Name:______________________________
Date:_______________________________

1 Characterizing Exoplanets

1.1 Introduction

Exoplanets are a hot topic in astronomy right now. As of January, 2015, there were over 1500 known exoplanets with more than 3000 candidates waiting to be confirmed. These exoplanets and exoplanet systems are of great interest to astronomers as they provide information on planet formation and evolution, as well as the discovery of a variety of types of planets not found in our solar system. A small subset of these planetary systems are of interest for another reason: They may support life. In this lab you will analyze observations of exoplanets to fully characterize their nature. At the end, you will then compare your results with simulated images of these exoplanets to see how well you performed. Note that the capabilities required to intensely study exoplanets have not yet been built and launched into space. But we know enough about optics that we can envision a day when advanced space telescopes, like those needed for the conclusion of today's lab, will be in Earth orbit that will directly image these objects, and obtain spectra to search for the chemical signatures of life.

2 Types of Exoplanets

As you have learned in class this semester, our solar system has two main types of planets: Terrestrial (rocky) and Jovian (gaseous). Because these were the only planets we knew about, it was hard to envision what other kinds of planets might exist. Thus, when the first exoplanet was discovered, it was a shock for astronomers to find out that this object was a gas giant like Jupiter, but had an orbit that was even smaller than that of Mercury! This lead to a new kind of planet called "Hot Jupiters". In the two decades since the discovery of that first exoplanet, several other new types of planets have been recognized. Currently there are six major classes that we list below. We expect that other types of planets will be discovered as our observational techniques improve.

2.1 Gas Giants

Gas giants are planets similar to Jupiter, Saturn, Uranus, and Neptune. They are mostly composed of hydrogen and helium with possible rocky or icy cores. Gas giants have masses greater than 10 Earth masses. Roughly 25 percent of all discovered exoplanets are gas giants.

2.2 Hot Jupiters

Hot Jupiters are gas giants that either formed very close to their host star or formed farther out and "migrated" inward. If there are multiple planets orbiting a star, they can interact through their gravity. This means that planets can exchange energy, causing their orbits to expand or to shrink. Astronomers call this process migration, and we believe it happened early in the history of our own solar system. Hot Jupiters are found within 0.05-0.5 AU of their host star (remember that the Earth is at 1 AU!). As such, they are extremely hot (with temperatures as high as 2400 K), and are the most common type of exoplanet found; about 50 percent of all discovered exoplanets are Hot Jupiters. This is due to the fact that the easiest exoplanets to detect are those that are close to their host star and very large. Hot Jupiters are both.

2.3 Water Worlds

Water worlds are exoplanets that are completely covered in water. Simulations suggest that these planets actually formed from debris rich in ice further from their host star. As they migrated inward, the water melted and covered the planet in a giant ocean.

2.4 Exo-Earths

Exo-Earths are planets just like the Earth. They have a similar mass, radius, and temperature to the Earth, orbiting within the "habitable zone" of their host stars. Only a very small number of Exo-Earth candidates have been discovered as they are the hardest type of planet to discover.

2.5 Super-Earths

Super-Earths are potentially rocky planets that have a mass greater than the Earth, but no more than 10 times the mass of the Earth. "Super" only refers to the mass of the planet and has nothing to do with anything else. Therefore, some Super Earths may actually be gas planets similar to (slightly) smaller versions of Uranus or Neptune.

2.6 Chthonian Planets

"Chthonian" is from the Greek meaning "of the Earth." Chthonian Planets are exoplanets that used to be gas giants but migrated so close to their host star that their atmosphere was stripped away leaving only a rocky core. Due to their similarities, some Super Earths may actually be Chthonian Planets.

3 Detection Methods

There are several methods used to detect exoplanets. The most useful ones are listed below.

3.1 Transit Method/Light Curves

The transit method attempts to detect the "eclipse" of a star by a planet that is orbiting it. Because planets are tiny compared to their host stars, these eclipses are very small, requiring extremely precise measurements. This is best done from space, where observations can be made continuously, as there is no night or day, or clouds to get in the way. This is the detection method used by the *Kepler* Space Telescope. *Kepler* stared at a particular patch of sky and observed over a hundred thousand stars continuously for more than four years. It measured the amount light coming from each star. It did this over and over, making a new measurement every 30 minutes. Why? If we were looking back at the Sun and wanted to detect the Earth, we would only see one transit per year! Thus, you have to continuously stare at the star to insure you do not miss this event (as you need at least three of these events to determine that the exoplanet is real, and to measure its orbital period). The end result is something called a "light curve", a graph of the brightness of a star over time. The entire process is diagrammed in Figure 1. We will be exclusively using this method in lab today.

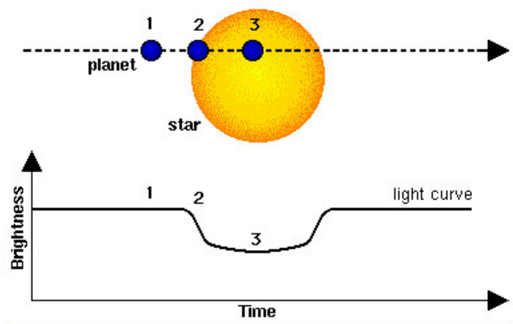

Figure 1: The diagram of an exoplanet transit. The planet, small, dark circle, crosses in front of the star as seen from Earth. In the process, it blocks out some light. The light curve, shown on the bottom, is a plot of brightness versus time, and shows that the star brightness is steady until the exoplanet starts to cover up some of the visible surface of the star. As it does so, the star dims. It eventually returns back to its normal brightness only to await the next transit.

In Figure 1, there is a dip in the light curve, signifying that an object passed between the star and our line of sight. If, however, *Kepler* continues to observe that star and sees the same sized dip in the light curve on a periodic basis, then it has probably detected an exoplanet (we say "probably" because a few other conditions must be met for it to be a confirmed exoplanet). The amount of star light removed by the planet is very small, as all planets are much, much smaller than their host stars (for example, the radius of Jupiter is 11 times that of the Earth, but it is only 10% the radius of the Sun, *or 1% of the area = how much the light dims*). Therefore, it is much easier to detect planets that are larger because they block more of the light from the star. It is also easier to detect planets that are close to their host star because they orbit quickly so *Kepler* could observe several dips in the light curve each year.

3.2 Direct Detection

Direct detection is exactly what it sounds like. This is the method of imaging (taking a picture) of the planets around another star. But we cannot simply point a telescope at a star and take a picture because the star is anywhere from 100 million (10^8) to 100 billion (10^{11}) times brighter than its exoplanets. In order to combat the overwhelming brightness of a star, astronomers use what is called a "coronagraph" to block the light from the star in order to see the planets around it. You may have already seen images made with a coronagraph to see the "corona" of the Sun in the Sun lab.

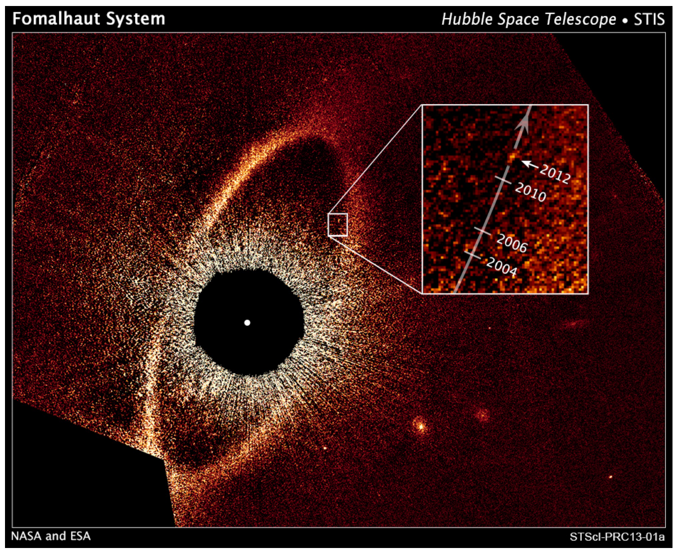

Figure 2: A coronagraphic image of an exoplanet orbiting the star Fomalhaut (inside the box, with the arrow labeled "2012"). This image was obtained with the Hubble Space Telescope, and the star's light has been blocked-out using a small metal disk. Fomalhaut is also surrounded by a dusty disk of material—the broad band of light that makes a complete circle around the star. This band of dusty material is about the same size as the Kuiper belt in our solar system. The planet, "Fomalhaut B", is estimated to take 1,700 years to orbit once around the star. Thus, using Kepler's third law ($P^2 \propto a^3$), it is roughly about 140 AU from Fomalhaut (remember that Pluto orbits at 39.5 AU from the Sun).

So if astronomers can block the light from the Sun to see its corona, they should be able to block the light from distant stars to see the exoplanets right? While this is true, directly seeing exoplanets is difficult. There are two problems: the exoplanet only shines by reflected light, and it is located very, very close to its host star. Thus, it takes highly specialized techniques to directly image exoplanets. However, for some of the closest stars this can be done. An example of direct exoplanet detection is shown in Figure 2. A new generation of space-based telescopes that will allow us to do this for many more stars is planned. Eventually, we should be able to take both spectra (to determine their composition) and direct images of the planets themselves. We will pretend that we can obtain good images of exoplanets later in lab today.

3.3 Radial Velocity (Stellar Wobble)

The radial velocity or "stellar wobble" method involves measuring the Doppler shift of the light from a particular star and seeing if the lines in its spectrum oscillate periodically between a red and blue shift. As a planet orbits its star, the planet pulls on the star gravitationally just as the star pulls on the planet. Thus, as the planet goes around and around, it slightly tugs on the star and makes it wobble, causing a back and forth shift in its radial velocity, the motion we see towards and away from us. Therefore, if astronomers see a star wobbling back and forth on a repeating, periodic timescale, then the star has at least one planet orbiting around it. The size of the wobble allows astronomers to calculate the mass of the exoplanet.

4 Characterizing Exoplanets from Transit Light Curves

Quite a bit of information about an exoplanet can be gleaned from its transit light curve. Figure 3 shows how a little bit of math (from Kepler's laws), and a few measurements, can tell us much about a transiting exoplanet.

The equations shown in Figure 3 are complicated by the fact that exoplanets do not orbit their host stars in perfect circles, and that the transit is never exactly centered. Today we are going to only study planets that have circular orbits, and whose orbital plane is edge-on. Thus, all of the terms with "cos$i$" ("i" is the inclination of the orbit to our site line) or an "e" (which is the eccentricity, the same orbital parameter you have heard about in class for our solar system planets, or in the orbit of Mercury lab) disappear.

First, let's remember Kepler's third law $P^2 \propto a^3$, where P is the orbital period, and a is the semi-major axis. For Earth, we have P = 1 yr, a = 1 AU. By taking ratios, you can figure out the orbital periods and semi-major axes of other planets in *our* solar system. Here we cannot do that, and we need to use Isaac Newton's reformulation of Kepler's third law:

$$P^2 = \frac{4\pi^2 a^3}{G(M_{star} + M_{planet})} \tag{1}$$

"G" in this equation is the gravitational constant (G = 6.67 x 10^{-11} Newton-m^2/kg^2), and $\pi = 3.14$.

We also have to estimate the size of the planet. As detailed in Fig. 3, the depth of the "eclipse" gives us the ratio of the radius of the planet to that of the star:

$$\frac{\Delta F}{F} = \left(\frac{R_{planet}}{R_{star}}\right)^2 \tag{2}$$

Now we have everything we need to use transits to characterize exoplanets. We will have to re-arrange equations 1 and 2 so as to extract unknown parameters where the other variables are known from measurements.

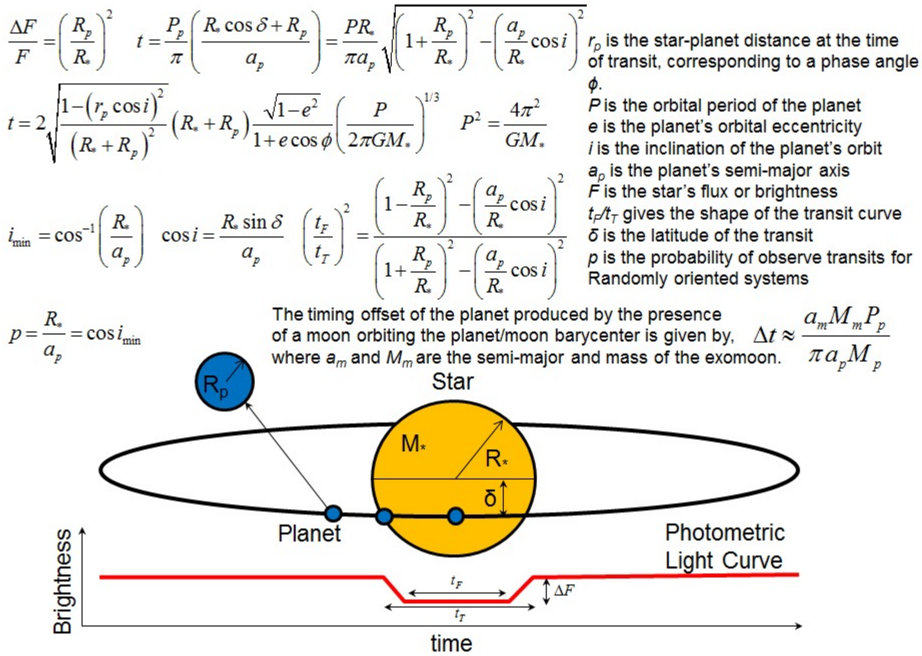

Figure 3: An exoplanet transit light curve (bottom) can provide a useful amount of information. The most important attribute is the radius of the exoplanet. But if you know the mass and radius of the exoplanet host star, you can determine other details about the exoplanet's orbit. As the figure suggests, by observing multiple transits of an exoplanet, you can actually determine whether it has a moon! This is because the exoplanet and its moon orbit around the center of mass of the system ("barycenter"), and thus the planet appears to wobble back and forth relative to the host star.

5 Deriving Parameters from Transit Light Curves

The orbital period of the exoplanet is the easiest parameter to measure. In Figure 4 is the light curve of "Kepler 1b", the first of the exoplanets examined by the *Kepler* mission. Kepler 1b is a Hot Jupiter, so it has a deep transit. You can see from the figure that transits recur every 2.5 days. That is the orbital period of the planet. It is very easy to figure out orbital periods, so we will not be doing that in this lab today.

In the following eight figures are the light curves of eight different transiting exoplanets. Depending on your TA, your group either needs to pick two of these to work on, or your TA will assign you two transits to work on. If you choose, your group will want to select two planets with dramatically different orbital periods (say, one with a period of a several days, and the other with a period of several hundred days). Now we have real data to work with, but some of the work has been done for you. Each panel lists the orbital period of the exoplanets ("xxx day orbit"), ranging from 3.89 days for exoplanet #3, to 3.48 years for exoplanet #2. You should be able to guess what that means already: one is close to its host star, the other far away. The other information contained in these figures is a measurement of "t", the total time of the transit ("eclipse takes xxx hours"). When working with the

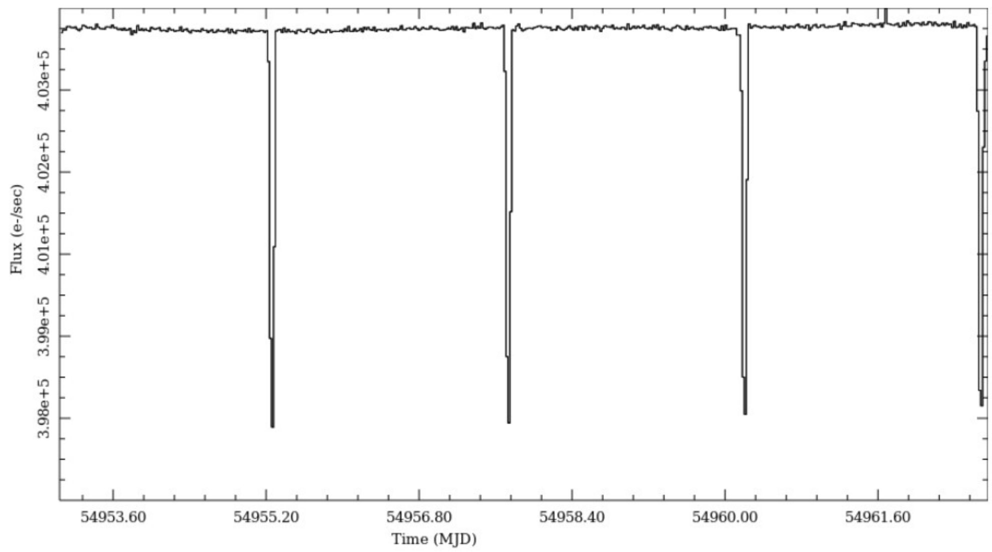

Figure 4: The light curve of Kepler 1b as measured by the *Kepler* satellite. The numbers on the y-axis are the total counts (how much light was measured), while the x-axis is "modified Julian days". This is a system that simply makes it easy to figure out periods of astronomical events since it is a number that increases by 1 every day (instead of figuring out how many days there were between June 6^{th} and November 3^{rd}). Thus, to get an orbital period you just subtract the MJD of one event from the MJD of the next event.

equations below, all time units must be in seconds! Remember, 3600 seconds per hour, 24 hours per day, 365 days per year (there are 3.15×10^7 seconds per year).

Exercise #1:

1. The first quantity we need to calculate is the size of the planet with respect to the host star. How do we do that? Go back to Figure 3. We need to measure "ΔF/F". The data points in the exoplanet light curves have been fit with a transit model (the solid line fit to the data points) to make it easy to measure the *minimum*. For both of the transits you selected, take a ruler and determine the value on the y axis by drawing a line across the model fit to the light curve minimum. Estimate this number as precisely as possible, then subtract this number from 1, and you get ΔF/F. (**2 points**)

   ΔF/F for transit # _________ = _______________________

   ΔF/F for transit # _________ = _______________________

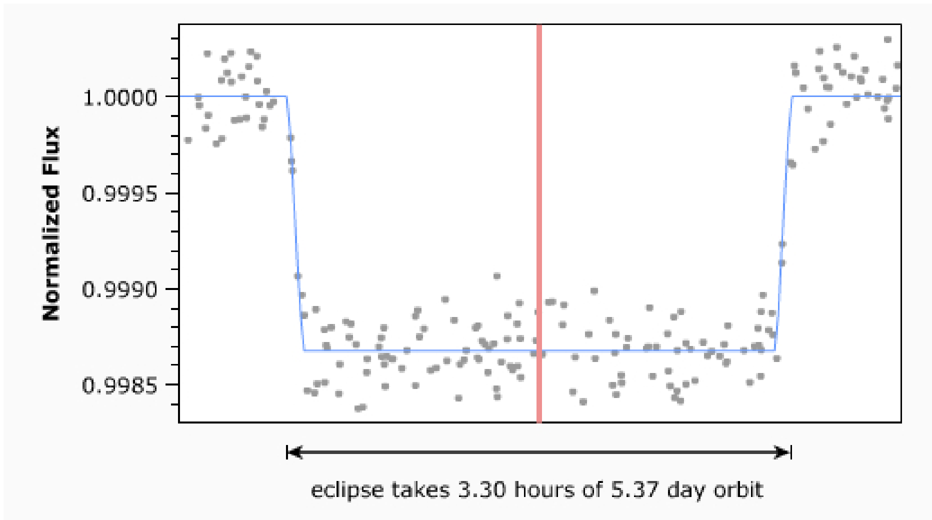

Figure 5: Transiting exoplanet #1. The vertical line in the center of the plot simply identifies the center of the eclipse.

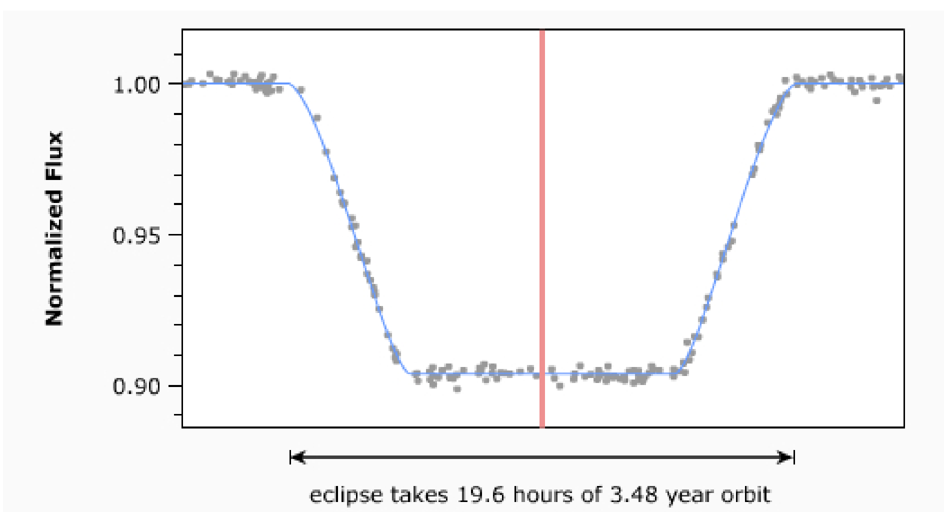

Figure 6: Transiting exoplanet #2.

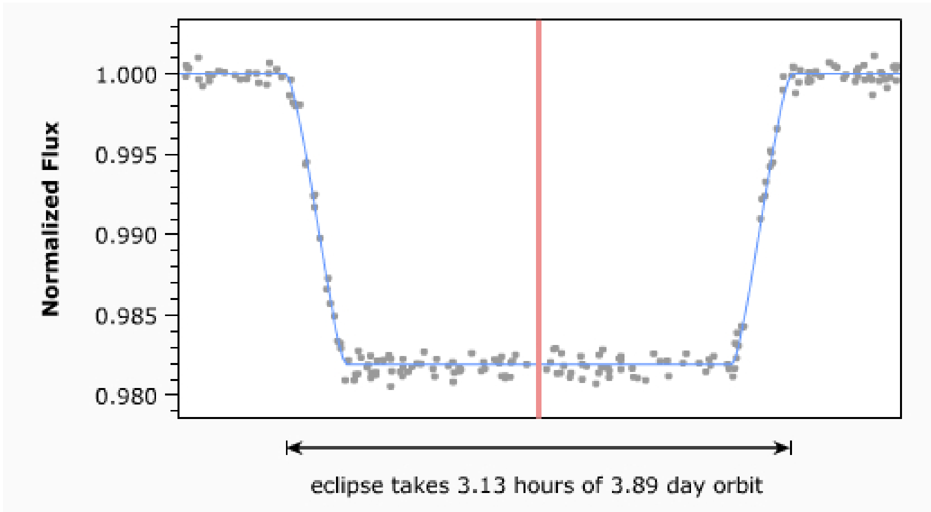

Figure 7: Transiting exoplanet #3.

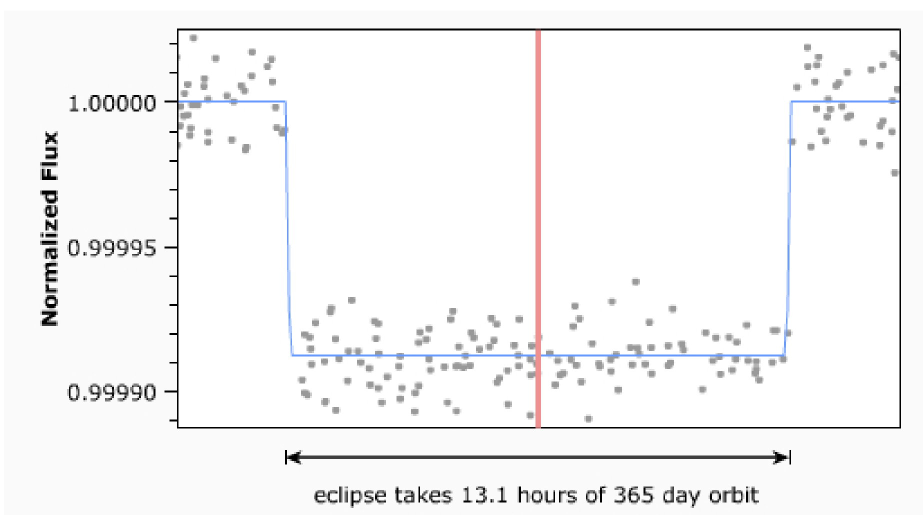

Figure 8: Transiting exoplanet #4.

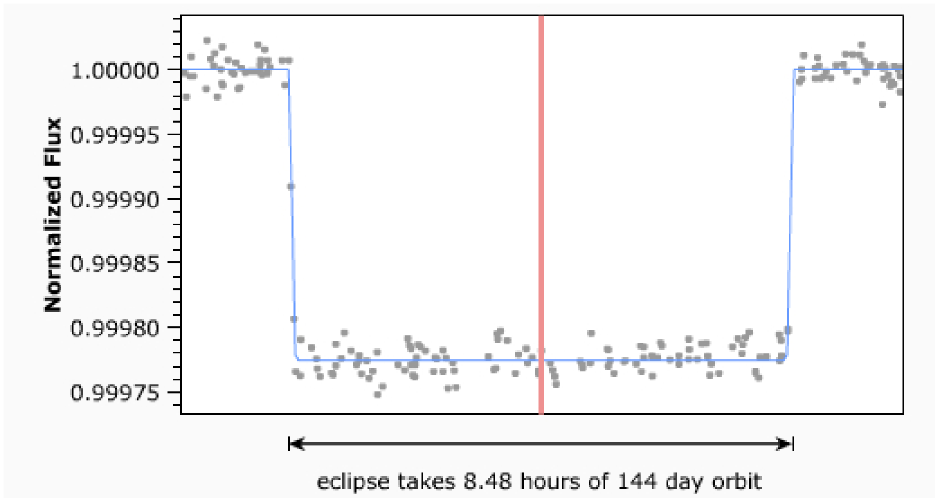

Figure 9: Transiting exoplanet #5.

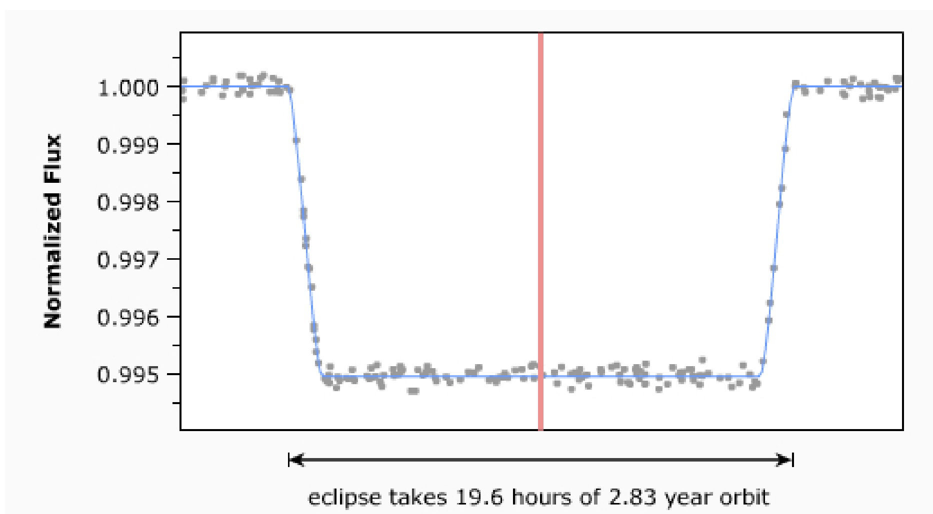

Figure 10: Transiting exoplanet #6.

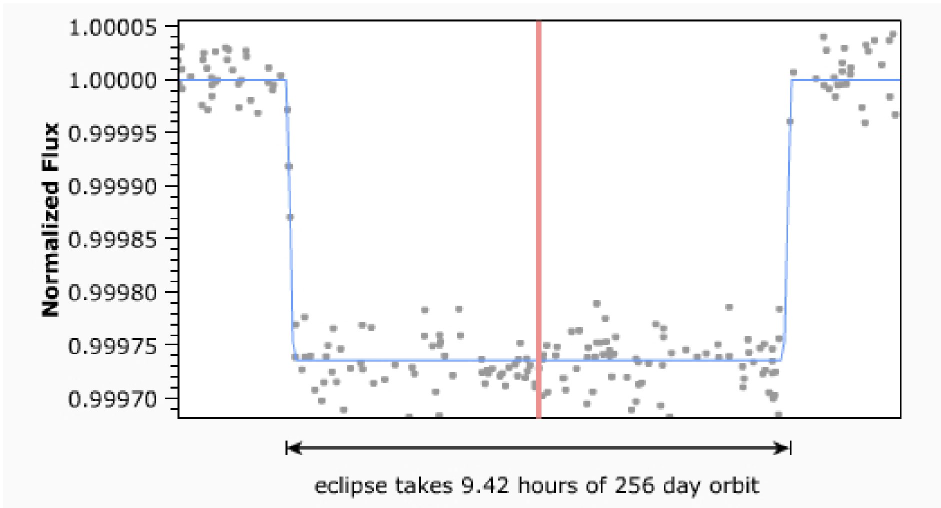

Figure 11: Transiting exoplanet #7.

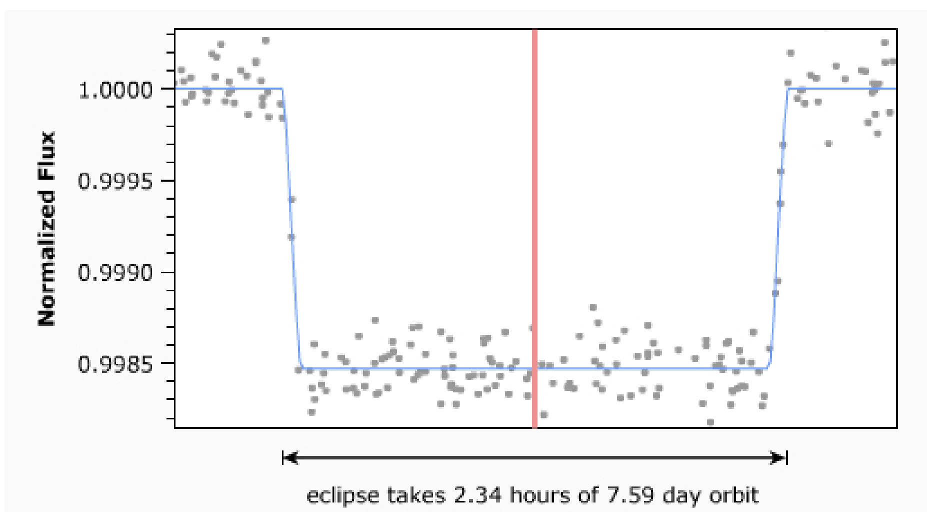

Figure 12: Transiting exoplanet #8.

Going back to equation #4, we have:

$$\frac{\Delta F}{F} = \left(\frac{R_{planet}}{R_{star}}\right)^2$$

2. Taking the square roots of the ΔF/F from above, fill in the following blanks (**4 points**):

   R_{planet} for transit # ________ = ______________________ R_{star}

   R_{planet} for transit # ________ = ______________________ R_{star}

You just calculated the relative sizes of the planets to their host stars. To turn these into real numbers, we have to know the sizes of the host stars. Astronomers can figure out the masses, radii, temperatures and luminosities of stars by combining several techniques (photometry, parallax, spectroscopy, and interferometry). Note that stars can have dramatically different values for their masses, radii, temperatures and luminosities, and these directly effect the parameters derived for their exoplanets. The data for the eight exoplanet host stars are listed in Table 1. Note these values (except for temperature) are relative to the Sun: $M_{\odot} = 2 \times 10^{30}$ kg, $R_{\odot} = 7 \times 10^{8}$ m, $L_{\odot} = 4 \times 10^{26}$ Watts.

Table 1: Exoplanet Host Star Data

Object	**Mass** ($M_{\odot}$)	**Radius** ($R_{\odot}$)	**Temperature** (K)	**Luminosity** ($L_{\odot}$)
#1	1.00	1.00	5800	1.0
#2	0.65	0.71	4430	0.07
#3	1.10	1.08	6160	2.9
#4	1.00	1.00	5800	1.0
#5	0.80	0.84	5050	0.6
#6	1.00	1.00	5800	1.0
#7	0.70	0.75	4640	0.12
#8	0.50	0.57	3760	0.01

3. Now that you calculated the radius of the exoplanet with respect to the host star radius, use the data in Table 1 to convert the radii of your two planets into meters, and put them in the correct rows and columns in Table 2. (**5 points**)

4. Astronomer Judy, and her graduate student Bob, used the spectrograph on the Keck telescope in Hawaii to measure the masses of your planets using the radial velocity technique mentioned above. So we have entered their values for the masses for all of the exoplanets in Table 2. You need to calculate the density of your two exoplanets and enter them in the correct places in Table 2. Remember that density = mass/volume,

Table 2: Exoplanet Data

Object	**Radius** (m)	**Semi-major axis** (m)	**Mass** (kg)	**Density** (kg/m^3)	**Temperature** (K)
#1			1.9×10^{26}		
#2			1.9×10^{28}		
#3			5.7×10^{27}		
#4			6.0×10^{24}		
#5			1.5×10^{25}		
#6			8.0×10^{26}		
#7			4.0×10^{24}		
#8			5.5×10^{25}		

and the volume of all of the planets is V = $4\pi R^3/3$, as we know that they all must be spherical. (**5 points**)

5. By calculating the density, you already know something about your planets. Remember that the density of Jupiter is 1326 kg/m^3 and the density of the Earth is 5514 kg/m^3. If you did the Density lab this semester, we used the units of gm/cm^3, where water has a density of 1.00 gm/cm^3. This is the "cgs" system of units. To get from kg/m^3 to gm/cm^3, you simply divide by 1000. Describe how the densities of your two exoplanets compare with the Earth and/or Jupiter. (**5 points**)

The next parameter we want to calculate is the semi-major axis "a". While we now know the size and densities of our planets, we do not know how hot or cold they are. We need to figure out how far away they are from their host stars. To do this we re-arrange equation #1, and we get this:

$$a = \left(\frac{P^2 G(M_{star} + M_{planet})}{4\pi^2}\right)^{1/3} = (1.69 \times 10^{-12} P^2 M_{star})^{1/3}$$

6. Remember, you must use seconds for P, kg for the mass of the star, and meters for the radii of the star (note: you can ignore the radius of the planet since it will be very small compared to the star). We have simplified the equation by bundling G and $4\pi^2$ into a single constant. Note that you have to take the cube root of the quantity inside the parentheses. We write the cube root as an exponent of "1/3". Ask your TA for help on this step. Fill in the column for semi-major axis in Table 2 for both your exoplanets. (**5 points**)

6 The Habitable Zone

The habitable zone is the region around a star in which the conditions are just right for a planet to have liquid water on its surface. Here on Earth, all life must have access to liquid water to survive. Therefore, a planet is considered "habitable" if it has liquid water. This zone is also colloquially know as the "Goldilocks Zone".

To figure out the temperature of a planet is actually harder than you might think. We know how much energy the exoplanet host stars emit, as that is what we call their luminosities. We also know how far away your exoplanets are from this energy source (the semi-major axis). The formula to estimate the "equilibrium temperature" of an exoplanet with a semi-major axis of a around a host star with known parameters is:

$$T_{planet} = T_{star}(1.0 - A)^{1/4}\left(\frac{R_{star}}{2a}\right)^{1/2} \tag{3}$$

The "A" in this equation is the "Albedo", how much of the energy intercepted by a planet is reflected back into space. Equation #4 is not too hard to derive, but we do not have enough time to explain how it arises. You can ask you professor, or search Wikipedia using the term "Planetary equilibrium temperature" to find out where this comes from. The big problem with using this equation is that different atmospheres create different effects. For example, Venus reflects 67% of the visible light from the Sun, yet is very hot. The Earth reflects 39% of the visible light from the Sun and has a comfortable climate. It is how the atmosphere "traps heat" that helps determine the surface temperature. Alternatively, a planet might not even have an atmosphere and could be bright or dark with no heat trapping (for example, the Albedo of the moon is 0.11, as dark as asphalt, and the surface is boiling hot during the day, and extremely cold at night).

Let's demonstrate the problem using the Earth. If we use the value of A = 0.39 for Earth, equation #4 would predict a temperature of T_{Earth} = 247 K. But the mean temperature on the Earth is actually T_{Earth} = 277 K. Thus, the atmosphere on Earth keeps it warmer than the equilibrium temperature. This is true for just about any planet with a significant atmosphere. To account for this effect, let's go backwards and solve for "A". With R_{Earth} = 6,378,000 m, $a = 1.50 \times 10^{11}$ m, T_{Earth} = 277 K, and $T_{\odot}$ = 5800 K, we find that A = 0.05. Thus, the Earth's atmosphere makes it seem like we absorb 95% of the energy from the Sun. We will presume this is true for all of our planets.

If we assume A = 0.05, equation #4 simplifies to:

$$T_{planet} = 0.70\left(\frac{R_{star}}{a}\right)^{1/2} T_{star} \tag{4}$$

[To understand what we did here, note that (1.0 − A) = 0.95. The fourth root of 0.95 = $0.95^{1/4}$ = 0.99 (remember the fourth root is two successive square roots: $\sqrt{0.95} = 0.95^{1/2}$ = 0.97, and $0.97^{1/2}$ = 0.99). We then divided 0.99 by $\sqrt{2}$ (= 1.41) to have a single constant out front.]

7. Calculate the temperatures of your two exoplanets using equation #5 and enter them into Table 2. (**5 points**)

As we said, the habitable zone is the region around a star of a particular luminosity where water might exist in a liquid form somewhere on a planet orbiting that star. The Earth (a = 1 AU) sits in the habitable zone for the Sun, while Venus is too close to the Sun (a = 0.67 AU) to be inside the habitable zone, while Mars (a = 1.52 AU) is near the outer edge. As we just demonstrated, the atmosphere of a planet can radically change the location of the habitable zone. Mars has a very thin atmosphere, so it is very cold there and all of its water is frozen. If Mars had the thick atmosphere of Venus, it would probably have abundant liquid water on its surface. As we noted, the mean temperature of Earth is 277 K, but the polar regions have average temperatures well below freezing (273 K) with an average annual temperature at the North pole of 263 K, and 228 K at the South pole. The equatorial regions of Earth meanwhile have average temperatures of 300 K. So for just about every planet there will be wide ranges in surface temperature, and liquid water could exist somewhere on that planet.

8. Given that your temperature estimates are not very precise, we will consider your planet to be in the habitable zone if its temperature is between 200K and 350 K. Is either of your planets in the habitable zone? (**4 points)**

7 Classifying Your Exoplanets

At the beginning of today's lab we described the several types of exoplanet classes that currently exist. We now want you to classify your exoplanet into one of these types. To help you decide, in Table 3 we list the parameters of the planets in our solar system. After you have classified them, you will ask your TA to see "images" of your exoplanets to check to see how well your classifications turned out.

9. Compare the radii, the semi-major axes, the masses, densities and temperatures you found for your two exoplanets to the values found in our solar system. For example, if the radius of one of your exoplanets was 8×10^7, and its mass was 2.5×10^{27} it is similar in "size" to Jupiter. But it could have a higher or lower density, depending on composition, and it might be hotter than Mercury, or colder than Mars. Fully describe your two exoplanets. (**10 points**)

Table 3: Solar System Data

Object	**Radius** (m)	**Semi-major axis** (m)	**Mass** (kg)	**Density** (kg/m^3)	**Temperature** (K)
Mercury	2.44×10^6	5.79×10^{10}	3.3×10^{23}	5427	445
Venus	6.05×10^6	1.08×10^{11}	4.9×10^{24}	5243	737
Earth	6.37×10^6	1.49×10^{11}	5.9×10^{24}	5514	277
Mars	3.39×10^6	2.28×10^{11}	6.4×10^{23}	3933	210
Jupiter	6.99×10^7	7.78×10^{11}	1.9×10^{27}	1326	122
Saturn	6.03×10^7	1.43×10^{12}	5.7×10^{26}	687	90
Uranus	2.54×10^7	2.87×10^{12}	8.7×10^{25}	1270	63
Neptune	2.46×10^7	4.50×10^{12}	1.0×10^{26}	1638	50
Pluto	1.18×10^6	5.87×10^{12}	1.3×10^{22}	2030	43

As Table 3 shows you, there are two main kinds of planets in our solar system: the rocky Terrestrial planets with relatively thin atmospheres, and the Jovian planets, which are gas giants. Planets with high densities (> 3000 kg/m^3) are probably like the Terrestrial planets. Planets with low densities (< 3000 kg/m^3) are probably mostly gaseous or have large amounts of water (Pluto has a large fraction of its mass in water ice).

10. Given your discussion from the previous question, and the discussion of the types of exoplanets in the introduction, classify your two exoplanets into one of the following categories: 1) Gas giant, 2) Hot Jupiter, 3) Water world, 4) Exo-Earth, 5) Super-Earth, or 6) Chthonian. What do you expect them to look like? (**10 points**)

11. Your TA has images for all eight exoplanets of this lab obtained from NASA's "Exoplanet Imager" mission that was successfully launched in 2040. Were your predictions correct? Yes/no. If no, what went wrong? [The TA also has the data for all of the exoplanets to help track down any errors.] (**10 points**)

Name:______________________________
Date:_______________________________

8 Take Home Exercise (35 points total)

Please summarize the important concepts discussed in this lab. Your summary should include:

- Discuss the different types of exoplanets and their characteristics.
- What are the measurements required for you to determine the most important parameters of an exoplanet?
- What requirement for an exoplanet gives it the possibility of harboring life?

Use complete sentences, and proofread your summary before handing in the lab.

8.1 Possible Quiz Questions

1. What are some of the different types of exoplanets?
2. What are some different exoplanet detection methods?
3. What is the habitable zone?

8.2 Extra Credit (ask your TA for permission before attempting, 5 points)

Your TA has the data for all of the exoplanets for today's lab. With that data, go back and answer questions #8 and #9 for all of the exoplanets.

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