	30.07	164.791
Pluto	1137	39.48	247.920