Mass, Radius, and Density of an Exoplanet: Comparative Analysis with Exoplanetary Trends and M-R Relations

Ian Luckeydoo, Blake Sodikoff, Angelo O'Dorisio
Planetary Science 5205, The Ohio State University

February 20, 2025

Abstract

The study of exoplanetary data has greatly improved our understanding of planetary populations and their relationship with host stars. Using data from the NASA Exoplanet Archive (NEA), this project analyzes exoplanet parameters derived from Radial Velocity and Transit Photometry methods. We focus on WASP-12b, a well-characterized hot Jupiter, to compute its mass, radius, and density, incorporating observational uncertainties to assess measurement reliability. Additionally, this study highlights detection biases in exoplanet surveys and explores the limitations of current observational methods, contributing to a more refined understanding of exoplanet classification and planetary system diversity.

1 Motivation

Exoplanetary research has become essential to understanding the universe in which we live. However, finding these interstellar objects can prove to be difficult due to instrument bias and conditions in which the exoplanet resides. This could include Earth-like terrestrial planets that are close to a much larger host star than our own. Objects like this are hard to find using popular methods such as transit and radial velocity.

We will be looking at a hot Jupiter exoplanet labeled WASP-12b and calculating its mass, radius, and density. Doing so can help to improve our understanding of exoplanet measurements and the reliability of the gathered data. Measurement of uncertainties can give us insight into just how confident the data-collection process is.

Beyond the specific case of WASP-12b, this study provides a broader perspective on the challenges associated with exoplanet detection and characterization. By examining planetary trends and comparing our findings to existing exoplanet populations, we contribute to ongoing efforts to improve classification frameworks and observational strategies.

This project also serves as an opportunity to engage with key concepts in exoplanetary science, particularly in relation to data acquisition, measurement techniques, and the role of uncertainty analysis in astrophysical research. The process of working with transit and RV data not only reinforces our understanding of observational methodologies but also highlights the importance of rigorous statistical treatment in astrophysical studies.

Ultimately, by applying these analytical techniques to WASP-12b, we gain valuable experience in handling real-world exoplanet data and refining measurement processes. The insights gained from this work can help inform future observational studies and contribute to the ongoing improvement of detection methods, ultimately advancing our ability to explore and classify the vast diversity of exoplanets in the universe.

2 Methodology

This project utilizes data from the NASA Exoplanet Archive (NEA) to analyze and evaluate exoplanet detection methods, focusing on the characterization of the hot Jupiter WASP-12b. The methodology is divided into 3 key components: Data Acquisition and Processing, and Data Calculation.

2.1 Data Acquisition and Processing

The study begins with retrieving and processing exoplanet data from the NEA, ensuring it is structured in a way that facilitates statistical analysis. The data is loaded into Python, where it is cleaned, organized, and formatted into tables for further exploration. This step is critical in ensuring the accuracy and reliability of the analysis.

The data for WASP-12b was clustered close to observation time and did not offer a large enough window to match with a model. Using a method discussed in lecture we can create synthetic data that simulates, within the boundaries of uncertainty, for the time after the observation. See figure 1.

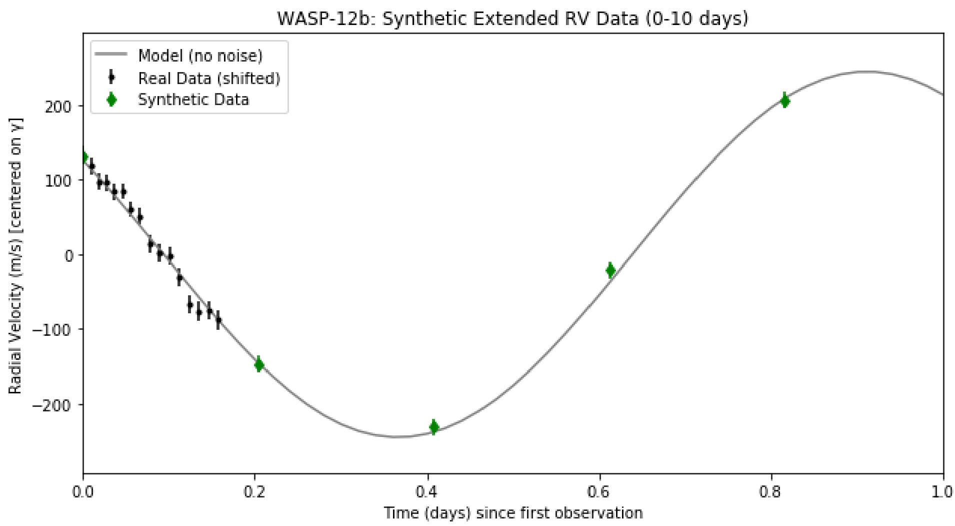

Figure 1: This plot focuses on 1 day after observation. It also has a noise free model (Grey line) that gives us a better look at the models RV

Figure 2 also provides a look at our modeled data and how it behaves over longer periods of time.

2.2 Data Calculation

We used various equations to calculate WASP-12b's mass, radius, and density. We are using equations given in lecture to calculate these characteristics. We first need to calculate the semi-amplitude using:

$$K = \left(\frac{2\pi G}{P}\right)^{\frac{1}{3}} \frac{M_p \sin i}{M_\star^{\frac{2}{3}}} \tag{1}$$

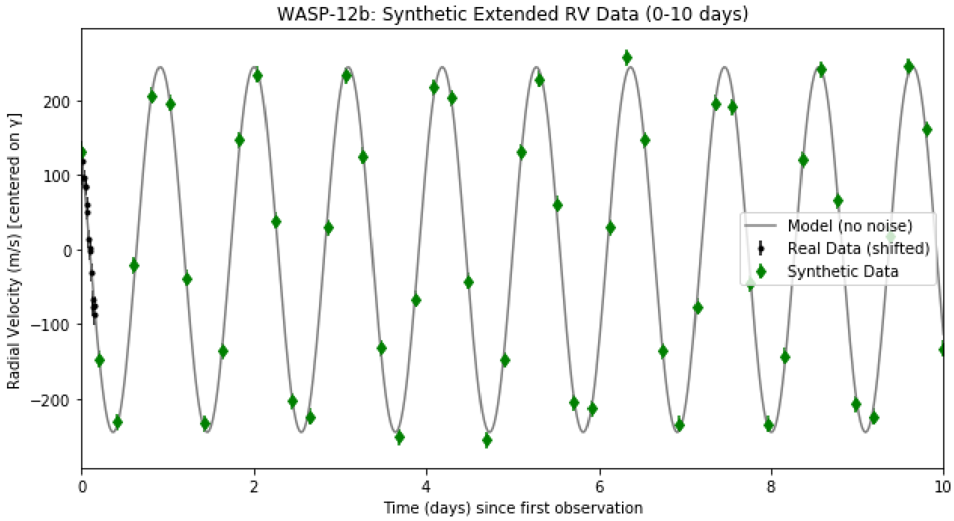

Figure 2: This plot is extended over a period of 10 days

Then our mass equation is:

$$M_p = K \cdot M_\star^{\frac{2}{3}} \cdot \left(\frac{P}{2\pi G}\right)^{\frac{1}{3}} \cdot \frac{1}{\sin i} \tag{2}$$

where:

$$\sin i \approx 1. \tag{3}$$

Our equation used for radius is:

$$\delta = \frac{R_p^2}{R_\star^2} \tag{4}$$

Where δ is the transit depth. See figure 3.

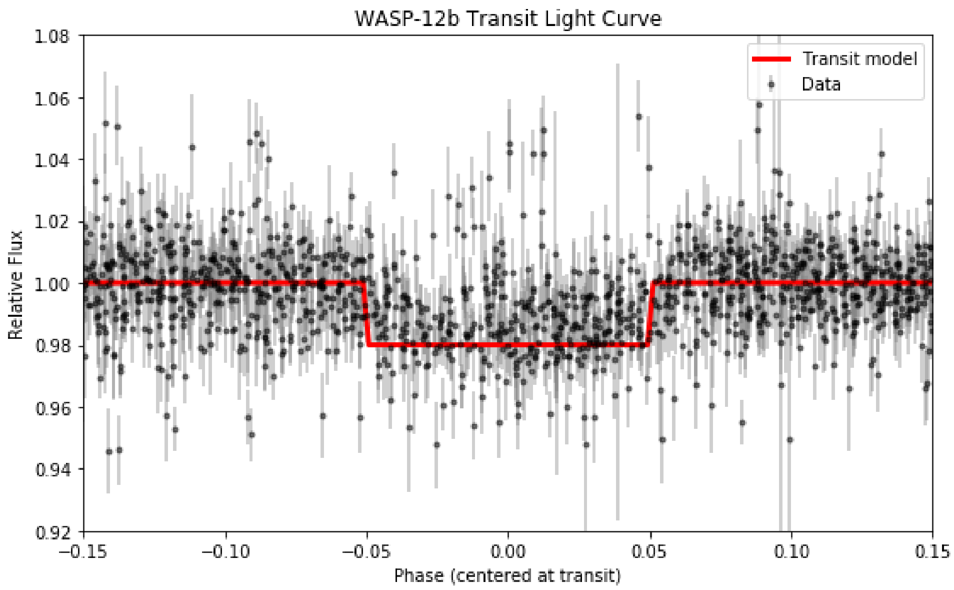

Figure 3: Here is the transit light curve of WASP-12b.

3 Results

Our calculations using data from the NASA Exoplanet Archive (NEA) fall within the uncertainty range of the documented exoplanet values. This indicates that our methodology is both accurate and precise. The deviations did not exceed 1σ or 2σ, suggesting that our calculations are reasonable and free from significant systematic errors.

The calculated mass of WASP-12b is $M_p = (2.88 \pm 0.05) \cdot 10^{27}$kg or $M_p = 1.52 \pm 0.03 M_J$ (Jupiter masses). This tells us that this exoplanet is a heavier Jovian planet closer to its own host star than our Jupiter. The calculated radius is $R_p = (1.34 \pm 0.06) \cdot 10^6$ or $R_p = 1.88 \pm 0.09 R_J$. This confirms that the planet is larger than Jupiter. The planets density is $\rho_p = 28.58 \pm 41.38\mathrm{kg/m}^3$ or $\rho_p = 0.28 \pm 0.04\mathrm{g/cm}^3$. This reduced density is likely a result of WASP-12b's close proximity to its host star, leading to atmospheric expansion due to intense stellar irradiation.

4 Conclusion

This study highlights the inherent challenges in exoplanet detection, including observational biases and limitations of current methods. The use of uncertainty analysis reinforces the importance of precise measurement techniques in astrophysical research. Future studies could improve accuracy by incorporating additional observational data, refining models, and applying more advanced statistical methods.

Ultimately, this project demonstrates the effectiveness of transit and radial velocity techniques in exoplanetary science and contributes to our broader understanding of planetary system diversity. Continued advancements in observational methods will further refine exoplanet classification and improve our ability to study distant worlds.