Project 4: Building GJ 1132 b

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Section 1: Introduction and Motivation

GJ 1132 is an M dwarf star located 12 parsecs from our Sun [1]. M dwarf stars are considered useful targets for studying Earth-like exoplanets due to their size and temperature [2], however our current methods of detecting exoplanets (such as radial velocity, transit timing, and astrometry) tell us only the planet's mass and radius, and little about its internal composition. It is possible to use spectroscopy to discover the makeup of a planetary atmosphere, but to explore the interior of the rocky planet itself, other methods are needed.

The goal of this project is to model the chemical composition of the interior of planet GJ 1132 b, based on its known mass, and to compare its chemical makeup with the interior of the Earth. In this way, we can hope to make some comment on its habitability, and whether it resembles Earth in more ways than just its size. This planet was selected as a useful case study as both its mass and radius are known.

Section 2: Methods

The NASA Exoplanet Archive (NEA) is a database with information on thousands of exoplanets outside our solar system. Using this database, we confirm that GJ 1132 b has a known mass of $1.66 \pm 0.23\ M_E$, and a radius of $1.130 \pm 0.056\ R_E$ based on a recent study of the planet [3]. Given these values, if we model our planet as a homogeneous sphere:

$$\rho = \frac{3M}{4\pi R^3}$$

we calculate a bulk density of 6.321 g/cm^3, which is similar enough to the bulk density of Earth (5.513 g/cm^3) that we can call it a reasonable estimate [4].

Our goal is to make predictions regarding the chemical makeup of this planet's interior. To do this, we first need to know the elemental abundances of its host star. Elemental abundances are typically calculated in one of three different ways:

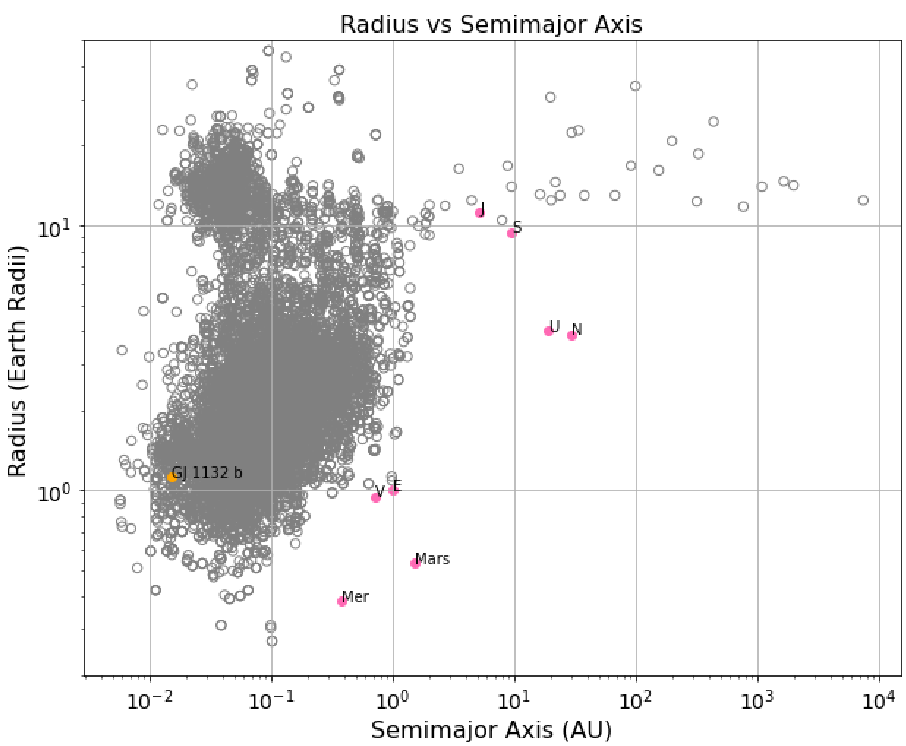
Mol ratio between elements	Log of mol ratio with offset	Stellar metallicity ratio
N_1/N_2	$12 + \log(N_1/N_2)$	$\log[(N_1/N_2)_*/(N_1/N_2)_\odot]$

Table 1: Methods of calculating chemical abundance in stars

Berta-Thompson et al. (2015) provides an abundance value for [Fe/H] of -0.12 ± 0.15, meaning that GJ 1132 has a fairly similar iron content to our Sun. Given this similarity and its relative proximity to our host star, we can assume that much like our Sun, GJ 1132 has abundances of Fe, Si, and Mg which are nearly equal to one another. Using this assumption, Table 1 in Griffith et al. (2021) shows that an [Mg/H] metallicity of -0.14 (the value closest to -0.12) gives an expected [Si/Mg] value of -0.036 and an expected [Fe\Mg] of 0.040. [5]

Knowing that the log molar ratios of Mg, Si, and Fe in the Sun are 7.54, 7.52, and 7.48 respectively [6], we use the equations in **Table 1** above to calculate a molar ratio of 0.9311 for Fe/Mg, and a molar ratio of 0.8790 for Si/Mg. We assume that chemical abundances for the star are equal to the chemical abundances of the planet, given that planets and stars form out of the same protostellar cloud.

So far we are also assuming that GJ 1132 is terrestrial, but we need to verify this before we go further. NEA data provides an orbital distance for the planet of 0.0153 AU. Plotting the radius and orbital semi-major axis of GJ 1132 b against other planets in the NEA database, we can see that its characteristics are consistent with those of other terrestrial planets. While it's considerably closer to its star than planets in our own solar system, its radius is similar to Earth and Venus:



It has also been observed that planets below 1.6 R_E are predominantly rocky [7], and we've already shown that its density is similar to Earth, so we can be reasonably certain that our planet is terrestrial in structure.

Having confirmed the planet's structure, we can now use the code package ExoPlex to explore its core and mantle composition. Entering the values for Fe/H, Si/Mg, and Fe/Mg which we calculated above, as well as the mass of the planet from literature, ExoPlex provides an expected radius for the planet, elemental abundances for the core and mantle, and the mass/radius fractions of the core itself.

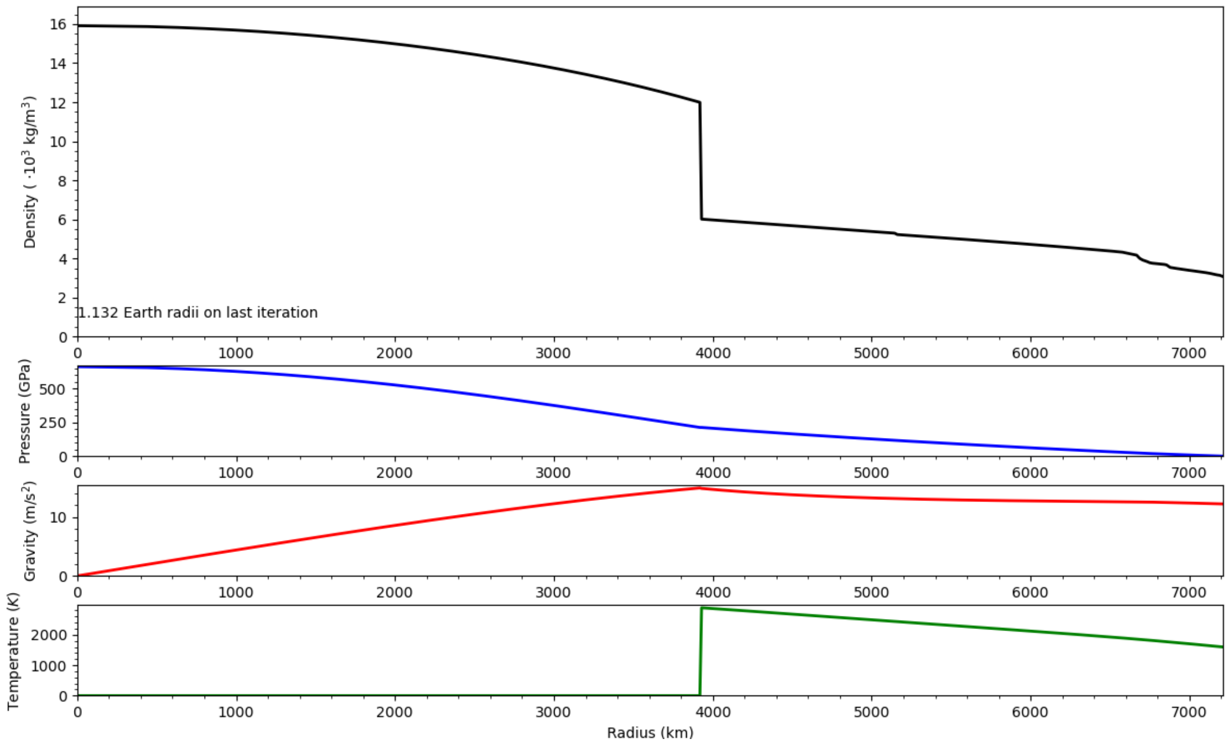
Section 3: Results

Given a planetary mass of 1.66 M_E, and the elemental abundances for Fe/Mg and Si/Mg calculated above, ExoPlex gives a density of 5.98 g/cm^3 and a planetary radius of 1.149 R_E. This is already within the radius uncertainty reported by Bonfils et al. (2018), so we can see that our assumptions are reasonable. The literature mass uncertainty is ± 0.23 M_E, setting an upper and lower limit of 1.43 M_E and 1.89 M_E (this particular upper mass limit generates errors in ExoPlex, so we lowered it to 1.82 M_E for the purposes of testing). The upper mass limit generates an upper radius of 1.179 R_E, and the lower mass limit generates a lower radius of 1.102 R_E, with densities of 6.07 g/cm^3 and 5.83 g/cm^3. Radii and densities are both within the literature uncertainties (the literature value for density is 6.3 ± 1.3 g/cm^3), so again our calculations seem reasonable. Our next steps are to decrease the radius and increase density to better match the expected values.

Within ExoPlex, we are able to vary the planet's mass, abundances for Fe/Mg and Si/Mg, the molar fraction of iron in the mantle (as opposed to the core), and the fraction of silicon in the core. We find that increasing the Fe mantle fraction and Si core fraction both increase the planet radius. However, the radius decreases if we increase Fe/Mg and decrease Si/Mg. To reach our desired radius, we must assume that our planet has slightly more iron and slightly less silicon than its host star. Adjusting Fe/Mg upward to 0.98, and Si/Mg downward to 0.80, we achieve a desired radius of 1.132 R_E with a density of 6.03 g/cm^3.

With this radius, we find a core mass fraction of 36.22, a core radius fraction of 54.50, and a CMB pressure of 212.25.00 Gpa. This is similar to the values ExoPlex gives for Earth, only more dense. For Earth we find a core mass fraction of 32.95, a core radius fraction of 53.02, and a CMB pressure of 141.56 Gpa.

Below we plot the density, pressure, gravity, and temperature of GJ 1132 b as a function of radius, using the values above. We see a clear bend in each plot around 3900 km, where the planet's interior changes phase from core to mantle layer:



Our model shows that the core of GJ 1132 b is composed entirely of iron, and the mantle is composed of a mixture of SiO_2, MgO, CaO, and Al_2O_3. Comparing the composition of our planet's interior to the composition of Earth given by ExoPlex:

	Fe	**Si**	**O**	**S**	**FeO**	**SiO_2**	**MgO**	**CaO**	**Al_2O_3**
Earth (Core)	100.0	0.0	0.0	0.0					
GJ 1132 b (Core)	100.0	0.0	0.0	0.0					
Earth (Mantle)					0.00	52.55	39.17	3.81	4.46
GJ 1132 b (Mantle)					0.00	49.61	41.60	4.05	4.74

We find that the interior composition resembles Earth closely, matching our expectation of a terrestrial planet. Given the similarities, we can be confident that our numbers are reasonable.

Section 4: Discussion and Conclusion

We have calculated a radius for GJ 1132 b of 1.132 R_E, which closely matches the literature value of 1.130 ± 0.056 R_E. We find that most adjustments to the core and mantle of the planet tend to increase its radius rather than decrease it, and the best way to match radius was to assume that Fe/Mg and Si/Mg are slightly different from the stellar abundances of the host star.

Given the planet's structural similarity to Earth, we return to the question: is it potentially habitable? One controversy surrounding GJ 1132 b is the presence of its atmosphere. After the planet was discovered in 2015, a 2017 study claimed the discovery of a large, thick atmosphere, giving it a much larger radius of 1.43 ± 0.16 R_E [8], and a significantly lower bulk density (2.98 g/cm^3 by our calculations). In 2018, Bonfils et al. refuted this claim, and provided evidence for only a very thin atmosphere (the data from this paper is what's mainly used in our models). More recent work suggests that the planet either has essentially no atmosphere, or possesses an atmosphere of high mean molecular weight or high-altitude aerosols [9], or possibly a cloudy hydrogen-dominated atmosphere or enriched secondary atmosphere [10]. Not only does this make radius and density measurements at least somewhat uncertain, but drastically affects any question of habitability.

We also note again that this planet is very close to its star. Using a pair of equations to calculate the habitable zone of GJ 1132 [11]:

$$r\,min \;=\; 0.95\sqrt{L\,Star/L\,Sun}$$

$$r\,max \;=\; 1.37\sqrt{L\,Star/L\,Sun}$$

we find that its habitable zone should lie between 0.069 and 0.099 AU. At only 0.015 AU from its host star, GJ 1132 b orbits 4.5 times closer than the inner limit of the habitable zone. From our plot above, ExoPlex calculates its surface temperature as well over 1000 K. Although this planet does resemble Earth in a number of ways, it would seem to be much too hot, and with too rarified an atmosphere, to be potentially habitable.

Contribution Statement

Jacob provided calculations on composition, assisted with the ExoPlex calculations, and provided research.
Leandra provided the vast majority of ExoPlex calculations, provided research, and explored how different parameters affected the final outcome.
Karish assisted with composition calculations, provided research, and performed the class presentation.
Andrew wrote the paper, provided research, and insisted against all odds that GJ 1132 b could still be inhabited by a race of intelligent dinosaurs. Maybe they're astronauts from GJ 1132 c?

References

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