# Exoplanet Characterization: GJ 8999 b

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July 9, 2025

**In this question, you will estimate the mass and radius of a planet from its radial velocity and transit data. A mysterious new (and fictional) planet, GJ 8999 b, has been detected orbiting the M dwarf GJ 8999. GJ 8999 is a very small star, with a mass of $0.2\,M_\odot$ and a radius of $0.2\,R_\odot$. ($M_\odot$ and $R_\odot$ represent the mass and radius of the Sun, respectively.)**

**As the keen astronomer you are, you have been collecting transit and radial velocity data of this star to determine the mass and radius of the planet. Let's characterize GJ 8999 b.**

## 1 What is the inclination of GJ 8999 b?

Since both transit and radial velocity data are observed for GJ 8999 b, its orbit must be nearly edge-on. Hence, the inclination is:

$$\boxed{i \approx 90^\circ}$$

**New transit data from the Transiting Exoplanet Survey Satellite (TESS) has come in, and it very much looks like we have some exoplanet transits! A plot of the flux from the full 28-day observation period of TESS is shown here, as well as a plot that is zoomed into a single transit.**

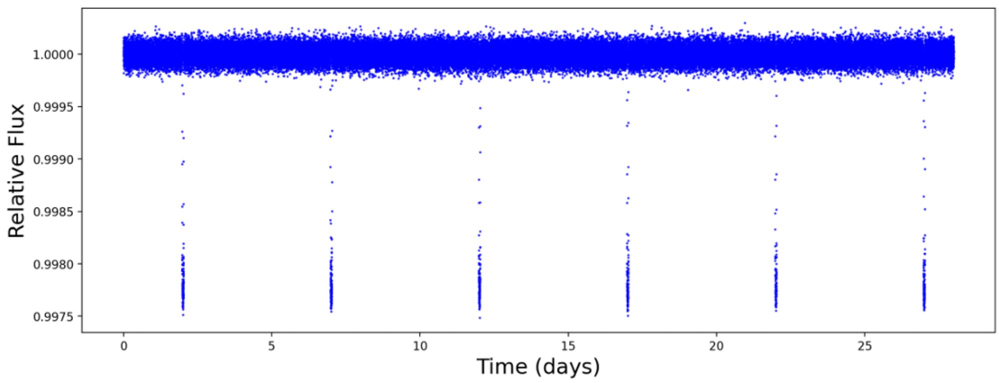


Figure 1: A plot of the flux of GJ 8999 over time over a 28-day period.

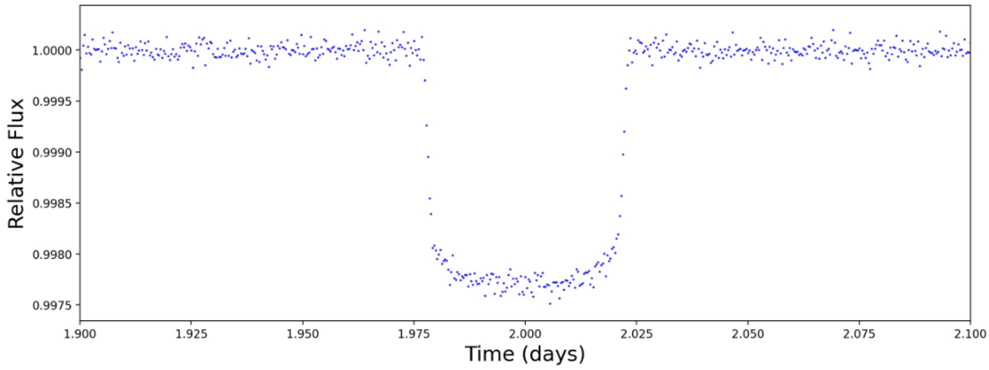


Figure 2: A plot of the flux of GJ 8999 over time, zoomed into a single exoplanet transit.

## 2 What is the period of this exoplanet?

From the TESS light curve (Figure 1), six equally spaced transits are observed over a 28-day window. The time between successive transits is approximately:

$$\boxed{P \approx 5 \text{ days}}$$

This is the orbital period of the planet.

## 3 What is the radius of this planet?

The transit depth tells us how much light the planet blocks when it passes in front of its star:

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

From Figure 2:

$$\Delta F = 1.0000 - 0.9975 = 0.0025 \Rightarrow \frac{R_p}{R_*} = \sqrt{0.0025} = 0.05$$

Given:

$$R_* = 0.2R_\odot \Rightarrow R_p = 0.05 \times 0.2R_\odot = 0.01R_\odot$$

We know that the radius of the sun is about 109 times than that of the earth, so,

$$R_p \approx 0.01 \times 109 \approx 1.09R_\oplus$$

$$\boxed{R_p \approx 1.09R_\oplus}$$

So the planet GJ 8999 b is **almost Earth-sized** in radius.

**Luckily for us, we have gotten some radial velocity data to figure out this planet's mass, too. This data, taken over a period of 30 days, measures the star's Doppler shift as it moves back and forth due to the planet's gravity.**

## 4 What is the semi-amplitude $K$ of this planetary signal?

From the RV plot (Figure 3):

- Maximum RV $\approx +2$ m/s
- Minimum RV $\approx -2$ m/s

Thus, the semi-amplitude:

$$K = \frac{\Delta V}{2} = \frac{4}{2} = \boxed{2 \text{ m/s}}$$

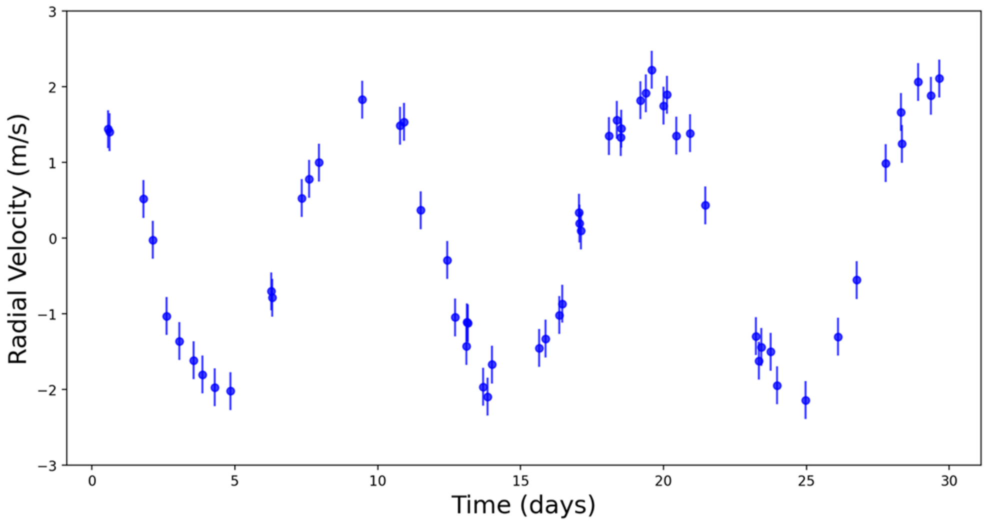


Figure 3: A plot of the radial velocity of GJ 8999 over time.

## 5 What is the mass of this planet?

We use the equation:

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

Assuming a circular orbit ($e = 0$) and $M_p \ll M_*$:

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

Solving for $M_p$, we obtain,

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

Using the values:

$$\begin{aligned} K &= 2 \text{ m/s} \\ P &= 5 \text{ days} = 432000 \text{ s} \\ M_* &= 0.2 M_\odot = 3.978 \times 10^{29} \text{ kg} \\ G &= 6.674 \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2} \\ i &= 90^\circ, \sin i = 1 \end{aligned}$$

We obtain:

$$M_p \approx 1.174 \times 10^{25} \text{ kg} \Rightarrow \boxed{M_p \approx 1.97 \ M_\oplus}$$

So, we observe that this exoplanet is **almost twice** as massive than the Earth.

**So, now that we've found the mass and radius of our planet, let's try to figure out what it's made of! The following plot shows (very rough) 'mass-radius curves' of rocky exoplanets of different compositions. A planet lying on a given curve has a mass and radius consistent with being made of the corresponding composition.**

**The five rocky planets (plus Ganymede) are all shown on the plot as well. For example, Earth lies very near the '67% rock, 33% iron' curve, and Earth's composition IS indeed about 67% rock and 33% iron.**

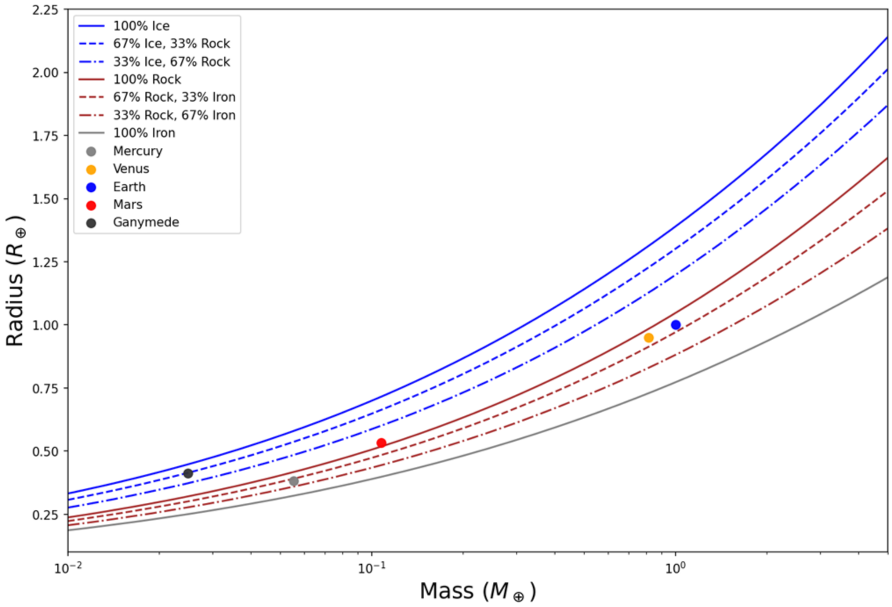


Figure 4: Mass-radius curves for different planetary compositions.

# 6 What is the composition of GJ 8999 b?

With:

$$M_p \approx 1.97\ M_\oplus, \quad R_p \approx 1.09\ R_\oplus$$

We can find out the average density of the planet relative to the Earth.

$$\rho_P = \frac{1.97}{(1.09)^3} \approx 1.52\rho_\oplus$$

So, the planet is about 1.52 times denser than Earth.

From Figure 4, we observe that the planet lies close to the curves corresponding to **"67% iron + 33% rock"**. It is denser than Earth, suggesting a more iron-rich composition, but not fully metallic like Mercury.