Density of Exoplanet HD 189733b from Radial Velocity Spectroscopy and Transit Photometry

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20 February 2025

1 Motivation

HD 189733b is a large exoplanet that orbits very close to its host star, HD 189733. Ever since it was discovered in 2005, it has been the subject of intense research seeking to discover more about its true nature. In this paper, we source spectroscopy and photometry data for the HD 189733 system from the NASA Exoplanet Archive to calculate the density of HD 189733b. We find the mass of the planet by analyzing the spectroscopic data using the radial velocity method, then we find the radius of the planet by observing the transit depth of the dips in the photometric data. From these two values (and the assumption that HD 189733b is spherical), we can calculate the density and report our uncertainties.

2 Methods

2.1 Planet Mass from Radial Velocity)

We use the Lomb-Scargle periodogram statistical tool to estimate the period of HD 189733b's orbit around HD 189733, and find the best-fitting period to be 2.218 ± 0.004 days (Figure 1).

To find the planet's mass, we use the following equation:

$$M_p \sin i = \frac{M_* P}{2\pi G}^{\frac{1}{3}} K, \tag{1}$$

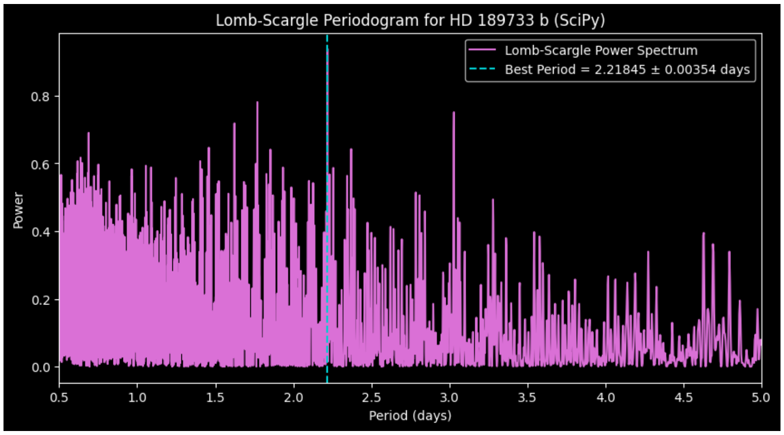

Figure 1: The Lomb-Scargle Periodogram for HD 189733b, including the power spectrum and the best-fitted period.

where M_p is the mass of the planet, M_* is the mass of the star, P is the orbital period, and K is the semi-amplitude of the radial velocity curve. We roughly estimate the semi-amplitude of HD 189733b to be the average of the largest and smallest measurements for the radial velocity, which we find to be $196.9 \pm 0.9\ \frac{m}{s}$. We then use this value as an initial value for a fitting function to produce a sinusoidal phase-folded radial velocity curve that will refine our measurement of the semi-amplitude (Figure 2). We find the best fit for the semi-amplitude parameter to be $K = 204.75\frac{m}{s}$. By inserting our values for the semi-amplitude of the radial velocity curve, the period of the planet's orbit, the mass of the host star ($M_* = 0.82 M_J$), and the known constants G and π into Equation 1, we find the minimum mass of HD 189733b to be

$$M_p \sin i = 1.151 M_J.$$

2.2 Planet Radius from Transit Photometry

The relative radii of the transiting planet (R_p)and star (R_*) are related to the depth of the transit-induced dip in the photometric light curve (δ) by the equation

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

which can be rearranged to be

$$R_p = R_* \sqrt{\delta}. \tag{2}$$

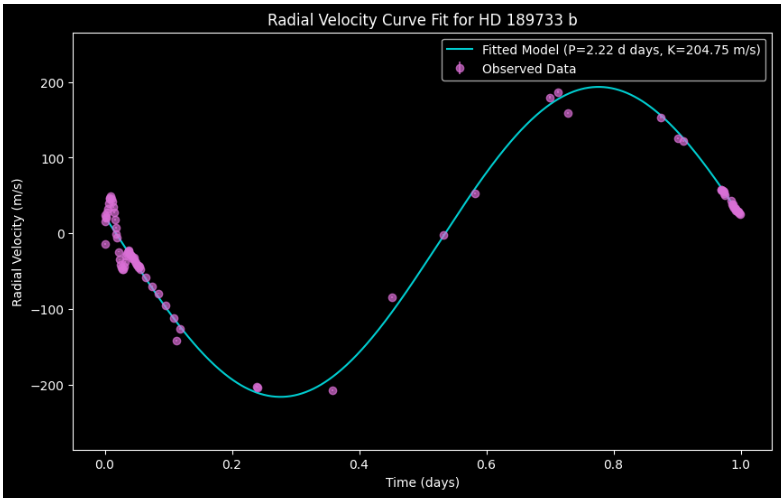

Figure 2: The phase-folded radial velocity curve for HD 189733b, with a sinusoidal model fitted to the data.

The plot of the light curve of HD 189733b shows a clear dip in the brightness of the star. If we estimate δ as the difference between the lowest point in the transit and the average flux of the star, then Equation 2 gives us a radius of $R_p = 1.34 R_J$, which is a very poor approximation. Clearly, we need to fit a model to the data that uses the transit depth as a parameter. However, a simple box-shaped model fits the data very poorly (Figure 3). Instead, we use the `TransitModel` functon offered in the `batman` package to fit the transit model, which fits much more closely to the data (Figure 4). Using `batman`, we find that the radius of HD 189733b is $1.17 R_J$, which is a much more reasonable value.

3 Results

3.1 Calculating Density

Assuming HD 189733b is a perfect sphere, then its density will be given by

$$\rho_p = \frac{M_p}{V_p} = \frac{M_p}{\frac{4}{3}\pi R_p^3}. \tag{3}$$

Using the values we found in Sections 2.1 and 2.2 for the radius and mass of HD 189733b (converted from Jupiter units to SI units), we find the density

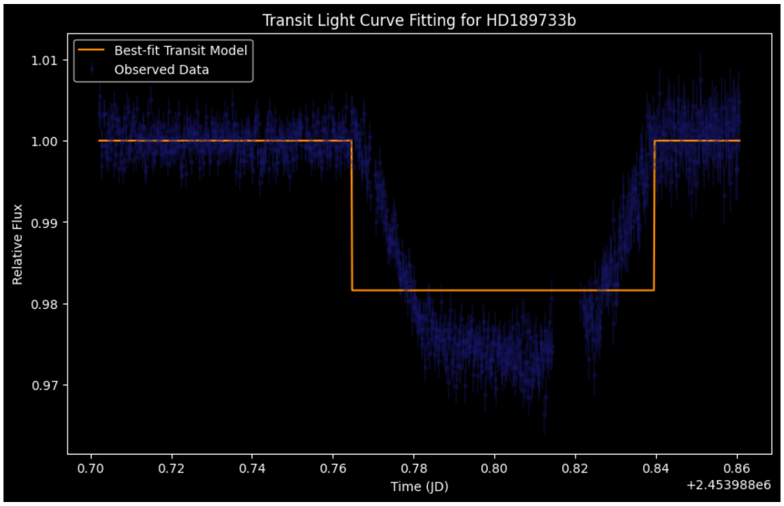

Figure 3: A basic box-like model is fitted to the transit data; the fit is poor.

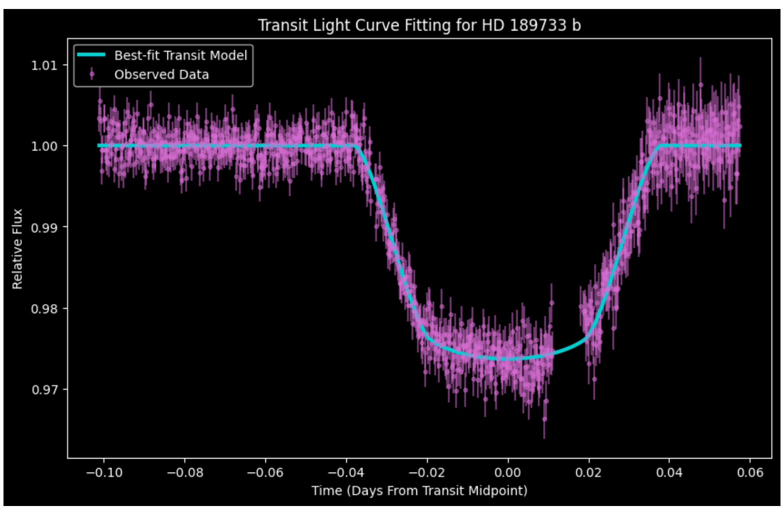

Figure 4: The `batman` package fits a much better transit model to the transit data.

to be $908.38 \frac{kg}{m^3}$.

3.2 Calculating Uncertainties

The uncertainty in our value for the mass is determined by the following uncertainty propagation:

$$\sigma_{M_p} = \sqrt{(\frac{\sigma_K}{K})^2 + (\frac{2\sigma_{M_*}}{M_*})^2 + (\frac{1}{3}\frac{\sigma_P}{P})^2}, \tag{4}$$

with the uncertainties in K, M_*, and P calculated from our data.

The uncertainty in our value for the radius is determined by the following uncertainty propagation:

$$\sigma_{R_p} = \frac{R_*}{2\sqrt{\delta}}\sigma_\delta + \frac{R_p}{R_*}\sigma_{R_*}, \tag{5}$$

with the uncertainty in δ and R_* calculated by the transit dip light curve fitting function.

With these uncertainties, we can propagate the uncertainty in density as

$$\sigma_{\rho_p} = \rho_p\sqrt{(\frac{\sigma_{M_p}}{M_p})^2 + (3\frac{\sigma_{R_p}}{R_p})^2} = \pm 24.9\frac{kg}{m^3} \tag{6}$$

4 Conclusion

In conclusion, using the radial velocity and transit photometry data of HD 189733, we have found that that the mass, radius, and, thus, density of HD 189733b are

$$M_p = 1.15 \pm 0.03 M_J, \quad R_p = 1.165 \pm 0.005 M_J,$$

and

$$M_p = 900 \pm 25\frac{kg}{m^3}.$$

These values are close to the previously-measured values in the literature, but our uncertainties are very small compared to the difference between our values and the literature's values. This discrepancy is worth further investigation. Either way, we have shown that HD 189733b is a roughly Jupiter-like planet that orbits very close to its host star.

5 References

1. https://www.aanda.org/articles/aa/abs/2005/46/aahi291/aahi291.html

2. https://arxiv.org/pdf/astro-ph/0609506

3. https://arxiv.org/pdf/astro-ph/0612224