Exoplanets and Habitable Zones

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**Goal of the Lab**
The goal of this lab is to understand how astronomers detect the presence of an exoplanet in orbit around another star and determine whether or not a planet is within the star’s habitable zone.

1. Know the difference between the Radial Velocity Method and the Transit Method.
2. Become familiar with the current number and types of extrasolar planets discovered.
3. Understand what is meant by the phrase “habitable zone.”
4. Using the luminosity of the host star, be able to determine the inner and outer distances of the habitable zone.

Tools used in this lab:
- Microsoft Excel
- The NASA Exoplanet Archive: [https://exoplanetarchive.ipac.caltech.edu/](https://exoplanetarchive.ipac.caltech.edu/)
- UNL Astronomy Simulation: Circumstellar Habitable Zone Simulator [https://astro.unl.edu/naap/habitablezones/animations/stellarHabitableZone.html](https://astro.unl.edu/naap/habitablezones/animations/stellarHabitableZone.html)

1. Background

![Kepler The Numbers](image1)

Figure 1. The NASA Kepler Space Telescope Mission (2009 – 2018) was responsible for monitoring hundreds of thousands of stars in the constellation Cygnus. Over its 9.6 year mission, Kepler discovered and confirmed 2,662 extrasolar planets. Credit: NASA

The Milky Way Galaxy is populated with hundreds of billions of stars. Long before we had the scientific capability to prove the existence of other planets around those stars, we dreamed of those foreign worlds. With no evidence outside our own solar system, we dreamed of the extraterrestrial terrains explorers might encounter. Science Fiction and fantasy is filled with fantastic fictional encounters with alien civilizations on those worlds. The idea of extrasolar planetary travel intrigues the human inclination to explore. Sadly, technology has not caught up to science fiction with respect to space exploration, but it has achieved positive proof of the existence of other worlds.

The first extrasolar planet (frequently just exoplanet) was discovered in 1992, when several planets were detected orbiting a pulsar. The first extrasolar planet, 51 Pegasi b, orbiting a main sequence star came three years later in 1995. 51 Pegasi b surprised astronomers because it was roughly the size of Jupiter, but
orbited its host star a distance closer than Mercury orbits the Sun. Such planets are now referred to as a 'hot jupiter' planets. At an astoundingly close distance of 0.05 AU away from a star very similar to our Sun, 51 Pegasi b reaches temperatures as high as a roaring 1200 Kelvin on the day side. Since those first discoveries though, astronomers have found thousands of extrasolar planets, largely by the work of the Kepler Space Telescope team, and more currently by the Transiting Exoplanet Survey Satellite (TESS). The extrasolar planet discoveries range in mass from approximately Earth-sized, or slightly smaller, to nearly star sized (these objects are called brown dwarfs). Since that discovery, we've also established several other methods for Extrasolar planet detection that have broadened the search parameters to include Earth-scale planets.

Current statistical estimates made by extrapolating from the density of extrasolar planets in nearby star regions indicate that each star in the Milky Way should have at least one planet orbiting it. Current estimates and statistical analysis suggest that 1 out of every 6 of these planets are terrestrial planets made out of metal and rock with sizes between Mercury and Earth-size. The key to detecting these planets is to employ a variety of search methods over widely different parts of the galaxy, because each method of extrasolar planetary detection has its own strengths and weaknesses.

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**Figure 3. The Transit Method to detect extrasolar planets.** Astronomers observe the brightness of a star over time, a light-curve, and look for periodic dips in brightness as the planet moves in front of the star, travels across the disk of the star, and then moves away. This is called a transit. For a planet to transit its star, the planetary system must have a near zero inclination along the line of sight between the Earth and the planetary system. Credit: NASA Goddard.

### 1.1 The Transit Method

Planets do not emit their own visible light, so when an extrasolar planet passes in front of its host star, the light we see is actually dimmed very slightly by the planetary eclipse. By observing stars for long periods at high accuracy, astronomers can record the little decreases in brightness, and so indirectly observe the planet. An examination of the brightness of an object over time is called a light-curve. If a planet is orbiting a star such that the planet passes in front of the star giving a dip in the light, the light-curve will show a dip in the brightness. This passage of a planet in front of a star to cause a dip in brightness is called a transit, and therefore this method of detecting an extrasolar planet is called the **transit method**. This is the method employed by the Kepler Space Telescope and TESS. For a planet to
pass in front of a star viewed along a line-of-sight to Earth, the planetary system must be near zero-inclination.

1.2 The Radial Velocity Method
An important feature of gravity is that the force of attraction is mutual and in the radial direction. To illustrate this, think of yourself standing on the surface of the Earth. You know that you stay attached to the surface because the Earth's gravity is pulling you down towards the Earth's core. What you may not immediately realize is that just as you are being pulled down to the Earth, the Earth is being pulled towards you. The reason this reaction on the Earth isn't immediately noticeable is the Earth has a mass of 5.97x10^{24} kg, and you might have a mass of 100 kg. So, you could never measure the tiny acceleration your gravity causes on the Earth.

The same feature applies to stellar gravity. As the Sun pulls on the Earth and other planets to keep them in orbit, the planets pull on the Sun. But in this case, the combined masses of the planets is enough to make a measurable force on the Sun. Saying that the planets orbit the Sun is a simplification. As explored in the Kepler’s Laws Lab, the Sun and planets both orbit their combined center of mass, in a sort of massively complex dance. For our solar system, that center of mass is almost always inside the Sun's radius, but this means that an outside observer would see that the Sun wobbles around while the planets orbit! The motion of a host star in response to the presence of a planet is called reflex motion. Therefore, if scientists want to find other stellar systems, they can watch for the star the shows reflex motion as it dances gravitationally with its planets!

![Figure 4. The Radial Velocity Method of detecting extrasolar planets. The presence of planet causes the star to have its own orbit around the center of mass of the system. This causes the star to periodically move toward and away from the Earth at the orbital period of the planet. Astronomers can observe the spectral lines of the star and use the Doppler Effect to look for a periodic blue-shift, red-shift, of the spectral lines as the star experiences reflex motion.
Image Credit: http://www.scienceinschool.org/2011/issue19/exoplanet](image)

Detecting the wobble of the star becomes a matter of looking for the Doppler effect in its light spectrum. When a light source is moving radially away from us, the light appears to have a longer wavelength, this is known as red-shifting because red has the longer wavelengths in the visible spectrum. As the light source moves towards us radially, it's light appears to have shorter wavelengths, known as blue-shifting. So, by watching the spectrum of the star as it dances with its planets, we can see the whole spectrum shift towards the red when it's moving away, and to the blue when it's moving towards us.

1.3 The Habitable Zone
In the field of extrasolar planetary hunting, it is an exciting achievement to discover a planet of any description. The true treasure that every team is hunting for though, is another planet that can
support life as we know it. As far as biologists have been able to tell, there is only one feature of the Earth that every one of its organisms requires for survival: the presence of liquid water at the surface. Thus, the hunt is on for extrasolar planets with conditions that allow liquid water at their surface. Such a planet is in the Circumstellar Habitable Zone (CHZ), or “Goldilocks’ Zone” around its star. It is far enough from its star so that water wouldn’t boil away (not too hot), close enough that water wouldn’t freeze to ice at its surface (not too cold), and the right size to allow molecular hydrogen to be trapped on its surface by gravity (just right). There are a lot of complications to this idea. Firstly, that the CHZ around a star would change dramatically as the star ages in its life cycle, changing luminosity and size. Secondly, that size and composition of atmosphere for a planet can dramatically change the temperature at its surface. However, as a means of ruling out planets where life as we know it could not possible exist, the concept of the CHZ is extremely useful.

Figure 5. Depiction of the potential Circumstellar Habitable Zone (CHZ) for stars ranging in surface temperatures cooler than the Sun ($T = 3,000 \, \text{K}$) to stars hotter than the Sun ($T = 7,000 \, \text{K}$). The inner, red boundary is the hot innermost distance where there is a possibility of liquid water existing on the surface. The yellow line shows the distance expected for a planet with an atmosphere similar to Earth’s to experience a runaway greenhouse effect. The central blue line is Earth-like conditions. The outer blue line is the cold outer boundary of the CHZ where water is expected to freeze. Credit: NASA Kepler

The very general formula for calculating the CHZ of a main-sequence star is:

$$R_{\text{inner}} = \frac{L_{\text{star}}}{\sqrt{1.1}} \quad R_{\text{outer}} = \frac{L_{\text{star}}}{\sqrt{0.53}}$$

Where $L_{\text{star}}$ the intrinsic luminosity of the star, $R_{\text{inner}}$ is the radius of the innermost circle of a star's habitable zone (in AU), and $R_{\text{outer}}$ is the outermost circle of the star's habitable zone (in AU). The area in between makes up a disk where liquid water won't be frozen or boiled away by the host star. The numbers 1.1 and 0.53 represents the stellar flux at those orbital radii.
Today's exercise comes in two parts. The first part will use the above simple estimates of the Habitable Zone to compare with the known conditions in extrasolar planets. The first part appears to have a lot of math, but don't get bogged down by the formulas! You will use Excel to complete the calculations for you! The second will use the more detailed simulation found at http://astro.unl.edu/naap/habitablezones/animations/stellarHabitableZone.html to examine the habitable zones of a select few stellar systems.

1.4 NASA’s Eyes on Exoplanets exploration tool

NASA provides a wonderful tool to explore the currently discovered exoplanets called “Eyes on Exoplanets.” This tool allows you to see the location of all the currently discovered exoplanets. You can click on any planet and zoom into that exoplanetary system. As of March 2020, it is still in beta-testing. NASA’s Eyes on Exoplanets: https://exoplanets.nasa.gov/eyes-on-exoplanets/#/.

This tool is not used in the current version of the lab, but it is highly encouraged that you explore it.
2 In-class Activities

2.1 Exploring the NASA Exoplanet Archive

The NASA Exoplanet Archive is available at https://exoplanetarchive.ipac.caltech.edu/. On the main page it lists the total current number of confirmed exoplanets, the current totals for the TESS spacecraft, and a button for more information. Click on the button associated with the current total number of confirmed planets. This will bring you to the archive in the form of a massive table.

**Task 1: Locate 10 nearby Stellar Systems**

1. Scroll on the table almost all the way to the right until you find the “Distance” column. The distances are listed in parsecs (pc). Sort the list from nearest to farthest extrasolar planets.
2. The first system with a determined distance should be the Proxima Centauri at a system a distance, \( D = 1.301 \) pc. On an Excel Spreadsheet (this time you have to create it) to record:
   a. The host star’s name (e.g., Proxima Centauri, GJ 411, YZ Cet),
   b. The number of planets in the system (e.g., YZ Cet has 3 planets: YZ Cet b, c, and d),
   c. The semi-major axis in AU of each planet in the system
   d. The orbital period in days of each planet in the system
   e. The planet’s discovery method
3. Record the data in (2) for 6 systems. The selected systems need to include
   The 3 nearest planetary systems
   2 systems discovered by the Transit Method
   The TRAPPIST-1 Planetary System

**Task 2 Find the Luminosities of the Host Stars with Stellarium**

Open the program Stellarium by double clicking the icon on your desktop. When the program opens up, the display should appear with the current sky over Knoxville, TN. Hold the cursor over the side bar until you locate the search tool. Select Search and host star’s name (e.g., Ross 128) for each star in the planetary systems you found above. From the information that Stellarium displays with each star, record in your Excel sheet the Absolute Magnitude (Mv) of the Star and its spectral class/type (e.g., YZ Cet is a M4V star).

The reason that we needed the spectral class of each star, was that the color of star represents the temperature of the star, and so dramatically effects the habitable zone. The Bolometric Correction (BC) for each spectral class is:

<table>
<thead>
<tr>
<th>Spectral Class</th>
<th>B</th>
<th>A</th>
<th>F</th>
<th>G</th>
<th>K</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bolometric Correction, BC</td>
<td>-2.0</td>
<td>-0.3</td>
<td>-0.15</td>
<td>-0.4</td>
<td>-0.8</td>
<td>-2.0</td>
</tr>
</tbody>
</table>

Now with this information, you will use Excel to calculate the luminosity of the star, in units of Solar-Luminosities (\( L_{\text{Sun}} \), the natural Unit for Stellar Luminosities).

\[
L_{\text{star}} = 10^{\frac{M_p + BC - 4.42}{-2.5}}
\]
To keep a convenient record of your Excel calculations, fill out the following table:

<table>
<thead>
<tr>
<th>Planetary System</th>
<th>Star Name</th>
<th>Absolute Magnitude, $M_v$</th>
<th>Spectral Class</th>
<th>Luminosity $[L_{\text{Sun}}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>TRAPPIST 1</td>
<td>18.4</td>
<td>M8</td>
<td>$5.2 \times 10^{-4} L_{\text{Sun}}$</td>
</tr>
</tbody>
</table>

**Task 3: Calculate the Habitable Zone Disc for each star.**
You should now have an Excel sheet with 6 Luminosities in units of $L_{\text{Sun}}$ that are recorded in Table 1. You will now add two new columns to your Excel Spreadsheet: A column for the inner distance of the habitable zone ($R_{\text{inner}}$) and a column for the outer distance of the habitable zone ($R_{\text{outer}}$)

\[
R_{\text{inner}} = \sqrt{\frac{L_{\text{star}}}{1.1}} \quad \quad \quad R_{\text{outer}} = \sqrt{\frac{L_{\text{star}}}{0.53}}
\]

Where $R_{\text{inner}}$ and $R_{\text{outer}}$ are in AU, and $L_{\text{star}}$ is in solar units ($L_{\text{Sun}}$).

**Task 4: Planets in their Habitable Zone**
Identify which of the extrasolar planets found on the list lies in the habitable zone of its star. To do this, look at the semi-major axes you recorded in your Excel spreadsheet for each of the planets within a system. Which of the extrasolar planets in each system fall in the Circumstellar Habitable Zone for their star? That is which planet(s) in a given system have semi-major axes between the $R_{\text{inner}}$ and $R_{\text{outer}}$ distance you calculated in Task 3?

**2.2 The Habitable Zone by Stellar Temperature and Age**
Go to the UNL Astronomy Simulation: Circumstellar Habitable Zone Simulator [https://astro.unl.edu/naap/habitablezones/animations/stellarHabitableZone.html](https://astro.unl.edu/naap/habitablezones/animations/stellarHabitableZone.html)

The window in the simulation shows the orbits of planets in our solar system and provides you with a planet you can move in semi-major axis distance. Below the window, you have a control panel where you can change the initial star mass and the initial planet distance. At the bottom, you have Timeline window where you can run a simulation of how the habitable zone will change over the lifetime of the host star. It also shows the planet is within the habitable zone or if it is “Too Hot” or “Too Cold” as a function of the age of the system. At first do not select any of the preset star systems. Take a minute to move the star mass and planet distance sliders. If you want, run the timeline for the star’s life.

In this lab activity, you will explore how the habitable zone changes with the mass of the host star and the age of a host star. We will consider three different star systems:

- A small, cool star: $M_{\text{star}} = 0.3 \, M_{\text{Sun}}$
- The Sun: $M_{\text{star}} = 1.0 \, M_{\text{Sun}}$
- A Vega-like star: $M_{\text{star}} = 2.5 \, M_{\text{Sun}}$
Set the mass and age conditions to the values shown in the table. Move the planet to find the inner and outer distances for the habitable zone and record those values in the table. If there is any planet or planets within our Solar System that would be within the habitable zone record that in the last column.

<table>
<thead>
<tr>
<th>Stellar Mass</th>
<th>Stellar Age</th>
<th>$R_{\text{inner}}$ [AU]</th>
<th>$R_{\text{outer}}$ [AU]</th>
<th>Planet(s) in our Solar System in Habitable Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 $M_{\odot}$</td>
<td>0.0 Gyr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 $M_{\odot}$</td>
<td>4.6 Gyr (Current Age)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 $M_{\odot}$</td>
<td>10.0 Gyr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3 $M_{\odot}$</td>
<td>0.0 Gyr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3 $M_{\odot}$</td>
<td>200 Gyr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3 $M_{\odot}$</td>
<td>440 Gyr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 $M_{\odot}$</td>
<td>0.0 Gyr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 $M_{\odot}$</td>
<td>300 Myr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 $M_{\odot}$</td>
<td>700 Myr</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Lab Instruction:**
  For each of the simulations, set the age to 0.0 years. Set the rate to about 1/4. Press Run.

Based on the data you gathered in the table and on each of the simulations, answer the following questions.

1. How does the Habitable Zone change with the mass of the star?

2. How does the Habitable Zone change with the age of the star?
3. For the Sun, when did the Earth first find itself in the Habitable Zone? How many years in total does it have in the Habitable Zone? Given that the Solar System is currently 4.6 Gyr old, how much longer will Earth be in the Sun’s Habitable Zone?

4. Rerun the simulation for the history of the Sun. What is causing the Habitable Zone to move as the Sun ages. Hint: Watch the values for the Sun’s luminosity and temperature.

5. Select the preset for 55 Cancri A. 55 Cancri is a binary star system 41 ly away from the Earth. The larger of the two stars is 55 Cancri A, an K-type star that has a mass of about $M_A = 0.90 \, M_{\odot}$ and a surface temperature of 5,165 K. The binary companion star 55 Cancri B is an M-type star with mass, $M_B = 0.255 \, M_{\odot}$ and surface temperature 3,230 K that is 1,065 AU away from 55 Cancri A. Amazingly, 55 Cancri A has 5 known extrasolar planets: b (Galileo), c (Brahe), d (Lipperhey), e (Janssen), and f (Harriot).
   
   a. 55 Cancri A is estimated to be 8 Gyr old. Are there any planets in the Habitable Zone?

   b. How many years was this planet in the Habitable zone? How many more will it remain in the habitable zone? Compare that time it spent in the habitable zone to Earth’s time in the habitable zone.