Measuring the Mean Density of HD 189733b

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1 Introduction

The information astronomers can obtain from a single detection method is limited. The radial velocity method can set a lower limit for the planet's mass, but it can determine nothing about the planet's radius. Conversely, the transit method can determine the ratio between the planet's and star's radii, but it can determine nothing about the planet's mass [2]. To learn the most about an exoplanet's properties, we must combine data collected using different methods. The property we are interested in here is the mean planet density.

A planet's mean density can tell us about its composition. Whether the planet is a rocky, terrestrial planet, an ice giant, or a gas giant will have a major effect on its density [4]. A planet's composition can give us clues about that planet's formation history and it can influence the planet's habitability. In this project, we will combine radial velocity and transit data for the planet HD 189733b to determine the density of the planet, and what it means about its potential composition.

2 Methods

2.1 Calculating Planet Mass

Radial velocity data can be used to calculate the mass of an exoplanet. The RV amplitude is given by [2]

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

where M_* is the mass of the star, M_p is the mass of the planet, a is the semimajor axis of the planet's orbit, and i is the inclination of the orbit. Rearranging this equation to solve for the M_p:

$$M_p \sin i = M_* K\sqrt{\frac{a}{GM_*}} \tag{2}$$

We cannot generally know the inclination of the orbit, so we derive the minimum planet mass. However, since we choose a planet that also transits, the $\sin(i)$ term is very nearly 1. We can therefore say that we will derive the actual mass of the planet. To derive the mass, we also need to know the semimajor axis. This can be found using the period of the RV signal and Kepler's Third Law [2].

$$a = \left(\frac{P^2}{4\pi^2}GM_*\right)^{\frac{1}{3}} \tag{3}$$

Here, P is the period of the RV signal. Using these expressions, we can derive the minimum mass of an exoplanet using the radial velocity signal.

2.2 Calculating Planet Radius

A transit signal can be used to calculate the radius of an exoplanet. The depth of the transit is given by [2]

$$f = \left(\frac{R_p}{R_*}\right)^2 \tag{4}$$

where R_p is the radius of the planet, and R_* is the radius of the star. Rearranging this expression to solve for R_p:

$$R_p = R_*\sqrt{f} \tag{5}$$

Using this expression, we can derive the radius of an exoplanet using the transit signal.

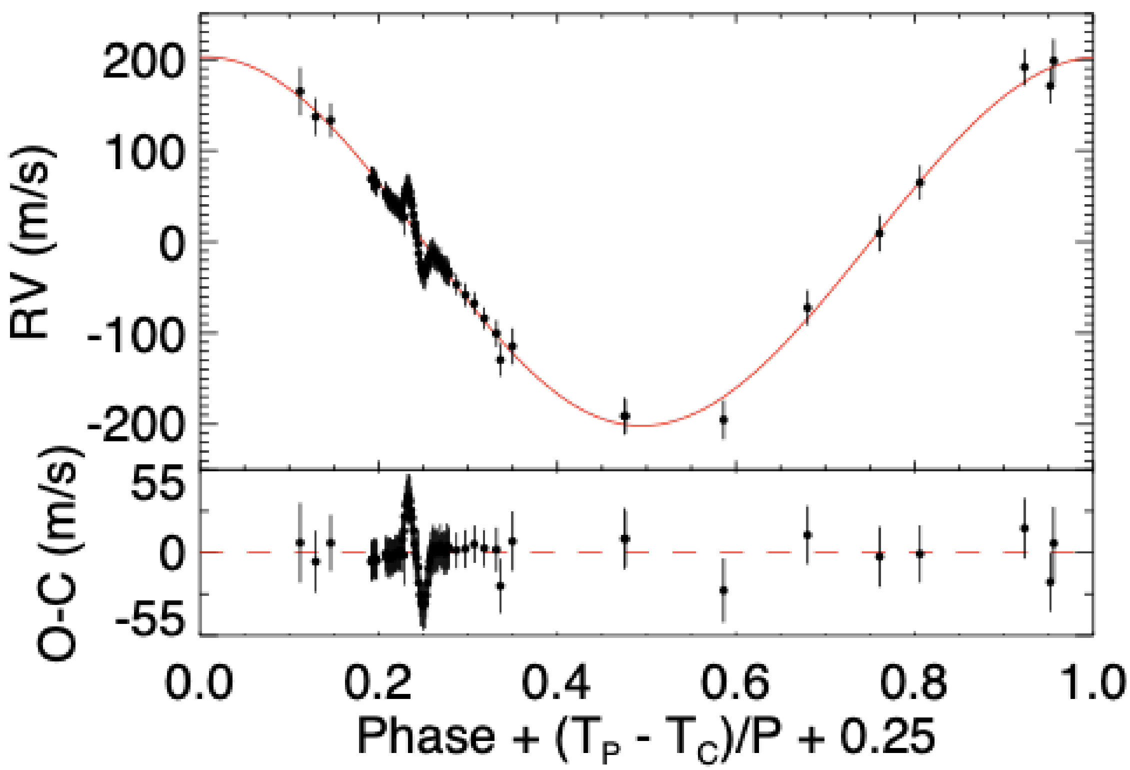

Figure 1: This figure shows the radial velocity fit for HD 189733b. The top panel shows the radial velocity over the orbital phase. The red line is the EXOFAST fit to the data. The bottom panel shows the residuals (observed-minus-calculated). The blip around 0.2 is the result of the transit of the planet blocking some of the light from the star.

2.3 Calculating Planet Density

We assume a sphere of radius R_p. The volume of the sphere is

$$V = \frac{4}{3}\pi R_p^3 \tag{6}$$

Assuming the planet mass, M_p, is uniformly distributed within the sphere, the density is

$$\rho = \frac{M_p}{V} = \frac{3M_p}{4\pi R_p^3} \tag{7}$$

3 Results

Figure 1 shows the RV signal of HD 189733b. We perform a χ^2 fit of the data using EXOFAST then run an MCMC analysis and find that the mass of the planet is

$$M_p = 1.18 \pm 0.04\, M_J$$

Figure 2 shows the transit of HD 189733b. To determine the transit depth, we find the average flux out of transit and the average flux in transit. The difference is the transit depth f. We calculate a transit depth of $f = 0.025$, which corresponds to a planetary radius of

$$R_p = 1.20 \pm 0.02\, R_J$$

This calculation was done using Eq 5, with a stellar radius of $R_* = 0.7827\, R_\odot$ [].

We then perform a calculation of the density. Using Eq 7 and the mass and radius values we just derived, we find that the mean density of HD 189733b is

$$\rho = 0.847 \pm 0.06\, g/cm^3$$

This density is similar to the density of the gas giants in our Solar System ($\rho_{Jupiter} = 1.31\, g/cm^3$, $\rho_{Saturn} = 0.687\, g/cm^3$) [1]. This means that HD 189733b is most likely a gas-giant planet, specifically a Hot Jupiter, due to its short orbital period.

We look at NASA Exoplanet Archive (NEA) data to determine consistency between our calculated mass and radius and known exoplanets [6]. Fig 3 shows all known exoplanets, plotted by their

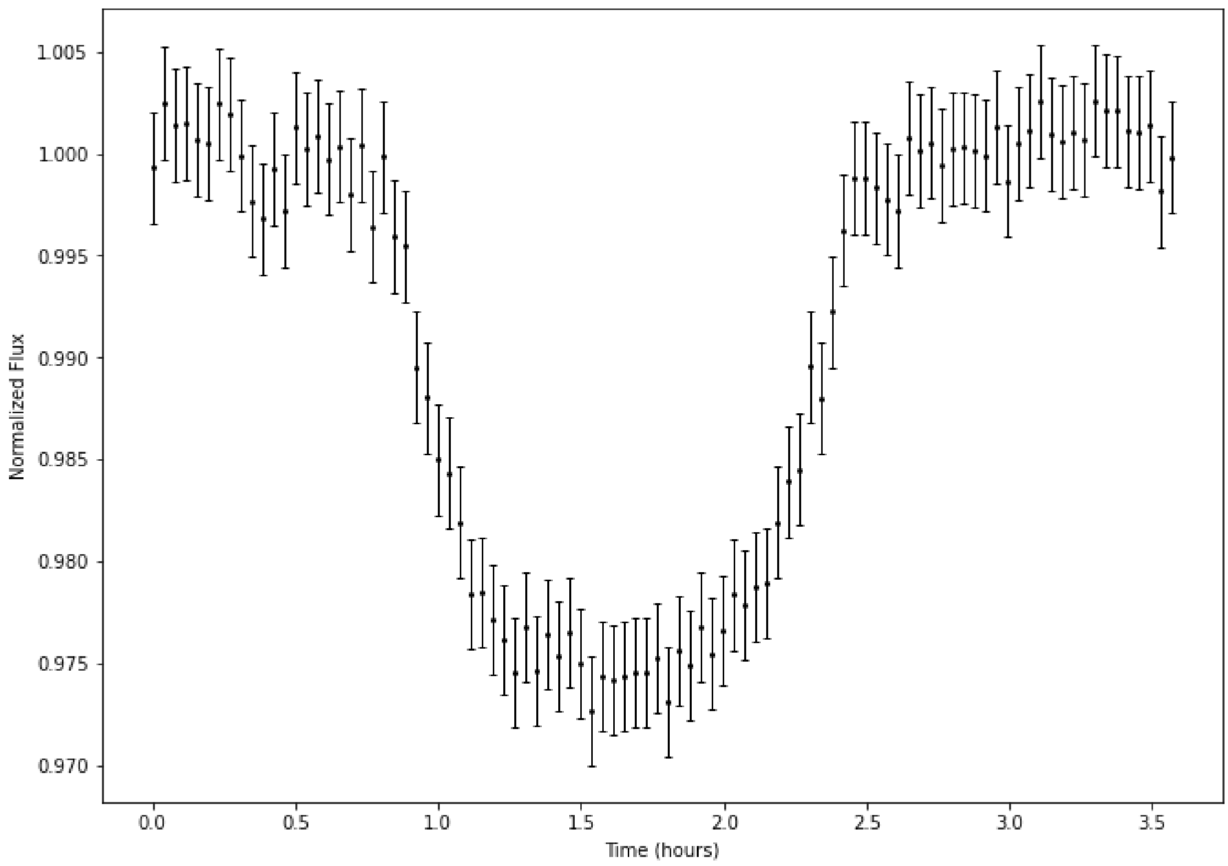

Figure 2: This figure shows the transit signal for HD 189733b. The average out-of-transit flux is normalized to one. The x-axis is time in hours, with the beginning of the dataset set to $t = 0$ hr.

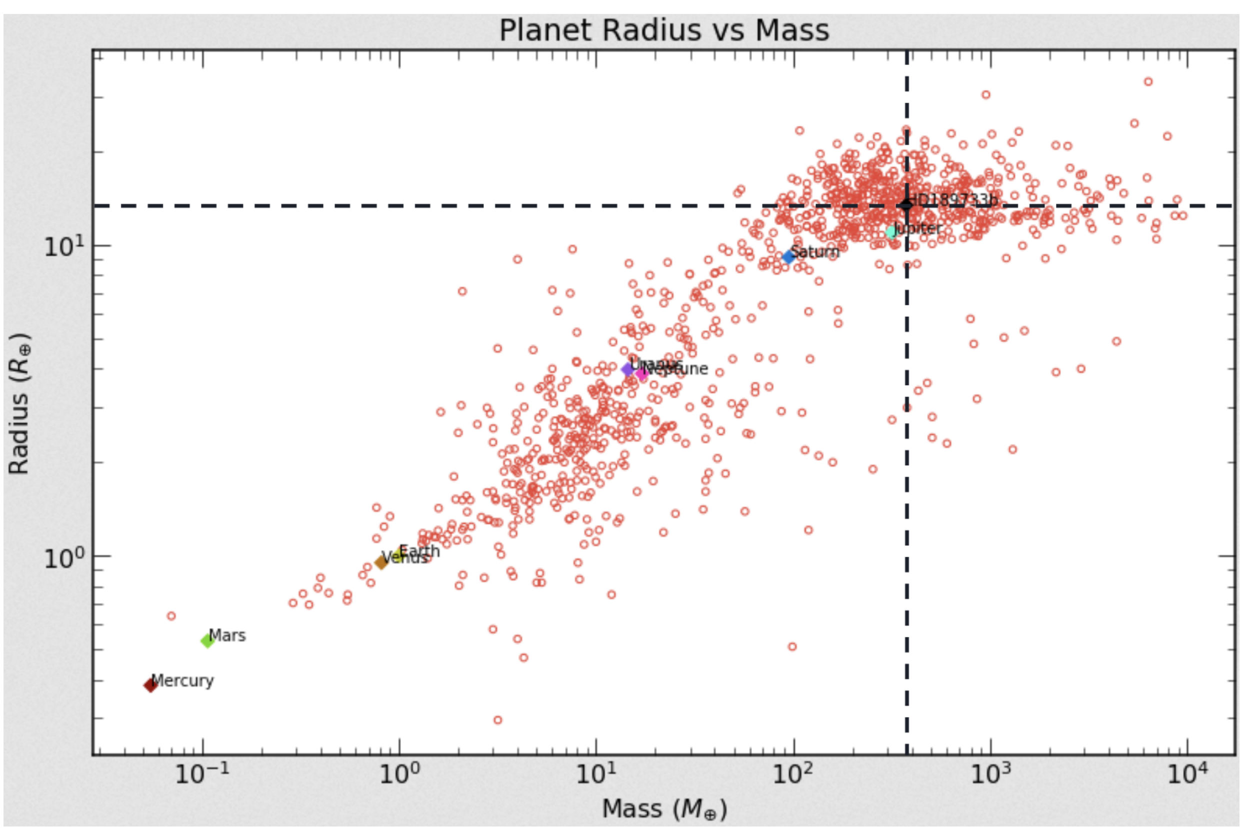

Figure 3: This plot shows all known exoplanets, taken from NEA. The radius of each planet (in Earth radii) is plotted against the mass (in Earth masses). The solar system planets are overlayed on the plot. The dashed lines show the location of HD 189733b on this plot.

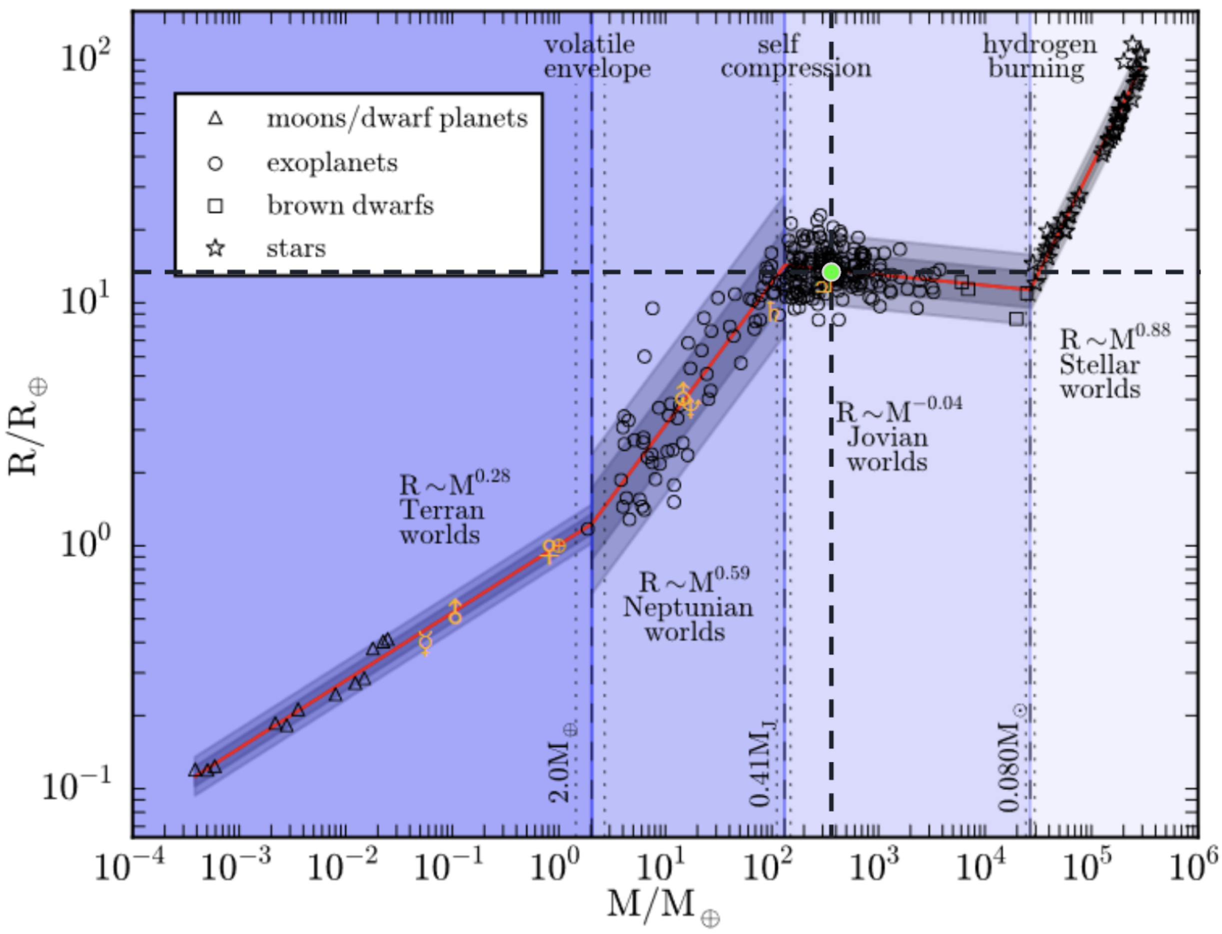

Figure 4: This is Fig. 3 from Chen & Kipping (2016). We overlay our calculated parameters for HD 189733b.

radius and mass. We plot HD 189733b on the same plot. The calculated mass and radius for HD 189733b places it in the upper-right of Fig 3, with other gas giant planets. This is consistent with the calculated density, which implied the composition of HD 189733b is most likely gas.

We also check if the calculated mass and radius are consistent with the mass-radius relation from Chen & Kipping (2016) [5]. They posit that the mass-radius relation for Jovian planets (planets with masses between 0.41 M_J and 0.08 $M_{\odot}$) is $R \sim M^{-0.04}$. Plugging in our calculated mass, we predict a radius of $\sim 0.99 R_J$. This is the same order of magnitude as our calculated radius. Additionally, Fig 4 shows where HD 189733b falls on their mass-radius distribution. We find that our calculated values for HD 189733b are consistent with the mass-radius relationship from Chen & Kipping (2016).

4 Conclusion

Combining multiple detection methods does increase the information we can obtain about an exoplanet. Here, we combined RV and transit data to determine the mass and radius of HD 189733b, respectively. These two pieces of information allowed us to calculate the density of HD 189733b. The density we calculated is consistent with a gas-giant planet. This composition would make this exoplanet uninhabitable. Comparing our calculated mass and radius to NEA data for other exoplanets, we find that HD 189733b lies in the group of other gas-giant planets, like Jupiter and Saturn. Our values are also consistent with the mass-radius relationship demonstrated by Chen & Kipping (2016).

5 References

[1] NASA Planetary Fact Sheet
[2] Week 2 Exoplanet Detection and Population, PowerPoint
[3] Week 3 Mass Radius Relation, PowerPoint
[4] Ryden, Barbara & Peterson, Bradley M., Foundations of Astrophysics, Pearson, 2011
[5] Jingjing Chen and David Kipping 2016 ApJ 834 17
[6] NASA Exoplanet Archive
[7] Exoplanet Transit Database

6 Contribution Statement

Kolya Larson downloaded and fit the transit data and calculated the radius of the planet. Cassie Moats downloaded and fit the radial velocity data and calculated the mass of the planet. Kolya Larson calculated the density and compared to NEA data. Matt Lastovka wrote the written report. Sam Eckart wrote and gave the presentation.