Exploring Exoplanet Properties

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Motivation

The purpose of this paper is to explore how we measure planet mass, radius, and density based on an assortment of observed data. Our given data sets explore radial velocity and transits of a planet-star system and from here we can calculate the features we're interested in. Additionally, we will evaluate the uncertainties in these measurements as well as the implications that our uncertainty has on truly understanding planetary dynamics and evolution. Once collected, it's good to compare our data with known data samples for other exoplanet systems, and the best paper for this step is the M-R relation from Chen & Kipping (2016). By measuring these planetary properties using radial velocities and the transit methods, and comparing them to known data and values, we can deepen our understanding of these relations, exploring the abundance of different types of exoplanets scattered throughout the universe.

Methods

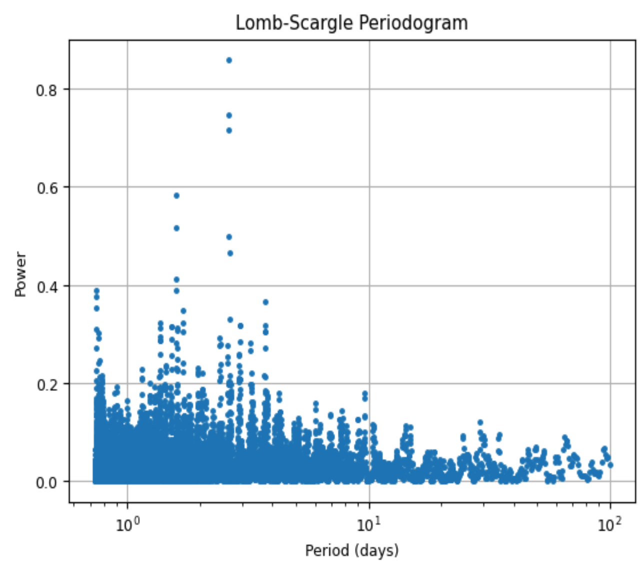
Throughout our process, there were a variety of different methods that were integral to us deriving our results and forming conclusions in this paper. We first grabbed data from the NASA exoplanet archive, which included a Julian date time scale, stellar radial velocity, relative flux for the star through the transit region, and uncertainties for radial velocity data for our planet-star system. Broadly, we used google colab to analyze this data, implementing mathematical processes and plots in Python. Its structure helped to organize this paper's format as well.

For radial velocity (RV) analysis, we used two major methodologies. The first was using a Lomb-Scargle Periodogram. This statistical tool is a built-in function made to find periodic signals. Since our radial velocity information is not evenly spaced across a time period, this method will also linearize the data in a time series to better estimate the planet's true period. The second method used for RV analysis is a python package called RadVel. This resource models orbits of planets purely from the radial velocity data. Similar to the Lomb-Scargle Periodogram, this method works by understanding the time series of the data and flexibly interpreting the periodicity of it. The best part of this tool is that its mathematical framework is based in Keplerian orbital physics, meaning it can be applied to a huge list of objects since the mathematics transcends beyond the specifics of planetary and stellar masses, distances, radii, and densities. We will directly apply our given catalog of stellar radial velocities to this package to receive a sinusoidal periodic relationship between observed radial velocities and time.

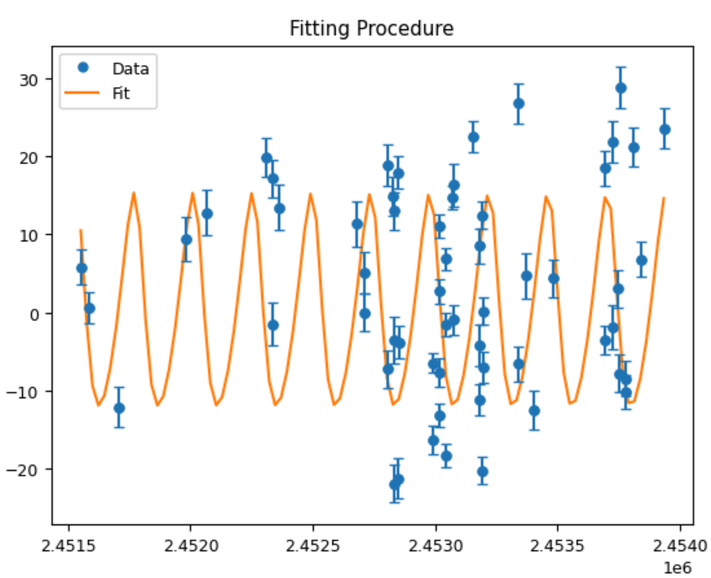
For transit analysis, we first used simple matplotlib plotting techniques to easily plot the relative flux against Julian date. To calculate the uncertainty for this data, we found the standard deviation of points prior to and after the region of decreased relative flux (which we know is the transit). By understanding the usual dispersion of observed values in regions without transit, we can see the natural uncertainty propagated by instrumentation. The tools used must be the same for all of the data throughout the observation, so we can justify applying this systematic uncertainty to all of the points in the plot. Next, we fit the data with a model, visualizing how the non-transit regions keep a consistent relative flux at a value of one but the transit regions have smaller relative flux since the planet blocks part of the light from its parent star. To build this model, we take the region of transit in question and map out the curve that it is creating. The model itself should have sharp relative flux changes right when the planet begins to pass and stops passing its host star but a fairly flat and consistent minima of relative flux during the period where the planet is completely in front of the star.

Results

The first graph we will look at is the Lomb-Scargle Periodogram. This mathematical tool helps us find periods for data sets that are unevenly spaced, as our radial velocity data is. This is extremely important to this project as it is crucial to finding the planet's periods and therefore both creating the plots that follow and getting our planetary mass. Notice the sharp spikes in the graph between 1 and 10 days. This graph seems to have an abundance of data at the earlier periods compared to the later periods. That implies that our planet has a relatively short period, at least shorter than 10 days, which is somewhat unusual to us. The peak of this periodogram sits right at a period of around 2.64 days, helping us to determine that this is the true period of our planet.

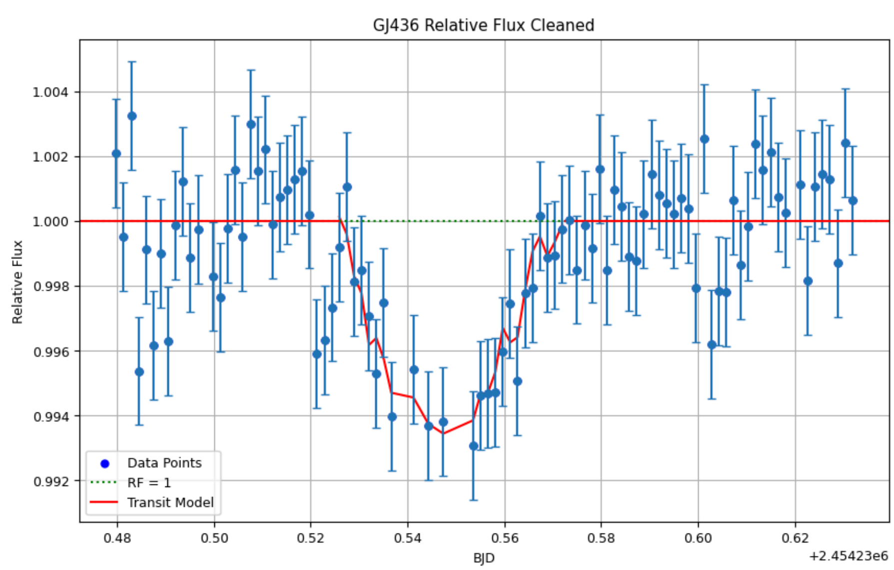


For the next plot we will look at how we created our fitting procedure. The graph here shows our radial velocity data, with given error bars in the background. We start by using RaVel to solve for the planet's semi-major amplitude, a value written as K which helps us to better understand the planet's dynamics. Then, we let RadVel solve for the periodic behavior of our plot. We first have to understand the initial parameters of the system. Giving this tool incorrect estimations for planetary masses, periods, or eccentricities can lead to widely different models.



Luckily, our Lomb-Scargle Periodogram gives us a very precise value for the period of our planet and the eccentricity can not take that wide a range of values. Then, we give RadVel our range of time and RV data and it builds a sinusoidal model to best justify the observations we are getting. We can see in the plot above that the model created is fairly smooth and evenly periodic. Now, we can take the information this model gives us and solve for the planetary mass. Using known equations about keplerian motion, the eccentricities the model gives us, and the period we have derived, we can mathematically solve. Our result is a planet of just over 20 Earth masses in size. Comparing the possible bounds and errors of our solution, we have also derived a simple uncertainty in the planetary mass of 1.99 Earth Masses.

Our final graph takes us to a relation between the relative flux and julian date. This is the money graph. Here we can clearly see a significant dip in the middle of the graph, which we know to be the transit of the planet. With this graph, we can determine the difference between the depth of the transit depth with the initial value of 1 for the relative flux. Using this, we can solve for the planet's radius. We do this by using the transit depth equation of $\delta = (\frac{R_p}{R_*})^2$. We know the parent star's radius from exterior sources, and we now have the transit depth from our graph, leaving just some simple algebra to our answer for the radius of the planet. When we run this simple calculation we find a radius of the planet of 0.3659 ± 0.02201 Jupiter Radii.



Now, with precise calculations for the planet's mass and radius, we can begin to understand its density and where it fits along Chen & Kipling's mass-radius relationship plot. Dividing our mass calculation by a spherical volume with our derived radius, we get a density of 1.593 g/cm^3. This puts its value just between the densities of Uranus and Neptune. We also solved for the uncertainty in this value by propagating through the uncertainties of our mass and radius calculations, gaining an uncertainty of 0.186 g/cm^3. These calculations combined place our planet right in the center of the Neptunian worlds region for Chen & Kipling, with a mass and radius slightly larger that of both Uranus and Neptune.

Conclusion

Overall, this project went over a lot of important topics relating to analyzing data from radial velocity measurements and uncertainties. Our main motivation for this project was to explore exoplanet mass, radius and density so that we could make conclusions about the abundance of exoplanet types throughout the cosmos. After completing this project, we can definitely say our motivation was successful. Throughout the course of this two week project, we enjoyed learning more about the radial velocity and transit detection methods, and how they can be used to find real planetary features like mass, radius, and density. We also enjoyed getting more practice with the python coding language, as well as solving issues relating to the coding software. Overall, our experience with this project was mostly positive, despite hiccups relating to the coding software and data we were given. We are encouraged by the work we have done and anticipate future projects to be even better than this one.