Project 1: Detecting Earth-Like Exoplanets

Jacob Borison, Andrew Miller, Karish Seebaluck, Leandra Hogrefe

Section 1: Introduction and Motivation

Life in our universe has been discovered on only one, small planet. The search for extraterrestrial life begins with finding Earth-like planets with the possibility of harboring life. With large sums of exoplanet population data, astrophysicists can study the ingredients necessary for life in the universe. The NASA Exoplanet Archive (NEA) is exactly this, a massive database holding valuable information about thousands of exoplanets outside of our solar system. With this data, exoplanets can be located and studied in detail.

The NEA data is compiled using various exoplanet detection methods and the exoplanets are compared to the planets within our solar system, specifically Earth. In this investigation, the specific properties studied for each exoplanet are mass, radius, orbital period, and semi major axis. With these values, the collection of exoplanet data can be combed through to search for an exoplanet resembling the Earth.

Section 2: Methods

No single data point can summarize all the information of an exoplanet in one detection. Various detections using different equipment and methods are combined to paint a fuller description of an object. Specifically, the information stated above is collected for each exoplanet using three primary detection methods - Radial Velocity, Transit, and Direct Imaging.

Radial Velocity locates exoplanet systems by recording the light emitted by their host stars. When large planets orbit in close proximity to a star, both bodies orbit the combined center of mass. For the star, this results in a small circular orbit about the center of mass, appearing as a wobble. This wobble causes a doppler shift in the star's emitted spectrum, sinusoidally changing the light frequency received by the observational hardware. The change in frequency is measured and used to understand the mass, period, and semimajor axis of the star-exoplanet system [2]. The measurement signal, K, is taken and input into the following equation to determine the mass of the exoplanet.

$$K = \frac{M_p}{M_*}\sqrt{\frac{GM_*}{a}}sin(i) \rightarrow M_p = KM_*\sqrt{\frac{a}{GM_*}} \tag{1}$$

The measurement signal is dependent on the state-of-the-art equipment used to make the detection. M_p and M_* are the masses of the planet and star respectively, a is the semi-major axis of the orbit and G is the gravitational constant. Additionally, the inclination angle, i, is assumed to be 90° (edge on with respect to the orbit), so the sin term goes to unity.

While Radial Velocity detections observe the spectrum of starlight emitted by the host star, Transit detections observe the intensity or amplitude of the host star's light. When viewing a system edge on (i = 90°) , exoplanets will periodically eclipse their host stars and block a portion of their light from reaching the observer. On an intensity plot, this can be seen as a large dip occuring every orbital period of the exoplanet. This will occur with a probability dependant on the star's and exoplanet's radius, R_* and R_p respectively, and the semi major axis of the orbit a.

$$P = \frac{R_* + R_p}{a} \tag{2}$$

This measurement offers information about the exoplanet's size in comparison to the host star, relaying the fraction of light blocked from the star. Specifically, the area ratio of the star and exoplanet is equivalent to the depth of transit, f,

$$f = (\frac{R_p}{R_*})^2 \tag{3}$$

Where R_p and R_* are the radii of the exoplanet and star. Determining the true values of the exoplanets mass and radius require the integration of information obtained from Radial Velocity measurements, and other information regarding the host star [5].

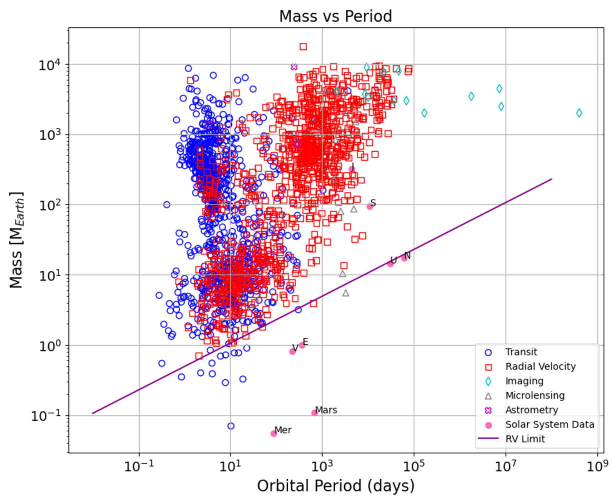
Direct Imaging arguably offers the most information about an exoplanet within each measurement. Using this method, exoplanets are directly photographed conveying information regarding the size, orbit, temperature, atmosphere, and composition. This is accomplished by using precise instrumentation to block the host star's light in order to resolve the much dimmer exoplanet. Without blocking the star, the starlight would greatly overwhelm the instrumentation and the exoplanet would not be visible. Instead, the star emits light, a small fraction of which reflects off of the exoplanet and is measured. This fraction of starlight reflected off the exoplanet is dependant on the exoplanet radius, R_p, Albedo, A, and semimajor axis a.

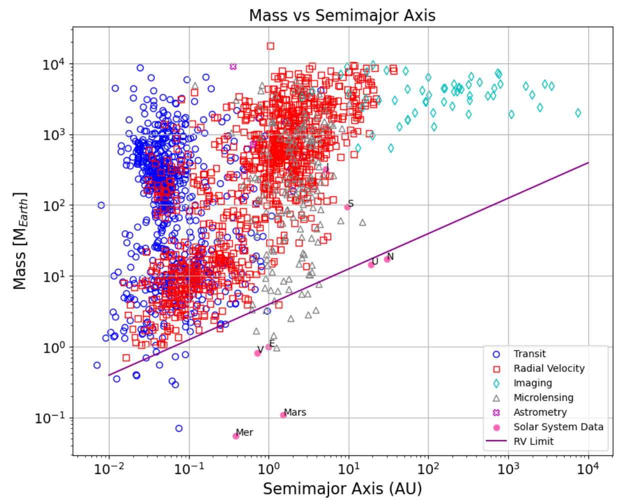
$$f = 4A(\frac{R_p}{a})^2 \tag{4}$$

Combining multiple exoplanet images of the same system relays additional orbital and rotational information of the exoplanet. The atmosphere and composition are studied by observing the spectrum of light absorbed and reflected by the exoplanet, allowing researchers to search specifically for the ingredients of life [4].

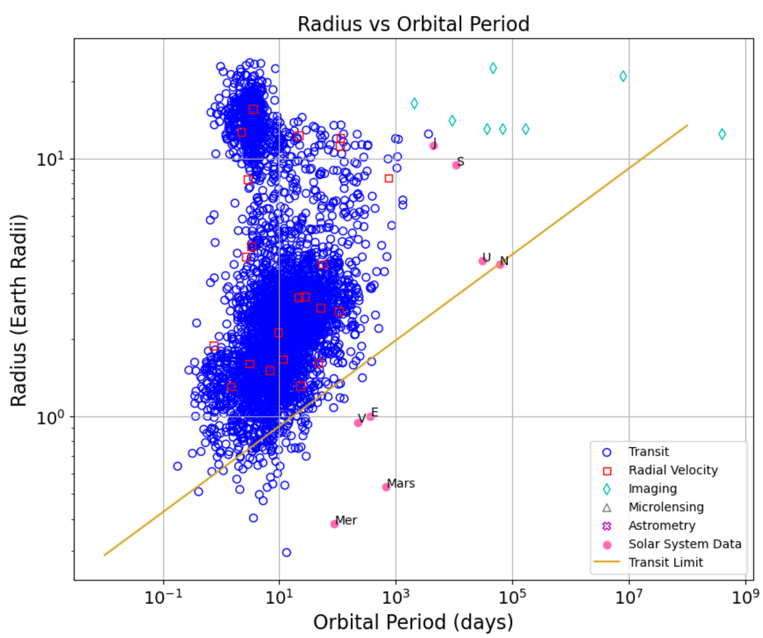
Section 3: Results

Understanding these five detection methods, the NEA data can be studied and analyzed. The results of this study are presented by the leading researchers for each objective. First, Leandra Hogrefe presents the relationship between exoplanet mass and period, as well as mass and semi major axis. Karish Seebaluck presents the relationship between exoplanet radius and period, while Andrew Miller presents the relationship between radius and semi major axis. Lastly, Andrew Miller also calculates the expected detection signal for a temperature Earth-like exoplanet orbiting around a Sun-like star.

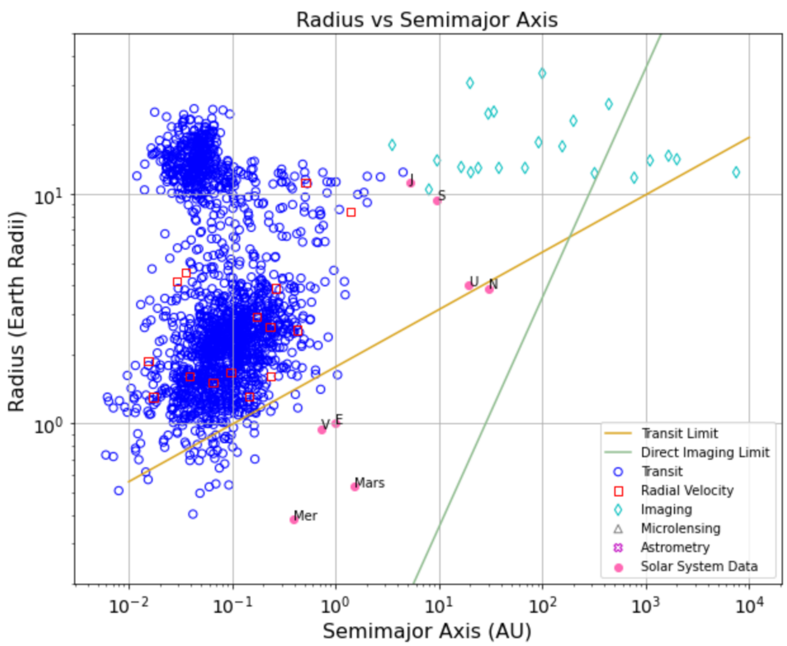




The plots above show the mass of the detected exoplanets (in Earth masses) plotted against the orbital period in days (left) and semi-major axis in AU (right). In both cases, the Radial Velocity method provides the most data points. The Radial Velocity method gives direct information about a planet's mass in contrast to the Transit method, where only the exoplanet radius is known and mass information requires further analysis. For shorter periods (<1,000 days) and small semi-major axis values (<1 AU), the data points are very close to the state-of-the-art detection limit, which is also plotted as a line. For greater values, the data points move farther away from the predicted limit showing how the method favors short periods and small semi-major axes.



The plot above shows the radii of detected exoplanets plotted against their orbital period. The vast majority of exoplanets in this plot were detected via the Transit method. This is because unlike the Radial Velocity method, the Transit method allows for the direct measurement of exoplanet radii. It's clear from the plot that the Transit method is strongly biased towards detecting planets with very short orbital periods, with most found exoplanets having shorter periods than Mercury. This bias comes from the fact that far away planets will transit in front of their star less often, have a lower probability of transiting, and a lower fraction of blocked starlight. There also appears to be a gap of exoplanets between Neptune and Jupiter sized planets. This gap occurs due to the short time span dictating the gas accretion of rocky planets as they become gas giants.



The final plot shows the semimajor axis in AU plotted against exoplanet radius measured in Earth radii. Most planets here are still found via the Transit method, as transits are the most reliable method for viewing the radius of a planet silhouetted against the sun. Direct imaging also offers a strong method for confirming radius, where possible. As a result, both methods are biased toward detecting large planets, with Direct Imaging even more biased toward extremely large planets far from their host star. We also see a gap between ice giant and gas giant sized detections with very few exoplanets forming in the range in between them, hinting at a fundamental difference between the formation of Jovian and Neptune type exoplanets.

We now arrive at the question of whether current technology is sufficient to detect a temperate Earth like planet around a sun-like star. Looking at the Direct Imaging method, we find that the JWST is able to detect a planet to star contrast of 10^{-4} [6]. Here we assume a generic bond albedo of 0.32, which is typical for planets in our solar system. An Earth-like planet at 1 AU would generate a contrast of 2×10^{-5} according to equation 4, showing that Direct Imaging is not capable of detecting an Earth-like exoplanet.

Using Radial Velocity we will assume that K = 0.5 m/s is the current state of the art, and the detection is made perfectly edge-on (i = 90°). Once again, the resulting signal is too small for detection, as its Radial Velocity signal would only be K = 0.09 m/s. Therefore, an Earth-twin could not be detected using Radial Velocity either.

Our last hope, then, is the Transit Method. Analyzing data released by the Kepler K2 extended mission [7], we see that the faintest transit depth detected by that mission was $f = 0.0134\%$. Since this is the smallest transit depth recorded by the mission, we assume this value to be state-of-the-art, and the smallest possible value to still be detected. Calculating the transit depth from Earth's radius compared to the Sun results in a value of $f = 0.0084\%$, which is smaller than anything detected by K2. So, the Transit Method again is currently unable to detect an Earth-like exoplanet.

Section 4: Discussion and Conclusion

Over the past few decades, there have been many advances in exoplanet detection technology. However, the unfortunate fact is that no current methods, apparently, are able to detect Earth-like exoplanets in their star's habitable zone. This explains why NEA data seems to show our own planet and solar system as being unique. While we may be detecting more exoplanets than ever before, we would not find an Earth-like planet even if we were looking directly at it. The current detection methods being used are seemingly not strong enough to detect a terrestrial planet similar to our own. This means that, for now, humanity is unable to detect Earth-like exoplanets.

References

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