# PHSX 815 Project 4: The Distribution of C/O and Mg/Si Abundances Among Stars and its Implications for Exoplanet Interiors

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## 1 Introduction

### 1.1 Background on Abundances

Many of the studies involved in the detection and characterization of exoplanets are indirect and rely on observing the exoplanets' host stars rather than the exoplanets themselves. These host stars are far bigger and brighter than their planetary companions and thus easier to observe from Earth-based telescopes. Fortunately, stars also contain numerous clues into galactic and planetary formation processes via their atmospheric and internal composition. Unfortunately, large-scale surveys (e.g. Gaia) tend to bypass abundance measurements and determine only the most fundamental parameters of stars such as mass, radius, luminosity, and temperature. Though important, these parameters do not provide the context necessary to accurately determine the composition and interior structure of exoplanets of interest.

Stellar abundances are an important component in exoplanet studies because they provide us with an insight into the mechanisms behind star formation/evolution and likewise planetary formation/evolution. Since stellar atmospheres evolve slowly, the elemental abundances of exoplanet hosts tend to reflect the composition of their planet-forming disks [1] and have the potential to yield constraints on planet formation processes and, in turn, even the physical properties of exoplanets themselves. This is because abundances can often be used as tracers of exoplanet chemical composition during formation as planets steal heavy elements away from the host star or post-formation as host stars accrete planetary material [2]. Exoplanetary scientists rely heavily on elemental abundances to model exoplanet atmospheres and interiors because we do not yet have the technological capabilities necessary to observe them directly.

### 1.2 Abundance Ratio Variation

Abundance ratios may vary from star to star across the galaxy for a multitude of reasons stemming from chemical evolution on a galactic scale and the chemical evolution of the star itself. For example, stars formed earlier in the galaxy's history are not as metallic as present-day stars. This is because heavier elements like carbon, oxygen, magnesium, and silicon and their isotopes are mainly produced via Type-II (core collapse) supernovae. It's only the stars formed LATER in the galaxy's history that have had the chance to form from and incorporate these supernova products. And so, over time, stars acquire more isotopic species, and their abundances ratios of neutral elements to isotopic elements decrease towards 1. There is also a strong correlation between refractory (Fe, Mg, Si) or alpha process elemental abundance ratios and stellar age over an age interval of 8 Gyr [3]. These age correlations are likely due to a greater number of Type I supernovae (SNe) relative to the number of Type II SNe over the course of time [3]. Since Type I SNe do not produce heavy elements to the extent that Type II SNe do, younger stars with low metallicities (i.e. Fe/H ratio) must have formed metal-poor regions. There is also the matter of the star's own chemical evolution. Stars of different masses, with the same initial metallicity, will eventually have different abundances in their atmospheres as they evolve. The star's temperature, surface gravity and convective zone depth all play a role in the diffusion of heavier elements out of the photosphere [4]. In summary, there are many factors that influence elemental abundance ratios to produce ones much different than anytihng in our solar system.

# 2 Significance: Implications of Non-Solar Abundance Ratios on Exoplanet Interiors

Carbon, Oxygen, Magnesium, and Silicon abundances are particularly important to know when studying exoplanet atmospheres and interiors. Carbon and oxygen are the two most abundant heavy elements throughout the Galaxy and in the Sun and are present predominantly as the CO molecule [2]. Whichever of these elements is in excess determines which element is available to form other compounds (other gases, condensates, or rocks with Mg and Si) from the gas [2]. All together, the abundances of oxygen, carbon, and major rock-forming elements like Mg, Si, and Fe determine a planet's minerology which in turn affects heat transfer between the planet's interior and its surface, planetary mantle dynamics and tectonics, volcanism, the water cycle, the carbon cycle, and even the presence of a magnetic field [5] as seen on Earth.

The Earth's atmospheric processes and aqueous chemistry rely on temperature regulation maintained by a balance of incoming solar radiation combined with moderate greenhouse warming from $CO_2$, $H_2O$, and $CH_4$. Moreover, these processes depend on plate tectonics specifically to recycle material between the planet's surface and mantle [6]. This material transport produces the buoyant continental crust and captures atmospheric $CO_2$. Plate tectonics on Earth depend heavily on the sinking of the cold subducting plate into the underlying mantle; this sinking occurs because of the thermal contraction of the lithosphere and on the metamorphic transitions within basaltic oceanic crust and lithospheric mantle– which depends on the abundances of elements like Mg, Si, Fe Ca, AL, and Na [6]. Planetary geologies are very complex, and it becomes difficult to study them given current observational capabilities: it is impossible to directly observe an exoplanet's composition and minerology. These properties are instead inferred from mass-radius relations; however, this results in a considerable amount of degeneracy in exoplanet composition and interior structure [6]. This degeneracy is reduced when the host star composition of terrestrial planet-building elements like Mg, Si, and Fe are used as a proxy for exoplanet composition. Thus, we need precise stellar abundance measurements to characterize exoplanet atmospheres and interiors because there's really nothing else to use at this point!

## 2.1 Non-Solar C/O Ratios

Clearly, the C/O ratio has a great influence on exoplanet ice, gas, and rock chemistry which is why it is a fundamental parameter in exoplanet atmosphere and interior models. Oxygen, in particular, is important to exoplanet interiors because of its reactivity. Because oxygen is so reactive and easily combines with most elements, it is often locked out of the atmosphere as water/ice and solid minerals unless there exists some source of replenishment on the planet [4]. The processes that we know to increase the amount of atmospheric oxygen are biological and thus make oxygen an ideal biosignature to look for in the search for habitable planets and extraterrestrial life. In systems with C/O $<< 1$, excess oxygen forms refractory silicate minerals and eventually $H_2O$ [2] meanwhile C can condense into CO or $CO_2$ ices or graphite [5]. In systems with a C/O ratio near a critical value $0.88$, there is no oxygen left over from silicate condensation and so planets accrete from dry material [2]. In systems with C/O $\geq 1$, carbides and graphite become more stable, they replace silicates in the condensation sequence, and ultimately form planets with very un-Earth-like minerologies, atmospheres and interiors [2]. To recap, in the high C/O regime, planets form primarily out of carbonates since there is very little free oxygen available to form silicates whereas in the low C/O regime, planets form mainly from magnesium silicates as dictated by the Mg/Si ratio [1].

Our solar system has a C/O ratio of 0.54 [1].

## 2.2 Non-Solar Mg/Si Ratios

Similarly, the Mg/Si ratio is a fundamental parameter in the interior models of terrestrial planets and helps constrain the planetary core-to-mantle mass ratio. It's also thought that Mg/Si ratios significantly different than those on Earth can lead to drastically different balances of rocky compounds like olivine and pyroxene and this has the potential to alter geological processes such as planetary differentiation, energy transport, and plate tectonics [1] [3]. When Mg/Si $< 1$, however, most of the Mg is used up to produce pyroxene with the remaining silicon producing feldspars [1]. Stars with Mg/Si ratios $1 \leq$ Mg/Si $< 2$ result in planetary compositions similar to the Earth's with a mix of pyroxene and olivine [1]. When Mg/Si $> 2$, magnesium compounds like olivine MgO and MgS dominate the planet's geology [1].

Magnesium and Silicon tend to form in equal abundance, and this is the case in our Solar System which has an Mg/Si ratio of 1.05 [1].

Understanding how certain elemental abundances affect planetary atmospheres and interiors helps us to recognize different planetary structures. By looking at the distributions of these abundances in a large sample of stars, we can study how common certain planet types are and thus estimate the likelihood of finding a habitable, Earth-like planet. As you can see from the Figures 1 and 2, it's very likely that we could encounter exoplanets with interior structures different than what we're familiar with here on Earth. These stellar abundances then become pretty important bits of information to have when you begin analyzing exoplanet atmospheres with JWST. They help link host star properties to their exoplanets.

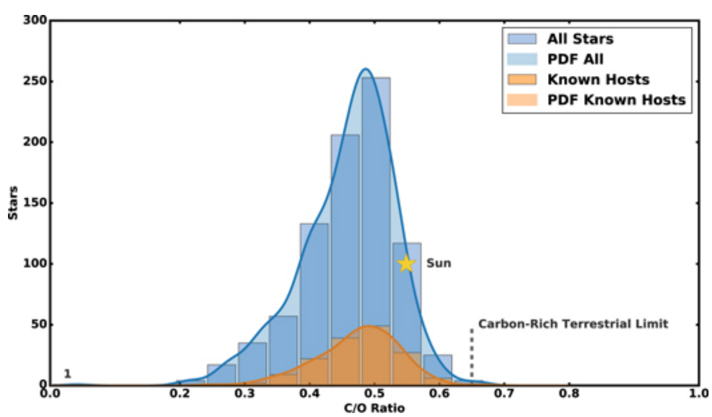


Figure 1: Distribution of the C/O ratios in a large sample of stars, both host and non-host stars [1]. Notice that the Sun has a higher abundance ratio than the mean of the sample. This implies that it'll be harder to find a carbon-rich planet, and easier to find an oxygen-rich planet.

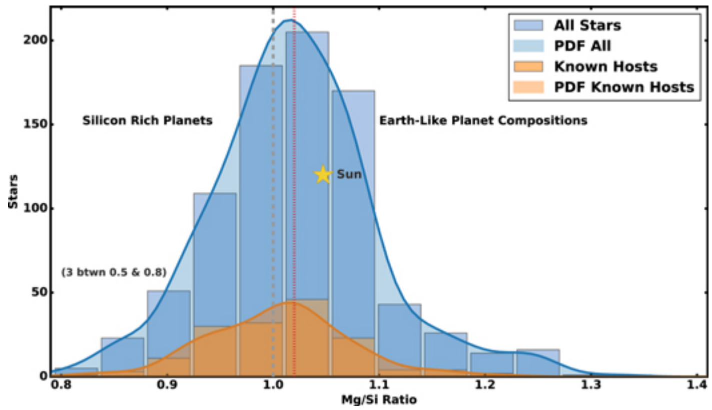


Figure 2: Distribution of the Mg/Si ratios in a large sample of stars, both host and non-host stars [1]. The Sun is much closer to the mean of the Mg/Si distribution; however, it seems more likely to find a silicon-rich planet than it is to find one with an Earth-like composition.

## 3 Goals

I will use data from Brewer and Fischer's 2016 catalogue of C/O and Mg/Si ratios in a sample of 849 F, G, and K dwarfs in the solar neighborhood [1] to recreate their distribution plots and determine the mean C/O and Mg/Si ratios for all stars in the sample and for only exoplanet hosts in the sample. I will then use Python to fit a normal distribution to this data and use scipy to determine the distributions' probability distribution functions and cumulative distribution functions to calculate some probabilities associated with finding a star within different C/O and Mg/Si regimes. Each of these regimes, as explained above, represents a different terrestrial planet geology. Use data [1] to determine the likelihood of finding an exoplanet with sub- or super-solar C/O or Mg/Si abundances

## 4 Code

The code for this project is a very simple script designed to recreate distribution plots from Brewer and Fischer's 2016 catalogue of C/O and Mg/Si ratios, fit a normal distribution to each, and then use the probability and cumulative distribution functions of the data fits to perform some calculations regarding the probability of finding a star that falls into certain C/O and Mg/Si regimes of interest.

First, I use Microsoft Excel to convert the html table that stores our data into a comma separated values (.csv) file that is much easier to work with using pandas. Next, I read the data into my script and use scipy.stats.norm.fit to fit a normal distribution to both the distribution of C/O ratios and to the distribution of Mg/Si ratios.

Because I'd like to look for any differences in these distribution between all of the stars in the sample and only the exoplanet host stars, I also have to isolate the C/O and Mg/Si ratios for host stars from the rest of the data. This is done using a simple for loop that stores the abundance ratios given that the column listing number of planets the star hosts is not zero.

Now that I have the abundance ratios separately for host stars, I can fit a normal distribution to both the distribution of C/O ratios and to the distribution of Mg/Si ratios as before. I then plot all of the distributions: C/O for all of the stars, C/O for only host stars, Mg/Si for all of the stars, and Mg/Si for only host stars. The same thing is done for the models that fit the data. The plots produced by this code are shown in Figures 3 and 4.

Finally, I use the cumulative distribution function generated (using scipy.stats.norm) for each distribution to calculate the probabilities listed below in the Analysis section. The CDF evaluated at a certain abundance ratio gives the probability of finding a star with an abundance ratio less than the specified value. The probability of finding a star with an abundance ratio within the range [a, b] is found by evaluating the CDF at both points and then taking the difference i.e. CDF(b) - CDF(a).

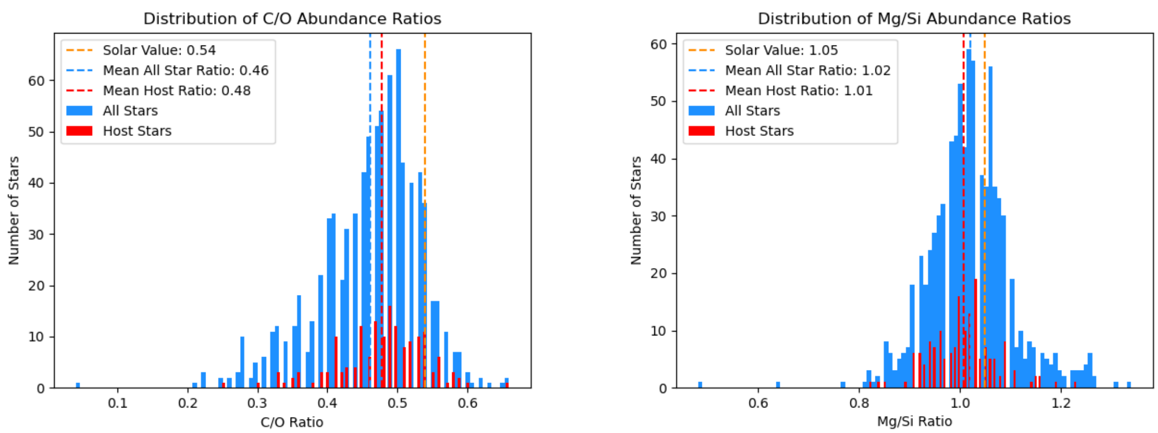


Figure 3: Here are the C/O and Mg/Si abundance ratio distribution plots recreated from Brewer and Fischer's 2016 catalogue of C/O and Mg/Si ratios. Note that the solar C/O ratio is much further from the mean of the sample than solar Mg/Si.

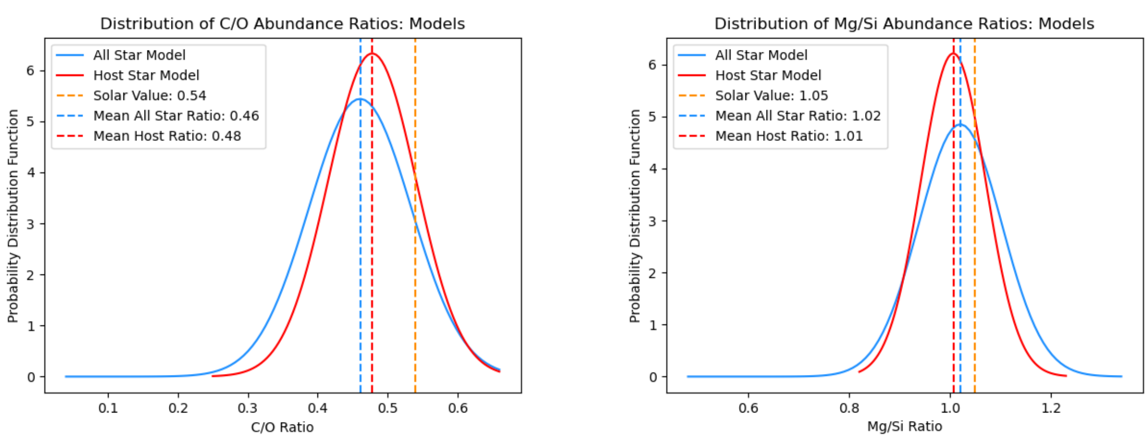


Figure 4: These plots show the probability distribution functions that I fit to the C/O and Mg/Si histograms above.

# 5 Analysis

Among all stars in the Brewer and Fischer 2016 [1] catalog, the probability of finding a star with a sub-solar C/O ratio is 86.0%, and so the probability of finding a star with a super-solar C/O ratio is 14%. Among host stars ONLY, the probability of finding a star with a sub-solar C/O ratio is a little lower at

84.0%, which means there is a slightly higher 16% chance of finding a star with a super-solar C/O ratio.

Similarly for Mg/Si ratio, the results are as follows:

Among all stars in the Brewer and Fischer 2016 [1] catalog, the probability of finding a star with a sub-solar Mg/Si ratio is 64%, and so the probability of finding a star with a super-solar Mg/Si ratio is 36%. Among host stars ONLY, the probability of finding a star with a sub-solar Mg/Si ratio is a bit higher at 75%, which means there is a 25% chance of finding a star with a super-solar Mg/Si ratio.

Now, let's do a simple calculation. What is the likelihood of finding an Earth-like planet among all of the stars in this sample? Let's define an Earth-like composition as having $0.5 <$ C/O $< 0.8$ AND $1.0 <$ Mg/Si $< 2.0$. The lower C/O bound is chosen too be near Solar value. The upper bound is chosen to be lower than the critical value where we expect no water to form i.e. C/O  0.88. The bounds for the Mg/Si ratio come from Brewer and Fischer 2016 [1].

Using the models created above, I come up with the following probabilities among all stars in the sample:

Probability of finding a star with Earth-like C/O is 29.6%

Probability of finding a star with Earth-like Mg/Si: 59.8%

Probability of finding a star with Earth-like C/O AND Mg/Si: 17.7%

Using the models created above, I come up with the following probabilities among ONLY host stars in the sample:

Probability of finding a star with Earth-like C/O is 36.4%

Probability of finding a star with Earth-like Mg/Si: 54.0%

Probability of finding a star with Earth-like C/O AND Mg/Si: 19.6%

Neither 18% or 20% seem very high, but in the whole scheme of things, this gives us a decent chance of finding a star capable of hosting an Earth-like planet. However, the true probability is MUCH smaller since we haven't even begun to take into consideration all of the requirements that make an exoplanet habitable!

# 6 Conclusion

Since the bulk of C/O ratios for other stars are similar to that of the Sun, it appears that carbon-rich terrestrial planets are rare. Although most of the stars in this sample have similar C/O ratios, the broad distribution of Mg/Si ratios (< 1 indicating silicon-rich mineralogy and > 1 implying a magnesium silicate composition) suggests that there may still be a lot of diversity in terrestrial planet compositions. Ultimately, the likelihood of a terrestrial planet being capable of maintaining surface oceans and plate tectonics is a complicated function of chemical composition, the planet's formation and its dynamical state [6]. Further constraints on exoplanetary geologies will require direct observation and so, once we are able to begin probing the interiors of nearby exoplanets, we can surely expect to find one with a composition, atmosphere, and geology unlike anything we've seen before!

## References


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