Finding Exoplanet Radius, Mass, and Density Using the EXOFAST Method

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Introduction

For the past few decades, humans have been looking for a new home, in case Earth becomes uninhabitable. As astronomers find more exoplanets, we are able to learn more about worlds beyond our own. The first key step in studying exoplanets is to determine their characteristics, such as mass, radius, and density. By examining these properties, we are able to start finding information on the composition of exoplanets. This is the process by which exoplanet astronomers determine whether a new world would be potentially habitable or not. In this project, we analyze data on the exoplanet HD 189733 b from NASA's Exoplanet Archives in order to derive physical properties of the planet. Our group was excited to undergo this project, as it would be our first experience with determining physical properties of a real exoplanet based on its observational data. Our goal in transforming the raw data into physical properties was to gain a better understanding of how the properties were found.

Methods

In order to find the mass of the planet, we used data from the radial velocity observations of the planets host star, and to fin the radius of the planet we analyzed data from the observed transit of the planet. The first step to analyzing this data was obtaining it from NEA. After we downloaded the data, we uploaded it to an online tool called EXOFAST. This tool allows us to analyze the raw exoplanet data and find the best fit models for different parameters.

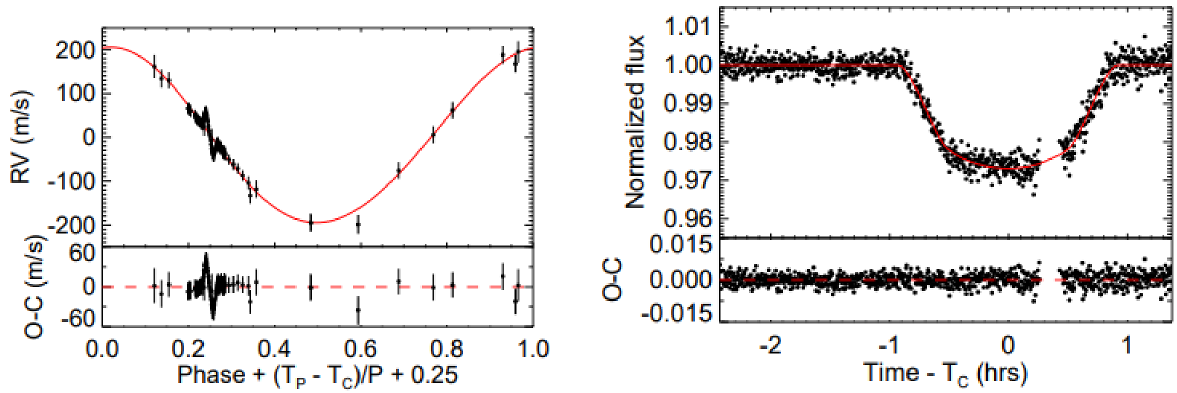

Figure 1: Left shows the radial velocity curve caused by HD 189733b, as a function of time. It shows a radial velocity value of 200.8 meters per second. Right shows the normalized flux of the host star as a function of time, clearly depicting a strong transit curve caused by the target exoplanet. It exhibits a transit depth of 2.474%. Both graphs were produced by EXOFAST from data obtained from NEA via B.K.

Note the strange 'blip' on the left side of the radial velocity graph, at phase of around 0.2. This is caused by the planet transiting in front of the host star. During this transit, it partially blocks some of the blue shifted light from the star's rotation, and then rapidly some of the red shifted light as it passes to the other side of the star. This causes a larger degree of error, as the telescope picks up less light than it normally would in this area of the curve.

With the values, and errors, provided by EXOFAST, J.K. was able to derive the mass via the following equation:

$$K = v_* \sin i = \left(\frac{M_p}{M_*}\right)\sqrt{\frac{GM_*}{a}} \sin i$$

Using this equation, we can plug in the known mass of the star M*, the radial velocity of the star K, and semimajor axis a of HD 189733 b (based on its period), in order to solve for the mass of the planet Mp.

In order to find the radius of the planet, we used the transit data as well as the following equation:

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

This equation simply gives the radius of the planet Rp based on the known radius of the host star R* as well as the transit depth f.

From these two properties, mass and radius, it is a simple calculation to determine the density of the planet, by simply dividing the mass of the planet by it's volume. The volume of the planet is determined by assuming the planet is a sphere.

It was also necessary to propagate the error in the original measurements, in order to make sure that we accurately presented the results. J.K. did this through the normal error propagation methods by adding the uncertainties in quadrature.

Results

After analyzing the data on HD 189733 b, we were able to accurately determine its mass to be 360 ± 36 Earth masses, or 1.13 ± 0.11 Jupiter masses. We were also able to determine its radius to be 13.2 ± 0.4 Earth radii, or 1.18 ± 0.04 Jupiter radii. These measurements lead to a calculation of the planet's density to be 1173 ± 164 kilograms per cubic meter, which corresponds to 88.5% of the density of Jupiter. This means that the planet would not float in water!

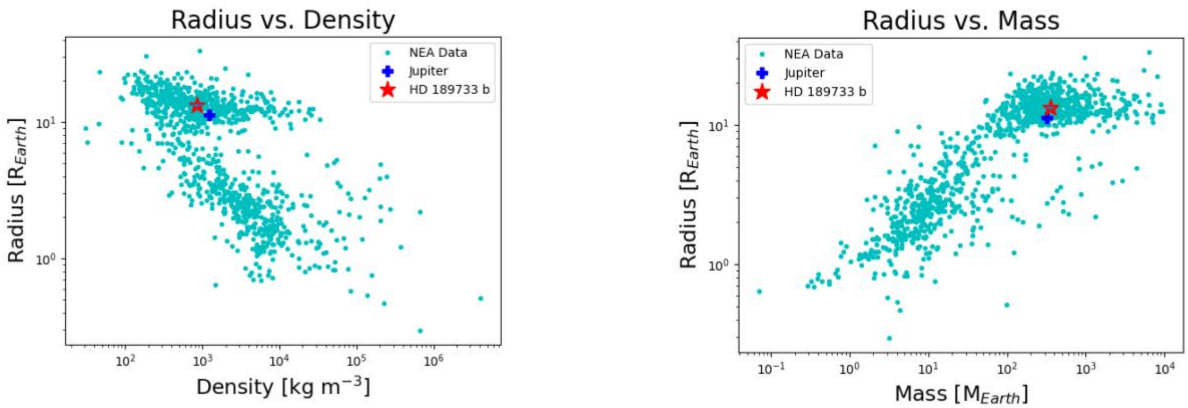

Figure 2: Left depicts the target exoplanet on a scale of mass against radius, compared with Jupiter, as well as many other exoplanets from the NEA. The right depicts a similar scenario, with radius against density. Plots produced via B.K.

After we obtained this data, we wanted to compare it to other known values to see how similar our exoplanet was to other known exoplanets. These graphs are shown above in Figure 2. It is obvious from these graphs that HD 189733 b is very similar to large, massive exoplanets, as well as almost exactly having the same properties as Jupiter.

Conclusion

Looking at the results from figure 2 it is clear that HD 189733 b is similar to many gas giant planets. As a result of this, we declared that it must be a gas giant as well. We decided to confirm this using Chen and Kipping (2016) paper which explains the relationship between mass and radius for different types of planets. This is shown below in figure 3. The orange dot, around 360 Earth masses represents the target exoplanet. It is clear from this depiction that HD 189773 b falls squarely in the 'Jovian Worlds' category, setting it apart as a Jupiter-like gas giant.

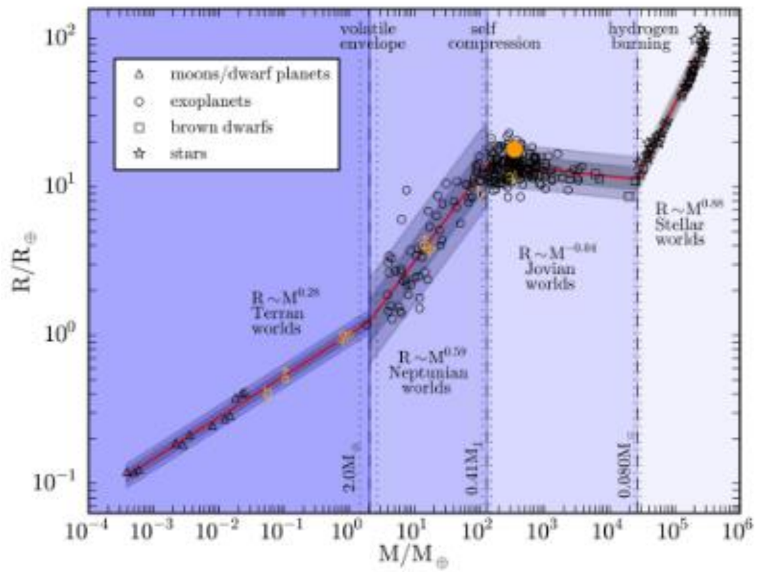

Figure 3: Depicts data from Chen and Kipping's (2016) paper, overlayed with our calculated data of HD 189733 b, via A.W.

We also thought it would be a good idea to check that our data was sensible, and F.H. found it to be consistent with official data, as our error overlapped with the official data on HD 189773 b via exoplanet.eu, an accredited exoplanet archive.

This project helped us to become more comfortable with the process of turning raw exoplanet data into useable properties of the planet, and we are excited at the future prospects of continuing these types of observations and calculations.

References and Acknowledgements

"Planet HD 189733 b." *The Extrasolar Planet Encyclopaedia - HD 189733 b*, http://exoplanet.eu/catalog/hd_189733_b/.

Chen, Jingjing, and David Kipping. "Probabilistic Forecasting of the Masses and Radii of Other Worlds." *The Astrophysical Journal*, vol. 834, no. 1, 2016, p. 17., https://doi.org/10.3847/1538-4357/834/1/17.

EXOFAST Acknowledgments, https://exoplanetarchive.ipac.caltech.edu/docs/exofast/exofast_ack.html.