Exploring Exoplanet Detection Techniques

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Motivation

The purpose of this paper is to understand the different detection methods used for finding exoplanets. The methods of detection we will explore include Transits, Radial Velocities, and Direct Imaging. Each technique merits its own benefits but also contains setbacks due to the properties they observe. Some use the planet's mass, its distance from its star, or its orbital period to better understand the object. If we can pinpoint which method is better for distinct situations, then we can develop a fuller picture of the night sky, using detection techniques when best applicable. Overall, diving in can teach us more about the pattern of planet formation throughout the universe and our own detection biases.

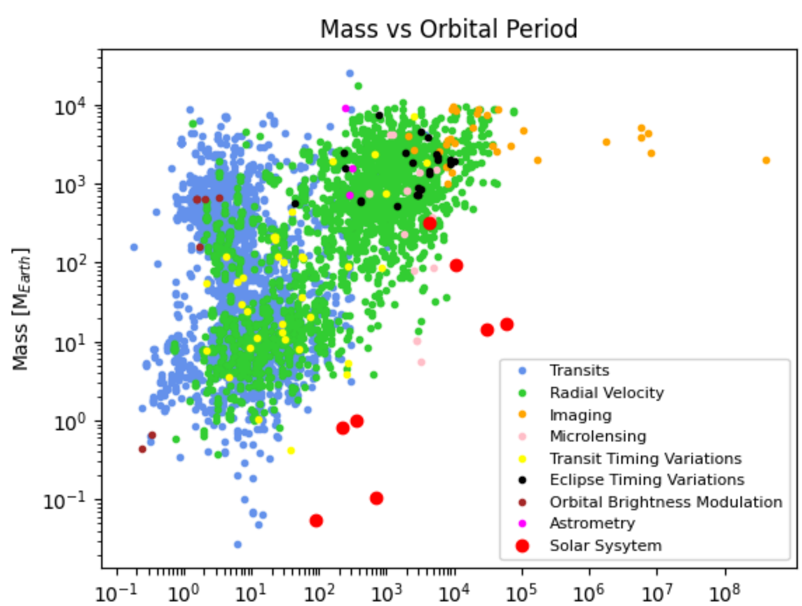
Methods

Our planetary data set is a collection of over 38,000 exoplanets orbiting their hosts. It includes over 90 columns of information for each planet's masses, periods, semi-major axis, etc. If we want to understand our detection bias, we will plot these columns against each other and look at the qualities of the graphs they produce, both recognizing full and empty regions in visual comparison. Using python, we can plot these relationships easily. Throughout this paper, we will plot planetary mass and radii against the planet's period and semi-major axis. Then, we can apply known equations used for each detection type and overlay sensitivity lines on our graphs which will give us insight into the detection limits for each method.

Our first exploration begins with transit sensitivity. The transit detection method deals with a planet passing in front of its host star and blocking some of the light that would otherwise reach us. By measuring the drop in light from its host star and the frequency of its occurrence, we can determine information about the planet. Therefore, this method deals with the radius of the planet and its period around the star. Then, we work with the radial velocity method. This observational tool works by measuring the doppler shift of spectral lines as the star moves towards us and away from us. It has this movement because the star and its planet orbit their shared center of mass. So by measuring this shift in light, we can tell where the center of mass is, which tells us the mass of the planet and its semi-major axis. Finally, we look at direct imaging sensitivity. This method is purely based upon the instrumentation used, with dependencies on the diffraction limit of the telescope since this is a direct approach to observation. So the bigger the planet's radius, the better. We can map their distances from their host star against these radii and see how this relationship exhibits sensitivity limits to detection as well.

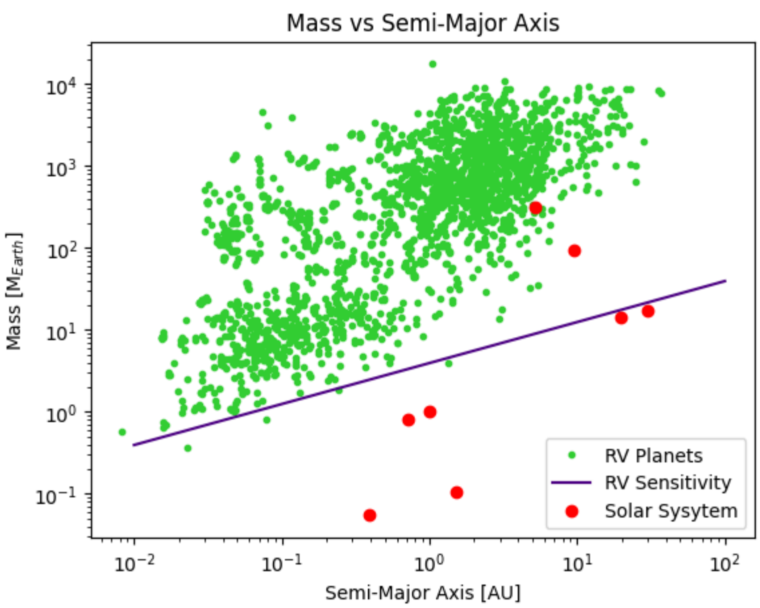
Results

The first relationship that becomes clear when exploring these data columns is the planetary mass and orbital period relationship. While the mass of the body does not directly affect the period of the orbit, we can see patterns and gaps in our data. For example, around 100 earth masses and above, we see a gap of planets between the periods of 10-70 days. This is our first indication of the migration of large bodies. Some planets that form beyond the snow line can move slowly inwards towards their host star. Since this process occurs very quickly compared to the lifetime of planets, this accounts for why so few observed planets



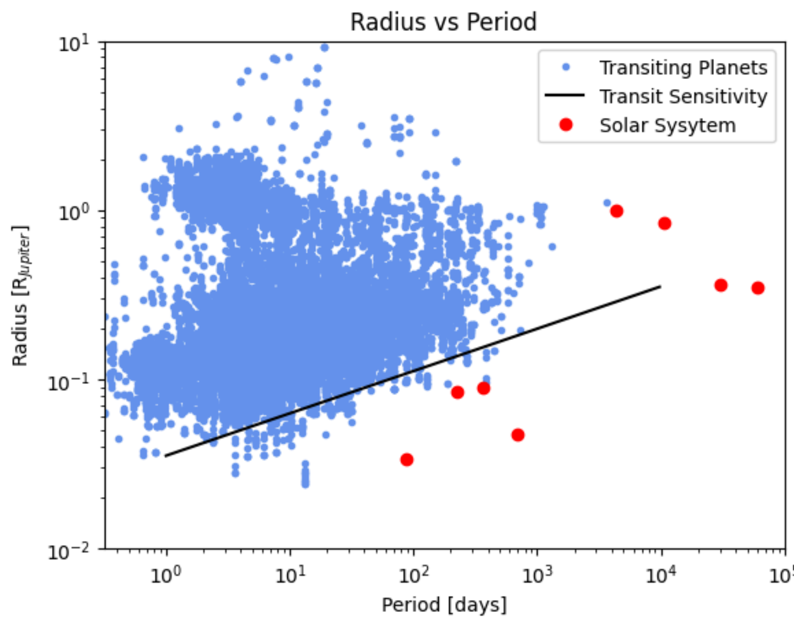
fall in this gap. Another possible explanation is purely selection bias. Some methods of exoplanet detection are good with bodies close to their host star, like the transit method. Others have better observations when farther from their star. Radial velocities deal with the planet's semi-major axis, and a farther semi-major axis makes the star's precession more apparent. The biggest piece of information that this mass vs period plot teaches us is that the rocky planets in our own solar system fall away from much of the observational data. There are failings in our detection methods and this produces selection bias in our observations.

The next comparison we can make is a mass vs semi-major axis plot. As described above, this graph can tell us about the limitations of radial velocity detection. We begin by plotting all

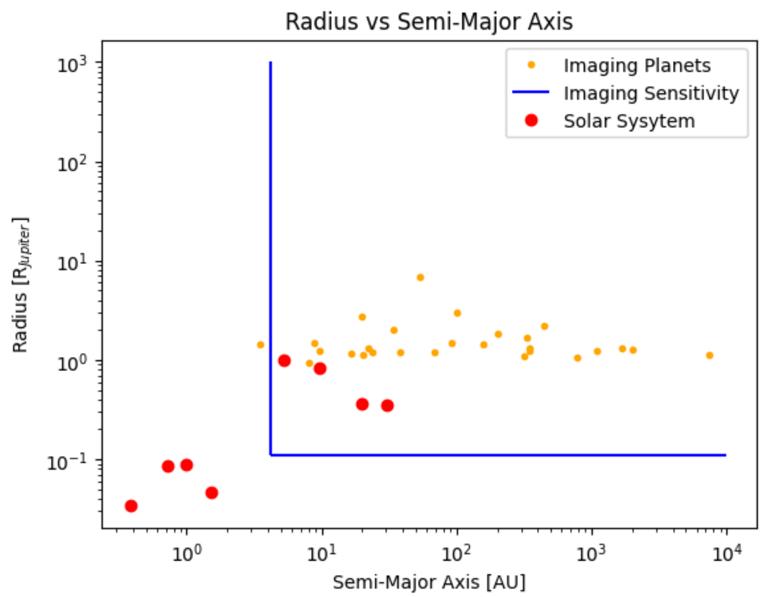


the planets found with the radial velocity method, using their distance from their star on the x-axis and mass in units of earth mass on the y-axis. This method's sensitivity is defined by the equation: $m_p = K m_{star}\sqrt{\frac{a}{G m_{star}}}$. So, the limiting factors on this detection is related to how far a body is from their star, labeled as a, and the mass of the planet, labeled m_p. K is set as a value of 0.5 meters per second, which is state-of-the-art performance for this detection technique, and we assume a stellar mass m_{star} of around half a solar mass. If we now build this sensitivity line and superimpose it onto the mass vs semi-major axis plot, we can see how this sensitivity has affected our past detections. The line itself clearly cuts under all the data, with a handful of straggling points left around due to their host star's true stellar mass. Like our mass vs period plot, however, we find much of our own solar system sitting below the sensitivity line. It reinforces the idea that our detection has room to improve and that there's a lack of data for planets similar to ours.

Now, let's begin to see how the radius of a planet affects its detection. The graph below exhibits the relationship between the radii of planets and their periods around their stars. Similar to the mass vs orbital period plot, there is no direct correlation between a body's radius and its orbital period. However, there are specific qualities of outer orbits that make them more likely for some planet types. Planets with larger radii have an easy time forming farther away from their parent star where conditions are cooler, making the accumulation of gases for thick atmospheres easier. For transiting planets, their radius directly affects the ability to be observed, since they can block more light from their parent star. Again though, we can see a failure of our detection. Almost all the planets in our solar system fall short of the transiting planet sensitivity, either because they are too small or because their period is so large that periodic observation of their transits are made impossible.



The final comparison is of the radius of a planet against semi-major axis. From this graph we can best understand the sensitivity of the direct imaging method. Unlike other methods, this technique relies purely on telescopic precision, such as the size of the telescope used and the wavelengths of light that put limits on detection. We first used the minimum orbital separation, drawn as a vertical line, to show the starting point of possible observation. Using the diffraction limit, we can then put a limit on the size of an object we're trying to observe, shown as a horizontal line on the graph. This method is obviously the least robust of the bunch, with much larger limits on the possibility of detections, but nonetheless, it is worth exploring since it has led to a number of discoveries for exoplanet research.



Like the two other detection techniques above, the rocky planets of our solar system lie outside these limits.

Conclusion

This project as a whole covered a large amount of material relating to exoplanet discovery. With this being said, our main motivation within this project was to learn more about the different ways planets form within a star system, and how our detection of these planets can vary greatly using alternative methods. We conclude through this project that our motivation was successful, as we have not only understood the different ways planets evolve throughout their formation, but we have also seen the limiting factors of our detection methods. Throughout this project, we have enjoyed our experience with handling the data as well as the coding process. It has allowed us to improve our own skills by learning new methods of data organizing, and refreshed us on old functions that haven't been used in a long time. Overall, our experience with this project was positive and we are excited to continue these projects.