Modeling the Composition of GJ 1132 b

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April 2022

1 Motivation

In order to understand a planet fully, it is important to know the composition and structure occurring within that planet. Yet, with our current detection methods we can only gather surface level information such as the mass and radius. However, in the case of rocky planets, we are fortunate enough to live on and understand a very good marker for estimating the interior structures of other rocky worlds. Thus with researchers' understanding of Earth's structure a program known as ExoPlex was developed which can be used to predict the structures and mineralogy of rocky exoplanets. In this paper we plan to put this to the test by modeling the interior of a proposed super-earth, GJ 1132 b, and attempting to explain its size and structure on a deeper level.

2 Methods

2.1 Finding the Stellar Composition

Before calculating the composition of GJ 1132 b we must understand the composition of its host star. Since all bodies in a solar system were formed from the same dust cloud, the makeup of the host star should hint at GJ 1132 b's relative abundances. This host star, GJ 1132 a, has an iron to hydrogen log mole ratio of [Fe/H] $= -0.12 \pm 0.15$ [5].

From this value we can derive other elemental abundances within GJ 1132 a. Recent papers have defined numerous mean averages for various elemental abundances of stars as a function of [Fe/H] or as a function of [X/Mg], where X is the abundance of a given element [3]. Using **Figure 1**, we can graphically determine the elemental abundance of [Fe/Mg]. This yields a value of [Mg/Fe] $\approx$ 0.13. However we need this fraction in the form of [Fe/Mg]. We do this by rearranging the equation as

$$0.13 = \log\left(\frac{Mg/Fe}{Mg_\odot/Fe_\odot}\right)$$

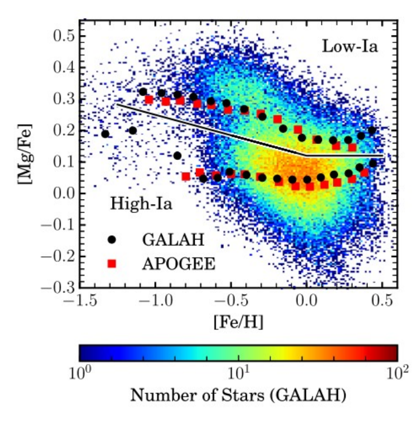

Figure 1: Magnesium stellar abundance scaled to iron abundances

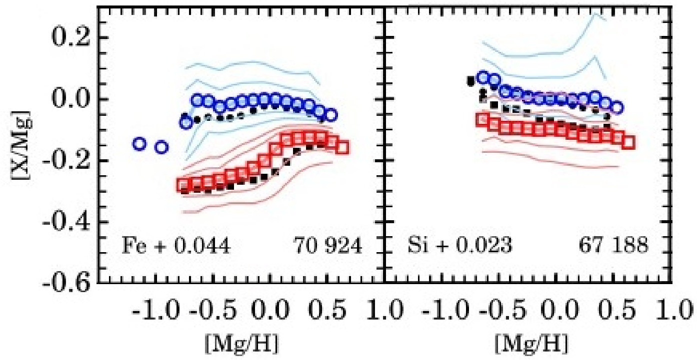

Figure 2: Predicted elemental abundances scaled to magnesium abundances in stars

Where Mg represents the number density of magnesium and Fe is the number density of iron in each respective star. From this we obtain the stellar abundance of iron in terms of magnesium is [Fe/Mg] = -0.13. Using this result and **Figure 2**, we can determine the relative abundance of magnesium to hydrogen in GJ 1132 a.

This yields an abundance of [Mg/H] ≈ 0.5 and [Si/Mg] ≈ -0.2. With these abundances in mind we now have the tools to continue our construction of a model for the composition of GJ 1132 b.

2.2 Planet's Size and Orbital Distance

In order to use ExoPlex, our given exoplanet must be a rocky world. Hence, it is necessary to prove whether or not GJ 1132 b satisfies this requirement.

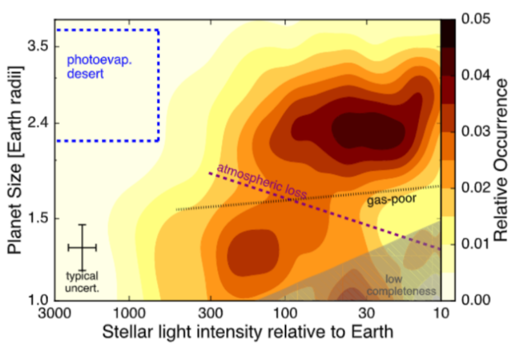

Figure 3: Magnesium stellar abundance scaled to iron abundances

Firstly, we must consider the size of GJ 1132 b. According to Bonfils et al(2018) GJ 1132 b has a mass of M = $1.66 \pm 0.23 M_{\oplus}$ and a radius of R = $1.13 \pm 0.053 R_{\oplus}$ [1]. With this in mind this size puts GJ 1132 b into the upper limit of the terrestrial planet regime defined by Chen and Kipping in their 2016 paper.

Another factor we must take into account is the distance that GJ 1132b is from its host star. This is important as the closer the planet is, the more irradiated it becomes, which leads to the removal of volatile substances and atmosphere from the planet. To determine the relative irradiation the planet experiences we can take a ratio of the flux experienced to that of Earth using the equation

$$\frac{f}{f_\oplus} = \frac{L}{L_\odot} * \left(\frac{a_\oplus}{a}\right)^2$$

Where L is the luminosity of GJ 1132 a given as $0.005L_\odot$ a is the semi major axis of GJ 1132 b at 0.0153AU [4]. Calculating this we find that the flux experienced by GJ 1132 b is ≈ 21.36 times greater than that of Earth. Consulting **Figure 3** we can interpret the effect this level of radiation would have in regards to an atmosphere.

As we can see here combining the radius and flux ratio, GJ 1132 b would be well below the gas poor and atmospheric loss lines displayed in **Figure 3**. Thus we can expect the planet to have a negligible atmosphere for our calculations, and will be treating it as a rocky planet.

2.3 Generating a Model

With our assumptions laid out we can now begin constructing our model utilizing ExoPlex, which will take in initial elemental abundances and return likely compositions and a planetary radius. However, ExoPlex requires that input abundances be in the form of mole ratios rather than the log mole ratios given with [Fe/Mg] and [Si/Mg]. To remedy this we can solve for the mole ratios in the form of

$$\frac{N}{M} = \frac{N_\odot}{M_\odot} * 10^{[N/M]}$$

With this we find the mole ratios of $\frac{Si}{Mg} = .567$ and $\frac{Fe}{Mg} = .667$. Our next step will then be running three different trials to obtain potential densities, compositions, and radii for GJ 1132 b. These will use the bounds given by the error in the known mass, running a trial for $1.43M_\oplus, 1.66M_\oplus$, and $1.89M_\oplus$. Additionally, all trials assume one percent iron in the mantle, 1 percent silicate in the core, and abundances of [Ca/Mg] = 0.07 and [Al/Mg] = 0.09.

3 Results

3.1 Probable Planet Structure

From our three trials we were able to generate a number of different potential structures for GJ 1132 b, the results of which can be seen in the table below.

Mass ($M_\oplus$)	**Radius** ($R_\oplus$)	**Density** (g/m^3)	**CM**F	**CRF**	**CMB Pressure** (GPa)
1.43	1.114	5.686	30.25	50.95	200.17
1.66	1.161	6.494	30.25	50.77	230.58
1.89	1.204	5.953	30.25	50.61	261.16

Table 1: Potential models of GJ 1132 b generated by ExoPlex

In this table we use a few abbreviations with CMF being the core mass fraction, CRF being the core radius fraction, and CMB being the core mantle boundary. Across all trials we observe CMF at exactly 30.25%, and CRF values all hovering just over 50%. This indicates a relatively large core, with a significant portion of the mass being allocated to the mantle. Additionally for each of the predicted radii and density values we are within two standard deviations of known values of R = 1.13 ± 0.53 $R_\oplus$ and $\rho = 6.3 \pm 1.3\ g/cm^3$. This indicates that the assumption of a nearly pure iron core with overall composition similar to the host star is a likely contender for modeling this planet. Additional tests were also conducted modifying the core silicate content and the mantle iron content but when they include higher fractions of these elements our predicted radius began to grow larger than observed values. Thus the trials with modified elemental distributions were deemed insufficient in predicting the composition of this planet. Also due to adequate predicted radii, it was sufficient to say that no significantly large atmosphere was needed in these models as well.

In addition to the table above we were also able to generate graphs that detail the pressure, gravity, and density throughout the planet. For our purposes we will be analyzing the interior generated by the $1.66M_\oplus$ trial.

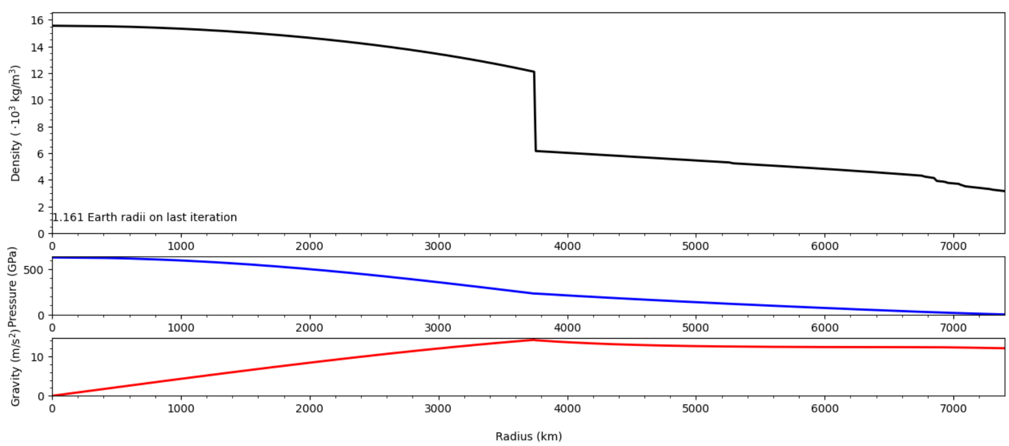

Figure 4: Model interior density, pressure, and gravity of GJ 1132 b generated by ExoPlex

From these plots we can discern a few notable features. In the top chart we see around 3700 km there is a steep drop off indicating a switch from the iron core to the silicate mantle. Then around 6800 km there are noticeable steps in the density line, indicating phase changes of the various minerals making up the mantle at those depths. Taking a look at the pressure graph we can see a gradual curve downward throughout the iron core, and a shallower trend once in the mantle. Finally, observing the gravity within the planet we see a peak at 14 m/s^2 just before the core mantle boundary, and then resting at a surface gravity of roughly 12 m/s^2.

3.2 Similarities to Earth

When comparing this planet to Earth, as they are both rocky planets, it is most useful to compare the abundances of certain compounds in their mantles. Looking at **Table 2**, it is clear to see that GJ 1132 b has a large difference in composition relating to FeO, SiO_2, and MgO. Containing 12.9% less SiO_2 in its mantle, this common mineral is generally rarer in

Planet	% FeO	% SiO_2	% MgO	% CaO	% Al_2O_3
GJ 1132 b	2.20393886	39.65339497	48.00307505	4.67510892	5.4644822
Earth	0.0	52.55497015	39.17101638	3.81493827	4.45907521

Table 2: (ExoPlex model for mineral composition of the mantle for GJ 1132 b and Earth)

GJ 1132 b than in Earth. In addition to this, GJ 1132 b seems to have considerably higher levels of magnesium oxide in it's composition. Most sources of MgO are water and brine and it forms from calcification, but other formation methods exist. We can take our analysis further as through ExoPlex we were also able to generate predictions for which minerals occurred within the mantle of GJ 1132 b and at which pressures they dominated.

Mineral	Pressure (GPa) - GJ 1132 b	Pressure (GPa) - Earth
ferropericlase b	24.00322	N/A
perovskite	115.8942-28.9962	23.04124-23.83129, 116.28622-24.02943
olivine	13.64909-0.3	N/A
wadslyite	19.15416-14.46277	N/A
ringwoodite	22.84353- 19.99874	N/A
orthopyroxene	N/A	4.25949-0.3
akimotoite	N/A	22.06156-21.28506
garnet	N/A	19.55791-15.82379
postperovskite	230.583-118.3742	141.56487-116.76458

Table 3: (Pressure (GPa) each mineral dominates (accounts for greater than 50% of the mass at that regime) at from ExoPlex model results)

To place the mineralogy of our planet in context we have compared it to that of Earth. It appears that both Perovskite and Postperovskite are prevalent on both Earth and GJ 1132 b at relatively light to intermediate pressure regimes, with the former have a near identical overlap in one of the pressure regimes it dominates in. Postperovskite in the model of GJ 1132 b overlaps with the model of Earth for most pressures, but it also dominates at pressures even higher than the $\approx$141 GPa that the Earth's Postperovskite peaks at. We notice however, that the minerals that dominate on Earth do not necessarily dominate on the model of GJ 1132 b. For GJ 1132 b Olivine dominates at $\approx <$13 GPa, Wadslyite at $\approx$ 19-14 GPa, Ringwoodite at $\approx$ 22-19GPa, and ferropericlase b dominates at $\approx$ 24 GPa, but these minerals are not as prevalent as on Earth. Conversely, Garnet, Orthopyroxene, and Akimotoite all dominate on Earth in these same pressure regimes. Additionally, some minerals found on Earth did not appear at all on our model GJ 1132 b and vice versa. For instance, Spinel does not appear in our model Earth, but does appear in GJ 1132 b. These minerals that were unique to either model, often dominated at similar pressure regiemes; for example wadslyite in GJ 1132 b and garnet in Earth both dominate with pressures ranging from $\approx$ 19-15 GPa. These differences in minerals could be tied to the increased prevalence of magnesium predicted in GJ 1132 b when compared to Earth.

4 Conclusion

Our results have shown that ExoPlex is a valuable exoplanet modeling tool. We were able to generate a feasible model structure of GJ 1132 b that agrees with observed values and properties (with a proposed radius of 1.16 $R_\oplus$ and density of 6.494 g/m^3). We can also conclude that GJ 1132 b is likely have a near pure iron core, sizing to about 50 percent the radius of the planet, a negligible atmosphere, and a refractory composition similar to that of its host star. This composition could also result in a much different mineralogy than that of the Earth. Building on our initial study, future work using ExoPlex could be done to model GJ 1132 b more precisely, or to apply these methods to other known rocky exoplanets.

5 Acknowledgements

Tayt Armitage *Paper Lead, Background Research, Code Assistant*

Ethan Fahimi *Code Lead, Background Research, Paper Editor*

Caitlin O'Brien *Co-Presenter, Paper Editor*

Lauren Robinson *Code Lead, Background Research, Paper Editor*

Autumn Stephens *Co-Presenter, Paper Editor*

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