On The Hunt for Earth-Like Planets

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Motivation:

Studying the formation, composition and behaviors of exoplanets from other galaxies enables us to gain a better understanding on the history of our planet and solar system. By comparing the discovered exoplanets with Earth, we can discover the unicity of our planet and the possible existence of life outside our solar system. The comparison is complete by discovering the mass, period, radius and semi-major axis of our known exoplanets, but the use of multiple known methods to discover this data; including radial velocity, transits and direct imaging, leads to conflicting results. By finding each method's sensitivity limit, discovering their flaws and improving their accuracy, we can grasp a clearer idea on the behaviors of exoplanets. For this experiment, we are on the lookout for a 'target planet' with conditions similar to Earth, specifically looking for a temperate Earth-like planet around a Sun-like star.

Methods:

Using data collected from the *NASA Exoplanet Archive*(for the distribution of these data, see figure 1, 2, 4 and 5), we are able to see how many exoplanets are confirmed to exist, along with information on each, including their name, time of discovery and method used. In the database, three methods were used: Radial velocity, transit and imaging. Transferring the data into *Python*, we are able to find and plot the needed data. This will help provide us with a visual showing the dispersion of exoplanets and help us locate a 'target planet' with Earth-like behaviors.

Method 1: Radial Velocity

The formula to find the radial velocity of a planet is:

$$K = \frac{M_p}{M_s}\sqrt{\frac{GM_s}{a}}\sin i$$

K is the radial velocity, in m/s. The higher the value of K, the greater the chance of detection. M_p is the radius of the planet in meters, M_s is the radius of the planet's parent star in meters, G is the gravitational constant, a is semi-major axis, and i is the angle between the planet's direction of movement and our view, which is simplified to always be 90° in our simulation.

Method 2: Transit

The two formulas used to find the transit of a planet is:

$$P = \frac{R_s + R_p}{a} \qquad f = \left(\frac{R_p}{R_s}\right)^2$$

P and f is the probability of detection with P found in percent and f in ppm, R_s is the radius of the star, R_p is the radius of the planet, and a is the semi-major axis.

Method 3: Direct Imaging

The three formulas used with the direct imaging method are:

$$f_c = \left(\frac{R_p}{R_s}\right)^2 \frac{\exp(h\nu/k_B T_s) - 1}{\exp(h\nu/k_B T_p) - 1} \qquad \theta = 1.22\frac{\lambda}{D} \qquad Hz = \frac{c}{\lambda}$$

f_c is the star-planet contrast, R_s is the radius of the star, R_p is the radius of the planet, h is Planck's constant, v is the frequency, k_B is the Boltzmann constant, θ is the angular separation, λ is the wavelength, D is the diameter of the telescope, and c is the speed of light. In our simulation, the albedo is 0.3 and wavelength values from 0.5 to 20 μm are explored. Also, the Extremely Large Telescope (E-ELT) is used, which has a diameter of 39.3 m.

Results:

Using the radial velocity method, we calculated K to be 0.09 m/s. However, in order for the planets to be detected correctly, K must be greater than or equal to a value of 0.5 m/s (Seager 2010). Therefore, our target planet is undetectable with the radial velocity method(see figure 1 and 2).

Using the transit method, we found our value of P to be 0.469%, which is the chance of detection. Given the slim probability to detect a planet, this formula can be deemed undetectable. In the second formula, we found our value of f to be 84.05 ppm. For HST, the limit is 110 ppm, which our calculated value doesn't meet the criteria of baseline. Due to the solutions of both formulas not meeting the minimum criteria to detect exoplanets, our target planet is undetectable with the transit method(see figure 3 and 6).

Using the direct imaging method, we found our value of f_c to be 1.097 * 10^-6. In order for planets to be accurately detected, the telescope must be near-infrared with a vector vortex coronagraph of 1.5 m and a telescope pupil of 2.0 * 10^-5 (Seager 2010). Since our value of f_c fails to exceed the required star-planet contrast, our target planet is undetectable with the direct imaging method. However, this method was the closest of the 3 to being successful(see figure 6).

Since the telescope diameter in the direct imaging method was determined to be slightly too small for detecting our target planet, we can discover the telescope diameter most suitable for observing Earth-like planets. We have the relationship:

$$\frac{1.22 \cdot 1AU}{10pc} = \frac{20\mu m}{D}$$

For an Earth-like exoplanet, $\theta = 0.1$ arcsec (Seager 2010), illustrated by the left side of the provided equation. We also adjusted the wavelength to the maximum possible value at 20 µm, shown by the right side of the equation. With this, we can calculate the maximum value of f_c. After calculating, we discover the most suitable telescope diameter to be 41.253 m, which is less than 2 m longer than the diameter of the Extremely Large Telescope (E-ELT) at 39.3 m. Therefore, it is nearly suitable for discovering our target planet.

Conclusion:

The main goal of this research was to search for an Earth-like planet by using various detection techniques and compare them against one another. Each method came with its own set of assumptions, parameters, and estimations. What our team found was that despite experimenting with several techniques, we were unable to detect an Earth-like planet around a sun-like star. Between the Radial Velocity, Transit, and Direct Imaging, we found that the method yielding the most promising results (although still quite far by a longshot) was the transit method. Current planet-detection instrumentation techniques are simply not yet fit to complete such a task. However, by improving on these methods, particularly the transit method, it is possible that scientists in the near future will be able to achieve such feats.

References:

Seager, Sara, and Renée Dotson. *Exoplanets*. University of Arizona Press, 2010.

Graphs:

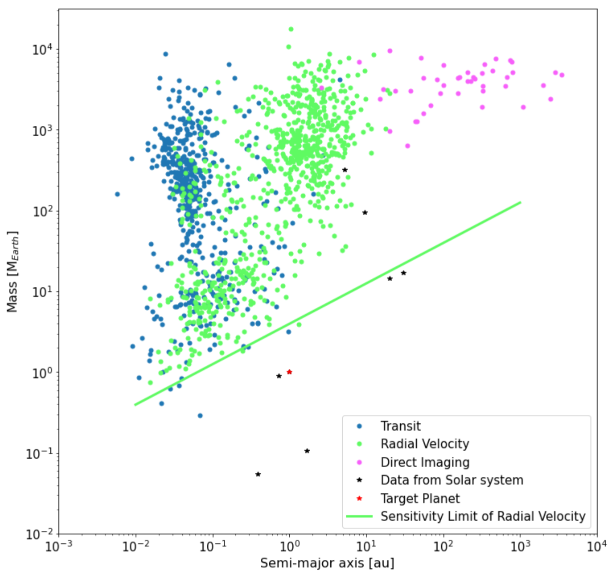

Figure 1 Mass vs Semi-major axis

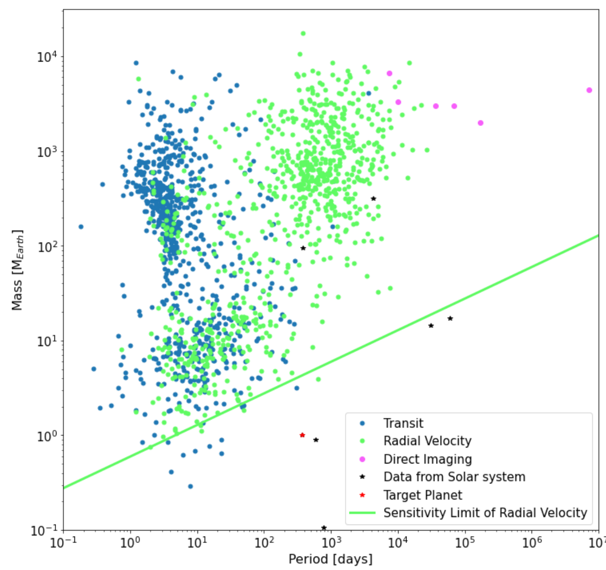

Figure 2 Mass vs Period

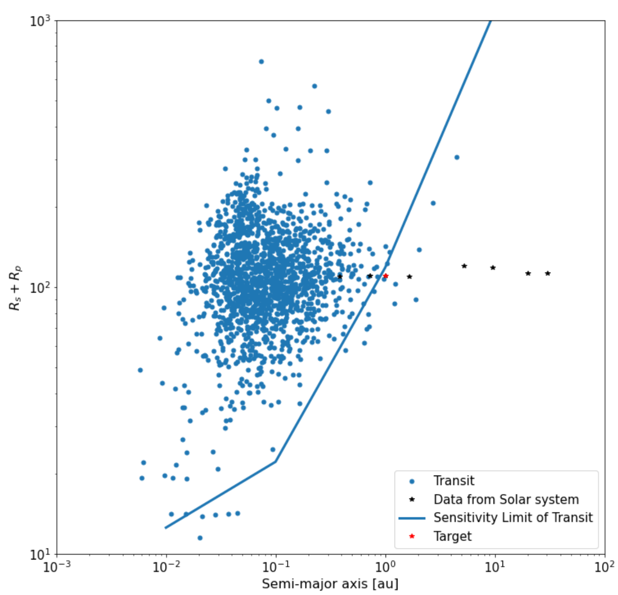

Figure 3 R_s +R_p vs Semi-major axis

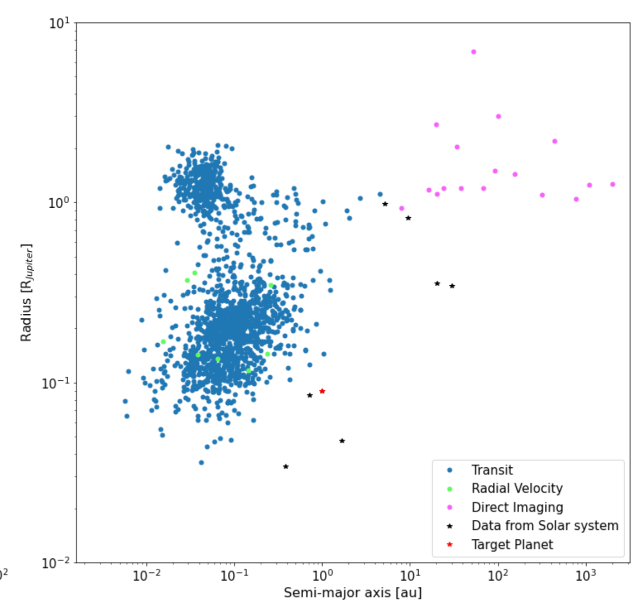

Figure 4 Radius vs Semi-major axis

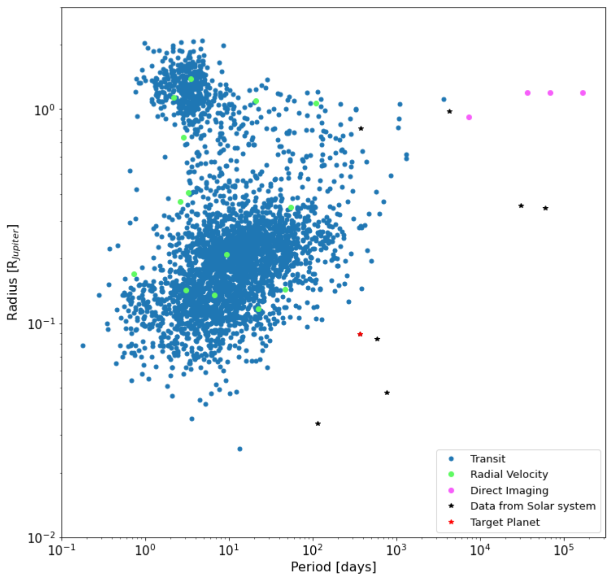

Figure 5 Radius vs Period.

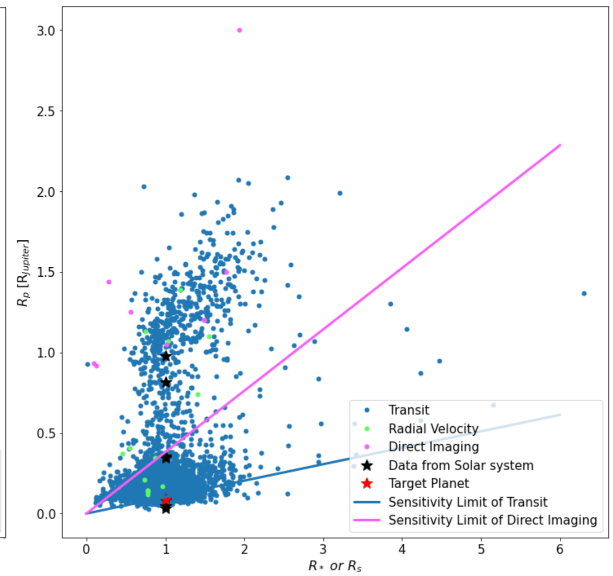

Figure 6 R_p vs R_s