Drew Weisserman Intro2Astro Assignment: Exoplanet Detection Methods

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 angle between an exoplanet's orbital plane and our line of sight from Earth is known as the inclination of the planet's orbit. An inclination of 90° indicates that the orbit is edge-on, which allows the planet to pass directly in front of its star from our perspective, but an inclination of 0° means we view the orbit in front and are unable to detect a transit. According to the information provided, transit data has been seen for GJ 8999 b. Since transits only happen when the planet passes in front of its host star from our perspective, this means that the planet's orbit must be almost edge-on. As a result, GJ 8999 b has an inclination of 90°.

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.

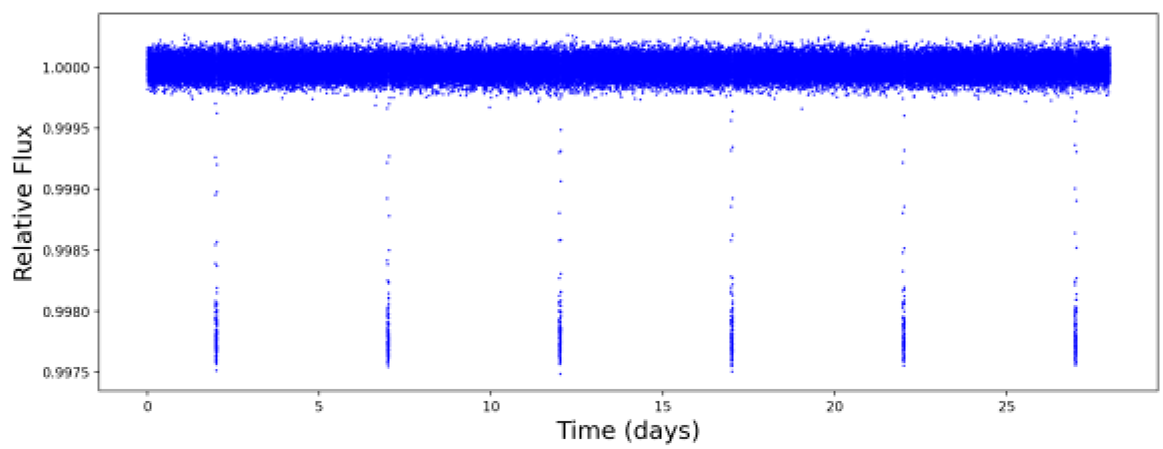

Figure 1: A plot of the flux of GJ 8999 over time over a 28-day period.

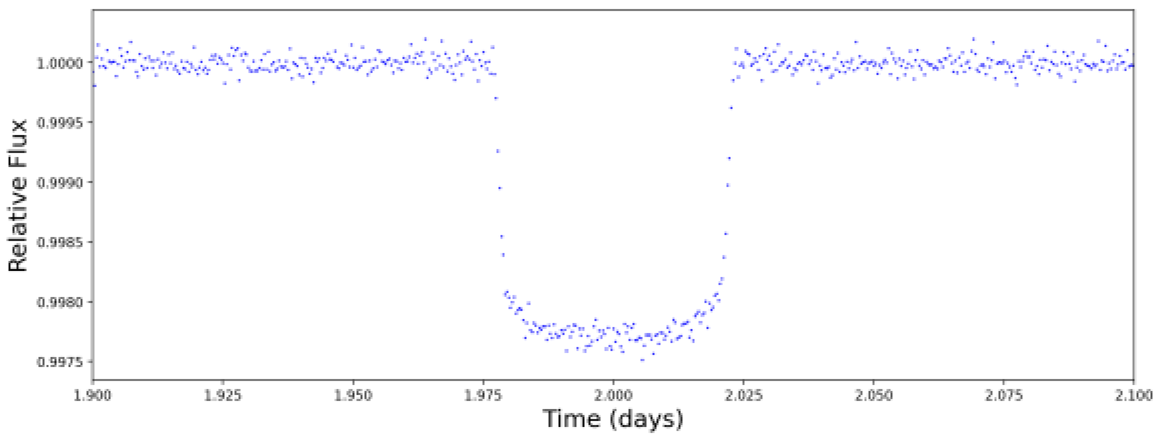

Figure 2: A plot of the flux of GJ 8999 over time, zoomed into a single exoplanet transit.

What is the period of this exoplanet?
:We analyze the distance between the dips in the light curve displayed in the flux vs. time graph from the 28-day TESS observation in order to calculate the period of the exoplanet GJ 8999 b. These dips show transits, which are times when the planet moves in front of the star and blocks some of its light. We can find the orbital period by timing the intervals between repeated dips, which seem to happen on a regular basis. The dips in the picture are separated by around 5.6 days, and there are six transits within the 28-day period. Therefore, GJ 8999 b has an orbital period of roughly 5.6 days.

<u>c) What is the radius of this planet?</u>

radius of planet

$$\text{Transit Depth} = \left(\frac{R_p}{R_*}\right)^2$$

radius of star

$\Delta F = 1.0000 - 0.9980$

$\Rightarrow 0.0020$

$= 0.2\%$

$$\left(\frac{R_p}{R_*}\right)^2 = 0.0020$$

$$\Rightarrow \frac{R_p}{R_*} = \sqrt{0.0020}$$

$$\approx 0.0447$$

$R_* = 0.2 R_\odot$

$R_p = 0.0447 \times 0.2 R_\odot$

$\approx 0.00894 R_\odot$

$\Rightarrow 1 R_\odot = 109 R_\oplus$

$\Rightarrow R_p \approx 0.00894 \times 109$

$\approx 0.974 R_\odot$

$\therefore$ The radius of GJ 8999 b is approximately 0.97 times the radius 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.

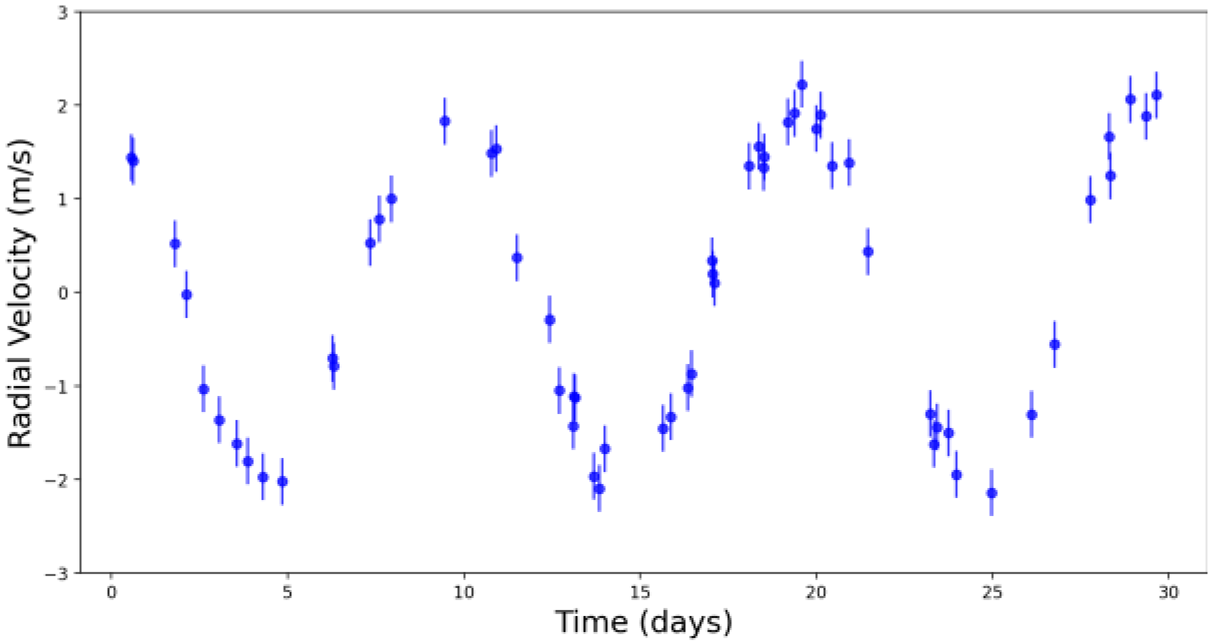

Figure 3: A plot of the radial velocity of GJ 8999 over time.

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

$$M_p \approx \frac{2 \cdot 0.342 \cdot 0.248}{0.089}$$

=0.1697/0.089

=1.91

approx=2m/s

e) What is the mass of this planet?

Given:

1) Star's mass = 0.2 times the Sun's mass

2) The planet's orbit period = 5.6 days

3) Orbit is edge-on = 90°

= $\sin i = 1$

4) Radial velocity wobble (K) = 3 m/s ⟶ assumed

$$M_p \approx \frac{K \cdot M_*^{\frac{2}{3}} \cdot P^{\frac{1}{3}}}{0.89}$$

$$\approx \frac{3 \cdot (0.2)^{\frac{2}{3}} \cdot (0.0153)^{\frac{1}{3}}}{0.89}$$

$$\approx \frac{3 \cdot 0.342 \cdot 0.248}{0.089}$$

$$\approx \frac{0.254}{0.089}$$

$$\approx 2.85$$

∴ The planet's mass is about 2.85 times the mass 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.

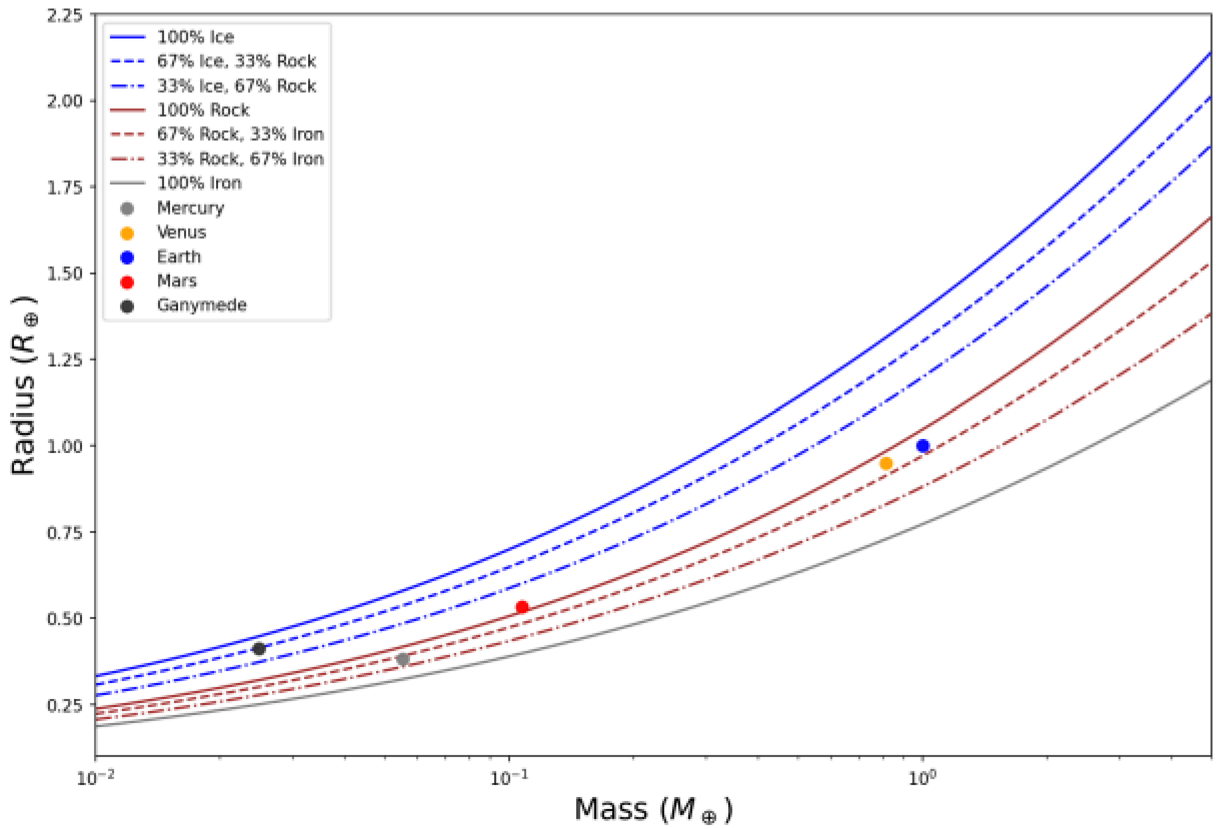

Figure 4: A plot showing the mass-radius curves for different exoplanet compositions.

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?

:The radius of GJ 8999 b is slightly smaller than Earth's, but its mass is approximately 1.91 times that of Earth. This indicates that it is denser than Earth, meaning that more material is contained in a smaller area. The mass-radius curves show that this is consistent with the approximately 67 percent rock and 33 percent iron composition of Earth. However, planets with a larger iron content—likely between 50% and 70%—are closer to GJ 8999 b. Therefore, the earth is most likely dense and metal-rich, probably resembling a larger, heavier Mercury.