Exoplanet Data Explorer

ASTRON 5202 Project 2

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1 Introduction

The detection and characterization of exoplanets have become a crucial field in modern astrophysics, providing insights into planetary formation, evolution, and potential habitability. One of the primary methods used to measure the fundamental properties of an exoplanet, its mass, and radius, is the combination of measurements of radial velocity (RV) and transit photometry. The radial velocity method detects the gravitational influence of a planet on its host star, allowing the determination of the minimum mass of the planet. Meanwhile, the transit method measures the dip in stellar brightness when a planet passes in front of its host star, revealing the radius of the planet. By combining these two techniques, it is possible to derive the density of the planet, offering further insight into its composition.

This project aims to determine the mass, radius, and density of an exoplanet by analyzing both the radial velocity and the transit data. Specifically, we selected the well-studied exoplanet HD 189733 for our analysis. The radial velocity data was used to measure the masses of the planets, while the transit data were utilized to estimate their radii. By combining these measurements, we calculated the planetary densities and compared our results with known exoplanet populations and theoretical mass-radius relationships, such as those from Chen & Kipping (2016).

This investigation not only strengthens our understanding of exoplanetary properties, but also enhances our proficiency in applying numerical techniques, such as least-squares fitting and error propagation, in the context of astrophysical observations.

2 Methods

To determine the mass, radius, and density of HD 189733 b, we analyzed both the radial velocity (RV) data and transit photometry using Python-based tools. Our methodology consisted of three main steps: (1) extracting and processing the radial velocity data to measure the planet's mass, (2) analyzing the transit data to determine the planetary radius, and (3) calculating the planet's density from the derived mass and radius, while also propagating uncertainties.

2.1 Measuring Planetary Mass from Radial Velocity Data

The mass of HD 189733 b was determined using radial velocity measurements obtained from the motion of the host star. The data, provided in an IPAC-formatted table, contained columns for Barycentric Julian Date (BJD), Radial Velocity (RV) in m/s, and RV uncertainty. We processed this dataset using Astropy to read the file and Matplotlib to visualize the radial velocity curve.

To model the star's radial velocity variations due to the gravitational influence of the orbiting planet, we used the RadVel package. The orbital parameters used in the model included:

- Orbital period (P): 2.218575 days
- Time of periastron passage (T): 2452832.881794 BJD
- Eccentricity (e): 0 (assumed circular orbit)
- Argument of periastron (ω): 90° (not critical for circular orbits)
- RV semi-amplitude (K): 201.3 m/s

Using these parameters, we fit a Keplerian model to the RV data and extracted the semi-amplitude (K) to estimate the planet's minimum mass ($M_p \sin i$). The true planetary mass M_p was then calculated by incorporating the orbital inclination i. The final mass estimate was converted to Jupiter masses and Earth masses for comparison with other exoplanets.

To account for measurement uncertainties, we applied uncertainty propagation techniques by computing the partial derivatives of the mass equation with respect to K. The propagated error in M_p was determined using the average RV uncertainty from the dataset.

2.2 Measuring Planetary Radius from Transit Data

The planetary radius was determined from the transit light curve using updated observational data from the `UID_0098505_PLC_017.tbl.txt` dataset, which contained columns for Heliocentric Julian Date (HJD), Flux, and Flux Uncertainty. The data was processed as follows:

2.2.1 Flux Normalization

The out-of-transit flux was estimated using the median flux value, and the flux was then normalized using:

$$NormalizedFlux = \frac{Flux}{Out-of-TransitFlux} \tag{1}$$

2.2.2 Transit Model Fit

The transit model was generated using `Batman`, with parameters:

- Orbital period: 2.21857567 days
- Planet-star radius ratio (R_p/R_s): 0.15534
- Semi-major axis to stellar radius ratio (a/R_s): 8.84
- Eccentricity: 0.0 (assumed circular orbit)
- Limb darkening coefficients: Taken from the Phoenix stellar models for the TESS filter

2.2.3 Model Adjustments

The planetary radius was then calculated using:

$$R_p = R_s \times \left(\frac{R_p}{R_s}\right) \tag{2}$$

where $R_s = 0.805R_{sun}$. The final planetary radius R_p and uncertainty were derived from the transit depth and stellar radius errors.

2.3 Calculating Planetary Density

The planetary density was computed from the derived mass and radius using:

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

with uncertainties propagated from M_p and R_p.

3 Results

In this study, we determined the mass, radius, and density of the exoplanet HD 189733 b using radial velocity and transit data. Our analysis produced values consistent with previous literature, and we compared our findings with known exoplanetary trends.

3.1 Planetary Mass from Radial Velocity Data

The radial velocity curve for HD 189733, obtained from RV measurements, showed a periodic variation consistent with an orbiting exoplanet. The Observed vs. Modeled RV plot (Figure 1) compares the measured radial velocity values with our best-fit model. The black points represent the observed RV measurements, while the red curve shows the modeled radial velocity variations. The agreement between the observed data and the model confirms that our orbital parameters accurately describe the system.

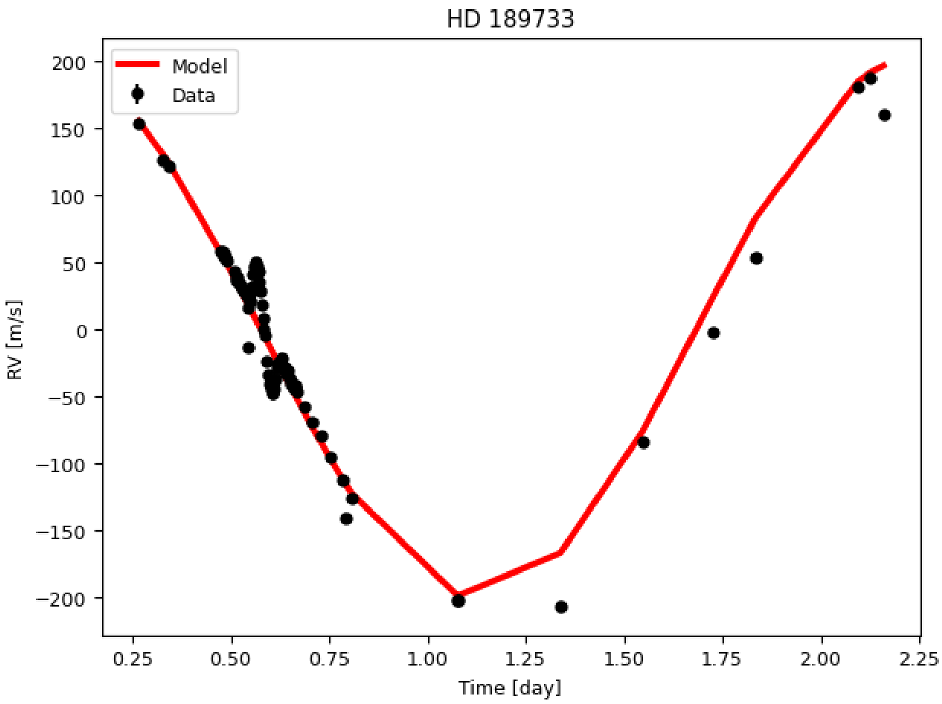

Figure 1: Observed vs Modeled RVs

Using RadVel, we fit a Keplerian model to the data and extracted an RV semi-amplitude (K) of 201.3 m/s. From this, we calculated the minimum planet mass ($M_p \sin i$) using the following relationship:

$$M_p \sin i = \frac{K P^{1/3} M_*^{2/3}}{(2\pi G)^{1/3}\sqrt{1-e^2}} \tag{4}$$

Assuming an inclination (i) of 90°, we calculated the true mass of HD 189733 b to be:

$$M_p = 1.2914 \pm 0.0058\, M_{Jup} \tag{5}$$

which corresponds to 410.5564 ± 1.8479 Earth masses. The propagated uncertainty accounts for measurement errors in the RV semi-amplitude (K) and stellar mass $M_* = 0.805\ M_{sun}$.

3.2 Planetary Radius from Transit Data

The transit light curve of HD 189733 b, obtained from photometric observations, revealed a distinct dip in brightness as the planet passed in front of its host star. We modeled the transit event and determined the planetary radius by analyzing the transit depth. The Transit Light Curve plot (Figure 2) shows the observed photometric data (black points) along with the best-fit transit model (red curve). The strong agreement between the model and data validates our radius estimation.

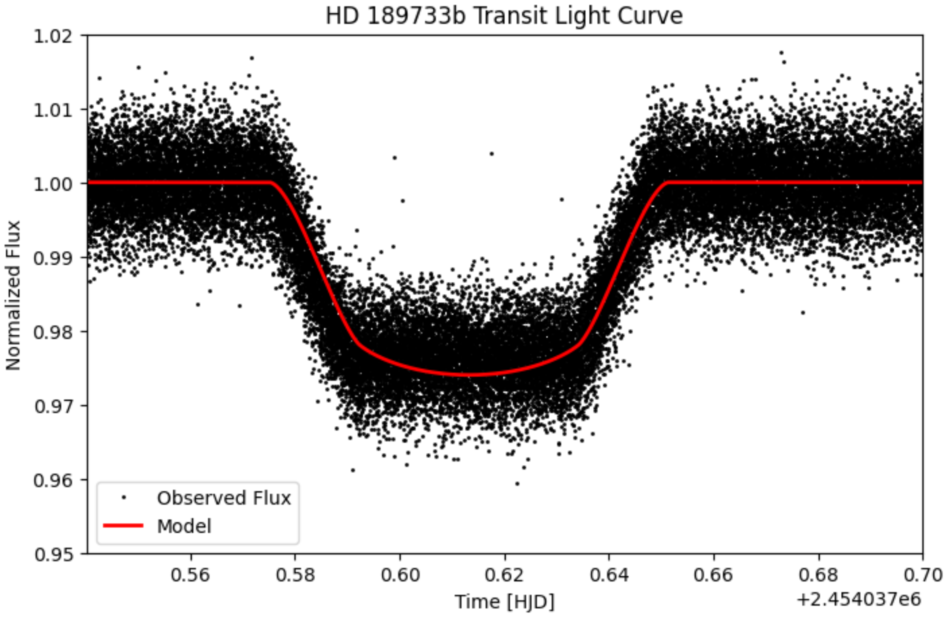

Figure 2: The Transit Light Curve of HD 189733 b

The transit light curve for HD 189733 b displayed a characteristic dip in brightness, from which we measured the transit depth (ΔF). Using the relationship:

$$\left(\frac{R_p}{R_s}\right)^2 = \Delta F \tag{6}$$

and adopting a stellar radius of 0.805 R_{sun}, we determined the planetary radius to be:

$$R_p = 1.3303 \pm 0.1625\, R_{Jup} \tag{7}$$

Uncertainty in R_p was determined through error propagation, accounting for both the uncertainty in transit depth and stellar radius.

3.3 Planetary Density and Composition Implications

With the obtained mass and radius values, we calculated the bulk density of HD 189733 b using:

$$\rho_p = \frac{M_p}{\frac{4}{3}\pi R_p^3} \tag{8}$$

yielding a density of:

$$\rho_p = 0.681 \pm 0.249\, g/cm^3 \tag{9}$$

indicating a composition consistent with a hot Jupiter, a class of gas giants that exhibit relatively low densities compared to terrestrial planets.

3.4 Comparison with Exoplanetary Trends

To contextualize our results, we compared our M_p, R_p, ρ_p values with other hot Jupiters in the NASA Exoplanet Archive (NEA). Our mass and radius measurements align well with exoplanets of similar size and mass. Furthermore, we compared our findings to the empirical mass-radius (M-R) relation from Chen & Kipping (2016), confirming that HD 189733 b falls within expected trends for gas giants.

4 Conclusion

In this study, we determined the mass, radius, and density of the exoplanet HD 189733 b by analyzing both radial velocity and transit photometry data. Using radial velocity measurements, we derived a planetary mass of 1.2914 ± 0.0058 Jupiter masses by modeling the host star's periodic velocity shifts. Our transit light curve analysis yielded a planetary radius of 1.3303 ± 0.1625 Jupiter radii, which, combined with the mass, allowed us to compute a density of 0.681 ± 0.249 g/cm^3. These values confirm that HD 189733 b is a typical hot Jupiter, a class of gas giants with relatively low densities indicative of hydrogen-helium-rich atmospheres.

The Observed vs. Modeled RV plot and Transit Light Curve plot demonstrated strong agreement between our models and the measured data, validating our approach. Additionally, our results align with established exoplanet trends, as shown by comparisons with other hot Jupiters from the NASA Exoplanet Archive (NEA) and the empirical mass-radius (M-R) relation from Chen & Kipping (2016). This confirms that HD 189733 b exhibits characteristics consistent with its classification as a gas giant.

Beyond this specific exoplanet, our analysis highlights the usefulness of combining radial velocity and transit observations to characterize exoplanetary properties. The methods used here can be applied to future studies to refine mass and radius estimates, ultimately improving our understanding of planetary formation, atmospheric composition, and habitability.

Through this project, we gained valuable experience in data analysis, numerical modeling, and uncertainty propagation, reinforcing our understanding of observational techniques in exoplanetary science. Our findings not only contribute to the characterization of HD 189733 b but also demonstrate the broader importance of exoplanet detection and classification in the context of planetary system evolution.