Build-a-Planet

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1. Introduction

Terrestrial planets in our solar system are differentiated into three layers. The first layer is a dense, metallic core composed mainly of iron, the second layer is a rocky mantle and crust made from silicate, and the last layer is a volatile envelope of gases and ice. On Earth, scientists can understand the planet's interior by studying seismic waves. On exoplanets, it is not possible to obtain these measurements. However, ExoPlex allows its user to model a rocky planet with a core, lower and upper mantle, and water/ice layer by inputting the composition of the host start as well as the mass and radius of a planet. Therefore, in this project we will build a planet and calculate its possible density and structure. Moreover, we will calculate the planet's mass-proportions and compare them to stellar composition. Lastly, we will analyze how our planet compares to Earth. We selected exoplanet GJ 1132b to model its internal structure based on the previously mentioned calculations.

2. Methods

Planet GJ 1132b orbits the red dwarf star Gliese 1132. Its orbit is approximately 1.6 days, and because of its proximity to its parent star, the surface temperature is approximately 505 °C. Previous calculations have revealed that the planet is likely to be rocky (Schaefer et al., 2016). Because stars and planets form from the same disk, understanding the composition of a star through its spectra provides insight to the composition of the planets in the system. Therefore, the first task to determine the Si/Mg and Fe/Mg ratios of GJ 1132b is to determine the metallicity of its host star.

2.1 Composition of the planet's host star

Gliese 1132 has an iron abundance of [Fe/H] = -0.12 and magnesium abundance [Mg/H] = 0.13 (Griffith et al. 2021). Moreover, the $(Mg/Fe)_{sun}$ is equal to 1.148. To convert from the star's metallicity to ratios predicting the composition of GJ 1132b, we use the following equation from (Griffith et al., 2021):

$$[X/Mg] \;=\; \alpha_{cc}[Mg/H] + \log\left[\frac{1 + R_{Ia}^{X}(A_{Ia}/A_{cc})10^{(\alpha_{Ia}-\alpha_{cc})[Mg/H]}}{1 + R_{Ia}^{X}}\right]$$

where

$$\frac{A_{Ia}}{A_{cc}} = 10^{0.3-[Mg/Fe]} - 1$$

and the refractory ratios for silicate and iron are Si/Mg = 0.8585 and Fe/Mg = 0.6453.

2.2 Expected Range of Radius & Density

We ran ExoPlex with the refractory composition ratios (obtained in Section 2.1) while keeping all other materials at their default (Earth-like) values. Additionally, we used the accepted mass Mp = 1.64 ME (Southworth et al., 2017). This yielded an expected radius of 1.159RE, which is in good agreement with the accepted radius Rp = 1.130 ± 0.056 $R_{\oplus}$. Therefore, we can conclude that we have estimated a reasonable composition to model the planet's interior structure. Furthermore, we can confirm this estimate by comparing our values for GJ 1132b to similar planets.

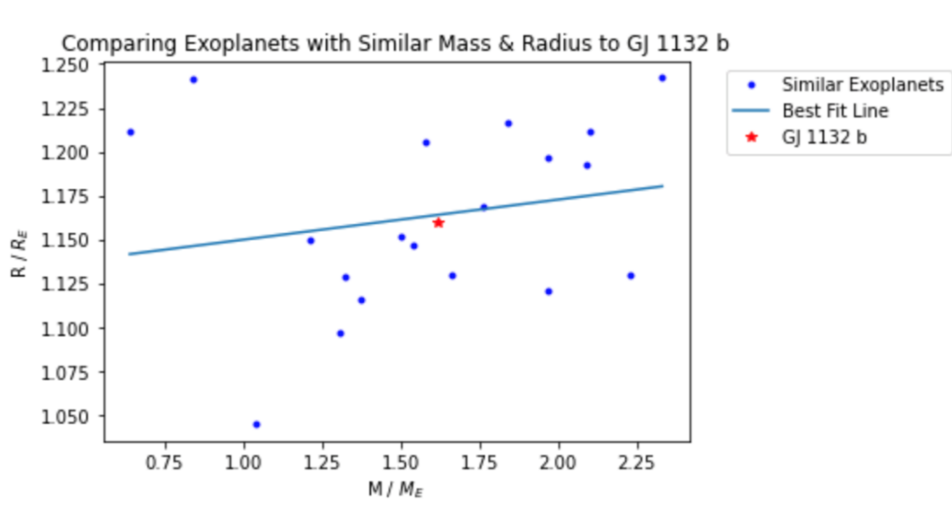

Figure 1. M-R Relationship for exoplanets similar to GJ 1132 b.

Here, we have plotted exoplanets like GJ 1132 b, whose radii are within 10% of our calculated radius. We see that our values appear to be in good agreement with other rocky exoplanets, and that it closely follows the best fit trend for this population. Furthermore, our radius follows the power law relationship between mass and radius for terrestrial planets defined in Chen & Kipping et al. (2016), where R ~ $M^{0.28}$. This would produce an estimate of 1.15 $R_\oplus$, which is less than a 1% error from our calculated radius.

2.3 Atmospheric Retention of GJ 1132 b

After obtaining the planet's radius, from its accepted mass, we can calculate its escape velocity using:

$$v_e = \sqrt{\frac{2GM_p}{R_p}}$$

which gives a value around v_e= 12 km/s. Based on this value and the planet's surface temperature, we can assume that the planet could retain an atmosphere composed of water or methane; however, due to its semi-major axis, the atmosphere was almost certainly irradiated away by the host star. There may be some sort of atmosphere, possibly due to volcanic activity, but the original atmosphere is no longer present.

3. Results

After running ExoPlex with the accepted mass value, we wanted to investigate how the expected radius and density would change based on the uncertainty in this measurement. We ran the upper and lower bounds for the mass from Southworth et al. (2017) in ExoPlex and obtained the following results:

Mass ($M_\oplus$)	**Radius ($R_\oplus$)**	**Density (g/cm^3)**
1.64 (expected)	1.16	5.74
1.11 (lower limit)	1.04	5.31
2.17 (break limit)	1.17	5.68

Table 1. Upper and lower bounds from Southworth et al. (2017).

The density is calculated assuming a solid sphere, where

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

We see that using the expected radius produces the highest density, with fall off at either extremum. Note that we had difficulty running ExoPlex at the upper limit, likely due to our high silicate fraction, which should be calculated more carefully next time. Instead, the last line in the table shows the values obtained at the highest mass that ExoPlex would run with our other inputs. After examining the variation in size and density of the planet, we wanted to compare the composition of the model for GJ 1132b to that of Earth.

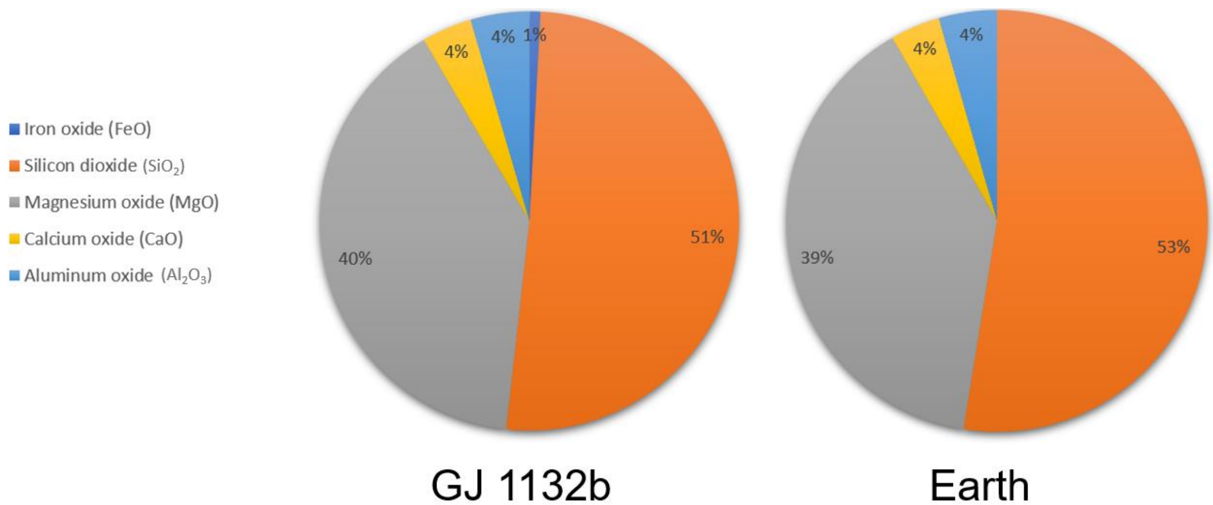

Figure 2: Mineralogy of the mantles for our model of GJ 1132b and Earth.

The composition of the mantle is quite like that of Earth's; however, it should be noted that GJ 1132b contains iron in its mantle while the ExoPlex Earth has none. This is yet another explanation for why the overall density is higher than that of Earth's.

4. Conclusions

We conclude that in our construction of the planet GJ 1132b, the expected value for the radius, mass, and density are as follows: Rp = 1.159 Re, Mp = 1.62 Me, and rho_p = 5.737 g/cm^3. However, if we account for a potential atmosphere due to volcanism, the radius "puffs up" slightly to Rp = 1.169 Re and the density decreases due to the less dense elements in the atmosphere to rho_p = 5.591 g/cm^3. Using Exoplex we determine that the likely refractory composition for GJ 1132b is Si/Mg = 0.86 and Fe/Mg = 0.65. Additionally, we note that Exoplex does not run for the upper limit of the mass due to the high silicate fraction and lack of data for planets with these compositions. GJ 1132b has a similar composition to Earth except for iron in the mantle, which accounts for its higher density.

Contributions

Alex calculated the refractory composition ratios described in Section 2.1, produced the plot for Figure 1, and helped with the PowerPoint. Yuanhao ran ExoPlex and helped interpret the results. Mariana created the charts in Figure 2, interpreted the mineralogy, and helped with the PowerPoint written report. Ashley helped with the written report and the PowerPoint. Missie helped with the report.

References

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