Project 1: Detecting Earth-Like Exoplanets

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Section 1: Introduction and Motivation

Life in our universe has been discovered on only one, small planet. 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 with the possibility of harboring life can be located and studied in detail. Other questions surrounding the formation of our solar system can also be probed using the same data.

Before answering such questions, the NEA data is first compiled using various detection methods and the exoplanets are compared to planets within our solar system. To locate a possible life harboring exoplanet, the mass of the exoplanet must be within a certain range. For example, the body cannot be too massive or runaway growth can occur resulting in a gas giant. The body also cannot be too small, or it will not be able to retain a substantial atmosphere. This general theme is consistent for any metric used to study a planet: for all values, the exoplanet must be within a goldilocks zone of not too large and not too small. In this investigation, the specific properties studied for each exoplanet are exoplanet mass, radius, orbital period, and orbital 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, 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.

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

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.

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

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,

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

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.

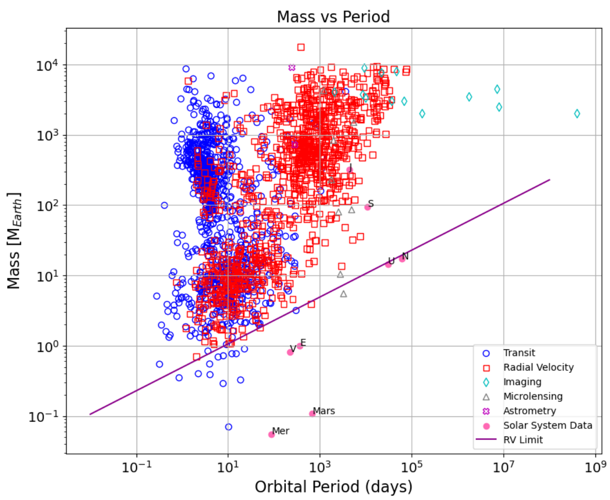
$$f = 4A(\frac{R_p}{a})^2$$

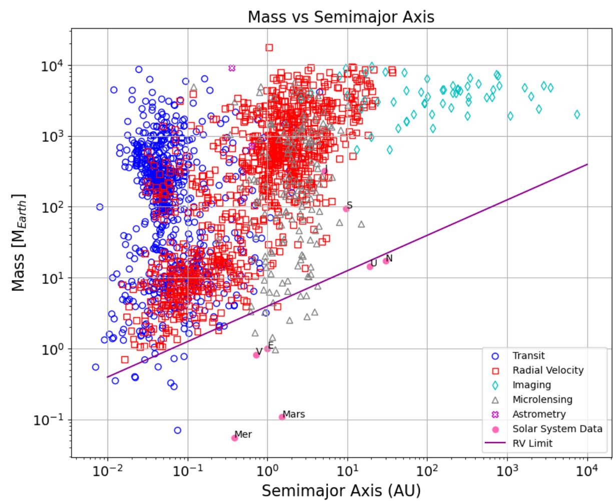
Combining multiple exoplanet images of the same system relays additional orbital and rotational information of the exoplanet. The atmosphere and composition are studied by observing the spectrum of light absorbed and reflected by the exoplanet, allowing researchers to search specifically for the ingredients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

Section 3: Results

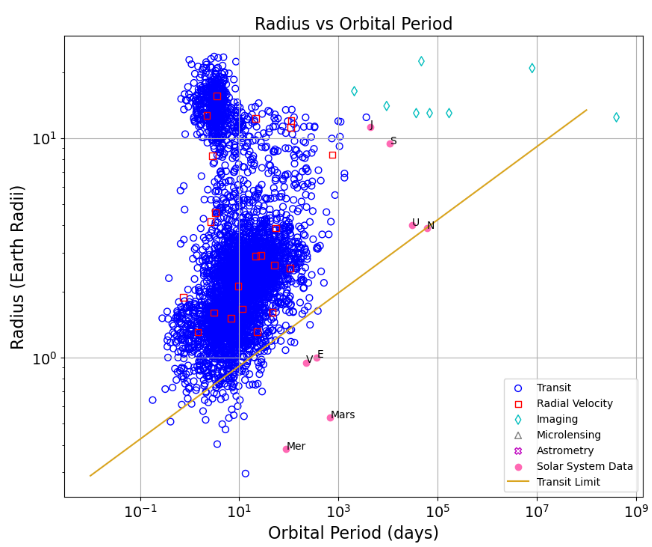
Understanding these five detection methods, the NEA data can be studied and analyzed. The results of this study are presented by the leading researchers for each objective. First, Leandra

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.

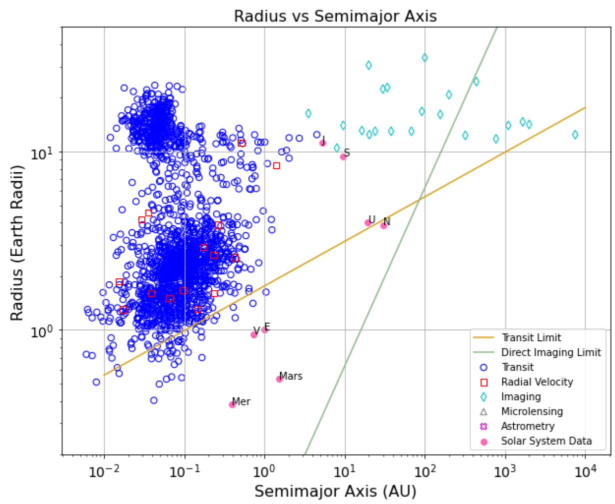




The plots above show the mass of the detected exoplanets (in Earth masses) plotted against the orbital period in days (left) and semi-major axis in AU (right). In both cases, the radial velocity method provides the most data points. This is due to the radial velocity method giving direct information about a planet's mass instead of its radius like the transit method where the mass can only be found through further analysis. For shorter periods (<1,000 days) and a small semi-major axis value (<1 AU), the data points are very close to the limit line also plotted. For greater values, the data points move farther away from the predicted limit showing how the method favors short periods and a small semi-major axis.



The plot above has 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 us to measure the radii of exoplanets. It's clear from the plot that the transit method is strongly biased towards detecting planets with very short orbital periods, with most of them having shorter periods than even Mercury. This bias comes from the fact that far away planets will transit in front of their star less often, and also have a lower probability of transiting. There also seems to be a gap of planets between Neptune sized and Jupiter sized planets. This gap occurs due to the short time available for rocky planets to accrete enough gas to become gas giants.



The above plot shows the semimajor axis in AU plotted against radius 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 the radii of ice giant planets and gas giant planets, with very few planets forming in the range in between them, which hints that there must be a fundamental difference in the formation of Jovian planets vs. Neptunes.

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 x 10^-5 according to $f = 4A(\frac{R_p}{a})^2$, showing that direct imaging is not strong enough to make a detection.

With Radial Velocity, if we assume that K = 0.5 m/s is the current state of the art, and assuming perfect edge-on viewing (sin(i) = 1), we see once again that an earth-twin would not be detectable, as its radial velocity signal would only be K = 0.09 m/s, too small to detect.

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%. Here we are making an empirical assumption that this value must be close to the smallest transit depth detectable by current technology, since no smaller depth was detected by this mission. Calculating the transit depth from Earth's radius compared to the Sun, we find a value of f=0.0084%, which again is smaller than anything which has been detected by K2.

Section 4: Discussion and Conclusion

While there have been many advances in exoplanet detection technology over the past several decades, the unfortunate fact is that none of our methods, apparently, are currently able to detect an Earth-like planet in the habitable zone of a Sun-like star. This explains why NEA data seems to show our own solar system as being unique, as the methods currently being used are seemingly not strong enough to detect a terrestrial planet similar to our own.

References

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