The Star–Planet Connection. I. Using Stellar Composition to Observationally Constrain Planetary Mineralogy for the 10 Closest Stars

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Abstract

The compositions of stars and planets are connected, but the definition of “habitability” and the “habitable zone” only take into account the physical relationship between the star and planet. Planets, however, are made truly habitable by both chemical and physical processes that regulate climatic and geochemical cycling between atmosphere, surface, and interior reservoirs. Despite this, an “Earth-like” planet is often defined as a planet made of a mixture of rock and Fe that is roughly 1 Earth-density. To understand the interior of a terrestrial planet, the stellar abundances of planet-building elements (e.g., Mg, Si, and Fe) can be used as a proxy for the planet’s composition. We explore the planetary mineralogy and structure for fictive planets around the 10 stars closest to the Sun using stellar abundances from the Hypatia Catalog. Although our sample contains stars that are both sub- and super-solar in their abundances, we found that the mineralogies are very similar for all 10 planets—since the error or spread in the stellar abundances create significant degeneracy in the models. We show that abundance uncertainties need to be on the order of [Fe/H] < 0.02 dex, [Si/H] < 0.01 dex, [Al/H] < 0.002 dex, while [Mg/H] and [Ca/H] < 0.001 dex in order to distinguish two unique planetary populations in our sample of 10 stars. While these precisions are high, we believe that they are possible given certain abundance techniques, in addition to methodological transparency, that have recently been demonstrated in the literature. However, without these precisions, the uncertainty in planetary structures will be so high that we will be unable to confidently state that a planet is like the Earth, or unlike anything we have ever seen.

Key words: planetary systems – planets and satellites: composition – planets and satellites: detection – solar neighborhood – stars: abundances

1. Introduction

Stars and planets are formed at roughly the same time and from the same original cloud of gas and dust. Whether the planets were formed thorough core accretion (Pollack et al. 1996) or gravitational instability (Boss 1997), the composition of the star and planet are inextricably linked. Provided optimum geometry, it is possible to measure the composition of an exoplanet atmosphere via the absorption of the host star’s light. Unfortunately, this technique is difficult because the atmospheric signal perturbation is very small, \( \sim 10^{-3} - 10^{-5} \), with respect to the stellar spectra (Deming & Seager 2017).

We are unable as yet to directly observe the composition of a solid planetary regime, which is an important consideration when discussing “habitable” and “Earth-like” planets (Tasker et al. 2017). Instead, an observed planet’s mass and radius are often used to constrain the solid, bulk composition of a planet: e.g., the relative size of its core and mantle (Dorn et al. 2015; Unterborn et al. 2016). However, the mass–radius relationship alone is limited in its utility for distinguishing fine detail for a terrestrial planet interior because of the degeneracies inherent when bulk composition is left as a free parameter. As a result, we are only able to simply state that a planet is rocky or icy. Therefore, stellar elemental abundance ratios are needed to break the mass–radius degeneracy and adopt a more holistic mass–radius-composition understanding of terrestrial exoplanets.

A planet’s host star composition, however, represents an indirect measurement of terrestrial planet composition that is currently not used to its full potential. Thibaud et al. (2015) explored the elemental relationship between a star and a planet, namely whether composition is determined via chemical equilibrium (minimizing the Gibbs free energy, Elser et al. 2012) or whether the Fe/Si and Mg/Si are the same as the host star’s composition. They concentrated on Mg, Si, and Fe, which are prone to being condensed into solid, rocky material because their condensation temperatures \( T_C \) are high. Elements with \( T_C \gtrsim 1200 K \) are considered refractory, while those with \( 900 K \lesssim T_C \lesssim 1200 K \) are moderately volatile. Additionally, Thibaud et al. (2015) analyzed C and O, or elements that are typically found in gases with \( T_C < \sim 900 K \), or volatiles. By employing a planet formation and composition model, while cycling through a range of abundance ratios, they were able to determine that elements present within a planet were identical to those within a star. Other recent work shows that the solar composition is a good proxy for the Earth’s and potentially Venus’ bulk composition using self-consistent mass–radius relations (Unterborn et al. 2016).

Terrestrial planets are built mostly via refractory elements, namely Mg, Si, Fe, and O. In other words, 95% of the structure within the bulk Earth (namely the silicate-shell containing the mantle and crust) can be created using a combination of only these four elements (McDonough 2003). The relative fractions of refractory elements, namely Si/Mg, affect the relative proportions of olivine to pyroxene at pressures and temperatures indicative of the upper mantle, as well as Mg-perovskite (bridgmanite is the phase bearing both Mg and Fe) and ferropericlase in the lower mantle. These mineral distributions can in turn affect melting relations, the viscous and elastic
(or viscoelastic) properties of the planet, and the potential for long-term sustentation of tectonic processes (Foley & Driscoll 2016; Unterborn et al. 2017b, and references therein). Additionally, Fe/Mg is shown to affect the relative size of a planet’s core, which in turn may alter the heat flow from the core into the mantle and subsequently out of the mantle at the surface. The prevalence of moderate volatiles can influence the crustal composition of the exoplanet and affect tectonic processes by preferentially fractionating and creating more andesitic conditions, or the interaction between converging plates that leads to continental crust formation. These conditions play a key role in geochemical cycling and buoyancy of subducting material, which governs the sideways and downward movement of tectonic plates (Unterborn et al. 2017b).

Volatile also play an important role. For example, planets with elevated C abundances are likely to contain reduced diamond in their mantles, limiting convective forces due to the diamond’s increased viscosity and thermal conductivity (Unterborn et al. 2014). As such, planet composition can drastically affect the geodynamic and geochemical processes present on a terrestrial exoplanet. Therefore, stellar composition provides us with a key, yet underused, observable for understanding the geologic nature of an exoplanetary system, and must be considered along with mass–radius studies when describing planets as “Earth-like.”

If we are to define a more holistic view of “habitability” and “Earth-like,” all of the available physical and chemical data therefore need to be used in order to understand planets at a meaningful level in our search for other Earths and even life. This is especially important with the upcoming missions focusing on characterizing exoplanets, i.e., the Transiting Exoplanet Survey Satellite, the Characterizing ExOPlanets Satellite (CHEOPS), the PLanetary Transits and Oscillations of stars (PLATO) mission, and the Wide-Field InfraRed Survey Telescope (WFIRST). In this paper, we look at the 10 stars closest to the Sun and analyze their stellar abundances with the help of the Hypatia Catalog (Hinkel et al. 2014), as outlined in Section 2. In Section 3 we briefly assess the mineralogies of fictive planets around these stars (explained in more detail in Paper II, C. Unterborn & N. Hinkel 2017, in preparation), which are similar as a result of the errors associated with the stellar abundances. In Section 4 we present an algebraic walkthrough to determine the abundance precision needed to distinguish two unique populations of planet mineralogy, both in our sample of 10 and within the Hypatia Catalog as a whole. In Section 5 we discuss what is physically known about the sample of 10 stars, such that any detected terrestrial planets can be quickly and easily characterized. Finally, we summarize our results in Section 6.

2. Sample Selection

For our sample of targets, we turn to the place that is most often observed by astronomers and that is most interesting for habitability: the stars closest to the Sun. From a technological standpoint, nearby stars will have higher measurement precision for the stellar properties and therefore will be more closely monitored for orbiting planets. Because of their proximity, they will also have more high-resolution stellar abundance measurements and have these measurements for a wider variety of elements. As a result, the properties of discovered planets will be very well known, as can be seen for Proxima Centauri b (Anglada-Escudé et al. 2016).

To begin, we adopt to the Hypatia Catalog (Hinkel et al. 2014, 2016, 2017), which contains stellar abundances for FGK-type stars within 150 pc of the Sun. Stellar abundances are defined such that an element ratio in a star (+) is compared to that same element ratio in the Sun (⊙):

$$\frac{[X/H]}{} = \log \left( \frac{N_X/N_Y}_+ \right) - \log \left( \frac{N_X/N_Y}_\odot \right),$$

where the square brackets indicate solar normalization, and $N_X$ and $N_H$ are the number of X and Y atoms (in mol) per unit volume, respectively. The associated unit is a logarithmic unit: dex. Hypatia is an amalgamate data set compiled of abundance measurements from more than 150 literature sources. It is the largest data set of main-sequence stellar abundances for stars near to the Sun and currently boasts approximately 28,000 abundance measurements for about 6000 stars. Additionally, it is unbiased in its inclusion: if a literature data set contains the abundance determination for Fe and one other element within main-sequence stars in the solar neighborhood (150 pc), then it is added to Hypatia. All data sets have their intrinsic solar normalization scale removed and replaced with the scale of Lodders et al. (2009) so that all abundance data are on the same baseline. Different solar normalizations can cause a shift of 0.06 dex, on average, for all of [X/H] abundances (Hinkel et al. 2014). We use Hypatia not only because of its breadth, but also because it allows a true understanding of how different groups using a variety techniques measure elemental abundances within a star, or the spread.

We searched the Hypatia Catalog for stars that are nearest to the Sun and also have abundance measurements for all five elements: Mg, Al, Si, Ca, and Fe. However, we did not wish to include gravitational or spectroscopic binaries in order to minimize overlap of the individual star’s spectra. We have listed those binary stars that are not included in our analysis in the Appendix. The one exception that we made was with respect to HIP 108870 (¢ Ind), which has a wide orbital brown dwarf at a distance of >1400 au (Scholz et al. 2003): we note that Pluto is at a distance of 40 au from the Sun (see Section 5). Additionally, we opted to exclude any nearby stellar systems that already had detected planets—also listed in the Appendix. In this way, we are able to analyze systems with simple theoretical planetary formation mechanisms that do not involve planetary migration or fractionation of the stellar abundances with respect to composition.

One of the most powerful tools within the Hypatia Catalog is the spread in the abundance data. When multiple literature sources measure the same element within the same star, the spread is defined as the range in those abundance determinations (after they are renormalized to the scale of Lodders et al. 2009). In many instances, the spread is larger than the quoted error from a given literature source, which reveals how truly “well understood” abundance measurements can be within a star (see Hinkel et al. 2014, particularly the top of Figure 3, for a more thorough discussion). In this vein, we found that a number of stars had abundance spreads that were > 0.70 dex for one or many of the element abundances. We found that the large spread, even when using the median values, did not give us reliable abundance values. Therefore, we retained stars that had

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3 http://www.hypatiacatalog.com
4 exoplanetarchive.ipac.caltech.edu
only had abundance spreads <0.50 dex—those that were removed are listed in the Appendix.

We therefore define a sample of the 10 “closest” stars for the purposes of our study, which are listed in Table 1 with physical properties included from the Hypatia Catalog (Hinkel et al. 2017). Of note, stellar distances vary from 3.62 to 7.53 pc. The optimistic (Opt) and conservative (Cons) habitable zone (HZ) distances were determined using the calculator offered by the Virtual Planetary Laboratory through the equations in Kopparapu et al. (2013, 2014; see Table 2). Additionally, the location on the sky for the 10 stars is shown on a Mollweide projection in Figure 1, where we see the large RA and Dec space covered by our selected sample.

### 2.1. Stellar Abundances for the Sample

The adopted stellar abundances from Hypatia for the sample of targets are given in Tables 3 and 4. According to the Hypatia method (Hinkel et al. 2014), the median value of measurements (as determined by multiple groups) are listed as [X/H], while the spread or range of these values are given as sp[X/H]. The only exceptions are HIP 73148 and HIP 99461, where the [Mg/H] abundance was measured by one group (Luck & Heiter 2005; Maldonado et al. 2015, respectively) and therefore had a spread = 0.0. For these two cases, we used the individual error for [Mg/H] within each star as reported directly by the literature source. Additionally, within Tables 3 and 4, we have listed the [Mg/H] abundances associated with each element. The ExoPlex code (see Section 3) requires that the molar ratios of the four elements (Ca, Al, Si, Fe) are listed with respect to Mg (see Section 3 and Table 5). The abundance and spread for [Mg/H]Y means that only those data sets that measured both [Y/H] and [Mg/H] were used to calculate the final [Mg/H]Y value. In this way, we are able to ensure that we were comparing similar quantities from like-sources, as opposed to taking the median value of, for example, seven data sets that measured [Fe/H], while only two also measured [Mg/H]. Therefore, a unique [Mg/H] calculation was needed for each of the four elements.

In Figure 2 (left), we have plotted the molar ratios of Fe/Mg versus Si/Mg for all stars within the Hypatia Catalog (orange) that have abundances for the three elements—and corresponding Mg measurements within the same data set. For a breakdown on how to convert stellar abundances into molar fraction, see Section 4. We have overlaid the ratios of our sample in black, including the Sun as reference, according to the values in Table 5. We see that the 10 closest stars are mostly centered within the plot, similar to the majority of the Hypatia stars, with some stars lie in the more extreme regions, namely HIP 99461 and HIP 73184. Similarly, we have plotted Si/Mg versus Al/Mg in Figure 2 (right), where the Hypatia stars are color-coded blue and the sample of 10 closest stars is black. Again, HIP 99461 and HIP 73184 are more extreme than the other stars in their molar ratios, in addition to HIP 12114. Finally, we show Si/Mg with respect to Ca/Mg in Figure 2 (bottom), with the Hypatia stars in light green. The sample of 10 stars shows molar ratios that are clustered together as compared to the Hypatia stars. Both HIP 3765 and HIP 17378 have relatively low Ca/Mg, while HIP 64394 is at the other extreme.

### 2.2. The Importance of the C/O Ratio

The C/O ratio of a planetary disk is a primary control on the oxidation state of the condensates from which terrestrial planets are built. Above the C/O ∼ 0.8–1.0 threshold, carbon as graphite (SiC and TiC) becomes the dominant condensate at refractory temperatures (Bond et al. 2010b). Stars in these systems are likely to produce terrestrial planets dominated by similar reduced carbon species (Bond et al. 2010b). The high C/O systems are also unlikely to produce geodynamically active planets (Unterborn et al. 2014), thus limiting degassing and any potential to be habitable.

Refractory carbon may be present in disks of solar composition; Lodders (2003) notes that this will likely only be in small amounts, thus limiting the effects on final planet chemistry. Moriarty et al. (2014) observed that the small amount of carbon may be as low as C/O ∼ 0.65 when dynamical effects within the disk are taken into account. Given

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**Figure 1.** Mollweide projection showing the sample of targets (see Table 1).
the impact of carbon on planetary formation, our sample of 10 stars was chosen such that C/O \lesssim 0.8 with the exception of HIP 73184 and HIP 12114, where either C, O, or both abundances were not available. Additionally, HIP 108870 has C/O = 0.88, since we assume that the threshold needed to take carbon chemistry into account within the disk as closer to 1.0. Future models and observations will likely help to constrain and narrow the C/O range of influence.

### 3. Building Planets

For the planets forming with C/O \lesssim 0.8, the dominant terrestrial planet-building condensates will be Fe and Mg- and Si-bearing silicates (e.g., forsterite Mg2SiO4), with comparatively minor portions of Al- and Ca-bearing species (e.g., corundum, Al2O3) present as well. While the specifics of planet formation and accretion may cause a greater or lesser fraction of accretionary material to coalesce into planets, little fractionation of these major elements relative to each other is expected. This is because in the case of Mg, Fe, and Si, the elements have condensation temperatures within 20 K of each other for both solar and non-solar disk compositions (Lodders 2003; Unterborn et al. 2016). When post-condensation dynamics are taken into account, the relative ratios (e.g., Si/Mg, Fe/Mg) are again found to change only on the order of 3 wt% for our solar system (Bond et al. 2010a, 2010b) compared to solar abundances. Thus, while metallicity and other absolute abundances of the elements are potentially useful for understanding other aspects of exoplanets (e.g., the mass–metallicity relationship for Jovian exoplanets, Thorngren et al. 2016), the major controls on terrestrial planet chemistry and mineralogy are the ratios of these five refractory elements: Mg, Al, Si, Ca, and Fe.

The relationship between stellar composition and terrestrial planets is well grounded in our understanding of the chemistry and physics of planet formation. Recent work has shown that the Sun’s refractory composition is an acceptable proxy for the Earth’s bulk composition in reproducing the Earth’s mass, radius, and bulk composition to within 20% (Dorn et al. 2015; Unterborn et al. 2016). The same is true for planets outside of our solar system with respect to their host star’s refractory element abundances (Thiabaud et al. 2015; Dorn et al. 2016, 2017). These compositional contrasts offer hope given the significant degeneracy in the inferred bulk interior structure and mineralogy of terrestrial exoplanets when mass and radius alone are adopted (Dorn et al. 2015, 2016, 2017).

The ExoPlex code iteratively solves for a planet’s density, pressure, gravity, and adiabatic temperature profiles that are consistent with the pressures derived from the mass within a sphere,

$$\frac{dm(r)}{dr} = 4\pi r^2 \rho(r), \quad (2)$$

the equation of hydrostatic equilibrium,

$$\frac{dP(r)}{dr} = -\frac{Gm(r)\rho(r)}{r^2}, \quad (3)$$

and the equation of state (EOS),

$$P(r) = f(\rho(r), T(r)), \quad (4)$$

where r is the radius, m(r) is the mass within a shell of radius \( r + dr \), \( \rho \) is the density, \( P \) is the pressure, \( T \) is the temperature, and \( G \) is the gravitational constant. The positions \( r \) of the shells is then recalculated using the volume calculated from the new density at depth and shell mass. This process is then iterated until convergence, which we define as the moment when the change in density in every shell between iterations does not change by one part in \( 10^{-6} \). We partition each modeled planet into a metal core composed of pure liquid-Fe and a rocky mantle. ExoPlex determines the mineralogy and density as determined by the EOS at each depth in the rocky mantle using the PerPlex Gibbs free-energy minimizer package (Connolly 2009). We adopt the thermally dependent EOS formalisms of Stixrude & Lithgow-Bertelloni (2005) for the mantle and the formalism of Anderson & Ahrens (1994) for the liquid-Fe core. While we neglect light elements in the core, the change to the mass–radius relation is only of a few percent at Earth-like light-element mass fractions (\( \gtrsim 10\% \), Unterborn et al. 2016).

For our sample of 10 stars, initial ratios from Table 5 were adopted and model mineralogies and density profiles were calculated for fictive terrestrial planets orbiting the stars, assuming to be 1 Earth radius. Models were run using the ExoPlex planet-building code (A. Lorenzo et al. 2017, in preparation; Unterborn et al. 2017a) along self-consistent adiabatic temperature profiles of 1500, 1700, and 1900 K, which cover a range of cold, hot, and “Earth-like” geotherms. For simplicity, all Fe is assumed to remain in the core and thus represents a planet with an oxidation state at or below any oxidized iron redox buffers (e.g., iron-wüstite/quartz-iron-fayelite). We show in Figure 3 the modeled

| Table 2 |
| --- |
| Calculated Stellar Properties of the Sample |

| HIP | Calc St. | Optimistic Inner | Conservative Inner | Conservative Outer | Optimistic Outer |
| --- | --- | --- | --- | --- | --- |
| Mass (M_\odot) | HZ | RV amp (m s^{-1}) | Period (days) | HZ | RV amp (m s^{-1}) | Period (days) | HZ | RV amp (m s^{-1}) | Period (days) |
| 108870 | 0.704 | 0.796 | 0.1699 | 309.18 | 1.008 | 0.1509 | 440.59 | 1.851 | 0.1114 | 1096.37 |
| 96100 | 0.865 | 0.772 | 0.1265 | 266.29 | 0.978 | 0.1124 | 379.70 | 1.751 | 0.0840 | 909.61 |
| 99240 | 0.937 | 0.761 | 0.1131 | 250.52 | 0.964 | 0.1005 | 357.17 | 1.710 | 0.0755 | 843.83 |
| 3765 | 0.793 | 0.783 | 0.1432 | 284.15 | 0.992 | 0.1272 | 405.20 | 1.796 | 0.0945 | 987.09 |
| 2021 | 1.006 | 0.750 | 0.1024 | 236.51 | 0.949 | 0.0910 | 336.64 | 1.674 | 0.0685 | 788.68 |
| 7981 | 0.844 | 0.776 | 0.1309 | 271.72 | 0.982 | 0.1164 | 386.81 | 1.765 | 0.0868 | 932.06 |
| 23311 | 0.745 | 0.790 | 0.1564 | 297.01 | 1.001 | 0.1389 | 423.62 | 1.826 | 0.1029 | 1043.70 |
| 17378 | 0.801 | 0.782 | 0.1412 | 282.21 | 0.991 | 0.1254 | 402.59 | 1.790 | 0.0933 | 977.32 |
| 57939 | 0.804 | 0.782 | 0.1403 | 281.66 | 0.990 | 0.1247 | 401.21 | 1.790 | 0.0928 | 975.44 |
| 64394 | 1.055 | 0.741 | 0.0959 | 226.77 | 0.939 | 0.0852 | 323.48 | 1.648 | 0.0643 | 752.12 |

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mineralogies and density profiles for a planet of solar composition (Lodders et al. 2009). Overlaid as a solid black line is the density profile of the preliminary reference Earth model (PREM; Dziewonski & Anderson 1981). While the PREM incorrectly predicts the size of the core (likely because it does not incorporate light elements into the metal), the density profiles of the “solar” planet and Earth are remarkably similar.

Similar models for Venus would elucidate the validity of our star/planet model, since Venus makes up nearly 40% of the total mass of terrestrial planets in the solar system. The bulk composition of Venus or even its core size (a key constraint in mass--radius models) is not known. Mars and Mercury, on the other hand, have modest constraints on their bulk composition, but given their small sizes (0.10 and 0.06 Earth masses, respectively, or <10% of all terrestrial planet masses in the solar system), low-pressure silicate phases will dominate the bulk of the silicate portion of the planet. These minerals will be more indicative of the Earth’s upper mantle, where changes in oxygen fugacity and minor element content will have a larger effect on the phase equilibria and behavior of the minerals. The threshold from upper-mantle-dominated planets occurs at roughly 0.2 Earth masses, and we would stress that it is not meaningful to apply star/planet models to any future exoplanet discoveries below this mass. Further details will be provided in Paper II, C. Unterborn & N. Hinkel (2017, in preparation).

The compositional space for the sample of 10 stars is similar and not wholly unlike the Earth, with varying proportions of the dominant terrestrial planet-building minerals: olivine, pyroxene, Mg–Al-perovskite, and periclase. Temperature has a minor effect, mostly changing mineralogies in the transition zone, from akimotoite-dominated for colder planets and wadsleyite-dominated for planets with potential temperatures greater than the modern Earth’s. While these models do not include the effects of Fe incorporation into these minerals, it should be noted that Fe partitioning into each of these species is possible. Geochemical and geophysical consequences of the abundance variations are explored more generally in forthcoming work (C. Unterborn & N. Hinkel 2017, in preparation). Of note, however, are the similarities between the mineralogies and structures for planets around these 10 stars. As shown in Tables 3 and 4, the bulk abundances vary to a significant degree between the stars, especially for the thick-disk star HIP 57939, which has [X/H] abundances consistently below −1.0 dex. However, the molar fractions of these elements (see Section 4) are markedly similar, as is visible from Equation (6) and Figure 2.

ExoPlex uses the spreads associated with the stellar abundances from the Hypatia Catalog, through the error propagation of the two abundances used to calculate this molar fraction; for example, the error for Si/Mg is determined from the spread associated with [Si/H] and [Mg/H]. The large spreads in the abundances create significant errors in the molar fractions, as shown in Equation (6). As a result, and as discussed more extensively in Paper II, C. Unterborn & N. Hinkel (2017, in preparation), the compositions for the 10 planets are markedly alike to within the error or spread.

4. Determining Distinct Planetary Mineralogies

We determined the errors (σ) for the molar fractions, shown in Table 5, by propagating the spread in the stellar abundances (according to Tables 3 and 4) for the anti-logarithm, base-10. In other words, the molar fraction X/Y is determined by the stellar abundances X = [X/H] and Y = [Y/H], such that

$$X / Y = 10^{(X + A - Y - B)},$$

where A is the solar composition of X and B is the solar composition of Y. We calculate the error on the molar fractions, $S_{X/Y}$, according to

$$S_{X/Y} = 2.303 \times \sqrt{S_X^2 + S_Y^2},$$

where $S_X$ and $S_Y$ are the spreads or errors on [X/H] and [Y/H], respectively, as given in Tables 3 and 4. For our purposes, we assumed that there was no error on the solar stellar abundances. Additionally, we used the spread in the Mg values associated with each respective element (see Section 2.1). In this way, we calculated the σ errors shown in Table 5. The “extreme” molar fractions from Figure 2 clearly show that the errors overlap for all of the stars in our sample.

However, while the spreads in the [X/H] stellar abundances are large, we would like to know what the spreads or ultimate error within the stellar abundances must roughly be in order to distinguish two unique planetary populations. We therefore compute the general precision that stellar abundance errors or spreads needed to achieve for the molar ratio errors to meet half-way between the “extreme” stars in our sample, not including the Sun. In this way, we can identify what stellar information is needed for the planetary models in our sample to be “different” to within the errors. According to Table 5, the extreme Si/Mg ratios are found in HIP 99240 and HIP 23311; for Fe/Mg we look at HIP 64394 and HIP 23311; for Al/Mg we examine HIP 23311/1088780 and HIP 57939; and finally,
for Ca/Mg, we look at HIP 64394 and HIP 3765/17378. For Si/Mg the maximum distance between the extreme stars is 0.25, which means that half of this is 0.125, which we call $\sigma_{\text{max}}$. For Fe/Mg, half of the maximum $\sigma_{\text{max}}$ is 0.215, for Al/Mg it is 0.025, and for Ca/Mg it is 0.015.

We give a pictorial diagram of the $\sigma_{\text{max}}$ errors for our sample in Figure 4. On the left, we reproduce Figure 2 (left) showing the sample of 10 stars as black dots and the Hypatia stars in orange. We have overlaid dark blue ellipses to show the extreme molar ratios between the stars in our subsample. In the case of the lower left dark blue ellipse, the extreme low in both Si/Mg and Fe/Mg is HIP 23311. However, for the upper right dark blue ellipse, there is not one single star with the highest Si/Mg and Fe/Mg for this sample, therefore we place the center of the ellipse where it would be. The ellipses have a width and height of extreme high-to-low sample, therefore we place the center of the ellipse where it would

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To the right of Figure 4, we have recreated Figure 2 (left), where we have again added green ellipses at the extreme molar ratios within the sample of 10. Since the same star does not have both the highest and lowest molar ratios of Al/Mg and Si/Mg, we have placed the center of the ellipses where the extremes occur (see Table 5). Again, the entire range of the $\sigma_{\text{max}}$ values in the x- and y-directions are encompassed by the width and height, respectively, of the ellipses. Finally, at the bottom of Figure 4, we have plotted Ca/Mg with respect to Si/Mg (as seen in Figure 2, bottom), where the center of the blue ellipses represents the extremes for both molar fractions.

We use these error maximum values as $S_{X/Y} = \sigma_{\text{max}}$, or half the width and height of the ellipses. Then, assuming that the spread or error in [X/H] is the same as [Y/H], and $S_{X} = S_{y}$, to make the calculations simpler, we can simplify Equation (6) to

$$\sigma_{\text{max}} > 2.303 \times \sqrt{2} \times S_{y}^2.$$  \hspace{1cm} (7)

From here, we solve for $S_{y}$, which results in

$$\sqrt{0.5 \times \left( \frac{\sigma_{\text{max}}}{2.303} \right)^2} > S_{y}.$$  \hspace{1cm} (8)

We now have an equation that will calculate the spread or error in the stellar abundances that in turn will produce an error in the molar ratio that spans half the range (or less) of our sample. For the Si/Mg molar ratio, $\sigma_{\text{max}} = 0.25$ so the [Si/H] and [Mg/H] stellar abundances need a precision of 0.01 dex or better, following Equation (4). Similarly, for the Fe/Mg ratio, [Fe/H] and [Mg/H] need a 0.02 dex precision (Figure 2, left). The [Al/H] and [Mg/H] abundance ratios need 0.002 dex for Al/Mg (Figure 2, right), while [Ca/H] and [Mg/H] need 0.001 dex for Ca/Mg. In other words, the stellar abundances have to be precise on the order of 0.001–0.02 dex in order to distinguish two distinct populations within the molar ratios. While very difficult, several groups have reported this precision for large groups of stars, see Section 4.3. With precise stellar abundances below these limits, we can define two unique populations of stars (as seen in Figure 4): if terrestrial planets were discovered in orbit, our model predicts that the planetary structures and mineralologies would be distinctly different to within the errors of both the stellar abundances and molar ratios. The third population of planetary systems, namely those that are not included within the ellipses, would have degenerate compositions that could not be indicated as having either low molar ratios of Fe/Mg versus Si/Mg versus Al/Mg versus Ca/Mg or high molar ratios.

Using ExoPlex (see Section 3), we have modeled the planetary compositions of the extreme high and extreme low molar fractions, taking into account the uncertainty required in our analysis to make the two distinct—see Figure 5. As expected, the high Fe/Mg population (top) has a larger core than the low Fe/Mg planet (bottom). In addition to this major structural difference, the lower Si/Mg sample contains a larger fraction of both olivine (in the upper mantle) and periclase (in the lower mantle) than the greater Si/Mg population. Furthermore, the transition zone mineralologies are significantly different, with the low Si/Mg sample containing little comparative garnet, thus increasing the overall water-storage capacity of this key mantle reservoir. Temperature also affects the mineralogy of the transition zone, with those planets run along a “hot” adiabat (1900 K mantle potential temperature), displaying no ringwoodite, whereas the “cold” adiabat stabilizes stishovite (a high-pressure polymorph of SiO$_2$) and akimotoite at the expense of ringwoodite. While these are only those indicative from a first-order equilibrium mineralogy model, these compositional changes can affect the dynamical state and rate of geochemical cycling on these planets.

| HIP   | [Ca/H] | sp[Ca/H] | [Mg/H]$_{\text{Cs}}$ | sp[Mg/H]$_{\text{Cs}}$ | [Fe/H] | sp[Fe/H] | [Mg/H]$_{\text{Fe}}$ | sp[Mg/H]$_{\text{Fe}}$ |
|-------|--------|----------|----------------------|----------------------|--------|----------|----------------------|----------------------|
| 108870| −0.08  | 0.48     | −0.08                | 0.37                 | −0.07  | 0.41     | −0.08                | 0.37                 |
| 96100 | −0.16  | 0.22     | −0.07                | 0.31                 | −0.15  | 0.35     | −0.11                | 0.31                 |
| 99240 | 0.32   | 0.24     | 0.41                 | 0.10                 | 0.37   | 0.27     | 0.40                 | 0.16                 |
| 3765  | −0.18  | 0.21     | −0.03                | 0.26                 | −0.29  | 0.26     | 0.26                 | 0.26                 |
| 2021  | 0.00   | 0.02     | 0.03                 | 0.08                 | −0.09  | 0.49     | −0.01                | 0.18                 |
| 7981  | −0.01  | 0.17     | 0.11                 | 0.01                 | 0.01   | 0.35     | 0.10                 | 0.15                 |
| 23311 | 0.32   | 0.36     | 0.45                 | 0.43                 | 0.32   | 0.26     | 0.55                 | 0.43                 |
| 17378 | 0.14   | 0.30     | 0.28                 | 0.32                 | 0.19   | 0.44     | 0.28                 | 0.32                 |
| 57939 | −1.05  | 0.17     | −1.01                | 0.27                 | −1.24  | 0.27     | −1.02                | 0.27                 |
| 64394 | 0.11   | 0.16     | 0.07                 | 0.08                 | 0.11   | 0.33     | 0.06                 | 0.23                 |
4.1. Planet Mineralogies within Hypatia

In this paper, we have chosen to look a small sample of nearby (<10 pc) stars. However, it is clear that these stars encompass only a small fraction of the molar ratio space, namely Fe/Mg versus Si/Mg versus Al/Mg versus Ca/Mg, as shown in Figure 4. So as not to say that abundance ratios of refractory elements do not exceed this range, we expand our exploration to consider the full sample of the Hypatia stars, as shown in Figure 4. In this way, we can analyze how the errors in stellar abundances propagate to molar fraction, and ultimately, how this impacts planetary structure and mineralogy for nearby stars.

| HIP   | Al/Mg | σ_{Al/Mg} | Si/Mg | σ_{Si/Mg} | Ca/Mg | σ_{Ca/Mg} | Fe/Mg | σ_{Fe/Mg} |
|-------|-------|-----------|-------|-----------|-------|-----------|-------|-----------|
| 108870 | 0.09  | 0.43      | 0.87  | 0.48      | 0.06  | 0.70      | 0.83  | 0.64      |
| 96100  | 0.06  | 0.47      | 0.78  | 0.43      | 0.05  | 0.44      | 0.74  | 0.54      |
| 99240  | 0.08  | 0.36      | 0.93  | 0.25      | 0.05  | 0.30      | 0.76  | 0.36      |
| 3765   | 0.06  | 0.41      | 0.74  | 0.32      | 0.04  | 0.38      | 0.63  | 0.45      |
| 2021   | 0.07  | 0.35      | 0.85  | 0.28      | 0.06  | 0.09      | 0.68  | 0.60      |
| 7981   | 0.07  | 0.28      | 0.78  | 0.24      | 0.05  | 0.26      | 0.66  | 0.44      |
| 23311  | 0.09  | 0.65      | 0.68  | 0.59      | 0.05  | 0.65      | 0.48  | 0.58      |
| 17378  | 0.08  | 0.46      | 0.76  | 0.47      | 0.04  | 0.51      | 0.66  | 0.63      |
| 57939  | 0.04  | 0.42      | 0.81  | 0.40      | 0.06  | 0.37      | 0.49  | 0.44      |
| 64394  | 0.08  | 0.18      | 0.89  | 0.30      | 0.07  | 0.21      | 0.91  | 0.46      |

Sun    | 0.09  | 0.95      | 0.06  | 0.81      |

4.2. Assumptions in the Planet Mineralogies

The purpose of this walk-through is to obtain a general idea for the precision needed in stellar abundances to produce (only two) distinct populations of terrestrial planets. However, we made some assumptions along the way, for simplicity’s sake, that have minor effects on our calculations. For example, we assumed that $S_{X} = S_{Y}$, or that the error or spread in $[X/H]$ was equal to $[Y/H]$. In general, the error reported for stellar abundances of Mg/H, Al/H, Si/H, and Ca/H are 0.07 dex, 0.06 dex, 0.05 dex, and 0.06 dex, respectively (Hinkel et al. 2014). For some of the higher-precision abundances, Nissen (2015) reported errors of 0.009 dex, 0.005 dex, 0.005 dex, and 0.006 dex, while Spina et al. (2016) had errors of 0.014 dex, 0.012 dex, 0.007 dex, and 0.013 dex. In total, it appears as though our assumption that $S_{X} = S_{Y}$ is not radically far from the truth, although the variation could contribute somewhat to the needed stellar abundance precision.

When determining stellar abundances, not all data sets are on the same baseline with respect to the solar normalization (see Equation (2)). Namely, different groups chose one of a variety of solar measurements, for example, Anders & Grevesse (1989), Grevesse & Sauval (1998), Asplund et al. (2009), Lodders et al. (2009), or simply measured their own either directly or as reflected light at the time of observations. To date, there are 45 individual solar normalizations taken into consideration within the Hypatia Catalog. The assortment of solar normalizations introduces an intrinsic scatter when comparing stellar abundances. For example, in Hypatia, the range in the absolute abundance of Mg in the Sun is 0.17 dex, while absolute Fe has a range of 0.26 dex. As a result, these solar normalization disparities create a variation of ~0.1 dex in the molar ratios (see Table 5). Within the Hypatia Catalog, we sought to correct the baseline differential by renormalizing all stellar abundances to the same solar scale, namely Lodders et al. (2009). However, for the analysis in this paper, we assumed that there were no errors on the solar composition. Looking at Lodders et al. (2009), they report absolute errors of Mg = 0.06 dex, Al = 0.07 dex, Si = 0.01 dex, and Ca = 0.02 dex for the Sun, while Asplund et al. (2009) lists Mg = 0.04 dex, Al = 0.03 dex, Si = 0.03 dex, and Ca = 0.04 dex. These solar abundance errors can contribute an additional ~0.007 dex precision needed in the stellar abundances to obtain two separate populations of terrestrial planets via the molar fractions.
Finally, we have used a specific subsample of 10 nearby stars in order to demonstrate our intention of determining two unique populations of planetary mineralogies. While we have expanded this demonstration to encompass the entire Hypatia Catalog in Section 4.1, our choice of location for the ellipses was approximate and not overly rigorous. Therefore we urge caution that the required abundance precisions quoted here are to be used a general criterion, such that they are tailored to meet the specifics of any future study.

4.3. High-precision Stellar Abundances

Through the works of Torres et al. (2012), Smiljanic et al. (2014), and Hinkel et al. (2014), it has become apparent that stellar abundance techniques are discrepant. In Hinkel et al. (2016), an international team of stellar abundance groups came together to uncover the underlying reason as to why stellar abundance measurement techniques varied. The study supplied six groups with the same stellar spectra and tested the effects of standardizing the stellar atmospheric parameters (namely, \( T_{\text{eff}} \) and \( \log(g) \)), the element line lists used to measure the abundances, and both in tandem. While some standardization helped somewhat, the kind of standardization and the extent varied between elements as well as methods. Ultimately, the experiment was not able to completely reduce the spread in abundances between groups.

In order to determine whether a planet’s interior structure falls into a low molar ratio, high molar ratio, or into a neither/both category, we found here that stellar abundances need to be nearly an order of magnitude more precise than current individual measurement techniques allow. Additionally, these measurement techniques need to be corroborated such that the range or spread of abundance measurements for the same element in the same star approaches zero. By applying the spread as the associated error in this study, we have used this important metric to illuminate how well measured stellar abundances truly are.

With this in mind, the abundance precision levels needed to calculate at least two independent populations of planetary interior structures are not impossible. A number of individual groups have been able to obtain stellar abundances with precisions in the thousandths of a dex, as mentioned earlier. For example, Ramírez et al. (2014) employed a differential approach that determined stellar abundances with respect to stars other than the Sun, namely HIP 74500 and HIP 14954, that were more similar in stellar properties with respect to the rest of their sample. Using this technique, they were able to remove systematic errors that are typically associated with temperature or metallicity. In a similar vein, Nissen (2015, 2016) measured the abundances in only those stars from the Sousa et al. (2008) sample that were solar twins, or stars that were within \( \pm 100 \) K in \( T_{\text{eff}} \), \( \pm 0.15 \) in \( \log(g) \), and \( \pm 0.10 \) dex in \([\text{Fe/H}]\) as compared to the Sun. Spina et al. (2016) chose a set of 14 solar twins based predominantly on their color in both the optical and infrared spectrum as compared to the Sun. Adibekyan et al. (2016) worked with a set of 40 stars that had ages close to the age of the Sun. Additionally, while they limited \( T_{\text{eff}} \) and \( \log(g) \) to be solar-like, they noted that the

Figure 2. Molar ratios for the sample of 10 stars, including the Sun, as labeled. Left: \( \text{Fe/Mg} \) with respect to \( \text{Si/Mg} \), where the Hypatia Catalog stars are plotted in orange. Right: \( \text{Si/Mg} \) vs. \( \text{Al/Mg} \), with the Hypatia stars shown in blue. Bottom: \( \text{Si/Mg} \) with respect to \( \text{Ca/Mg} \), where Hypatia stars are depicted in light green.
variation in their stellar parameters was likely the reason that they were not able to achieve the precision determined by other groups.

Finally, the implementation of local thermodynamic equilibrium (LTE) versus non-LTE within stellar atmospheric models has been found to yield dramatically different results for a number of elements (i.e., Gehren et al. 2006). In some cases, the effects of NLTE on certain elements is small, for example, in Bensby et al. (2014) and Luck (2017). However, NLTE seems to be particularly important for stars with a low metallicity, or [Fe/H] < −1.0, where the the stellar models deviate from solar (Zhao et al. 2016). On the other hand, a line-by-line differential method to determine the stellar abundances, as implemented by many of the above groups, is useful for canceling out the difference between LTE and NLTE.

Overall, in order to achieve high precision, the sensitivity of the stellar atmospheric models must be accounted for, such that the similar stars are compared to one another according to the abundance ratios. Additionally, spectra with extremely high resolution are required. While this approach severely limits the number of stars for which planetary interiors can be distinguished, it does highlight a path forward.

5. Physical Properties when Defining Habitable Planets

The chemical and physical properties of a star need to be considered in tandem. While we have examined the stellar abundances so far, we now consider the physical characteristics of the star that are important for habitability. For example, the measurement of stellar activity (via Ca II H and K lines defined as the $R_{HK}$ index) indicates the strength of the stellar magnetic field, which is directly responsible for the structure of the corona and propagation of solar winds and flares. Therefore, it is important for habitability that a star have relatively low stellar activity. In this section we analyze the properties of the stellar systems as they pertain to the habitability of potentially terrestrial planets. Additionally, we have provided both the optimistic and conservative HZ radii (Kopparapu et al. 2013, 2014) for all 10 stars in Table 2, indicating where liquid water could be expected on the surface of a planet. We have also determined an estimate of the periods and radial velocity measurements expected for potential Earth-like planets orbiting the 10 stars at both the conservative and optimistic HZ radii according to the equations in Kane (2007). Since we do not have stellar masses for our sample, we calculate an approximation using a main-sequence mass-temperature relationship: $(M/M_\odot)^{1.5} = (T/T_\odot)^{4}$, the values of which are listed in Table 2. In this way, we hope to provide a reference for the radial velocity (RV) precision required to detect potential planets in the context of upcoming space missions such as PLATO, which will be dedicated to searching for these types of planets.

5.0.1. HIP 108870—e Ind

As shown in Table 1, HIP 108870 is the closest star in our sample. Endl et al. (2002) used the RV technique, or the “wobble” method, which gauges the motion of a star’s center of mass that is caused by a companion, and found that the system had a low-amplitude linear trend. This behavior was determined to be a brown dwarf binary system separated by 2.65 au at a distance of 1459 au (Scholz et al. 2003; Volk et al. 2003; McCaughrean et al. 2004). Because of the large separation between the main-sequence star and the brown dwarf binary (note: Pluto is ∼40 au from the Sun), we found that the companion had little impact on the primary star, and we therefore kept this target in the sample. Janson et al. (2009) and Zechmeister et al. (2013) both came to a similar conclusion when searching for nearby Jupiter-mass planets, such that the binary dwarfs could only account for an acceleration of 0.009 m s$^{-1}$ yr$^{-1}$, an extremely small effect. Long-term trends were found in both studies in the RV, namely 2.4 m s$^{-1}$ yr$^{-1}$ (Zechmeister et al. 2013), and with respect to stellar activity per log $R_{HK}$. However, while the trends could be explained by massive planetary companion, there has been no detection of a giant planet. Additionally, the authors noted that the trends in RV and log $R_{HK}$ could be coincidental. Because of the high-precision RVs and imaging via the Hubble Space Telescope (HST)/NICMOS and the Very Large Telescope (VLT)/NACO (Geißler et al. 2007; Janson et al. 2009), it is safe to conclude that HIP 108870 is not an active star. Despite the presence of an extremely wide brown dwarf binary companion, the literature reports that HIP 108870 is a relatively quiet, inactive star. And while there appear to be indirect signs of a possible
orbiting planet, the search for one has not been successful. It is clear from the multiple previous observations that HIP 108870 is an excellent star for hosting a planet that has a good chance of being habitable from a physical perspective.

5.0.2. HIP 96100

HIP 96100 has an estimated radius of $R = 0.778 \pm 0.008 \, R_{\odot}$ and age of $\sim 5$–$10 \, \text{Gyr}$ based on multiple stellar isochrones as reported by Boyajian et al. (2008, and references therein). HIP 96100 is an RV constant star such that it was used to track the zero-point drift of HIRES on the 10.2 Keck telescope in Courcol et al. (2015). Therefore it is likely that there are no giant exoplanets in the system. Ultimately, the constant nature of the stellar activity means that HIP 96100 has all the physical qualities to host a habitable terrestrial planet.

5.0.3. HIP 99240—δ Pav

HIP 99240 is relatively stable in the RV, ruling out any massive secondary companions either close to the star or in a wide orbit (Wielen et al. 1999). Velocity oscillations via asteroseismology were found to be centered on 2.3 mHz, with peak amplitudes similar to the Sun (Kjeldsen et al. 2005). Additionally, with respect to potential planet formation, there does not appear to be a cold dust disk around HIP 99240 (Eiroa et al. 2010). In other words, if a planet is orbiting HIP 99240, it is likely a smaller terrestrial planet. The physical similarity of HIP 99240 to the Sun means that it would be a good location for a habitable Earth-sized planet.

5.0.4. HIP 3765—HD 4628

HIP 3765 shows low levels of stellar activity per the CaII H and K emission (Mathioudakis et al. 1994; Affer et al. 2005). The stellar age was determined to be $3 \pm 1.5 \, \text{Gyr}$ based on theoretical isochrones in Affer et al. (2005), although we note that the $\text{[Fe/H]}$ abundance value they used in that determination, namely $−0.27 \, \text{dex}$, is slightly lower than the value we report here in Table 4: $\text{[Fe/H]} = −0.20$. The consistency of the stellar activity means that such a planet around HIP 96100 would be physically stable in terms of habitability.

5.0.5. HIP 2021—β Hyi

HIP 2021 has been studied via astroseismology in order to (1) determine its mass and radius (North et al. 2007) as well as (2) measure the effect of stellar oscillation and granulation to minimize planetary detection limitations (Dumusque et al. 2011). While a number of studies have analyzed the RV data of this target (e.g., Endl et al. 2002), these data were compiled by Zechmeister et al. (2013), who found no obvious trend in the data. The lack of an RV trend may be due to a discrepancy in the RV data or perhaps a correlation with the star’s magnetic cycle. Despite the low activity of the star and techniques to
increase planet detectability, no giant planets have been discovered around HIP 2021.

5.0.6. HIP 7981—107 Psc

HIP 7981 is a chromospherically active star, which has an observed short-term pattern of star spots (Messina et al. 1999) and cyclical luminosity variations that can be multiple times that of the Sun (Radick 2001). From our literature search, it does not appear as though this star has been directly or pointedly observed, especially with respect to planetary surveys, in the last few decades.

5.0.7. HIP 23311—HD 32147

HIP 23311 is a member of the HR 1614 moving group (Eggen 1978, 1992), which is an association of stars from the same stellar birth cloud, with similar galactic velocity, that was later disrupted by differential galactic rotation to form an elongated “tube” (Antipova & Boyarchuk 2015). While studying the chemical abundances for stars in the HR 1614 group, Antipova & Boyarchuk (2015) found that unlike the other members that had $[\text{Fe}]/\text{H} \sim -0.2$–$0.3$ dex, HIP 23311 was anomalous: the atmospheric parameters $\log(g)$ and $T_{\text{eff}}$ were too low to be consistent with a dwarf star. Additionally, HIP 23311 had $[\text{Fe}]/\text{H} = -0.14$ dex while being enriched in Na, Mg, Al, and Si as compared to other members of the moving group. The authors concluded in a separate study (Antipova & Boyarchuk 2016) that the dwarf star exhibits solar-like activity in the form cool, dark, often large star spots. These star spots affected the equivalent widths of the spectral lines, which resulted in the anomalous and incorrect abundance measurements. The large star spots and corresponding high stellar activity, which can manifest in intense UV and X-ray radiation, could impose varying, perhaps unpredictable, physical conditions on an orbiting terrestrial planet (Garraffo et al. 2017).

5.0.8. HIP 17378—δ Eri

HIP 17378 has been classified as a variable of RS CVn type, which stars are defined as close binary systems that have high chromospheric activity and star spots. However, there has been no observation of any stellar activity, including the X-ray, photometric, or emission from the H and K lines (Thévenin et al. 2005, and references therein). Additionally, there is no RV variation or any considerable photometric change. Therefore, 

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Figure 5. Planetary minerology phase diagrams similar to Figure 3, representing the extreme high molar fractions (top) and extreme low molar fractions (bottom) as outlined in the text and represented as ellipses in Figure 4. The most notable differences are the sizes in core and variation in Si/Mg, which affects many aspects of the structure. See the text for details.

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http://simbad.u-strasbg.fr/simbad/sim-fbasic
Thévenin et al. (2005) pointedly searched for a companion star using the VLTI and found no companion to within $\pm 2\%$ of the luminosity of HIP 17378, or $L/L_\odot = 3.19 \pm 0.06$. The authors conclude that the RS CVn classification is doubtful. The first three oscillation modes in HIP 17378 have also been observed, namely $(l, m) = (1, -1), (2, 1),$ and $(1, 0/1)$, where the latter $m$-mode could not be disentangled (Hekker & Aerts 2010). Their work implied that the non-radial modes were the dominant frequency—a widely debated topic in red giant stars at that time. Additionally, while the classification of RS CVn means that an orbiting planet would receive much high-energy radiation, the lack of any observed stellar activity is encouraging for habitability.

### 5.0.9. HIP 57939—HD 103095

HIP 57939 originated from the halo of the Milky Way, making it the closest halo star to the Sun. It has also been chosen as a benchmark star for the Gaia mission (Jofré et al. 2014). It is difficult to measure not only the $T_{\text{eff}}$ of metal-poor stars, but also to match observations with models of stellar structure and evolution and therefore to determine the fundamental properties of the star (Creevey et al. 2012). The stellar parameters that were found by Soubiran et al. (2016) are listed in Table 1. Age estimations for this star vary from $5.261 \pm 0.089$ Gyr to $10.19 \pm 1.58$ Gyr, as laid out by Mishenina et al. (2017, and references therein) to $12.0 \pm 0.2^{\pm 0.2}_{\pm 0.2}$ Gyr (Creevey et al. 2012). Since little is known about the physical properties of the HIP 57939 star, it is unclear how it would influence an orbiting exoplanet.

### 5.0.10. HIP 64394—β Com

The magnetic field of solar-like HIP 64394 was measured by Gray et al. (1996) and Plachinda & Tarasova (1999). The latter used the $S$ index of the H and K lines over a baseline of 5 years and found a $\delta S \sim 0.025$ dip in activity, the largest seen since 1966. Additionally, there was a photometric dip $\approx 5$ mmag and a temperature variation of $\approx 30$ K during the same epoch as the magnetic activity (Plachinda & Tarasova 1999). The ultimate implication is that the magnetic change drove the variation in the $b$ and $y$ photometry and temperature. The physical properties and stellar activity of HIP 64394 are variable enough that it might detrimentally impact the habitability of an orbiting planet.

### 6. Conclusion

Defining planetary habitability and Earth-likeness is a difficult task that is compounded by the fact that there is only a single data point for reference, namely, the Earth. One of the most prevalent definitions of the HZ assumes “Earth-like” conditions on the planet and asserts that the most important factor to influence habitability is the presence of water in its liquid state since “all organisms with which we are familiar require liquid water during at least part of their life cycle” (Kasting et al. 1993). However, as our understanding of exoplanets and their ranges in sizes, masses, potential compositions, and stellar hosts has expanded as a result of the Kepler Mission (Batalha et al. 2013), so too must the definition of habitability (Tasker et al. 2017). It is still of paramount importance that a planet maintain a stable temperature that is conducive to Earth-life. However, the atmosphere is an important consideration—for example, Venus-analogs, which would not be considered habitable (Kane et al. 2014). Additionally, the geochemical activity of a planet, namely plate tectonics or other recycling processes, climate, and geodynamo, must also be taken into consideration (Foley & Driscoll 2016). Ultimately, the term “habitable” must be expanded to not only consider whether water could be in its liquid state on the surface of the planet, but if the geochemical processes necessary for life are present at all. It is only by applying a truly holistic approach, modeling both the chemical and physical properties along with interior and exterior cycling of a planetary system, that a planet can be considered “alive” or even “Earth-like.”

In this paper, we started by considering 10 stellar systems that are near to the Sun, namely stars around which it is most likely that a terrestrial, rocky exoplanet will soon be discovered. When determining the mineralogies and structures of these potential planets, we realized that they were remarkably similar (see Paper II, C. Unterborn & N. Hinkel 2017, in preparation). The reason for the model homogeneity was due in part to the fact that the stellar abundances were notably disparate (see Tables 3–4), the molar fractions were consistent (Table 6 and Figure 2). Additionally, when using the planet-building code ExoPlex, we took advantage of the spread in the stellar abundance measurements—or the range in determinations by different groups for the same element in the same star—as the true uncertainty in the abundances. These two factors resulted in planetary mineralogies and structures that were relatively uniform (C. Unterborn & N. Hinkel 2017, in preparation).

Our primary assumption within this paper is that the composition of the host star is that of the resulting terrestrial planets. This assumption is well founded given the materials that go on to form rocky planets within the disk: high temperature, refractory condensates, primarily silicates, and metallic iron. These refractory minerals are dominated by the so-called major planet-building elements: O, Mg, Si, and Fe (consequently, the four most abundant elements in the Earth, McDonough 2003). While each of these elements are broadly considered refractory, they do not each condense at the exact same temperature. Instead, they condense at an initial temperature, continuing radially over a range of temperatures until reaching temperatures where they are entirely stable within solid rather than gas species (Bond et al. 2010a, 2010b; Thiabaud et al. 2015; Unterborn & Panero 2017). The initial condensation temperatures of these refractory elements are within 3 K of each other, while the 50% condensation temperatures are within 30 K of one another (Lodders 2003). Mixing between various compositionally distinct radial zones within the disk is possible, but only small variations (~10%) away from host star abundances and their associated ratios are expected (Bond et al. 2010a, 2010b). The minor planet-building elements, such as the moderate volatiles (Na, K), do not follow this one-to-one trend. The reason is their inherent volatility, where disk processes such as melting and subsequent impacts during formation fractionate their abundances relative to the major elements. While the moderate volatile elements are important for the potential crustal composition of a rocky exoplanet (Unterborn & Panero 2017), they do not drastically affect the bulk mantle mineralogy of the planet, and therefore variations in minor element abundance will not be reflected in mass–radius studies (Dorn et al. 2015; Unterborn & Panero 2017). Thus, our assumption that the host star composition is
roughly that of the terrestrial planet is sound for our purposes of gauging the potential first-order mineralogy of these systems for broad comparative planetology.

While it is our intention to analyze the planetary structure for stars and planets that are very much unlike the Earth—in terms of molar fractions, we leave this analysis for another paper. Instead, we focused on calculating what uncertainty (or spread) is needed in the stellar abundances in order to determine two populations of planets with mineralogies and structures that were unique and discernible. For our sample of 10 stars nearest to the Sun, we found that the precisions in the abundances need to be $[\text{Fe}/H] < 0.02$ dex, $[\text{Si}/H] < 0.01$ dex, and $[\text{Al}/H] < 0.002$ dex, while for $[\text{Mg}/H]$ and $[\text{Ca}/H]$, it needs to be $< 0.001$ dex. Note that since all of the molar fractions were calculated with respect to Mg, there is a degeneracy for the precision required for $[\text{Mg}/H]$. However, since Ca/Mg required the most strict precision, we adopted this requirement as well. For all of the stars within Hypatia, the precisions in the abundances were not much better than our smaller subsample: $[\text{Fe}/H]$ and $[\text{Si}/H] < 0.03$ dex and $[\text{Al}/H] < 0.004$ dex, while $[\text{Mg}/H]$ and $[\text{Ca}/H] < 0.002$ dex.

While the precision levels required to determine unique planetary structures are high, they are not impossible. Ultimately, they require a more concerted effort on the part of both individual groups and the stellar abundance community as a whole to reduce both the error and the spread in the stellar abundances. Fortunately, within the last few years, there appears to be a more unified endeavor to better understand the measurement techniques between stellar abundance groups, for example, the teams that participated in studies such as Smiljanic et al. (2014), Jofré et al. (2015), and Hinkel et al. (2016).

However, even when stellar abundance compositions are measured consistently with high precision, the planetary interior and structure is only one aspect of habitability. The atmosphere, surface temperature, and activity levels of the host star need to be taken into account, such that the planetary surface and interior processes can be understood as a unified system. Therefore, we cannot say whether terrestrial planets orbiting the 10 stars nearest to the Sun, analyzed here, are habitable. However, given that many of the stellar hosts have low activity levels and that mineralogies are not too dissimilar to the Earth, we find that these 10 systems are a good place to look for potentially habitable, rocky planets.

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**Appendix**

In an effort to be transparent with respect to stellar systems that we did not analyze in this manuscript, below we list the particular systems we excluded and why, as noted in in the text.

Stars removed because they are gravitational or spectroscopic binaries: HIP 71683 and 71681 ($\alpha$ Cen A & B, respectively), HIP 104214 and 104217 (61 Cyg A & B, respectively), HIP 84405 (36 Oph), HIP 84478 (V′ V2215 Oph), HIP 19849 (om02 Eri), HIP 3821 ($\eta$ Cas), HIP 37279 ($\alpha$ CMi), HIP 88601 (70 Oph), HIP 99461 (HD 191498), HIP 73184 (HD 131977), HIP 12114 (HD 16160), HIP 5336 ($\mu$ Cas), HIP 113283 (Fomalhaut), HIP 88601 (70 Oph), HIP 73184 (HD 131977), HIP 99461 (HD 191498), HIP 12114 (HD 16160), HIP 86974 ($\mu$ Her), HIP 61317 ($\beta$ CVn), HIP 27913 ($\chi$01 Ori), HIP 32984 (HD 50281), HIP 84740 (41 Ara), HIP 99825 (HD 192310), and HIP 27072 ($\gamma$ Lep).

Stars removed because they are already known to host exoplanets: HIP 113020 (BD-15 6290), HIP 16537 ($\epsilon$ Eri), HIP 15510 (82 Eri), HIP 8102 ($\tau$ Ceti), and HIP 64924 (61 Vir) from our sample list.

Stars excluded because they had abundances values for any of the five elements $[X/H]$ with spreads $> 0.70$ dex: HIP 45343 (HD 79210), HIP 49908 (HD 88230), HIP 85295 (GJ 673), HIP 113576 (HD 217357), and HIP 1599 ($\zeta$ Tuc).

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