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17 An Eclipsing Extrasolar Planet

17.1 Introduction

One of the more recent new fields in astronomy is the search for (and discovery of) planets orbiting around stars other than our Sun, or "extrasolar planets." Detecting planets outside of our Solar System is an extremely difficult task. This is because the planets themselves are rather dim compared to stars (making them difficult enough to observe), and it is very hard to observe very faint objects when they are next to really bright objects (the star the planet is orbiting). As a result, actual images of extrasolar planets are few and far between. We need some other way of determining the presence of a planet.

Luckily, we are able to observe an extrasolar planet's influence upon its parent star. Just as the star's immense gravitational pull causes the planet to move around it, the planet's own gravitational pull has a small effect on the star as well. It is due to this gravitational interaction that the planet does not orbit around the star's center, but rather around a location between the two objects known as the *center of mass* of the system. Because the star is much more massive, this location is usually not far from the star's center. In the case of our own solar system, if we consider only the Sun and Jupiter (ignoring the other planets for now), their center of mass would be located at 0.005 AU, or about 1.07 times the radius of the Sun.

We have established that an extrasolar planet is too faint to observe. Can we see the parent star wobbling in its little orbit around the center of mass between the star and the extrasolar planet? Not directly. The star's motion is very small, so it would be quite difficult to observe the star wobbling around in the night sky. But all is not lost: we can use a neat application from physics to help us out.

An effect known as the Doppler effect (or Doppler shift) is involved when you have an object that is either moving towards you (the observer) or away from you. If there is, say, an ambulance racing past you with its siren wailing, you might notice that the siren sounds more high-pitched when it is approaching you, and more low-pitched when it is moving away. This is because as the ambulance is coming closer, the pulses of the sound waves are bunched closer together, and as the ambulance is moving away, the pulses are spread farther apart. How far apart these pulses are determines the siren's pitch. Something similar happens with light. If an object is moving towards you at a high speed, it appears as if the wavelengths of the light coming towards you have shortened a bit. The object's entire spectrum has shifted a little towards shorter wavelengths: this is known as blueshifting. If an object is moving away from you, the wavelengths become longer than normal, and everything is shifted to longer wavelengths: redshifting.

By looking at a star's spectrum (with the help of some absorption lines, for which we know the "rest frame" wavelengths), we can tell how fast a star is moving towards us or away from us. (Note: we *cannot* use this method to determine a star's motion in other directions, such as "up/down" or "left/right.") We observe that some stars are moving towards us, and some are moving away from us. This is quite normal, as the stars are all moving about within our galaxy. What is interesting is when we see a star wobble with a fixed period: sometimes it is moving a little faster towards us, sometimes a little slower. What could cause a star to do this? A planet!

By measuring how blue- or red-shifted the star is over time, we can learn some information about the planet, which we detect *indirectly* even though we cannot actually see it. The easiest thing to determine is the orbital period: if the star's wobble repeats every 2 years, then the planet's orbital period must be 2 years. From there, if we know the star's mass, we can use that information along with the orbital period to calculate the planet's average distance from its sun. So far, so good.

The larger the mass of the planet, the farther away from the star the system's center of mass will be, so a larger mass should result in a larger wobble. But this is where it gets tricky: we can only detect the star's motion in the *radial* direction: towards us or away from us. And there is no reason to expect that all planetary orbits would be nicely aligned with our line of sight. So if a planet's orbit causes a star to move up/down and left/right, but not towards/away, we will not be able to detect its presence using the Doppler method. Therefore, if a star has a very small wobble, we cannot be certain whether it has a small-mass planet orbiting it, or a larger-mass planet moving mainly in other directions. As a result, we can usually only figure out planetary masses in terms of i, the inclination of the planet's orbit relative to our line of sight.

No Earth-sized planets have been discovered yet (but we are getting very close!!!!), mainly because our technology is not advanced enough to detect such extremely small wobbles. So far, astronomers have been discovering the easiest planets to find: those that are the largest (so they will tug on their stars more) and with the shortest orbital periods (a star wobbling with a period of several days is more easily noticeable than one that wobbles once every 300 years). As a result, most of the planets that have been discovered have masses greater than that of Jupiter, and many of them orbit their sun in only a few days! This is unlike what we are used to in our Solar System, and we may have to revise some of our models of planetary formation and evolution to be able to explain how such different planetary systems can exist.

There are very few systems for which we do know the planet's orbital inclination; the best studied example is the star HD209458. The unique property of this system is that, from our point of view, the planet actually passes in front of the star, blocking out a small part of its light. Because of this, we know that the star's wobbling in our line of sight is not lowered significantly, so we can figure out the planet's actual mass. As an added bonus, we can also use how much of the star's light is blocked out to figure out the size of the planet. Figure 17.1 shows a schematic of a planetary system like that of HD209458.

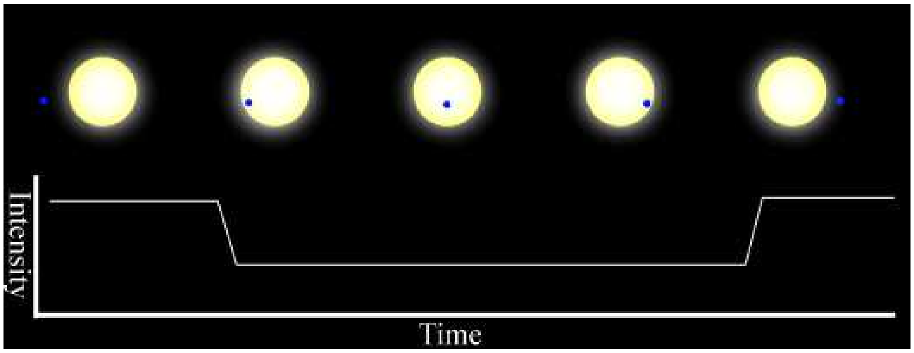

Figure 17.1: Schematic of an extrasolar planet transiting, or moving in front of, its parent star. The lines below the star images represent the amount of light one would receive from the star as the planet moves across it.

For further information, you can visit the following web site, which has an excellent description of how we detect planets outside of our solar system:
`http://planetquest.jpl.nasa.gov/science/finding_planets.html` . Once there, click on "Interactive: 4 Ways to Find a Planet." The site requires Flash and uses sound, so make sure you visit the web page on an appropriate computer. The voice on the Flash site sounds as if it is addressing children ("Let's see if we can find a planet!"), but it describes what is going on very clearly.

In this lab, we are going to focus on the eclipsing planet that is orbiting the star HD209458. (The planet is named HD209458b.) We will be using the star's velocity along our line of sight and its lightcurve to determine properties of the planet, and compare it to planets in our Solar System. Figures 17.2 and 17.3 show graphs of the star's lightcurve as the planet passes in front of it (17.2), and the star's forward/backward velocity based on where the planet is located (17.3).

17.2 In-Lab Questions

SHOW ALL OF YOUR WORK!

1. This planet is seen to have an orbital period of about 3.5 days. Using Kepler's Third Law, and assuming the star is the same mass as the Sun, calculate the planet's orbital semi-major axis (OSA). (Hint: don't forget to convert the period into years!) **(5 points)**

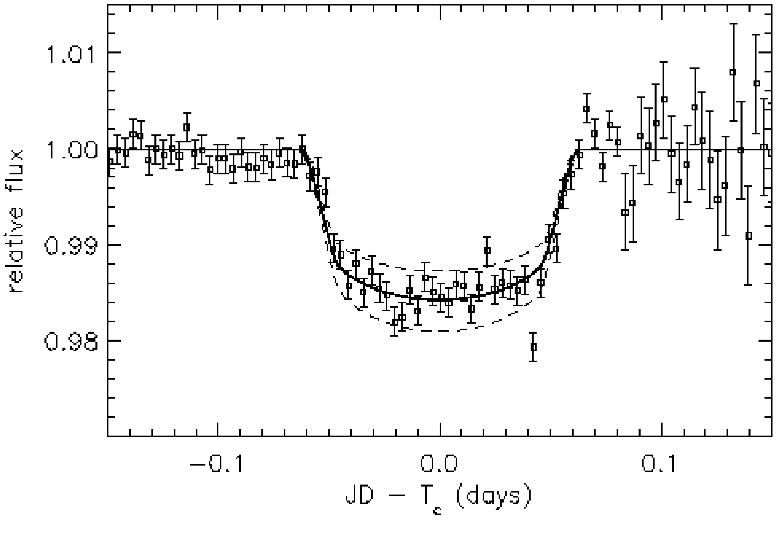

Figure 17.2: Brightness of the star HD209458 as a planet passes in front of it. Figure taken from `http://www.hao.ucar.edu/public/research/stare/hd209458.html`.

2. If this planet were placed in our Solar System at the same distance from the Sun, where (relative to the other planets) would it be? (For example, "between Earth and Mars," or "beyond Pluto.") **(3 points)**

3. Mercury's OSA is 0.39 AU. What fraction of Mercury's OSA is the OSA of this planet? **(4 points)**

4. a) The mass of this planet, calculated using its OSA and the speed of the star, is about 1.2×10^{30} g. How many Earth masses is this? (For your convenience, the properties of

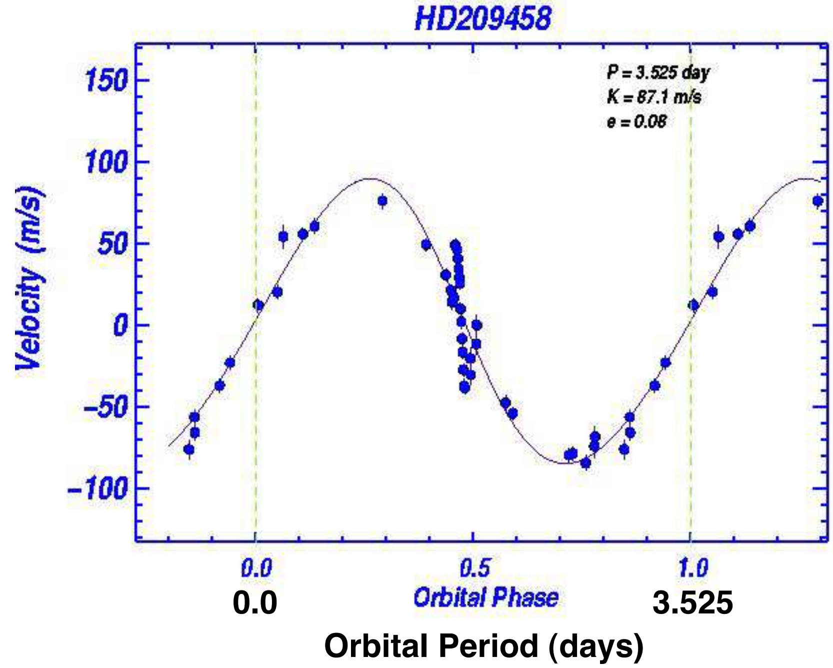

Figure 17.3: Doppler motion of the star HD209458 due to the presence of a nearby planet. Figure taken from `http://astron.berkeley.edu/g̃marcy/hd/doppler.html`.

Earth and Jupiter are given in Table 17.1, which appears later in this lab.) **(7 points)**

b) How many Jupiter masses is this? **(5 points)**

5. To estimate the radius of this planet, we can look at how much light it blocks out when it passes in front of its star. If nothing is in front of the star, then we see all πR_*^2 of the star's disk, where R_* is the radius of the star. When the planet is in front of the star, an area of πR_p^2 is blocked out (where R_p is the radius of the planet), so the fraction of the star's light that is lost is $\pi R_p^2 / \pi R_*^2$. Use this information and the graph of the star's brightness to estimate the radius of the planet. Assume that the star's radius is the same as that of the Sun: 700,000 km. **(15 points)**

6. The volume of a sphere is $\frac{4}{3}\pi R^3$. Using the radius you just calculated above, what is the volume of this planet in units of cm^3? (Don't forget to convert the radius from km to cm before calculating!) **(8 points)**

7. Now, using the values for this planet's mass and volume, calculate its density. Give the value in units of $\mathrm{g/cm}^3$. **(6 points)**

8. a) If we assume that all of our data and calculations are correct, what does the density suggest about this planet's composition? **(6 points)**

b) Do you think this planet is likely to have a significant amount of water or ice? Why or why not? **(6 points)**

Table 17.1: Comparison of HD209458b, Earth, and Jupiter.

Parameter	**This Planet**	**Earth**	**Jupiter**
Period (yr)		1	11.86
OSA (AU)		1	5.2
Orbital Eccentricity	0.1	0.017	0.048
Mass (g)		5.97×10^{27}	1.90×10^{30}
Density (g/cm^3)		5.5	1.3

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17.3 Take Home Exercise (35 points total)

In the space provided, answer the following questions:

1. In this lab, we determined the properties of a planet orbiting the star HD209458. If we compare this planet to the planets in our Solar System, which type of planet does it resemble more: a terrestrial planet (like Mercury, Venus, Earth, and Mars), or a giant planet (like Jupiter, Saturn, Uranus, and Neptune)? What characteristics did you use to figure this out? **(5 points)**

2. What property (or properties) of this planet might make it much different from the planets we see in our Solar System? Why? **(3 points)**

3. If, instead of this planet, we had a planet identical to Earth orbiting this star at 1 AU, how would the lightcurve and plot of velocity be different? Assume this new planet would still pass in front of the star. (Specifically, consider how much the star would wobble, the period of this wobbling, and how much starlight would be blocked out.) **(5 points)**

4. Describe the technique used to determine the forward/backward velocity of the star HD209458 (or any other star, for that matter). **(4 points)**

5. Out of the many extrasolar planets discovered so far, only HD209458b passes in front of its star, allowing us to determine its size. Why is it so rare for a planet to pass in front of its star like HD209458b does? How do we know that there are many more extrasolar planets out there, if they don't pass in front of their star and are too faint to see? **(8 points)**

6. You probably obtained a density for this planet that seems a bit outside the range of "normal" densities from our experience with planets in our Solar System. After careful inspection of spectra from this system, astronomers now believe that the planet's atmosphere is in the process of billowing out and leaving the planet... probably due to the intense heat. As a result, the planet ends up blocking out more of the star's light than the size of the actual planet would suggest (see an artist's rendition below). Thinking about the effects that this has on the star's lightcurve, does this new information help to explain why the planet's density is off in the way you found... or does it imply that the planet's real density is even further off? Explain your answer. **(10 points)**

Figure 17.4: This illustration shows the extrasolar planet HD 209458b depicted in orbit around its sun. The planet is a type of extrasolar planet known as a "hot Jupiter." Image taken from `http://www.nasa.gov/vision/universe/newworlds/poof.html`.

17.4 Possible Quiz Questions

1. What does the term "extrasolar" mean?
2. What is the "Doppler effect"?
3. What does "redshift" mean?
4. Why is it so hard to directly see/photograph an extrasolar planet?

17.5 Extra credit (ask your TA for permission before attempting, 5 points)

The difficulty with detecting very small planets is that 1) they do not block much light so their “eclipses” are hard to detect, and 2) they have very low masses, so the wobble of their parent star is very small. Review the current state of the art for detecting the smallest planets. The *Kepler* mission has detected some planets smaller than the Earth (“Kepler 37b”), while the radial velocity studies claim to have detected an object slightly more massive than the Earth (Gliese 581e). Discuss these planets, and the conditions found on their surfaces.