Name:_____

Date:_____

1   Exoplanets

1.1   Introduction

Exoplanets are a hot topic in astronomy right now. As of January, 2015, there are over 1500 confirmed exoplanet discoveries with more than 3000 candidates still waiting to be confirmed. These exoplanets and exoplanet systems are of extreme interest to astronomers as they provide insights into planet formation and evolution, as well as a number of exotic types of planets that are not found in our solar system. A small subset of the planetary systems are also of interest for another reason: They may support life. In this lab you will imitate a team of astronomers analyzing data on exoplanets and decide which systems you would like to pursue further with spacecraft flybys and then ultimately send down a lander. In doing so you will discover the variety of terrain, atmospheres, and geological processes that can occur on planets, while searching for the signatures of extraterrestrial life.

2   Types of Exoplanets

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 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.

2.5 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.

2.6 Chthonian Planets

Chthonian Planets are planets 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

This is the detection method utilized by the Kepler Space Telescope where it looks for exoplanets crossing in front of (transiting) the host star. Kepler picks a particular field of view in the sky and selects around a hundred thousand stars to observe over a given time period. It then measures how much light, or the intensity of light, that it receives from a particular star. Every 30 minutes, Kepler observes that star again, and keeps observing the same star for years (remember, if we were looking back at the Sun and wanted to detect the Earth, we only will see one transit per year!). This allows for the creation of an intensity vs. time plot, called a "light curve", as shown in Figure 1.

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 again sees the same 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 can observe several periodic dips in a
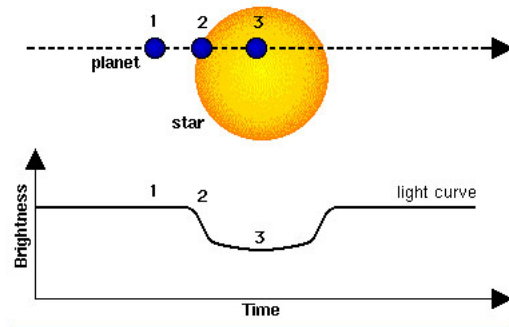
Figure 1: The diagram of an exoplanet transit. The planet, small, dark circle, crosses in front of the star as seen from Earth. In the process, it blocks out some light. The light curve, shown on the bottom, is a plot of brightness versus time, and shows that the star brightness is steady until the exoplanet 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.

light curve each year.

3.2 Direct Detection

Direct detection is exactly what it sounds like. This is the method of physically seeing 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 the 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 used in the Sun lab.

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, it's much more complicated. Because the stars are so far away, the planets are essentially in the same spot as the star on the sky so we can't always resolved them. However, for some of the closer stars it can be done. An example of direct exoplanet detection is given in Figure 2.

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 it oscillates periodically between a red and blue shift (see the Hubble's Law lab about Doppler shift). As a planet orbits a star, the planet pulls on the star gravitationally just as the star pulls on the planet, albeit much stronger.
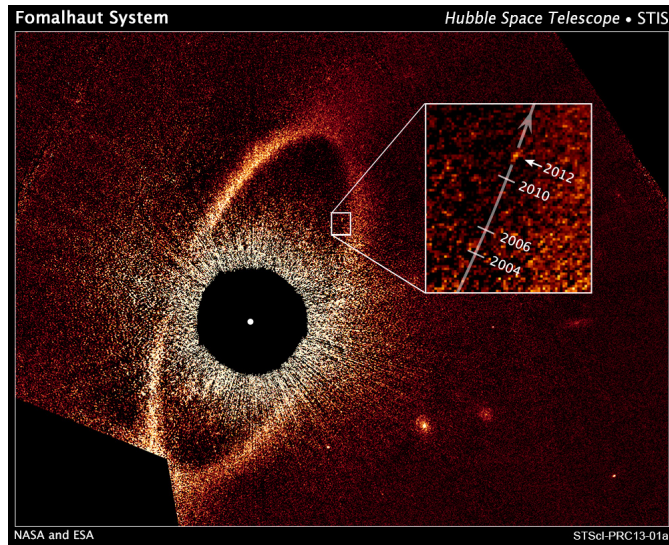
Figure 2: A coronagraphic image of an exoplanet orbiting the star "Fomalhaut B" (inside the box, with the arrow labeled "2012"). This image was obtained with the Hubble Space Telescope, and the star's light has been blocked-out using a small metal disk. Fomalhaut is also surrounded by a dusty disk of 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).

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.

4   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, so far as we know, 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".

The habitable zone is determined by how much energy a star outputs and the balance of how much energy a planet absorbs from the star and how much it re-emits. For simplicity, we assume that the planet is a perfect blackbody. If you have already done the spectroscopy lab you should know what a blackbody is. As a reminder, a blackbody is a perfect absorber of light and a perfect emitter of light (with a blackbody spectrum). That will allow us to determine what the surface temperature of the planet is to a rough approximation. Remember that water exists in its liquid form at a temperature between 0 and 100 degrees Celsius,

or between 273 and 373 Kelvin. A simple equation is given here that lets you calculate the distance (in AU) between the star and a planet with a specified temperature:

$$D = 6.67 \times 10^{-14} \sqrt{\frac{L_{star}}{16\pi\sigma T^4}} \qquad Equation \ \#1$$

Here L_{star} is the luminosity of the host star (in erg/s), σ is the Stefan-Boltzmann constant and it equals $5.67 \times 10^{-5} \frac{erg}{cm^2 s K^4}$ and T is the surface temperature of the planet (in Kelvin). To find the range of the habitable zone, plug in 373 for the temperature to find the minimum distance from the star (any closer and the planet would be too hot), and then do it again but this time with 273 for the temperature to find the maximum distance (any further and the planet would be too cold).

For an example, the Sun has a luminosity of 3.85×10^{33} erg/s so the habitable zone would be between 0.56 and 1.04 AU. The Earth is at 1 AU which we know is in the habitable zone. (The actual habitable zone for the Sun is shifted further out than this range because we are assuming the planet does not reflect any light, nor does it have an atmosphere in our calculation. So again, it's a rough approximation.)

5   Objective

In this lab you will simulate a scientific mission to explore several exoplanets in different systems from initial detection to flyby missions to even sending a lander to one of your choosing! You will work together in your group to make decisions regarding what you want to investigate, but then collectively decide as a class what will be investigated based on what is most frequently selected from the groups. This is similar to how real science works in to-day's world. Several different research groups present what they would like to investigate and based on what is collectively decided, that is the mission that gets funded.

You will be presented with three different FICTIONAL stellar systems and FAKE data that your instructor will provide. From this detection data you will pick two systems to send flyby missions to based on certain calculations you make regarding the data. The best part about this simulation is that you don't have to wait a ridiculously long time to wait for the spacecraft to arrive at the extrasolar system.

From there your instructor will provide you with the flyby data as well as the images. After answering a few questions, your group, and then the class, will decided which two planets to send landers to. The landers will then send back data from the planet, again, also with images. From this data you will answer questions regarding the geology, atmosphere, and possibly exobiology of the planet.

6   The Candidates

You will examine the three fictional extrasolar systems. They are Terranova, Terrafuego, and Terrafauna. Your instructor will now show you the observations for each of the systems. It is the job of your group to determine how many exoplanets are orbiting each system. Terranova has direct imaging data so determining the number of planets should be fairly simple.

Question 1: How many planets does the Terranova system have? **(2 points)**

Terrafuego has light curve data. Look for periodic dips to determine if there is a planet and different levels of dips for multiple planets.

Question 2: How many planets does the Terrafuego system have? **(2 points)**

Terrafauna also has lighcurve data. Again, look for periodic dips.

Question 3: How many planets does the Terrafauna system have? **(2 points)**

Question 4: How does the number of planets orbiting a planet affect the light curve data? **(5 points)**

Now we want to determine where the habitable zone is around each star as a possible indicator of which systems you might want to investigate. But in order to do that, we need to know the luminosity of each star. Luckily we have the information to figure it out. Photometric and parallax data were also taken from the stars, and from it, we can figure out

their luminosities. The data for each star is listed in Table 1.

Table 1: Star Data

Star	Distance to Star (parsec)	Apparent Magnitude	Star Classification
Terranova	6.13	5.137	K1V
Terrafuego	16.56	8.595	K6V
Terrafauna	9.81	4.708	G0V

We can determine the absolute magnitude of a star from its apparent magnitude and distance by using the distance modulus. And from absolute magnitude, we can determine its luminosity by comparing it with the Sun. The distance modulus is as follows:

$$m - M = 5\log(D) - 5 \qquad Equation \ \#2$$

where m is the apparent magnitude, M is the absolute magnitude, and D is the distance to the star (in parsecs). It is important to know that magnitudes are backwards to what you might intuitively think. That is, **the lower, or more negative the number, the brighter the object**. With our eyes, the dimmest magnitude we can see is 6, and the brightest star in the sky is Sirius with a magnitude of -1.4.

Question 5: Using Equation #2, what is the absolute magnitude "M" of each star? (**3 points**)

Terranova:_____

Terrafuego:_____

Terrafauna: _____

Now that we know the absolute magnitude of each star, we may calculate the intrinsic luminosity of the star (L_{star}) because we know the absolute magnitude and luminosity of the Sun (L_{Sun}). We calculate the luminosity using the following formula:

$$\frac{L_{star}}{L_{Sun}} = 10^{\frac{2}{5}(M_{Sun} - M_{star})} \qquad Equation \ \#3$$

where $M_{Sun} = 4.83$ and $L_{Sun} = 3.85 \times 10^{33} \ erg/s$. More simply, this becomes:

$$L_{star} = 3.85 \times 10^{(34.932 - 0.4 M_{star})} \qquad Equation \ \#4$$

Question 6: Using Equation #4, what is the luminosity of each star? **(3 points)**

Terranova:_____

Terrafuego:_____

Terrafauna: _____

Finally, calculate the habitable zone for each star. Here is a simplified version of Equation #1 in section 4. Recall you must calculate it twice, once for T=273K and once for T=373K.

$$D = 1.249 \times 10^{-12} \frac{\sqrt{L_{star}}}{T^2} \qquad Equation \ \#5$$

Question 7: Using Equation # 5, where are the edges of the habitable zone ("D" for 273 K, and for 373 K) for each star? (Don't forget units!) **(6 points)**

Terranova:_____

Terrafuego:_____

Terrafauna: _____

7   Flyby Decision

What good is learning about the habitable zone for each star if we don't know where the planets are in relation to it? Therefore, using the information in Tables 3, and 4, you should be able to figure out how far each planet is from its host star. We have direct imaging data of the Terranova system so you would be able to use geometry to figure out those planet-star distances if you had to. However, those distances have already been calculated for you. Table 2 is still there if you would like to try to confirm the planet-star distances on your own. Since we have light curve data for the other two systems, we can determine their planet-star distance using Kepler's third law:

$$P^2 = \frac{a^3}{M_{star} + M_{planet}}$$

or, solving for the semi-major axis, "a":

$$a^3 = P^2 M_{star}$$

or

$$a = (P^2 M_{star})^{1/3} \qquad Equation \ \#6$$

where P is the period of the planet (in years) and a is the distance between the planet and the star (in AU). You might wonder, "What happened to the M_{planet} term in Equation #6?" The mass of any planet is tiny relative to the star (usually less than 1%), thus we can still get an accurate estimate for "a" even if we ignore M_{planet}.

Table 2: Terranova Planet Data

Planet	Distance to Star (parsec)	Angular Distance from Star (arcseconds)
Inleus	6.13	.0504
Xeesle	6.13	.0721
Reorte	6.13	4.708

Table 3: Terrafuego Planet Data

Planet	Period of Planet (years)	Star Mass (Solar Masses)
Fernandin	0.027	0.8
Teaatis	4.547	0.8

Table 4: Terrafauna Planet Data

Planet	Period of Planet (years)	Star Mass (Solar Masses)
Chenko	0.041	1.06
Nimien	0.768	1.06
Bordack	2.422	1.06
Coronis	3.709	1.06

Question 8: Using Equation #6, what is the distance "a" in AU between each planet and its host star? **(12 points)**

Terranova: Inleus: <u>0.309 AU</u> Xeesle: <u>0.442 AU</u> Reorte: <u>1.211 AU</u>

Terrafuego: Fernandin_____ Teaatis_____

Terrafauna: Chenko _____ Nimien_____
Bordack_____ Coronis_____

Question 9: Based on everything you've read and done, what two systems would you like to send flyby missions to and why? **(4 points)**

You will now discuss your decision with the other lab groups and collectively decide as a class which two systems you would like to send flyby missions to.

Question 10: What two systems did you collectively decide to send missions to? **(6 points)**

8 The Planets Themselves

Your instructor will now show you the flyby images of each planet in the two systems you chose. Take note of what you see. Are they gas planets? Rocky planets? Something else? Do they look like they have an atmosphere? Is there evidence for wind, storms, volcanic activity, or impact craters? Do they have water or ice? What unique features do they have? Now, based on what you see from these flyby images, use the descriptions of the different types of exoplanets in the beginning of this lab to classify all the planets in the system you are examining.

Question 11: In one of the two systems, classify what type of exoplanet each planet is and why. **(6 points)**

Now, pick two planets from each system. The flyby spacecraft will release two smaller probes, one for each planet in each system, that will orbit the selected planet and map its surface. It will obtain images of the entire surface in both the planet's daytime and nighttime. It will also obtain elevation data to determine the relief of the planet as well as emboss maps to better display the edges of particular structures on the surface such as craters. Once you have decided on your four planets, share them with the class and the two most popular planets from each system will be investigated.

Your instructor will now display the topographic (elevation) data for you. Note that the cameras on the orbiter do not provide very high resolution, so the maps of the surfaces are a little bit coarse. Discuss what you see on each planet with your group members.

Question 12: Write down which planets your class decided to investigate and discuss two unique features that you observe about each planet's surface. **(3 points)**

9 Lander Missions

Finally, you need to decide to which planets you would like to have a lander visit. Not all the planets have a hard surface (i.e., gas giants), so if you decide to send a lander to a gaseous planet, it will be more of a suicide mission, and one that will take data as it falls through the atmosphere before eventually being crushed by the immense pressure inside the planet. So,

of the four planets you selected to obtain data for, discuss amongst your group and decide which ones you wish to land on. Pick one planet per system.

Question 13: Which two planets would you like to send a lander to and why? **(3 points)**

Now share your answer with the class and collectively decide to which planets you will send landers.

Question 14: Which planets did the class select? **(3 points)**

Your instructor will now show you the data the landers retrieved, including images, and atmospheric and surface data.

Question 15: Discuss several characteristics about the two planets learned from the images/data (geology, composition, atmosphere, etc.). Do you think these planets might be suitable for life? Why or why not? **(5 points)**

10   Take Home Exercise (35 points total)

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

- Discuss three different types of exoplanets and their characteristics.

- What are the pros and cons of using different exoplanet detection methods?

- Why do we rarely discover exoplanets that are orbiting far from their host star?

- Where is the best place to start looking for life on exoplanets?

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

10.1   Possible Quiz Questions

1. What are some of the different types of exopanets?

2. What are some different exoplanet detection methods?

3. What is the habitable zone?

4. Where is the best place to look for exoplanets?

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

Do a little research on the discovered exoplanets that have the highest possibility of harboring life? What are their names? What is special about them? What are their characteristics (size, composition, etc.)? How were they discovered?