Exoplanet Data Explorer and Calculating Detection Signal of Different Methods

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1 Introduction

When the Hubble Space Telescope was first launched in April 23, 1980, it already began a new and major chapter in astronomy research. Nowhere was this most apparent than two years after initial operation, when astronomers Alexander Wolszczan and Dale Frail detected the first exoplanets, a pair of rocky planets orbiting a pulsar [1]. Ever since then, the floodgates have opened. In the current day, there have been more than 5,000 exoplanets discovered, and with current space observatories like the James Webb Space Telescope as well as future projects such as the Roman Space Telescope, PLATO, and the Habitable Worlds Observatory, the age of discovery has officially begun [1].

Modern exoplanet research has its basis on a number of different discovery methods used to detect exoplanets. By far the most widely used detection method is transit. In simple terms, a star outputs an amount of flux over time with which we can observe. When an object like a planet passes in front of the star, this eclipse causes this flux to drop slightly [2]. If recorded and plotted, this creates a defined dip in the star's flux over a certain time, resulting in a transiting planet.

The second most used detection method is radial velocity. This method takes use of the Doppler Effect. A potential exoplanet exerts its gravity over its star, as does the star on the planet. This causes the star to have a distinct "wobble". From our point of view, the viewed starlight will redshift (star moving slightly further from us) then blueshift (star moving slightly closer to us) in periodic moments, which can be further analyzed to determine if an exoplanet orbits the star [3]. Radial Velocity is especially useful when trying to find the mass of the exoplanet, as a larger mass results in a more pronounced "wobble".

The potential future of exoplanet research comes from the direct imaging method. It is a much less used method, mainly due to it being a much newer method (first direct image exoplanets discovered in 2008) [4], and requires a number of conditions to be just right. These include: a planet that's big enough and far enough from the star so that the star's light does not overpower the reflected light of the planet, the reflected light is brighter than systemic noise, the star is small enough to not overpower the star, and more.

Another method of exoplanet detection is microlensing. This hinges on the process known as gravitational lensing, which is the bending of the light rays of a background source by some mass in between, but on a much smaller scale [5].

As more and more methods are discussed, the frequency of their use and the amount they discover continues to decrease. But this does not mean that they are useless, just highly specific. These range from astrometry, which measures the variation of coordinates in the sky, to pulsar timing, analyzing the changes in a pulsar's regular pulses, to even more.

In this project, we discuss the various detection methods used in modern exoplanet research. We compare the parameters of detected exoplanets to parameters of the planets of our Solar System, and we discuss the pros and cons of using each detection method. We also analyze an example exoplanet case and determine which detection method would be able to get a reasonable signal. This is all to further our understanding in the field of planetary science and exoplanets, as we continue to apply our learned skills both in the Astronomy 5205 planetary science class as well as in the future.

2 Methodology

This project is split into three main parts: the first part will be showcasing all (or as many available) of the detection methods used to discover exoplanets. The second will showcase highlight the sensitivity limit of three methods: transit, radial velocity, and direct imaging. The last part will pose the case of an example exoplanet system and apply these three detection methods and determine which would be best to discover such a planet.

All the data used in this project is taken from the NASA Exoplanet archive. We first plotted four plots that showcased interactions between different planetary parameters, with points corresponding to the detection method that was used to discover the planet. These were:

- Radius (R_J) vs. Period (days)
- Radius (R_J) vs. Semi-Major Axis (au)
- Mass (M_J) vs. Period (days)
- Mass (M_J) vs. Semi-Major Axis (au)

These were then plotted with parameters of our Solar System's planets for comparison.

We then plotted the sensitivity curves of each detection method, to showcase the primary regions that each method is not able to see. For sensitivity, the formula used to plot the sensitivity is

$$R_p = R_{earth}\sqrt{3\sqrt{\frac{P}{T}}}$$

For the sake of simplicity, we applied a period of 1 year to the formula.

For the sensitivity limit of the radial velocity detection method, we start with the formula

$$m_p = K * M_* \cdot \sqrt{}(\frac{a}{(GM_*))})$$

If we assume that we have a star mass of $M_* = 0.5M_\odot$ and a $K_* = 0.5ms^{-1}$, we get the equation

$$m_p = 0.25M_\odot \cdot \sqrt{}(\frac{a}{(G(0.5M_\odot))})$$

For direct imaging, it relies on the minimum angular resolution of a telescope. This is represented by the formula

$$\theta = 1.22\frac{\lambda}{D}$$

To standardize values, the blackbody wavelength of a jupiter-like planet is $\lambda \approx 10\mu m$. A high end telescope has a D value of $D \approx 10m$. Combining small angle apprximation and the fact that the furthest planet we have discovered due to direct imaging being $d \approx 200pc$, we get a formula of $a = 1.22d\frac{\lambda}{D}$

Each sensitivity curve represents the rough line where a detection signal can be deemed "significant" enough to be considered a planetary candidate, as opposed to random noise.

To show the differences and advantages/disadvantages between the different detection methods used in exoplanet research today, we calculated the detection signal for a temperate Earth-like planet orbiting around an M-type star. This was chosen because M-type stars are the most common type of stars to exist in the universe, and if astronomers want to find a habitable planet that is analogous to Earth, they would look at those types of star systems.

We assume that the strongest detection signal given will be via the transit method, as the proximity and size of the star relative to the planet would yield a good enough value. The next would be radial velocity, which would have a higher rv value than what Earth imparts onto our Sun, however would still be very small. The smallest signal would most likely come from direct imaging, as the distance to the star and size of the planet would both be too small to get any reasonable value.

To compute the detection signal via transit, we use the formula

$$signal = (\frac{R_p}{R_*})^2$$

giving a relation between the strength of signal and the radius of the planet, and inversely to that of the radius of the star. For radial velocity, we start with the equation $M_p = \frac{M_* V_*}{\sqrt{GM_* r}}$ [3]. If we assume we are observing at an edge on alignment (resulting in $K = V_* sin(i) = V*$), we get

$$V_* = \frac{M_p}{M_*} \cdot \sqrt{GM_*/r}$$

For our computation, the value of r will represent that of an M-type star habitable zone ($r \approx 0.1au$). For direct imaging, also assuming edge on alignment, we use the formula

$$C = A_g(\frac{R_p}{a})^2$$

where A_g is the geometric albedo of the planet [4].

3 Results

Figure 1 showcases the four parameters plotted against one another, as well as showcasing the vast array of detection methods used in modern exoplanet research.

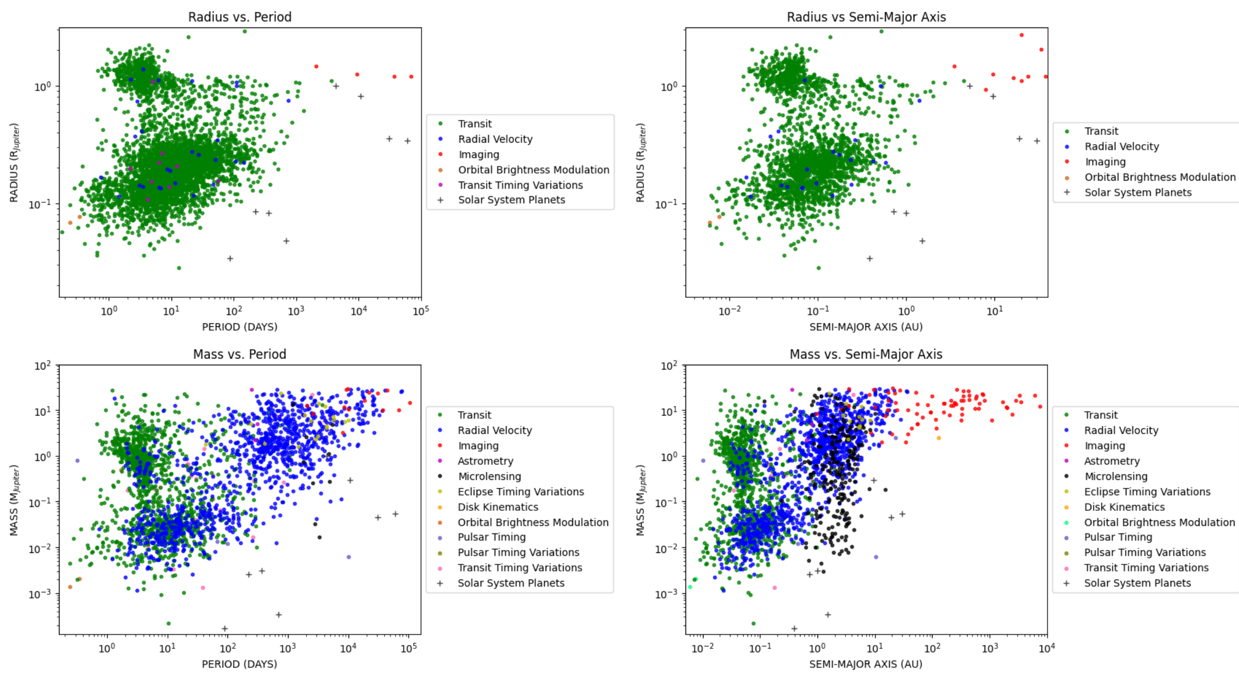

Figure 1: Plots comparing four parameters of exoplanets: Radius (R_J), Period (days), Semi-Major Axis (au), Mass (R_J). The different colored dots represent the different detction methods used to discover the exoplanet. Plus signs represent Solar System planets, plotted for comparison.

The vast majority of exoplanets are detected either via the transit or radial velocity method, as expected. These parameter interactions also create unique concentrations in certain areas, while also having distinct voids. For example, in the Mass vs. Semi-Major Axis plot, almost all the large planets (jupiter-like or larger) that orbit close to their star were found via transit. The further one moves away from their home star, the more likely they are to be found via the radial velocity method or microlensing. Moving further away results in direct imaging taking precedence in the planets that can be found.

An important feature to note in all four plots is the black plus-signs, denoting the parameter values of our Solar System Planets. Their placement in the plots highlights a unique aspect about our current day technology. If we were at a distant system with the same technology, most of our methods we would not have a very high / reliable likelihood of detecting any planets in our Solar System.

This leads into the sensitivity limits. If our Solar System planets would be unlikely to be detected, falling into a "frontier planet" zone, what would be the smallest, fastest, and closest-to-star planet be detected? To answer this question, we focused on three detection methods as stated before and plotted them below.

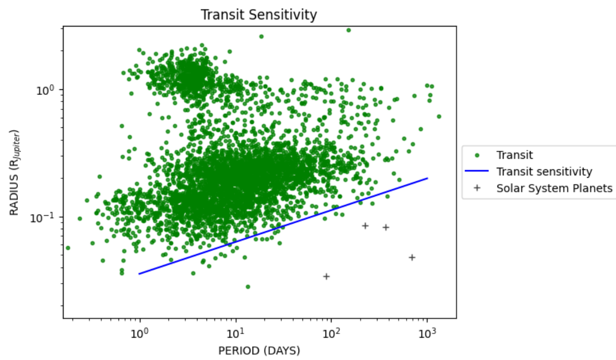

Figure 2: Plot of all exoplanets detected by the transit method. The blue line represents the transit detection sensitivity. Parameters pertinent to RV exoplanets are used here, thus the format of Radius vs. Period.

As shown in figure 2, the sensitivity line does not cut off all the planets detected by the transit method. This can be for a number of reasons, one of which being an increased time of observation on the system to fine tune measurements.

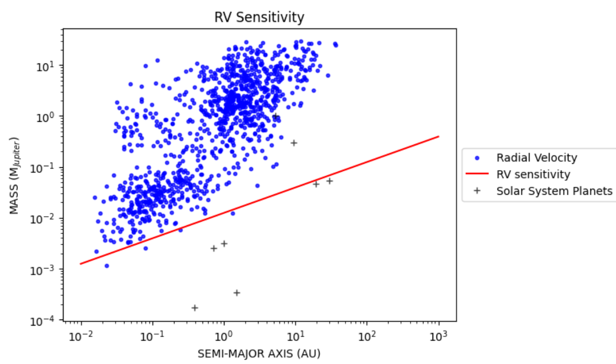

Figure 3: Plot of all exoplanets detected by the radial velocity method. The red line represents the RV detection sensitivity. Parameters pertinent to RV exoplanets are used here, thus the format of Mass vs. Semi-Major Axis.

The sensitivity of radial velocity, as shown in figure 3, exhibits similar features to that of the transit method. Most notably, both are unreliable in detecting planets that are simultaneously small and far from their star. RV is unique in that the sensitivity line covers the bottom of the concentration of discovered planets, but there is also a void to the right of the concentration, suggesting further possible tweaks when plotting the sensitivity line.

Direct imaging is both the newest method as well as the most groundbreaking. However, it is also the most particular detection method, as shown in figure 4. Since the sensitivity of direct imaging is based on a constant (minimum angular resolution relating to planet-star flux contrast), it does not follow a formulaic trend. Rather, it defines more generic boundaries/constants from which planets are more likely to be observed from this method or not. These are a Semi-Major Axis of approximately $a \approx 10au$ and a radius of $R \approx 1R_J$. However, this sensitivity line was challenging to plot, as there is no set formula / constant that we have found that properly determines the line.

We took these three detection methods and computed the detection signal / detection parameter, as show in table 1.

Detection Method	Detection Signal Parameter
Transit	0.000933890875247244
Radial Velocity	0.516486030769513 ms^{-1}
Direct Imaging	5.453220753512322e-08

Table 1: Computed detection signals corresponding to three detection methods: Transit, RV, and Direct Imaging.

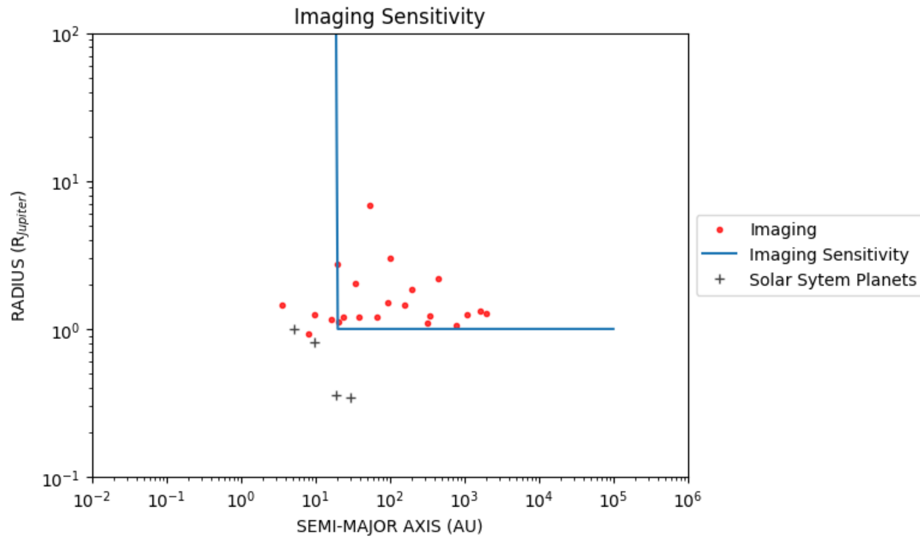

Figure 4: Plot of all exoplanets detected by the direct imaging method. The blue line represents the direct imaging detection sensitivity. Parameters pertinent to imaging exoplanets are used here, thus the format of Radius vs. Semi-Major Axis.

These values help prove our previous assumptions. All values would be fairly low. The radial velocity value would be slightly larger than that we see on our Sun as a result of the Earth. The detection signal from direct imaging is very small, making it unreliable in detecting Earth-like planets around M-type stars. Thus, the most reliable method to detect such a planet would be the transit method.

4 Conclusion

Every detection method used in astronomy has some slight overlap, but exhibit their own pros and cons and inhabit a useful part of research. Both transit and radial velocity have a similar ”dark zone” (low radius and long period for transit, low mass and long semi-major axis for radial velocity), and direct imaging is only reliable with large planets orbiting far away from their star. After analysis of sensitivity limits as well as applying the three previously mentioned methods of detection to our generic Earth-like orbiting around M-type star case, we find that the transit method is better for searching such useful types of planets.

References

[1] NASA. *Alien Worlds / Historic Timeline*. URL: `https://exoplanets.nasa.gov/alien-worlds/historic-timeline/#first-planetary-disk-observed`. (accessed: 1.28.2025).

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