Comparing Various Exoplanet Detection Methods for Finding an Earth-Like Planet Around a Sun-Like Star

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Abstract

The possibility of life somewhere out in the universe has been questioned throughout human history. To find an answer, we must look outwards, past our Solar System to other stars with planets orbiting them. As a result, various exoplanet detection methods have been created to find these planets and tell us information about them, such as the radial velocity method, the transit photometry method, and direct imaging. In this paper, we discuss the effectiveness of these methods as well as their limits and biases. We then compare each method on its ability to detect an Earth-like planet around a Sun-like star by downloading data from the NASA Exoplanet Archive. We then overlay it with the current sensitivity limits of these detection methods and then find signals of an Earth-like planet around a Sun-like star to determine what methods can be used to detect it. Based on our results, we find that none of the detection methods that we mentioned are sensitive enough to find a planet like ours outside our Solar System. So, unless the parameters of these methods are changed or a new method is discovered, it is unlikely that we will find an Earth-like exoplanet.

1 Introduction

Are we alone? This question continues to be one of humanity's greatest inquiries throughout time. Although we have yet to find an answer, the search for that answer has not ceased. We have looked to other planets and natural satellites, such as moons, in our Solar System for the possibility of life. However, the universe is much bigger than we may ever know, and if we truly wish to find life, we must also look outward from our Solar System and to other stars with planets, known as exoplanets, orbiting them. This then raises another question: How do we find these exoplanets? As technology and science have progressed, multiple exoplanet detection methods have become available to us. These detection methods include the radial velocity method, the transit photometry method, and direct imaging. They allow us to not only find exoplanets but also to learn about the conditions of those planets, including mass, radius, atmosphere composition, orbital period, and temperature. These are all essential components to consider when categorizing whether a planet is able to sustain life.

There is no guarantee that life on another planet or satellite will be the same as it is here on Earth, so how will we know when we find it? It is much easier to recognize life similar to us, so while we take care to study every planet, we tend to focus on planets with conditions similar to ours. The detection methods that were mentioned previously provide us with different information depending on the method. By comparing them, we will be able to better understand how to properly apply each method and increase their effectiveness. To do this, we will be using data from the NASA Exoplanet Archive (NEA) to compare how precise each detection method is when searching for an Earth-like planet orbiting around a Sun-like star.

2 Methods

First, we will go over the exoplanet detection methods in detail and derive the equations used in this study as well as how we applied them. We will begin with the radial velocity method, the transit method, and then direct imaging.

2.1 Radial Velocity Method

The radial velocity method is a cornerstone of exoplanetary astronomy research. Astronomers use this technique to measure Doppler shifts in a star's spectral features, which track the line-of-sight gravitational of a star caused by the planets that orbit it [1]. In short, when a planet orbits a star, that star "wobbles", causing a change in the appearance of its spectrum, known as the Doppler Shift. As a celestial object moves towards or away from us, their spectral lines will be shifted to a different wavelength by the Doppler Effect. For example, if a star was moving towards us, the wavelength looks compressed and the absorption lines appear at shorter or "bluer" wavelengths. This is known as being blueshifted. Whereas, if the star was moving away from us, the light is redshifted and the wavelength looks stretched out and the absorption lines appear at longer or "redder" wavelengths. This changing wavelength is directly related to relative speed. Astronomers can use the Doppler Shift to calculate the speed at which an object is moving towards or away from us [2]. Additionally, astronomers can track the Doppler Shift of a star over time to estimate the minimum mass and semi-major axis of the planet orbiting it [3]. There are limits to the radial velocity method, however. While it can estimate the minimum mass of the orbiting planet, we cannot calculate its actual mass due to the unknown inclination of the planet's orbit relative to our line-of-sight [4].

For this study, we utilize the following equation for calculating the observable signal of the radial velocity method, and solve it for the planetary parameters:

$$\begin{aligned} K =& \frac{m_p}{m_*}\sqrt{\frac{Gm_*}{a}}\sin i \\ m_p =& \frac{K}{\sin i}\sqrt{\frac{am_*}{G}} \end{aligned} \tag{1}$$

From here, we assume that the system is edge on (to take the upper limit of detectability), has a Sun-like host star, and that a minimum observable signal is 0.5 m/s. This gives us a planetary mass detectability limit that depends only on the semi-major axis of the planet. The given mass represents the lowest particular mass we can detect at this orbital distance.

2.2 Transit Photometry Method

The transit method is currently one of the most effective and sensitive ways of detecting exoplanets. When a planet passes in front of its host star, it causes the starlight to dim. This passage is know as a "transit" and if the dimming is detected at regular intervals and lasts a fixed, repeated amount of time, then it is likely that a dimmer object is passing in front of the star. How much a star dims during a transit relates directly to the sizes of the planet and the star. For example, if a small planet passes in front of a much bigger star, then there will be little change to the brightness of the star. However, if a big planet transits a small star, then it will have a much more noticeable effect on the star's brightness. With this method, we can get a hint of the atmospheric composition of the planet and its temperature. Additionally, the size of the host star can be known with great accuracy from its spectrum, and photometry gives us a good estimate on the diameter of the planet, but not its mass. Due to this, photometry compliments the radial velocity method very well as it gives us information on the minimum mass of the orbiting planet, but not its diameter. By using both methods, we can calculate the density of the planet which can tell us about the composition of the planet, whether it is rocky, icy or gassy. Like the radial velocity method, the transit photometry method has its disadvantages. The main difficulty with this method is that a transit needs to occur for us to be able to measure anything. The planet also must be seen from Earth with its path between its star and Earth, but this is only true for a small amount of distant planets. Furthermore, a planet's transit only lasts a small fraction of its orbital period. A planet could take months, even years to complete its orbit, and astronomers need to observe multiple transits occurring at regular intervals. As a result, this method is biased towards the discovery of exoplanets with short orbital periods. It is worth mentioning that many short-period planets have orbits that are quite close to their stars and are therefore within their habitable zones, which is the distance from a star where surface water can exist. So, it is possible to find habitable planets with the transit photometry method [5].

During this investigation, we use the calculated signal to noise ratio of a planetary transit to solve for the limiting planetary radius:

$$S = \frac{\delta}{\Delta} \tag{2}$$

Where δ represents the depth of the transit, and Δ represents the probability of detecting a planetary transit. This can be rewritten as:

$$\begin{aligned} S =& \frac{\left(\frac{R_p}{R_*}\right)^2}{\Delta\sqrt{\frac{P}{T}}} \\ R_p =& R_* \sqrt{S\Delta\sqrt{\frac{P}{T}}} \end{aligned} \tag{3}$$

This new Δ represents the sensitivity of our instruments, roughly 1 ppm (parts per million), where S is the signal to noise ratio to detect a planetary transit approximately 3, P is the orbital period of the planet, T the observation time, which we set equal to one year for the maximum signal, and the stellar radius we set to solar values. Thus, we have an equation relating the minimum detectable radius that depends only on the orbital period of the observed planet.

2.3 Direct Imaging

Nearly all the exoplanets discovered around other stars so far have been found indirectly. For example, with the radial velocity or transit photometry method, due to the effect they have on their host stars. However, advancements in technology has allowed astronomers to take real images and spectra of exoplanets through a method called direct imaging. Planets can be exponentially dimmer than their host stars and end up lost in the glare. By blocking the star's light with a coronagraph, which is a telescope attachment that blocks starlight, astronomers can take pictures of dimmer planets in orbit. By studying the images and spectra of planets, we can gain information about a planet's atmospheric composition which can give us clues about the natural processes occurring in these worlds. Knowing more about the atmospheric composition can help us determine if the planet is habitable by revealing signs of life, such as oxygen, water, and methane. This technique is most effective when searching for young, nearby planetary systems whose planets are especially bright [6]. Additionally, it is better if the planet has an orbit that is a great distance from its host star so that it does not get out-shined by the starlight. It also works best for systems that are positioned face-on when viewed from Earth. Since the radial velocity method is also limited by the position of the exoplanet relative to Earth, it is complementary to direct imaging and is ideal for finding planets orbiting close to their host stars as previously mentioned. With our current observation technology, directly imaging an exoplanet is very rare and it needs the conditions to be just right for it to be possible. As a result, direct imaging is not a good candidate for large-search surveys looking for new exoplanets [7].

In this analysis, we consider two factors for detecting planets through direct images. First, the planet must be bright enough to have a noticeable contrast against the star. This can be represented by the following equation for the contrast of a star:

$$f = \left(\frac{R_p}{R_*}\right)^2 \left(\left(\frac{R_p}{2a}\right)^2 + \frac{e^{\frac{hc}{\lambda k_B T_*}} - 1}{e^{\frac{hc}{\lambda k_B T_p}} - 1}\right) \tag{4}$$

We can further simplify by using Wien's law, $\lambda = \frac{b_w}{T}$, resulting in:

$$\begin{aligned} f =& \left(\frac{R_p}{R_*}\right)^2 \left(\left(\frac{R_*}{2a}\right)^2 + \frac{e^{\frac{hcT_p}{b_w k_B T_*}} - 1}{e^{\frac{hc}{b_w k_B}} - 1}\right) \\ R_p =& R_* \sqrt{\frac{f}{\left(\left(\frac{R_*}{2a}\right)^2 + \frac{e^{\frac{hcT_p}{b_w k_B T_*}} - 1}{e^{\frac{hc}{b_w k_B}} - 1}\right)}} \end{aligned} \tag{5}$$

Where we adopt solar values for R_* and T_*, earth values for a and T_p, k_B is the Boltzmann constant, h is Planck's constant, c is the speed of light, b_w is Wien's constant, and f is the unitless contrast between the planet and star, which modern detection limits can distinguish down to roughly $10^{-}7$. This gives us a value for the minimum radius a planet can be detectable under these assumptions, notably independent from period or semi-major axis. After running the calculation, we achieve a detection limit of 0.77 earth radii.

Thus, the second factor comes into play. The Rayleigh criteria denotes the angular separation at which two points of light become distinguishable from each other, described by:

$$\theta = 1.22\frac{\lambda}{D} \tag{6}$$

This time, we can note that angular separation by the small angle approximation is $\theta = \frac{a}{d}$, and again use Wien's law to simplify the equation to:

$$\begin{aligned} \frac{a}{d} =& 1.22\frac{b_w}{T_p D} \\ a =& 1.22\frac{d b_w}{T_p D} \end{aligned} \tag{7}$$

Where d is the distance to the host star, T_p the planetary temperature, assumed to be the same as Earth's for our detectability, and D is the diameter of the telescope used to detect it, state of the art being around 8 meters. This then gives us the minimum semi-major axis to which we can detect an object around a star a given distance away. For our sensitivity plots, we take the median distance of directly imaged exoplanets. Plugging in values we get that the limit is 13 AU.

3 Results

As a result of our calculations, we found that none of the methods we looked at are able to detect an Earth-like planet orbiting around a Sun-like star with our current technology. In order for the radial velocity method to detect an Earth-like planet, the star needs to have a velocity of at least 0.5 m/s. However, the signal we get is about 0.089 m/s. This is way off from our desired velocity value. Therefore, the radial velocity method is not a feasible method to use when searching for an Earth-like planet around an Sun-like star. If we look at the transit photometry method, we find that this method is also not suitable for searching for a planet like ours. The transit signal is a measurement of how many standard deviations, error, that we would get for the Earth if we measured it for one Earth year. To make sure that there is actually an Earth-like planet orbiting another star and that it is not just noise or something else, the signal needs to be about 3σ. When we consulted the data, we found that the signal only had a value of around 0.42 σ. So, the transit photometry method is not the best method to detect an Earth-like planet. Lastly, in order for direct imaging to be able to capture an image of an Earth-like exoplanet, the direct imaging contrast must be as high as 10^{-7}, which is what we are sensitive to. For an Earth-like planet, its direct imaging contrast is $1.67 * 10^{-7}$, which is slightly above the cutoff, so the planet does have enough contrast to stand out against the star. That being said, direct imaging relies on another factor: How close a planet is to its host star. For the planet to be considered Earth-like, it will have to be within the habitable zone of the star, which can be fairly close to the star itself. Due to this, direct imaging will not be able to image an Earth-like planet.

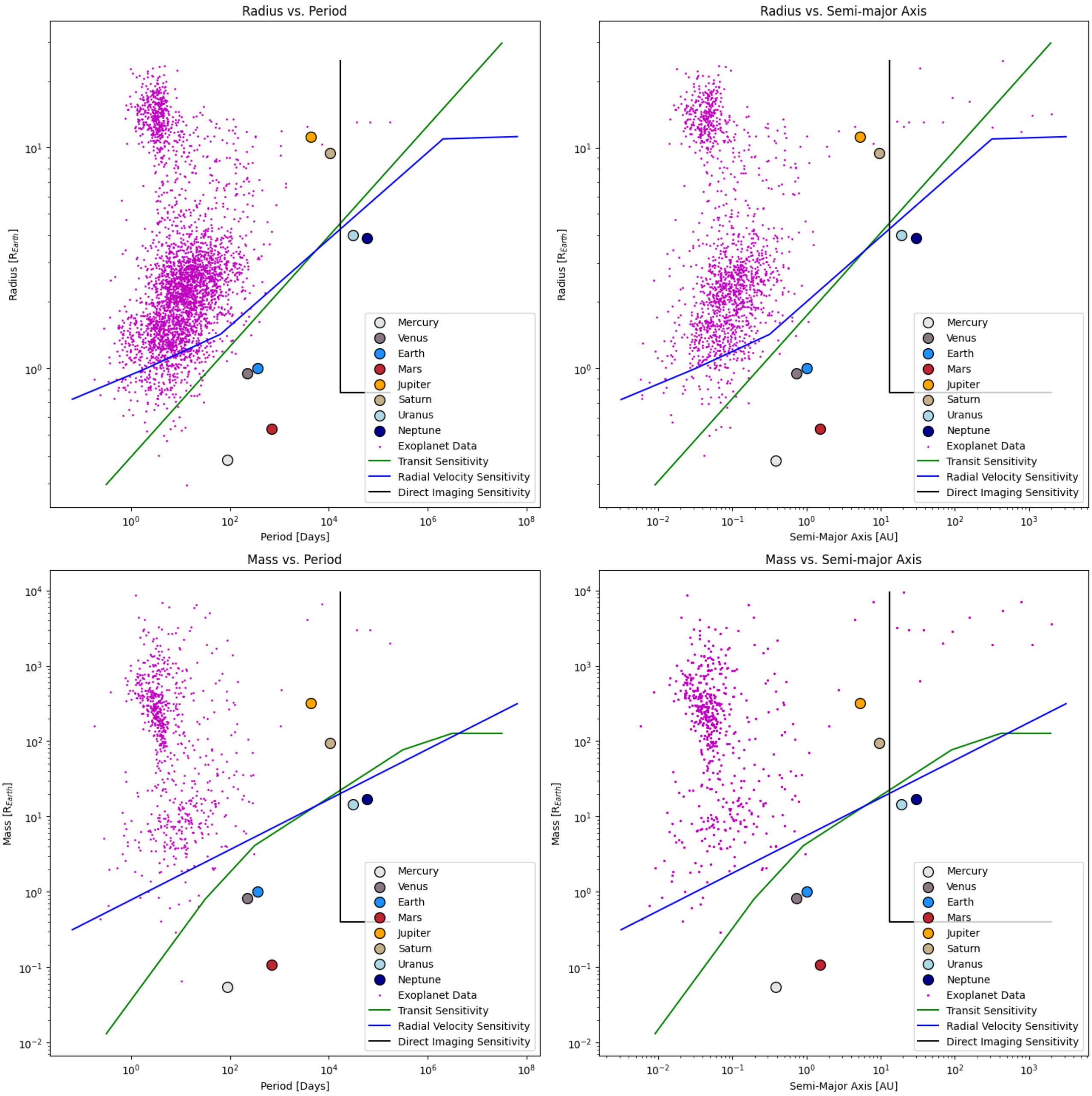

Figure 1: The top left plot displays the radius of the exoplanets against their periods, the top right displays the radius of the exoplanets against their semi-major axes, the bottom left displays mass against period, and the bottom right displays mass against semi-major axis. Overlaid on all four plots are the current sensitivity limits for various exoplanet detection methods, namely radial velocity (Section 2.1), transits (Section 2.2), and direct imaging (Section 2.3). The planets of the Solar System are also plotted for comparison, where each point is the color of the planet it represents.

4 Conclusion

In conclusion, based on our analysis of three different detection methods–the radial velocity method, the transit photometry method, and direct imaging–we found that none of these methods are suitable for detecting an Earth-like planet around a Sun-like star. All of these methods are not sensitive to planets with specifications similar to Earth. This reveals the biases and limits of these methods. In order for us to find an Earth-like planet in the future, either technology needs to advance further or a new method of detecting exoplanets must be discovered. Additionally, using these methods in parallel with each other may help us learn even more about the exoplanets that we have already discovered. So, do not give up just yet. Although the hope of finding an Earth-like planet seems unfounded right now, it is not impossible. Further research and technology advancements will help us to finally answer humanity's biggest question: Are we alone?

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