Question 1 – Exoplanet Characterization

In this question, you will estimate the mass and radius of a planet from its radial velocity and transit data.

A mysterious new (and fake!) planet, GJ 8999 b, has been detected orbiting the M dwarf GJ 8999. GJ 8999 is a *very* small star, with a mass of $0.2M_\odot$ and a radius of $0.2R_\odot$. (If you haven't seen those symbols before, $M_\odot$ and $R_\odot$ are the mass and radius of the Sun, respectively.)

The cunning astronomer you are, you have been measuring transit and radial velocity data of this star to figure out the planet's mass and radius of this planet, so you can publish a paper on the system! Let's characterize this planet now.

a) What is the inclination of GJ 8999 b?

The inclination of GJ 8999 b has to be approximately of **90 degrees**, i.e. ,

i ≈ 90 degrees

This is because, the planet can only transit the star if it is edge-on, i.e. , the planet passes in front of the star, thus having an inclination of **~90 degrees**.

b) 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.

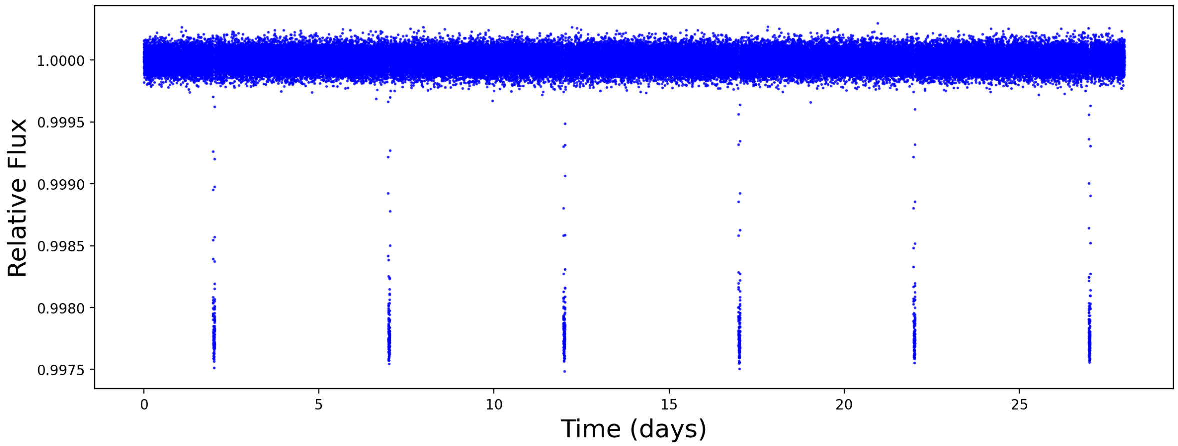

Figure 1: A plot of the flux of GJ 8999 over time over a 28-day period.

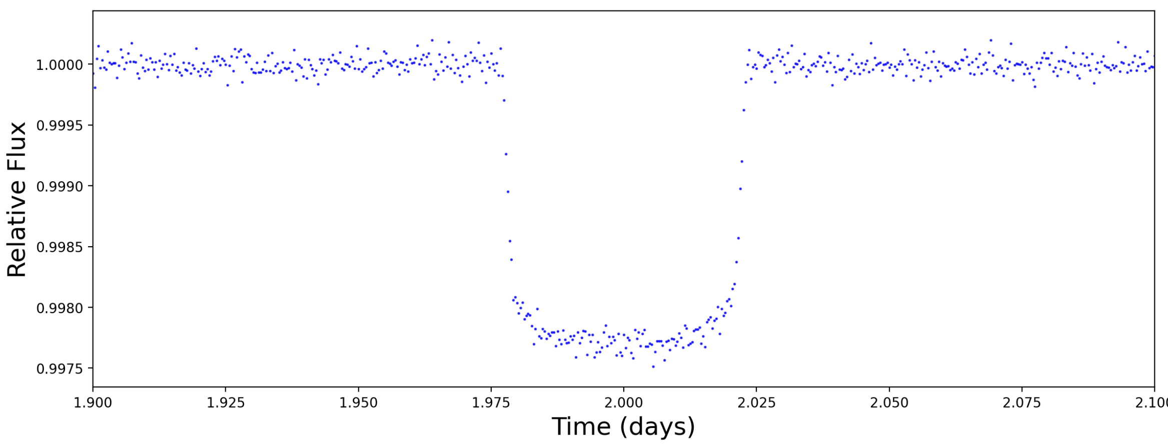

Figure 2: A plot of the flux of GJ 8999 over time, zoomed into a single exoplanet transit.

What is the period of this exoplanet?

From Figure 1, we can see that the full 28-day observation period of TESS is divided into ~6 periods.
Therefore,
The period of this exoplanet (P) is **~ 5 days**.

c) What is the radius of this planet?

The **Transit Depth** is actually a method to measure how much a star dims as a fraction of the star's brightness, i.e. , how much the star dims when the planet passes in front of the star.
It is denoted by 'Z' .

Z = (Rp / R*)^2 (Rp => Radius of the planet)
(R* => Radius of the star)

From Figure 2, we can see that

Z = 1.0000 - 0.9975 = 0.0025

Given, R* = 0.2 Ro (Ro => Radius of the Sun)

Therefore, (Rp / R*)^2 = 0.0025
=> (Rp / R*) = 0.05
=> Rp = 0.05 R* = 0.01 Ro

We know,
The Radius of the Sun is ~109 times the Radius of the Earth.

Therefore,
Rp ≈ 1.09 Re (Re => Radius of the Earth)

Therefore, the Planet has almost an equal length of radius (~ 1.09 times) as that of the Earth.

d) 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.

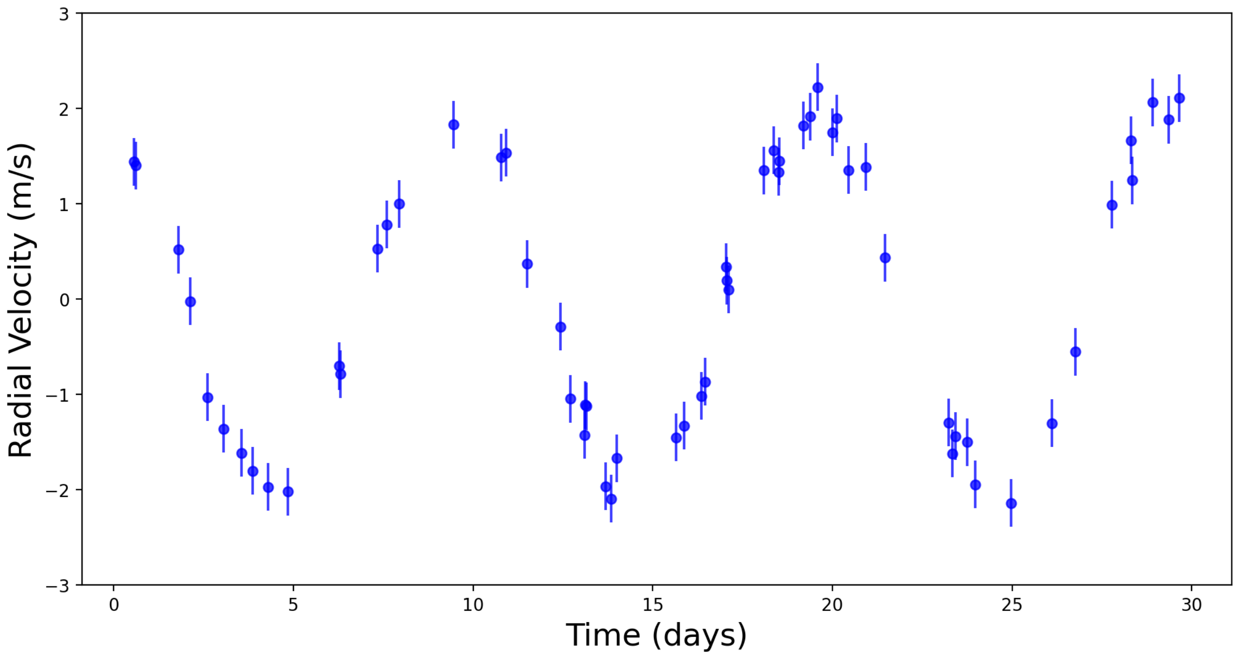

Figure 3: A plot of the radial velocity of GJ 8999 over time.

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

Semi-Amplitude (K) is actually the half the height between the crest and the trough of the Radial Velocity Curve (Figure 3).

Therefore, Crest => 2 m/s
Trough => -2 m/s

Therefore, K = (2-(-2)) / 2 = 4 / 2 = 2

Therefore, **K = 2**

e) What is the mass of this planet?

We know,

K = Mp (sin i) (((2 pi G) / (P ((M*)^2)))^(2/3))

where, Mp => Mass of the Planet
G = 6.674 x 10^11 m^3 kg^-1 s^-2
M* = 0.2 Mo = 3.978 x 10^29 kg (Mo => Mass of the Sun)
i = 90 degrees
P = 5 days = 432000 s
K = 2 m/s

By solving this Equation, we get

Mp ≈ 1.174 x 10^25 kg
=> Mp ≈ 1.97 Me (Me => Mass of the Earth)

Therefore, Mass of the Planet is almost twice (~1.97 times) as that of the Earth.

f) 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.

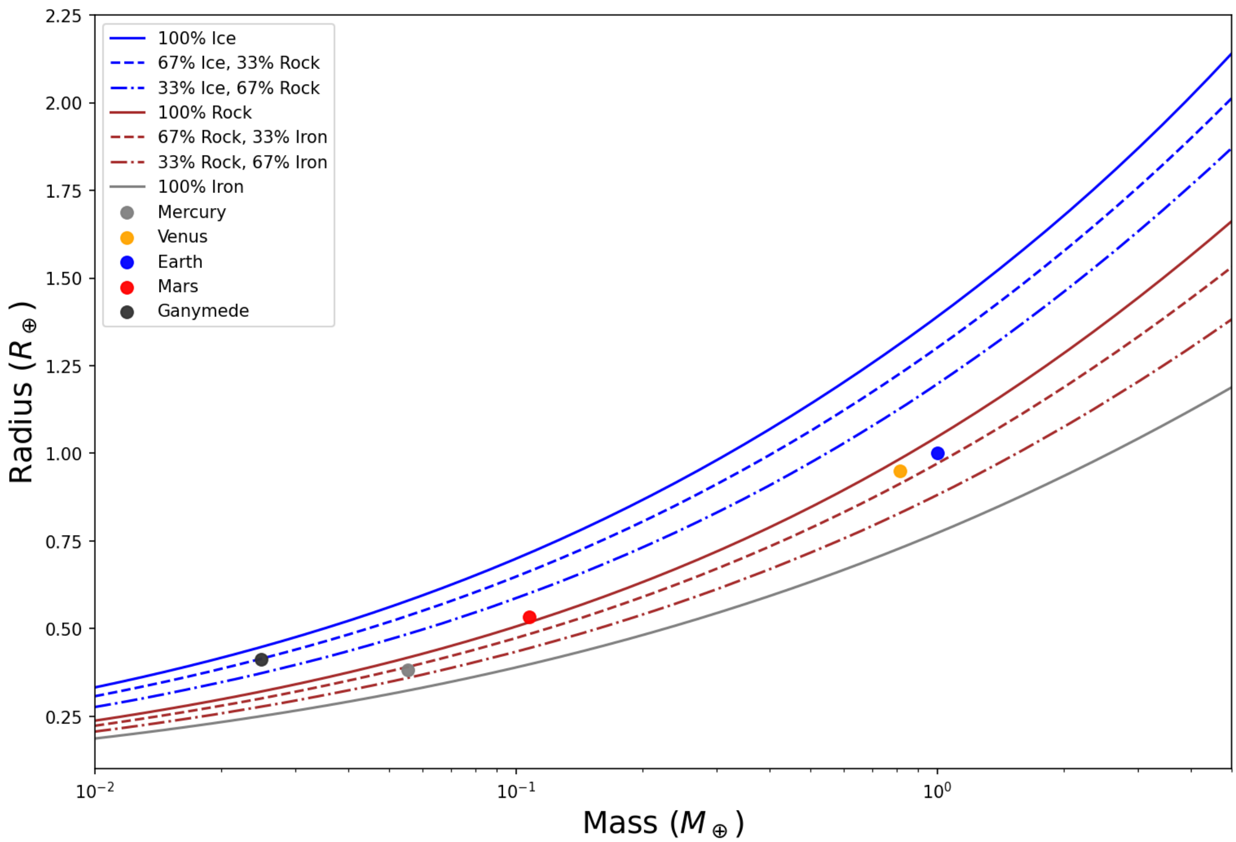

Figure 4: A plot showing the mass-radius curves for different exoplanet compositions.

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.

With this in mind, what is the composition of GJ 8999 b?

We know, Mp ≈ 1.97 Me & Rp ≈ 1.09 Re

Therefore, we can see that the planet is ~ 1.97/((1.09)^3) times denser than Earth, i.e. , **~1.52 times denser than Earth**.
From Figure 4, we can see that the planet is close to the curve "33% Rock, 67% iron" and the planet is ~1.52 times denser than Earth. This suggests that the planet has a **more iron-rich composition, but not fully metallic**.