Build-a-Planet

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1 Introduction and Motivation

Rocky exoplanets, like the planets in our own solar system, have unique chemical compositions. Discovering the composition of exoplanets is an interesting section of astronomy research, as it allows us to compare them to our home planets. After all, one of the greatest endeavors in this field is finding a planet similar to Earth.

2 Methods

We looked at the exoplanet Trappist-1e, which we believed to be rocky, as it has a radius similar to Earth's [1]. Its data was taken from the NASA Exoplanet Archive. ExoPlex, an academic software, was then used to calculate Trappist-1e's possible structure. Knowing the mass and radius only allows for the calculation of the planet's average density, but with the knowledge of the host star's composition (and by making reasonable assumptions), we could postulate Trappist-1e's structure. We were given several different tasks that eventually lead us to the results, all of which were done by Sam and Matt and are explained below.

2.1 Molar Ratios

In order to use Exoplex, we need to input the planet's mass and some of the molar ratios of its host star. We have Trappist-1e's mass from the exoplanet archive, but we need to calculate the molar ratios Si/Mg and Fe/Mg. The way that this was done was by first finding that [Fe/H]=0.0535 ± 0.088 [2]. Then, Figure 3 from Griffith et al. [3] was used to scale [Fe/H] to [Mg/Si] and [Fe/Mg]. Next, X/H, the log abundance between an element and Hydrogen was calculated using the following equation, from Lodders [4]:

$$A = 12 + log\frac{X}{H} \tag{1}$$

where A is the solar abundance of these elements. This was done for Fe, Mg, and Si. Finally, we had to convert these abundances to molar ratios:

$$\frac{X}{H} = 10^{X/H}(\frac{X}{H})\odot \tag{2}$$

However (2) gives us the mole ratios relative to Hydrogen, but as stated before, we wanted Si/Mg and Fe/Mg. So lastly, we found these ratios with some simple division.

$$\frac{Fe}{Mg} = \frac{\frac{Fe}{H}}{\frac{Mg}{H}} \tag{3}$$

$$\frac{Si}{Mg} = \frac{\frac{Si}{H}}{\frac{Mg}{H}} \tag{4}$$

2.2 Putting Trappist-1e into Context

The next task was to place Trappist-1e's size and orbital distance in the context of a rocky planet and its surface irradiation. The way size and orbital distance were investigated was by plotting the exoplanet archive data with Trappist-1e's data. Then, the solar irradiance was calculated using

$$SI = \frac{L}{4\pi a^2} \tag{5}$$

2.3 Radius and Density

Using the likely refractory composition of the host star, along with its mass from the exoplanet archive, we can estimate the radius and density of Trappist-1e. The way this was done was by using ExoPlex and changing the parameters to get results that match Trappist-1e's exoplanet archive radius.

2.4 Range of Structure

Then, still through ExoPlex, we found a structure model that explains both the mass and radius of Trappist-1e. This was done by adjusting the mantle FeO, the core mass fraction (through FeMg), and the core composition. Several assumptions were made, which include that Trappist-1e has no oceans and that its atmosphere is negligible.

2.5 Mantle Mineralogy

Finally, we wanted to compare Trappist-1e's mantle mineralogy to Earth's. This was another output given when answering the previous questions with ExoPlex's help.

3 Results

It was first found that Trappist-1e had molar ratios of 0.79 for Fe/Mg and 0.89 for Si/Mg (To reproduce the correct radius, a ratio of 0.56 for Fe/Mg was inputted into ExoPlex instead). When comparing Trappist-1e to other exoplanets, we see the following:

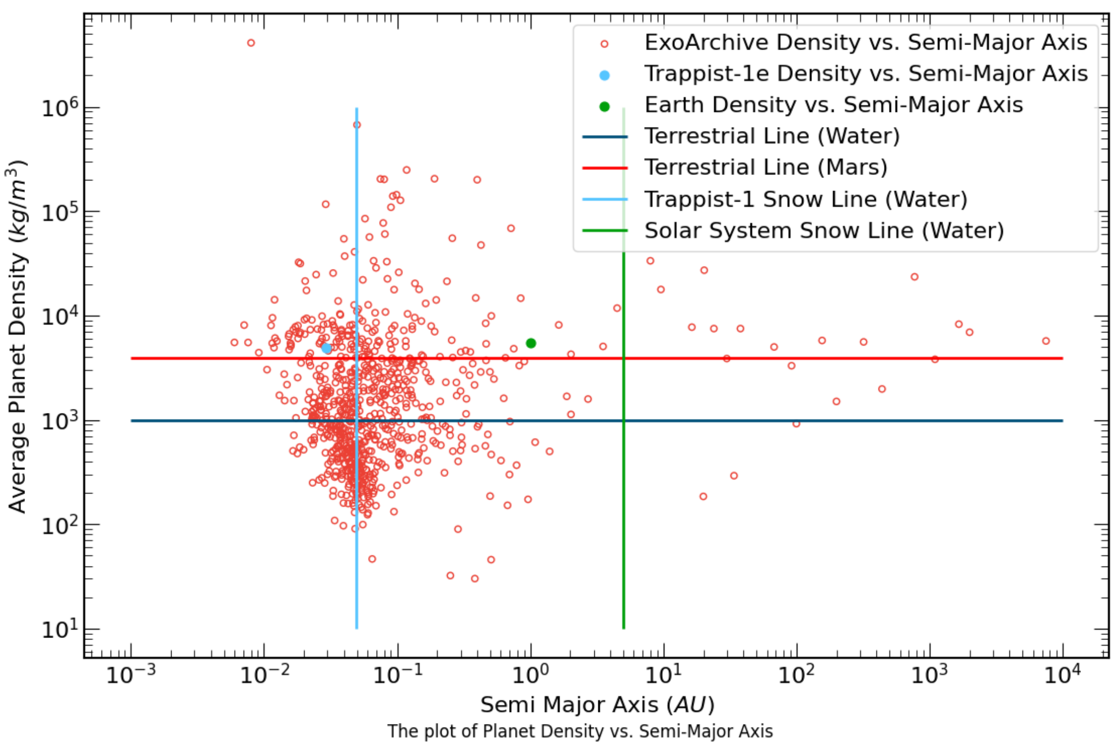

Figure 1: Plot of average density vs semimajor axis of exoplanets compared to Trappist-1e.

The "Terrestrial Line (Water)" is placed at $1000 kg/m^3$, the density of water. Typically, anything less dense is assumed to be gaseous, but that is a generalization – several of the "Gas Giants" in our solar system are denser than water, and they are far from what we might mean by "terrestrial." Therefore, we assume Mars has the minimum average density required to have a solid surface and plot that line as the Mars Terrestrial Line. Its surface irradiation was found to be $883.9 W/m^2$.

ExoPlex returned a radius of 0.920 $\pm$ 0.012 R_E, a mass of 0.692 $\pm$ 0.022 M_E, and a semimajor axis of 0.02925 $\pm$ 0.012 AU – slightly different compared to the values in the exoplanet archive, as shown in Fig 2.

Also from ExoPlex, we were given lots of information relating to the mantle composition and structure model of Trappist-1e. The model that explains both the mass and radius was found to be the structure shown in Fig 3.

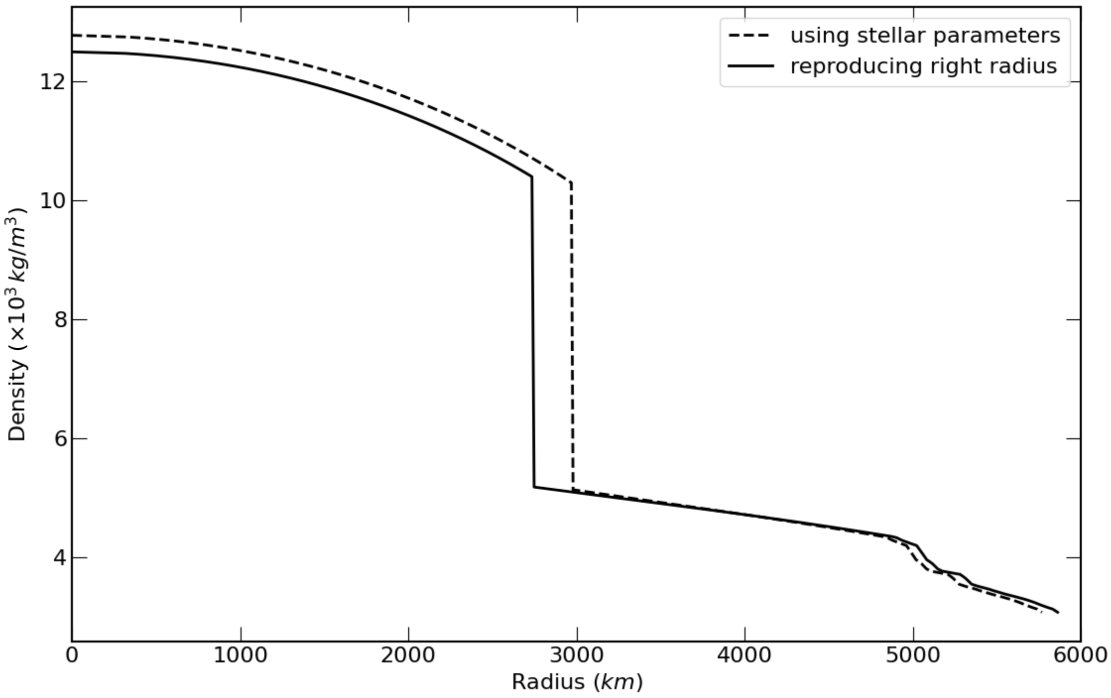

Figure 2: Plot of density vs radius for Trappist-1e using both the numbers we calculated and our known data.

	Earth	Trappist-1e
FeO	8.05	0.0
SiO_2	45.0	52.28
MgO	37.8	39.40
CaO	3.55	3.84
Al_2O_3	4.45	4.49

Table 1: Structure determined for Trappist-1e along with Earth's.

A bar graph was made to help us visualize how the structure composition of Trappist-1e compares to Earth, shown in Table 1.

Earth's mantle composition was found via [5].

4 Conclusion

Trappist-1e is closer to its host star than Earth is to the sun, and it is also slightly less dense at $4.883g/cm^3$ – not too different than the Earth's average density of $5.51g/cm^3$. So, Trappist-1e is clearly terrestrial with all the assumptions that have been made. Its surface irradiation, $883.9W/m^2$, is similar to the solar irradiation received by the Earth at $1367.5W/m^2$. This seems to indicate that the surface temperature of Trappist-1e is similar to that of the Earth, and may indicate that liquid water could be present on its surface.

The radius result calculated with the stellar parameters wasn't too different from the exoplanet archive radius, as shown in Fig 2. Given the uncertainties in mass, this is a reasonable result.

As for the mantle composition, Fig 3. shows the difference in Earth and our exoplanet's values. The core mass fraction (CMF) is the ratio of the core's mass to the total mass of the planet. Earth has a CMF of 32.5 percent, and, as we can see from the ExoPlex output, Trappist-1e has a CMF of around 23.6 percent. We have assumed that the core of Trappist-1e is pure iron, as this is the densest element the core of an exoplanet could be assumed to have. In reality, it is probably mostly iron but includes a small but not insignificant percentage of other lighter elements. That

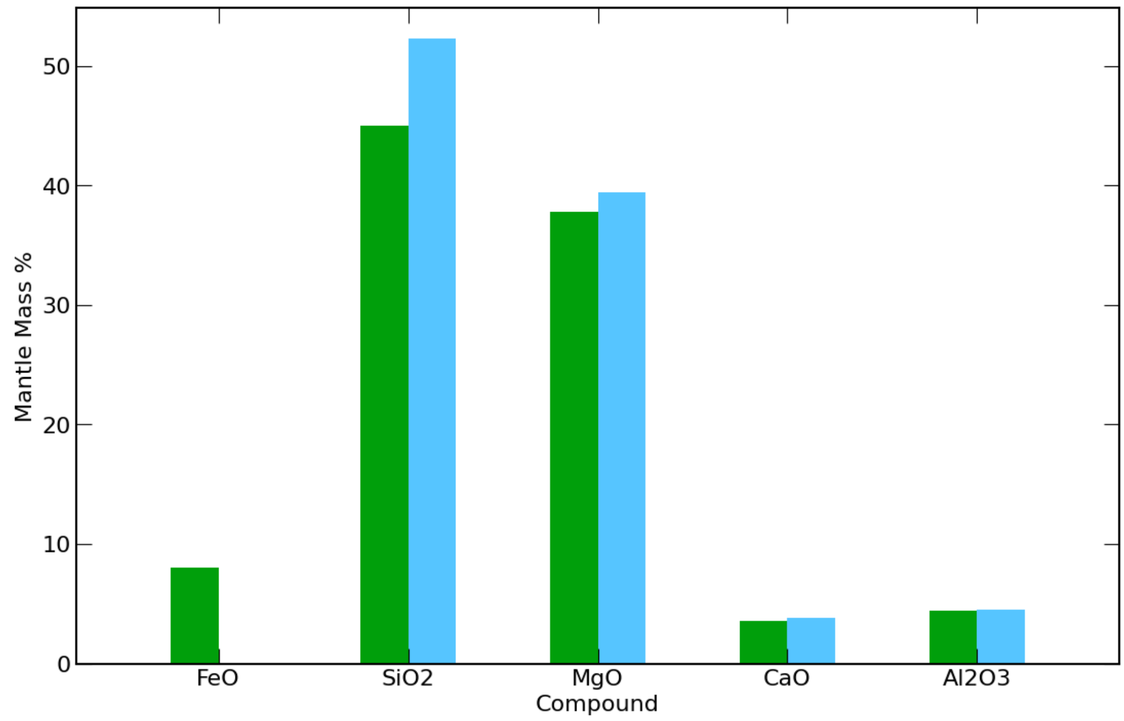

Figure 3: Trappist-1e's structure compared to Earth's. The green bars represent Earth data.

being said, Trappist-1e certainly has a less massive core relative to its total mass.

Thus, we can conclude that Trappist-1e is a rocky planet very similar to Earth in its composition, structure, and temperature.

5 References

[1] Fulton et al, 2017, A Gap in the Radius Distribution of Small Planets
[2] Ducrot et al, 2020, TRAPPIST-1: Global results of the Spitzer Exploration Science Program Red Worlds
[3] Griffith et al, 2021, The Similarity of Abundance Ratio Trends and Nucleosynthetic Patterns in the Milky Way Disk and Bulge
[4] Lodders, K. 2020, Solar Elemental Abundances, The Oxford Research Encyclopedia of Planetary Science
[5] McDonough, W.F. 1995, The Composition of the Earth