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A Statistical Approach to Planetesimal Condensate Composition beyond the Snowline Based on the Carbon-to-oxygen Ratio

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Abstract

The ratio between carbon and oxygen is regarded as an important driver of circumstellar and planetary chemistry, which can be used as a parameter to estimate the fractionation among refractory and volatile portions of a planet. From this motivation, nearly 500 stars including some with planets discovered around them are investigated. The relation between the C/O ratio and fractions of icy and refractory species is traced for planetesimals expected to form in their protostellar disks. It is found that low C/O ratios lead to planets rich in ice, but poor in organic and other refractory materials. With increasing C/O ratios, the ice fraction diminishes, where organics increase and other refractory materials dominate. Apart from that, the carbon portion incorporated in the solid phase and the redox state of the environment are altered to analyze their influence on bulk formation for generated planets. Under zero solid carbon contribution, ice formation decreases and refractory formation increases with increasing C/O ratio. When the carbon contribution is considered to be entirely in the solid phase, refractory materials are not significantly affected by the increasing C/O ratio while ice may even disappear. For reducing conditions, the C/O ratio is not an obstacle for ice formation no matter how high it is. Under oxidizing conditions, however, water is not found where the C/O ratio is greater than 0.8. Bulk densities are also calculated according to alternative scenarios along with compositional distributions, and results are compared to solar system objects. This study, therefore, exemplifies how a simple correlation can be drawn between stellar chemistry, redox state, and planetesimal composition.

Unified Astronomy Thesaurus concepts: [Protoplanetary disks \(1300\)](#); [Solar System \(1528\)](#)

1. Introduction

Extrasolar planet studies are confronted with uncertainties due to the lack of direct information about their chemical properties and limitations in spectroscopic observations. Although limited by their own uncertainties, measurements of elemental abundances and modeled physical conditions may be useful in predictions about exoplanet chemistry.

A key driver in planetesimal formation is the composition of the parent star (Delgado Mena et al. 2010; Johnson et al. 2012). Among the principal elements, the carbon-to-oxygen ratio is considered to be one of the fundamental parameters determining the bulk properties of planets (Petigura & Marcy 2011), along with the redox states of carbon, and its solid phase fraction (Johnson et al. 2011). Together, they constrain the ratios of refractory to volatile species in material condensed beyond the snowline, with a diversity from simple molecules to refractory organics (Johnson & Lunine 2005; Johnson et al. 2011, 2012).

Some modeling studies in the field have already pointed out positive or negative correlations between the C/O ratio and the composition of extrasolar planets, whether observed or modeled (Kuchner & Seager 2005; Delgado Mena et al. 2010; Fortney 2012), and connections are suggested between stellar abundances and planetary frequencies (Fortney 2012). The general appearance is that lower carbon abundance over oxygen leads to a contribution of water ice and other volatile compounds into the planetesimals higher than metallic and refractory ones (Léger et al. 2004). Alternatively, when abundances of both are close to each other, the compositional

distribution within refractory species becomes more interesting: silicate compounds are less abundant than the carbide ones (Kuchner & Seager 2005; Bond et al. 2010; Madhusudhan et al. 2011; Petigura & Marcy 2011; Fortney 2012), where planetary interiors and atmospheres could result differently from the objects found in the solar system (Madhusudhan et al. 2011).

As the observed range of stellar C/O values, as well as major planet-forming elements, extends far from the solar value, it could be expected that planets around these stars should exhibit interesting variations in their bulk compositions and densities (Johnson et al. 2012). With the assumption of a strong compositional influence of protoplanetary disks on the planetesimals formed in them, possible refractory to volatile fractions can be estimated when chemical compositions of the stars are available (Johnson et al. 2011, 2012). A reasonable amount of data for stellar metallicities and C/O ratios also gives the possibility of a statistical approach for such predictions based on stellar elemental abundances.

This paper presents a new work thanks to the use of a large data set, based on stellar C/O ratios, to predict planetary bulk properties in a systematic way to trace a relationship between stellar C/O ratios and planetary bulk compositions. The icy and rocky content distribution of the planetesimals is documented, as well. Straightforward comparisons of stellar C/O ratios and their planets are discussed. The results described in the paper are testable with observations from planned observatories such as the *James Webb Space Telescope*.

The stellar data set for the statistical study is taken from Petigura & Marcy (2011). This selection is based on the fact that

Petigura & Marcy (2011) collected nearby solar-type stars which have stellar atmospheres similar to that of the Sun. Out of 947 stars, 457 are considered for further investigation since their measurements of elemental carbon, oxygen, nickel, and iron are available. Their stellar parameters like V magnitude, distance, effective temperature, and $\log g$ are provided in Table 6 by Petigura & Marcy (2011).

The present study assumes that the planetary C/O ratio reflects that of the parent star, which may not always be the case as reported for systems like WASP-12, XO-1, and Corot-2 (Madhusudhan et al. 2011; Petigura & Marcy 2011; Thiabaud et al. 2015a, 2015b). It is acceptable to assume that the elemental ratios of an exoplanet and its host star are similar, in order to reduce the degeneracy on the planet’s composition (Brugger et al. 2017). For instance, the Fe/Si and Mg/Si bulk ratios of exoplanets are not easy to measure directly. Therefore, they are known to be derived from the host stars, and their stellar values provide a good approximation for those of the planets (Thiabaud et al. 2015b).

The outline of the paper is as follows: Section 2 presents the methodology used for the model. Section 3 documents the results of the calculations and the distributions of C/O ratio, composition, and density of planetesimals. In Section 4, a few highlighted cases are discussed on the basis of their C/O ratios, organic carbon, and CO gas fractions. And finally, Section 5 presents the conclusion.

2. Methodology

2.1. Data

Given that the original stellar data are presented relative to the solar values, they are therefore normalized to independent individual values using the solar data provided by Grevesse & Sauval (1998). As noted by Petigura & Marcy (2011), the stellar elemental abundances are expected to be insensitive to revisions in solar measurements. This expectation is confirmed here by calculations run with diverse solar data sets, for instance, the ones offered by Asplund et al. (2009) and Lodders (2003).

The abundance distribution of each star in this study follows the protosolar abundance pattern derived from the compilation of Asplund et al. (2009) based on a realistic three-dimensional hydrodynamic atmospheric model. Their set of solar elemental composition is also internally consistent and in agreement with the measurements collected from solar environment and pristine meteorites. As a consequence of this selection, the stellar C/O ratios given by Petigura & Marcy (2011) turn out to decrease by about 10%. Normalization from solar-relative logarithmic form to independent stellar elemental abundances is carried out as follows (Wong et al. 2008; Petigura & Marcy 2011):

$$[X/H] = \log(N(X)/N(H))_{\text{star}} - \log(N(X)/N(H))_{\text{solar}} \quad (1)$$

$$N(X)/N(H)_{\text{star}} = 10^{[X/H]} \times N(X)/N(H)_{\text{solar}}. \quad (2)$$

Here, $[X/H]$ stands for the logarithm of stellar abundance of element X relative to its solar counterpart and over the total abundance of hydrogen, whose dex value is fixed to 12. N is the absolute number of X atoms where hydrogen is standardized to 10^9 atoms. The solar abundances for elements considered are listed in Table 1. It should be noted that the protosolar abundances provided in Table 5 by Asplund et al. (2009) were preferred to the present observation values since

Table 1
Protosolar Abundances for Associated Elements (Asplund et al. 2009)

Element	Abundance
O	5.37×10^5
C	2.95×10^5
Fe	3.47×10^4
Ni	1.82×10^3
Si	3.55×10^4
S	1.45×10^4
H	1.00×10^9

the +.04 dex was already added to heavy elements in order to account for 4.5 Gyr of diffusion effect in the solar atmosphere. Although this does not lead to a considerable numerical difference, it is still desired to get as close to protoplanetary disk values as possible.

2.2. Distribution of Solid Phases

Following thermochemical models of the protosolar nebula (Lewis & Prinn 1980; Prinn & Fegley 1989), the strategy described in Johnson et al. (2012) is followed and it is assumed that the composition of condensed solids in protoplanetary disks beyond the snowline is mainly dominated by oxygen availability distributed among carbon monoxide (CO) gas, refractory silicates (principally anhydrous enstatite— MgSiO_3), and ice (principally water— H_2O). Here, a planet’s building block is composed of four different solid phases, namely metal, rock, ice, and organics. The relative proportions of these solid phases are determined below according to the composition of the protoplanetary disk. Each solid phase is associated with the principal element forming that phase as defined by Wong et al. (2008):

$$X_{\text{metal}} = N(\text{Fe}) + N(\text{Ni}) \quad (3)$$

$$X_{\text{rock}} = N(\text{Si}) \quad (4)$$

$$X_{\text{organic}} = N(\text{C}) \quad (5)$$

$$X_{\text{ice}} = N(\text{O}) - 3 X_{\text{rock}} - X_{\text{organic}} (1 - S_{\text{carbon}}) \frac{\text{CO}}{C_{\text{total}}} - N(\text{Fe}) (1 - 10^{([S]-[Fe])}). \quad (6)$$

Here, X_i is the amount of the component i , with $i = \text{metal}$, rock, organic, or ice. The metal amount is the sum of iron and nickel. Rocks and organics are straightforwardly related to the silicon and carbon contents, respectively. Since direct measurements of sulfur and silicon from the stars of concern are not provided by Petigura & Marcy (2011), their solar values are used as replacements. Considering that the stellar data set focuses on FGK stars in the galactic neighborhood with similar atmospheres to the solar one, this classical approach would not make a significant difference and the deviations from solar should remain moderate, although their ages and metallicities may differ (Casagrande et al. 2011).

The amount of water ice depends on the oxygen available after accounting for the proportion tied up in refractory (MgSiO_3), noncondensable organics (after CO formation), and metallic (FeO) compounds. $N(\text{O})$ stands for the initial oxygen amount before condensation. S_{carbon} is the carbon fraction in the solid phase, the leftover amount behind the gas and icy species. Since it is not determined observationally, a value of 0.2 is chosen theoretically on the basis of rough condensate proportions of rock (0.4), ice (0.4), and solid carbon

(0.2), where the entire carbon is found in the solid phase (Johnson et al. 2011). In order to see its influence on the fractionation and density results, the whole range from 0 to 1 is considered, and the consequences are discussed in Section 4.2. The $\text{CO}/C_{\text{total}}$ ratio is for the gaseous carbon fraction in the form of CO relative to CH_4 depending on the kinetics in the disks. It is the parameter to determine the oxidizing or reducing state of the environment. The oxidizing state is when all carbon is in the gaseous phase as CO, and the reducing state is when all carbon is in the gaseous phase as CH_4 (Johnson et al. 2011). Primarily, the conditions are assumed to be neutral with a $\text{CO}/C_{\text{total}}$ ratio of 0.5, then they are altered from 0 to 1 with outcomes presented in Section 4.3. And the last term accounts for the leftover iron abundance to form FeO after the formation of FeS.

The percentage fraction of each component (f) over the planetesimals is calculated considering their symbolic average molecular weights μ , where 1 mole of the carbon weight is standardized to 12 grams: $\mu_{\text{metal}}(\text{FeS} + \text{Ni}) = 88 \text{ g mol}^{-1}$, $\mu_{\text{rock}}(\text{MgSiO}_3) = 100 \text{ g mol}^{-1}$, $\mu_{\text{organic}}(\text{kerogen}) = 22.68 \text{ g mol}^{-1}$, and $\mu_{\text{ice}}(\text{H}_2\text{O}) = 18 \text{ g mol}^{-1}$.

$$(X \times \mu)_{\text{total}} = X_{\text{rock}} \times \mu_{\text{rock}} + X_{\text{metal}} \times \mu_{\text{metal}} + X_{\text{organic}} \times \mu_{\text{organic}} \times S_{\text{carbon}} + X_{\text{ice}} \times \mu_{\text{ice}} \quad (7)$$

$$f_{\text{metal}} = \frac{X_{\text{metal}} \times \mu_{\text{metal}}}{(X \times \mu)_{\text{total}}} \quad (8)$$

$$f_{\text{rock}} = \frac{X_{\text{rock}} \times \mu_{\text{rock}}}{(X \times \mu)_{\text{total}}} \quad (9)$$

$$f_{\text{organic}} = \frac{X_{\text{organic}} \times \mu_{\text{organic}} \times S_{\text{carbon}}}{(X \times \mu)_{\text{total}}} \quad (10)$$

$$f_{\text{ice}} = \frac{X_{\text{ice}} \times \mu_{\text{ice}}}{(X \times \mu)_{\text{total}}} \quad (11)$$

$$f_{\text{metal}} + f_{\text{rock}} + f_{\text{ice}} + f_{\text{organic}} = 1. \quad (12)$$

2.3. Bulk Densities

Uncompressed material density of the total condensate is calculated based on four fundamental components. The individual densities of each are provided below according to the representative compound (Wong et al. 2008). The bulk density is then determined by the relative mass fractions as described below: $\rho_{\text{metal}}(\text{FeS} + \text{Ni}) = 4.8 \text{ g cm}^{-3}$, $\rho_{\text{rock}}(\text{MgSiO}_3) = 3.36 \text{ g cm}^{-3}$, $\rho_{\text{organic}}(\text{kerogen}) = 1.5 \text{ g cm}^{-3}$, and $\rho_{\text{ice}}(\text{H}_2\text{O}) = 0.94 \text{ g cm}^{-3}$.

$$\rho_{\text{bulk}} = \left(\frac{f_{\text{rock}}}{\rho_{\text{rock}}} + \frac{f_{\text{metal}}}{\rho_{\text{metal}}} + \frac{f_{\text{organic}}}{\rho_{\text{organic}}} + \frac{f_{\text{ice}}}{\rho_{\text{ice}}} \right)^{-1}. \quad (13)$$

3. Results

3.1. C/O Distribution

The carbon-to-oxygen stellar ratios are calculated to vary from 0.21 to 1.35. This range is lower by about 10% more than that of Petigura & Marcy (2011) who stated it to be 0.24–1.55. As Petigura & Marcy also pointed out, this is due to the use of a newer source of solar data from Asplund et al. (2009).

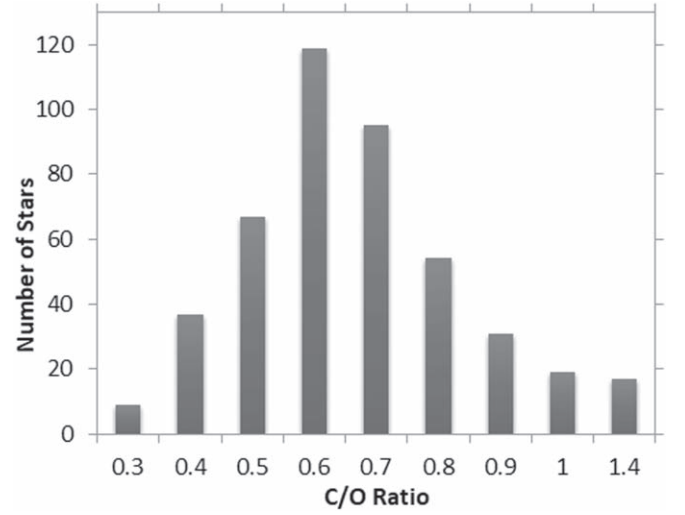


Figure 1. Distribution of the carbon-to-oxygen ratio among 457 stars given by Petigura & Marcy (2011), based on the adaptation of the solar data from Asplund et al. (2009).

Accordingly, the number of stars having a C/O ratio equal to or higher than 1 in the data set of Petigura & Marcy (2011) decreases from 47 (10%) to 21 (4.6%) in the calculations here, and 70 of 457 (15%) stars hold a C/O ratio equal to or higher than 0.8. These two ranks comprise 6%–10% and 25%–30% of the stars in the literature survey done by Fortney (2012), who criticized them as being quite high.

The frequency plot of C/O distribution of the stars is shown in Figure 1. The majority falls in the interval of 0.5–0.8. For comparison, the C/O ratio of the Sun is 0.55 (Asplund et al. 2009). The fact that the C/O ratios of most stars accumulate around the solar value is not unexpected since the stellar data is focused on FGK stars in the galactic neighborhood (Petigura & Marcy 2011).

When the paper was published in 2011, 72 out of those 457 stars were known to harbor a planet (or more) around them. The C/O ratio distribution range for the host stars is 0.35–1.35. The majority of their C/O ratios is observed again around 0.6 and 0.7. Therefore, contrary to the claim in the study of Kuchner & Seager (2005) and Petigura & Marcy (2011), it is not very easy to track a direct correlation between the possibility of being a parent star and having a high C/O ratio.

The irrelevancy between the stellar C/O ratio and hosting planets is also supported by Delgado Mena et al. (2010) who did not observe any remarkable difference in carbon or oxygen abundances between stars with and without known planets. Bond et al. (2010) also noticed that stars, host or nonhost, demonstrate the same C/O distribution.

3.2. Compositional Distribution

Although Petigura & Marcy (2011) worked on the same set of stars and identified some correlations between the C/O ratio and planetary chemistry, they did not consider the basic structural distribution of planetesimals on the basis of stellar chemistry. It is natural to expect different selections of rocky species with diverse compositional ratios in planetary systems around stars of nonsolar abundance (Bond et al. 2010; Delgado Mena et al. 2010; Fortney 2012).

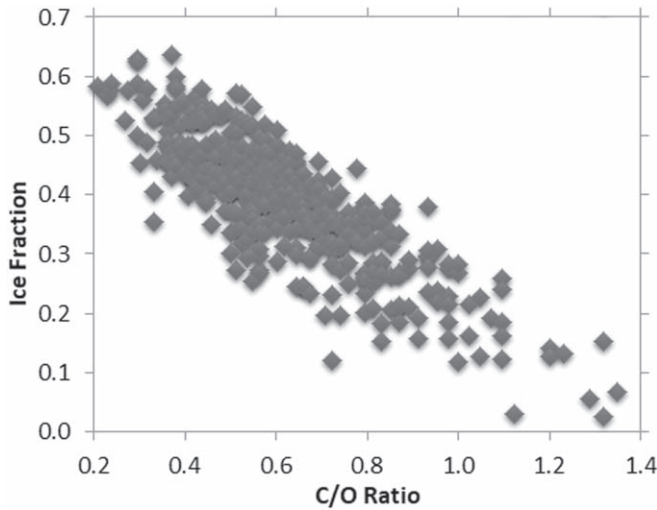


Figure 2. Distribution of water ice fraction over total material available, on the basis of carbon-to-oxygen ratio of parent stars. Results are derived from the data provided by Petigura & Marcy (2011).

For protoplanetary disks around stars with C/O ratios of 0.8 or higher, refractory materials are expected to have carbon-dominated composition instead of silicates, which will end in the formation of planets different from the ones in the solar system (Lodders 2010; Bond et al. 2010; Johnson et al. 2011, 2012; Fortney 2012; Nissen 2013). Here, 70 out of 457 stars (15.31%), and 11 out of 72 host stars (15.28%) are found to have $C/O \geq 0.8$, with the capacity of harboring exotic carbide planets. The probability of carbide planet production, on the other hand, is not distinguishable between stars known to be hosts or those without any planets.

It should be noted that in this section, the results are given for neutral conditions ($CO/C_{total} = 0.5$) and for a low solid carbon ratio ($S_{carbon} = 0.2$). Results for diverse redox states and physical phases are given and discussed in the following section.

The anticorrelation of ice availability with increasing C/O ratio is clearly observable in Figure 2. For the C/O ratio of 0.21–1.35, the highest ice contribution is 64%, where the lowest is 3%. This result gives the idea of finding volatile species, even slightly, for the planetesimals within a stellar disk of a C/O ratio up to 1.4. This result is consistent with the expectations of previous studies stating that the systems with subsolar C/O ratios should contain plenty of ice-rich planetesimals (Johnson et al. 2011, 2012), however, more generous in ice fraction for the systems with supersolar C/O values as they favored little or no ice contribution to planetesimals due to the unavailability of free oxygen (Johnson et al. 2011, 2012). In this study instead, the formation of ice seems to be still possible although very little, even if the C/O ratio is greater than 1.

The theoretical expectation of silicate and metallic contributions in extrasolar planetesimals has a strong dependence on the C/O ratio of a given disk (Delgado Mena et al. 2010; Johnson et al. 2011, 2012), which is confirmed in the results here. Figure 3 clearly shows that refractory fraction increases with the C/O ratio. The minimum refractory fraction expectation for planetesimals is 28%, whereas the maximum is 82%. If the remaining 18% for the maximum case is not composed of ice, then it should be organics instead. Both ice and refractory

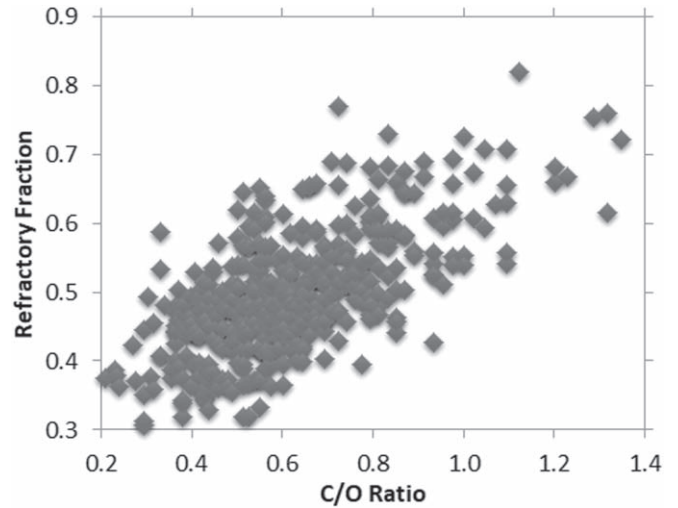


Figure 3. Distribution of refractory (silicate and metallic) fraction over total material available, on the basis of carbon-to-oxygen ratio of the parent stars. Results are derived from the data provided by Petigura & Marcy (2011).

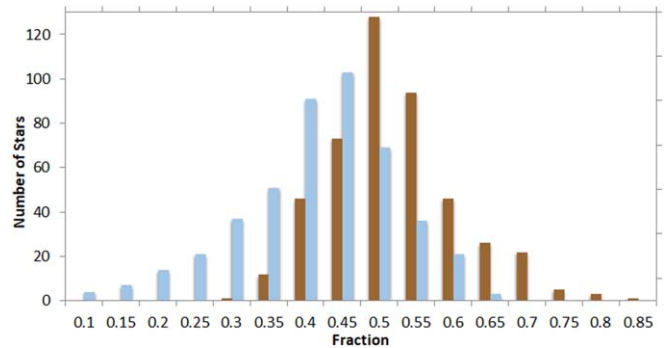


Figure 4. Distribution of refractory material (brown) and ice content (blue) for the planetesimals around the stars of the study.

species turn out not to be the total composition of a planet, as can be seen in Figure 4.

The general distribution of ice and refractory fractions (rock and metal) is displayed in Figure 4. Ice fraction from all data seems to reach maximum 65%, implying that the construction of planetesimals under any stellar chemical composition should not contain an ice ratio of more than this value. As for the refractory fraction, the maximum reaches to 85% where the minimum is 30%. The highest probability found for the refractory fraction is 50%, while it is 45% for the ice fraction. It seems therefore more common for planets to be comprised of more or less close ratios between volatile and solid contributors as both of them present a fairly smooth distribution accumulating toward intermediate values.

3.3. Density Distribution

Bulk density is an important parameter to relate to planetary components, mass and volume relation, and even distance of formation zone from the parent star. It should be noted that the densities are calculated solely based on planetesimal composition, being for the terrestrial and icy planets only, not for gas giants. Since other dynamic factors like planetary mass, formation epoch temperature, volume, or compression are not taken into account, a strict conclusion about planetary sizes

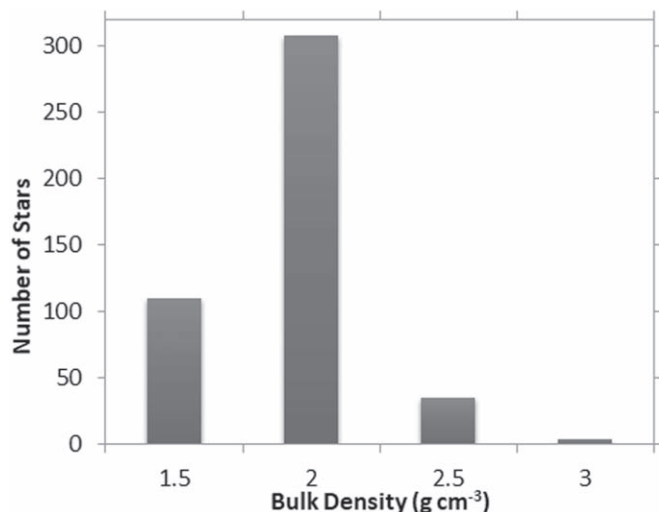


Figure 5. Distribution of bulk density of planetesimals around the stars of study.

cannot be given. Densities should be taken as only approximate for Earth-sized planets.

In the present study, the [Si/Fe] and [S/Fe] ratios have been set to the solar, although they are observed to vary with stellar metallicity (Adibekyan et al. 2012; Bensby et al. 2014; Mishenina & Paramonova 2015; Duffau et al. 2017). The absolute range of [Fe/H] listed in Table 3 of Petigura & Marcy (2011) is from -1.95 to 0.56 dex. However, we choose to disregard the outliers by taking the bulk of the stellar distribution expressed as the standard deviation around the mean in Table 3, that is, a range from -0.2 to $+0.34$ dex. Figure 15 of Bensby et al. (2014) shows that within that range, the value of [Si/Fe] is on or just slightly above solar. We tested the effect of changing [Si/Fe] and [S/Fe] with metallicity within the range cited above, and we found the resulting variation in planetesimal density to be 10% or less in about 80% of the cases, with the rest showing a change between 10% and 20% in the density. Even the larger changes do not exceed those which result from other poorly constrained effects such as porosity. Given the other uncertainties in our analysis, a change from [Si/Fe] = 0 to [Si/Fe] = 0.2 would therefore not qualitatively affect our conclusions.

The results shown in Figure 5 influence other factors beyond the ultimate bulk densities of planets formed around the stars. Composition of the solids affects the enrichment of heavy elements expected in the atmospheres of giant gas planets, not totally determining the overall density of such planets. Likewise, if the uncompressed material in a system is mostly chondritic rock and metal, then a terrestrial sized body is expected to have a high density like that of the Earth (5.51 g cm^{-3}). Lastly, in the sense of uncompressed density interval, discovering icy rocky planets around the density of Pluto (2.05 g cm^{-3}) seems the most probable.

Bulk densities whose distribution is given in Figure 5 are found within a range of 1.25 g cm^{-3} (Uranus: 1.27 g cm^{-3}) to 2.96 g cm^{-3} (Europa: 3.01 g cm^{-3}) with an average of 1.65 g cm^{-3} (Neptune: 1.64 g cm^{-3}). Density values are taken from NASA’s JPL solar system dynamics webpage.⁵

The relation of bulk density with C/O ratio is displayed in Figure 6. Since a greater C/O ratio implies more contribution

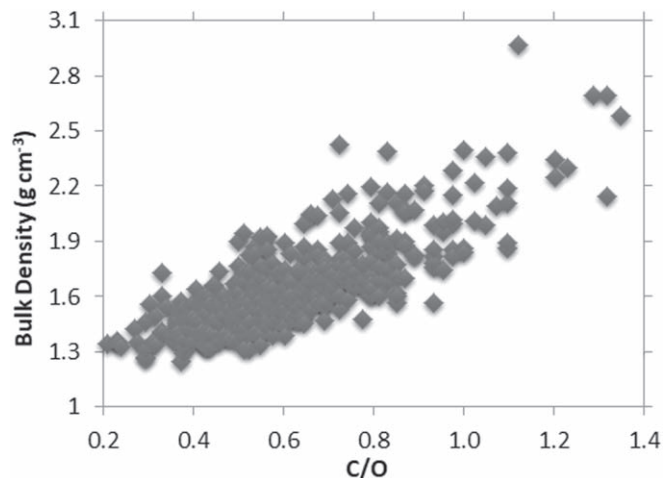


Figure 6. Statistical distribution of planetesimal bulk densities based on the C/O ratio.

from rocky and metallic compounds, a correlation is inevitable between the two. Still, it would be wise to remember the existence of dense terrestrial planets at least in the solar system, and not to consider the C/O ratio of a protoplanetary disk the only factor to account for the overall densities of the planets. Other physical dynamics like compression, atmospheric and hydrospheric loss, local heterogeneities throughout the disks, and chemical mechanisms like settlement, will be highly influential on the ultimate shape of a planet.

4. Discussion

Extraterrestrial planets discovered so far carry different characteristics compared to those of the solar system (Santos et al. 2000). In this section, the differentiation of the basic composition of five representative cases are discussed in further detail on the basis of their C/O ratios. Although the abundances of iron and/or magnesium relative to that of silicon have been commonly taken into account for the refractory composition of extrasolar planets (Grasset et al. 2009; Rogers & Seager 2010; Dorn et al. 2015; Brugger et al. 2017; Santos et al. 2017; Unterborn & Panero 2017), sometimes along with carbon and oxygen (Santos et al. 2015; Thiabaud et al. 2015b); we study the C/O ratio here whose relative distribution among gas, refractory, and icy species through a protoplanetary disk gives clues about water availability and the probable composition of planetesimals, in order to focus on the volatile phase.

Another point to note is that, for the sake of simplicity, we considered pyroxene (MgSiO_3) to be the only mineral formed in our model. If the formation of olivine (Mg_2SiO_4), whose molecular weight is 140.7 g mol^{-1} and density is 3.21 g cm^{-3} , is taken into account instead, the organic and metal fractions remain almost unaffected by this change. However, the fraction of rocks increases in the 4%–14% range, depending on the stellar C/O ratio, while the ice fraction decreases for 3%–12%. Accordingly, the overall density increases from 4% up to 21%.

We also tested the influence of a MgSiO_3 – Mg_2SiO_4 mixture in 50%–50% proportions on calculations by considering molecular weight and density averages of the two species, namely, 120.5 g mol^{-1} and 3.29 g cm^{-3} . From this, we find that the global density varies in the 2%–11% range, compared to the case of pure MgSiO_3 , and depending on the adopted

⁵ <http://ssd.jpl.nasa.gov>

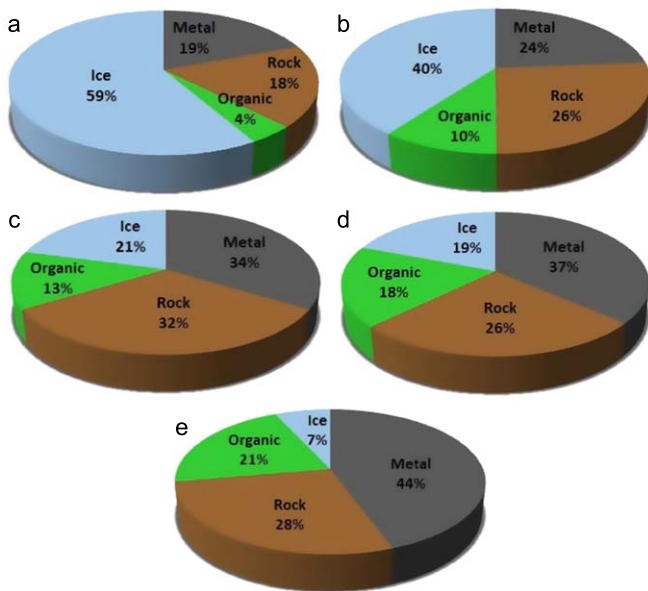


Figure 7. Basic planetesimal compositions based on the stellar chemistry for (a) HD 88656 (C/O: 0.21, bulk density: 1.35 g cm^{-3}); (b) the Sun (C/O: 0.55, bulk density: 1.61 g cm^{-3}); (c) HD 205353 (C/O: 0.81, bulk density: 2.11 g cm^{-3}); (d) HD 11506 (C/O: 1.07, bulk density: 2.09 g cm^{-3}); and (e) HD 45652 (C/O: 1.35, bulk density: 2.58 g cm^{-3}).

C/O ratio. The change in the organic and metal contributions is again as minor as 0%–2%. The fraction of rocks increases in the 2%–8% range, on the basis of the C/O ratio, while the ice fractions drop from 2% to 6%.

After a general comparison, various cases with diverse solid carbon contribution and CO gas ratios follow.

4.1. Case Studies

Out of 457 stars, those with minimum and maximum C/O ratios, the Sun and two other stars are chosen as case studies. Figure 7 shows a summary of planetesimal compositions with increasing C/O ratios where a full condensation of fundamental constituents is assumed. Three of them (Sun, HD 11506, and HD 45652) are already known to harbor planets around them. The first straightforward influence of the C/O ratio on the compositions is the ice fraction. The negative correlation between the two is visualized clearly from one C/O value to the next.

For the smallest C/O case of 0.21, HD 88656, ice contribution is 59%, covering more than half of a presumed planet. The organic fraction is as small as 4%, whereas the remaining is shared between the refractory components evenly: 18% rocky and 19% metallic. Due to the dominance of ice, the overall bulk density is calculated to be low at 1.35 g cm^{-3} . This value is comparable with the inner satellites of Uranus like Cordelia and Ophelia (1.3 g cm^{-3}), which are also thought to have approximately equal icy and rocky components (Hussmann et al. 2006). A structural differentiation might be imagined for the planet, where metallic compounds constitute a central core, rocky structures on top of the core, and a thick ice shelter covering the surface. Organics might be mixed and dissolved within the ice layer if ice accretion into the planet was provided by a mixture of ices and organics together, as well as clathrate hydrates, i.e., organics captured by water ice (Hersant et al. 2001; Johnson et al. 2009).

If the surface temperature is higher than the freezing points of various volatiles other than the water, they might make up a tenuous atmosphere, perhaps out of CO_2 like already observed on Ariel (Hussmann et al. 2006). Under the assumption that the composition of planetesimals reflects that of the protoplanetary disk, a planet orbiting the star HD 88656 can safely be expected to be an ice-rich planet. High water abundances in icy planets come from the fact that they are formed beyond the snowlines of the disks (Encrenaz 2010). If water is conserved in the solid phase, the planets are still found beyond the snowline. However, if they experience some migration toward the star, the ice will melt with increasing temperature, and convert them into ocean planets (Léger et al. 2004).

For the case of the Sun, whose C/O ratio is 0.55, the ice fraction drops to 40%. When compared to HD 88656, organic contribution is higher, 10%. Rocky and metallic fractions are richer as well, with 26% and 24%, respectively. This planetary model for the protosolar nebula might be presented mostly by some moons around solar giants, or objects that originated from the Kuiper Belt and beyond. Although this distribution implies the dominance in refractory components as observed in solar terrestrial planets, the contribution from ice would be too high for this category. For example, Earth, the wettest among solar rocky planets, contains only 0.02% water of its total planetary mass (Elkins-Tanton 2011). Abundant ice content along with organics may be reminiscent of the ice giants.

On the other hand, a major part of the distant objects in the solar system, especially those beyond Neptune, are thought to be composed of ice–rock mixtures with ratios of 1:1 or 1:2 (Hussmann et al. 2006). This composition model and the calculated density of 1.61 g cm^{-3} are compatible with some icy satellites of Saturn like Enceladus and Phoebe (1.61 g cm^{-3} and 1.64 g cm^{-3} , respectively), and some big satellites of Uranus like Ariel and Titania (1.59 g cm^{-3} and 1.66 g cm^{-3} , respectively).

The values calculated for HD 205353 with a C/O value of 0.81 and HD 11506 whose C/O ratio is 1.07 are close to each other. Compared to the Sun with a C/O ratio of 0.55, their ice fractions diminish to half, 21% and 19%, respectively. Organic contribution, on the other hand, slightly increases for HD 205353, 13%, yet it is almost double compared to the solar case, 18%. This straight relation between the C/O ratio and organic fraction is only natural. The rest of HD 205353 is distributed among the rocky (32%) and metallic (34%) portions almost evenly, where for HD 11506 they are 26% and 37%, respectively.

Bulk densities of HD 205353 and HD 11506 are calculated to be close, 2.11 and 2.09 g cm^{-3} , respectively. These distributions and densities resemble Ceres, the largest object in the Asteroid Belt, with a density of 2.16 g cm^{-3} . Ceres is known to contain water about 25% of its total bulk, and thought to have a rocky core covered with a thick crust of salt and ice mixture (Park et al. 2016). The largest Neptunian satellite, Triton, also falls in this planetary model with its density of 2.06 g cm^{-3} . Triton is believed to have a core of rock and metal, an icy mantle, as well as a crust of frozen nitrogen on top.⁶

The last case is HD 45652 with a bulk density of 2.58 g cm^{-3} , the heaviest among all. The ice ratio is the lowest with 7%, where the organic and the metal ratio are the highest

⁶ <http://solarsystem.nasa.gov>

with 21% and 44%, respectively. Rock content is close to the cases of the Sun and HD 11506 with 28%.

Compositional structure for the outer moons of Jupiter has not been studied so far; however, the density estimated for them is 2.6 g cm^{-3} except Adresthia, Thebe, and Metis. Since density calculations can be used in the service of ice-to-rock ratios of distant satellites (Wong et al. 2008), a bulk fractionation calculated for 2.58 g cm^{-3} can be proposed for these satellites. As their density is higher than the satellites of more distant planets, they may be expected to have less ice and volatiles, as found in cases with C/O ratios higher than the Sun.

Even if the C/O ratio is bigger than 1, a slight amount of ice formation in planetesimals can still be found, according to the results. A sample object in the solar system can be the Jovian moon Europa with a bulk density of 3.01 g cm^{-3} , greater than the densities calculated for high C/O cases in this study. Europa is thought to have a thick layer of ice and liquid water on the surface, whereas its overall density suggests a composition similar to terrestrial planets made of mainly silicate rocks and a metallic core at the same time (Kargel et al. 2000; Kivelson et al. 2000). This may imply that terrestrial planets rich in carbide or silicate material might have had some water in the beginning; however, dynamic and environmental factors like temperature, stellar winds, rotation, or gravitational insufficiency led to evaporation and loss of water and other volatiles from their surfaces.

Where the organic contribution is high, like for the cases of HD 205353, HD 11506, and HD 45652, there might be thick atmospheres of light organics in place of or along with a water ice layer, if the temperature is high enough to set volatiles free in gaseous form, as expected from the formation zone of planetesimals inside the snowlines. However, if the temperature is low, then volatile organics may cover the surfaces of planets as ice layers, or as oceans, such as Titan in the past (Tobie et al. 2006).

Using a C/O ratio as a basic clue can help estimate compositional distributions for planets possibly present around stars. A well-known case, for example, can be WASP-12 with a C/O value of 0.35. In the light of calculations presented here, the star's elemental composition leads to a distribution of 54% ice, 7% organic, 14% rock, and 24% metal with a density of 1.39 g cm^{-3} . This result is reminiscent of inner Uranian moons from Cordelia to Puck and inner Neptunian moons from Naiad to Proteus whose densities are found to be 1.3 g cm^{-3} . Half ice-half rock composition is also suitable for the mentioned objects; therefore, this estimation may be used as a hint for the composition of the planets around the star WASP-12.

4.2. Solid Carbon Ratio

Carbon partitioning between gas and solid phases might help reveal a planet's consistency with its protoplanetary disk composition (Wong et al. 2008), bulk density determination, or its type; a terrestrial or a gas planet. Large satellites of solar giants, for example, have densities that give clues about carbon ratios in volatile molecules, or precipitation as refractory phases (Wong et al. 2008).

The carbon fraction (S_{carbon}) incorporated into a solid phase is originally taken to be 0.2 in the calculations above. To compare the changes in the results according to the solid carbon ratio, calculations are run once more for the whole S_{carbon} range of 0–1, while other parameters are left unchanged.

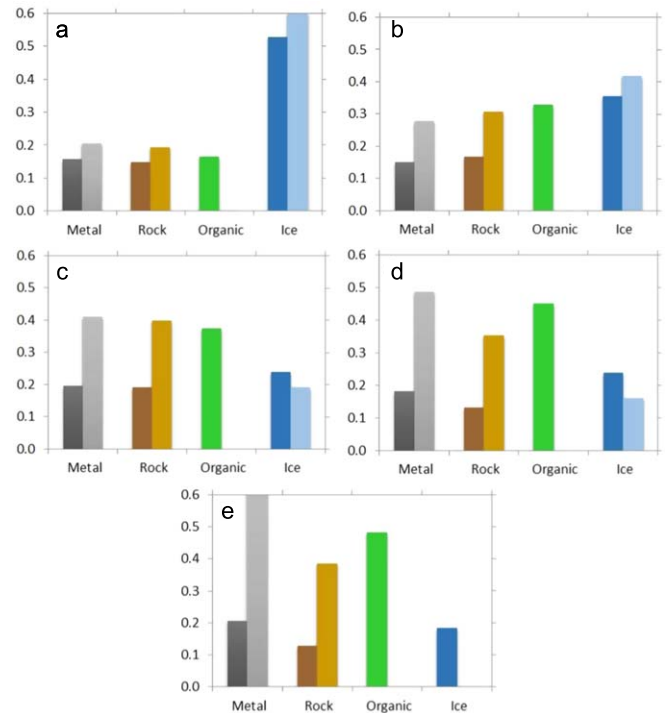


Figure 8. Comparison of planetesimal compositions calculated for a solid carbon ratio of 0% (light shades) and 100% (dark shades) based on fundamental stellar chemistry for (a) HD 88656 (C/O: 0.21); (b) Sun (C/O: 0.55); (c) HD 205353 (C/O: 0.81); (d) HD 11506 (C/O: 1.07); and (e) HD 45652 (C/O: 1.35).

A higher carbon fraction in the solid phase, whether combined with other elements or not, leaves less carbon available to form gas and volatile compounds, as well as leaving less oxygen available for the formation of the rest of the solids. Although the total refractory portion of planetesimals will increase, the metallic and rocky contributions will decrease. And this in turn will lower the overall bulk densities.

The icy fraction of light organics and water, on the other hand, decreases in the cases with low C/O, whereas it increases in high C/O cases.

In Figure 8, results for five cases studied are summarized in two comparative ways. Each plot is drawn for the results of 0% and 100% of solid carbon ratio for a certain disk, and the figure collects the cases together in the order of increasing C/O ratio. The shift of ice fraction toward organic and refractory species is easy to follow from one case to the other. As could be expected, none of the cases shows any organic fractionation while the entire carbon portion is incorporated into the solid phase. Naturally, the organic fraction is observed to increase with increasing C/O, while ice fraction diminishes.

The lowest C/O case with 0.21, HD 88656, is calculated to have an overall planetary density of 1.35 g cm^{-3} while the solid carbon fraction is 0%, which slightly decreases to 1.33 g cm^{-3} at 100%. The decreases of 4% in metals, 4% in rocks, and 7% in ice in the first case, contribute in organic species from 0% to 17% in the second case. The most abundant contributor is water ice, comprising more than half of the planet with or without organics, and ice:refractory ratio of 1:1 changes to volatiles:refractory of 2:1.

The case for the Sun yields bulk densities of 1.69 and 1.47 g cm^{-3} for the minimum and maximum solid carbon fractions. As the solid carbon increases from 0% to 100%,

metallic and rocky materials are diminished almost by half, while ice loses only 6%. The increase in organics is from 0% to 33%. General distribution changes from ice:refractory of 1:1 to volatiles:refractory of 2:1.

For the case where solid carbon is 0%, the planet for HD 205353 is made of 41% metal and 40% rock, leaving the other 19% made up of ice with a bulk density of 2.45 g cm^{-3} . If solid carbon content reaches 100%, metal and rock portions diminish to half, and density drops to 1.66 g cm^{-3} . Ice, on the other hand, increases to 24%, and organics appear with a ratio of 37%. This leads to a shift of distribution from ice:refractory of 1:4 to volatiles:refractory of 3:2.

The results for HD 11506 are not very different from the case of HD 205353. 0% of solid carbon produces a dense planet featuring 49% of its mass as metal, 35% as rock, and 16% as ice, with a bulk density of 2.65 g cm^{-3} . 100% solid carbon instead results in a density of 1.59 g cm^{-3} with fractions of 18% metal, 13% rock, and 24% ice, where the organics comprise 45% of the bulk. The bulk distribution changes from ice:refractory of 1:5 to volatiles:refractory of 3:1.

Lastly, the bulk density of HD 45652 is calculated 4.12 g cm^{-3} for 0% solid carbon contribution, and 1.67 g cm^{-3} for 100% contribution. The first case produces a dry planet composed of 62% metal and 38% rocks, where the second case offers a composition of 20% metal, 13% rock, 18% ice, and 48% organics. The general distribution changes drastically from entirely refractory to volatiles:refractory of 3:2. This noteworthy differentiation in the bulk ratios lead to a change in planetary type as well; from dry terrestrial, like Mercury or Moon, to an organically rich one, maybe like Titan. This is a good example showing that a planet's destiny can change dramatically from 100% to 0% of a solid carbon contribution.

The case where there is no solid carbon is included, increasing C/O ratio results in decreased ice fraction, even disappearing and under high C/O ratios, and increased metal and rock fractions. When the entire carbon is in solid form, on the other hand, refractory portions are not remarkably affected by an increase in C/O. Ice fraction still decreases due to the loss of oxygen into organic combinations, especially for high C/O ratios, where organic materials naturally increase with the C/O ratio. In the range of C/O ratio studied here, organic fraction presents a variation from 0.17 to 0.51, implying that a planet cannot be dominated solely by organics. However, it is possible for it to be dominated by volatiles, if organics and water are taken into account together.

4.3. CO Ratio Over Total Carbon

Carbon partitioning between CO and CH₄ is another important parameter controlling water abundance and refractory density, as well as the oxidizing/reducing states in the disks (Wong et al. 2008; Johnson et al. 2011). Where CO is the dominant gas, the conditions will be oxidizing, diminishing the oxygen availability for H₂O formation (Johnson et al. 2011). By contrast, reducing conditions, where CH₄ dominates, will give freedom for more water availability (Johnson et al. 2011). In other words, oxidizing conditions correspond to abundant CO yet scarce H₂O, and reducing conditions correspond to abundant CH₄ and H₂O.

Available oxygen under reducing conditions will be consumed for water production primarily, leaving less of it for silicates. When the environment is oxygen-poor, part of the silicate-forming elements which cannot find oxygen will

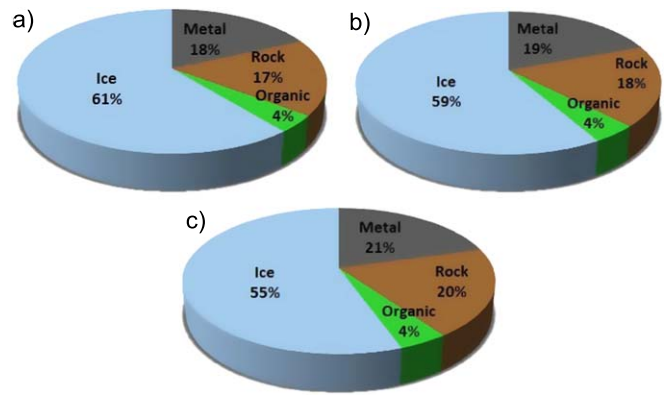


Figure 9. Planetesimal compositions in the stellar disk of HD 88656 with C/O: 0.21 calculated for (a) reducing (bulk density: 1.31 g cm^{-3}); (b) neutral (bulk density: 1.35 g cm^{-3}); and (c) oxidizing (bulk density: 1.39 g cm^{-3}) conditions.

combine with carbon, producing carbide species like SiC, TiC, or graphite (Bond et al. 2010).

The CO–CH₄ distribution, designated as CO/C_{total}, is originally taken as 0.5 in the calculations above. In order to compare changes in the results, with regards to the CO ratio over the total carbon, calculations are run for the complete range of 0–1, from reducing toward oxidizing conditions. Other parameters are preserved in their original values.

Calculations demonstrate that an increase in CO fraction over total carbon amount leads to decrease in water ice abundance. This is an expected consequence due to the fact that more oxygen will be consumed by CO for a higher C/O ratio, with less availability for water formation. As such, metal, rock, and organic fractions are observed to increase along with CO, resulting in higher bulk density values. Therefore, oxidizing conditions are more likely to produce planetesimals composed of heavily refractory materials, while reducing conditions of methane dominance facilitate the formation of water and other volatile organics. This finding may be useful for the estimation of what regions in a disk and under what type of circumstances planets and moons are formed, judging from their compositions and/or bulk densities.

Higher C/O ratios are plausible especially under reducing conditions, leading to condensates rich in rocky and metallic composition with little ice contribution (Johnson et al. 2011). This expectation is confirmed in the calculations here. An increase in C/O ratio means more carbon abundance over oxygen, whose excess amount is converted to other carbide compounds and CH₄. This reduces the redox state of the environment, and the oxygen released from CO will be used for water formation.

Five selected cases are documented in order to present these theoretical expectations and general outlines for three conditions where CO ratio over the gas is 0% reducing, 50% neutral, and 100% oxidizing.

The case of HD 88656 with the lowest C/O ratio is given in Figure 9. The retreat of ice fraction from 61% to 55%, and increase of bulk density from 1.31 to 1.39 g cm^{-3} are displayed on three pie charts. Organic content remains the same, and the difference coming from ice retreat is shared between rock and metal. The highest ice contribution is observed in the reducing case, where the refractory part is favored under the oxidizing circumstance.

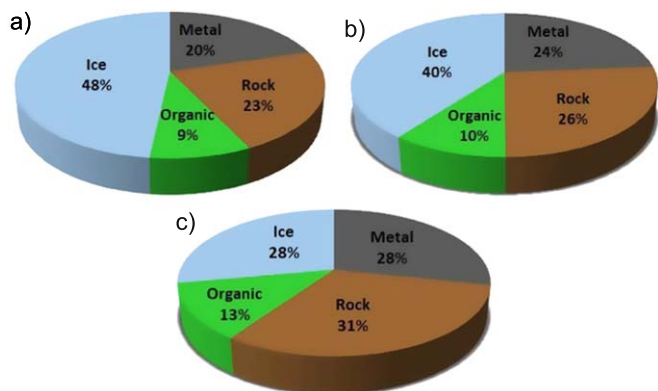


Figure 10. Planetesimal compositions in the protosolar nebula with C/O: 0.55 calculated for (a) reducing (bulk density: 1.47 g cm^{-3}); (b) neutral (bulk density: 1.61 g cm^{-3}); and (c) oxidizing (bulk density: 1.88 g cm^{-3}) conditions.

Figure 10 is drawn for the protosolar nebula. A reducing environment produces 48% water ice, 9% organics, and 43% refractory fractions with an overall density of 1.47 g cm^{-3} . Oxidizing circumstances give a fractionation of 28% water ice, 13% organics, and 59% refractory fractions with a bulk density of 1.88 g cm^{-3} . This density range is in accordance with that of Wong et al. (2008) who calculates it as $1.5\text{--}2.2 \text{ g cm}^{-3}$.

Evaluating from these ice-to-refractory ratios and densities, the evolutionary history of solar planets and moons, at least those beyond the snowline could be informed. Likewise, asteroid composition estimations from remote zones of the solar system may help determine the CO/CH₄ ratio from the epochs or locations where they were formed. For example, the Jovian satellites of Thebe, Adrastea, and Metis, with their estimated bulk densities of 3.0 g cm^{-3} , may be pointing out an origin of a highly oxidizing circumstance. On the contrary, low estimated densities of some Uranian satellites like Setebos, Stephano, or Francisco, with an average density of 1.5 g cm^{-3} , might have originated from reducing conditions. However, it should be noted that these solar objects are discussed only on the basis of their densities, as their inner structures are currently unknown.

A similar discussion is made by Johnson & Lunine (2005) on the importance of the CO/CH₄ ratio. They explain the overall densities and bulk compositions of some outer planet satellites based on the probable CO/CH₄ ratios of the zones from which the satellites originated. This method is considered useful to determine whether satellites were born within the planetary systems they belong to or included in the systems later on. For instance, Johnson & Lunine (2005) claim that regular icy satellites of Saturn should be formed under reducing circumstances, while Phoebe indicates an oxidizing origin, hence, joined the system as a captured object. Another example is Pluto, whose density was found to be consistent with an oxidizing environment in its origin, probably with a high solid carbon fraction, as well.

The case of HD 205353 is displayed in Figure 11. The most obvious change is the drop of ice content from 34% to 1% toward oxidizing conditions. A high C/O ratio of 0.81 does not leave enough space for H₂O formation. While the organic portion increases for only 5% of the bulk, the increase in metal and rock fractions are rather important. The gap between bulk densities of two cases is also huge: 1.74 g cm^{-3} for reducing; 3.10 g cm^{-3} for oxidizing case.

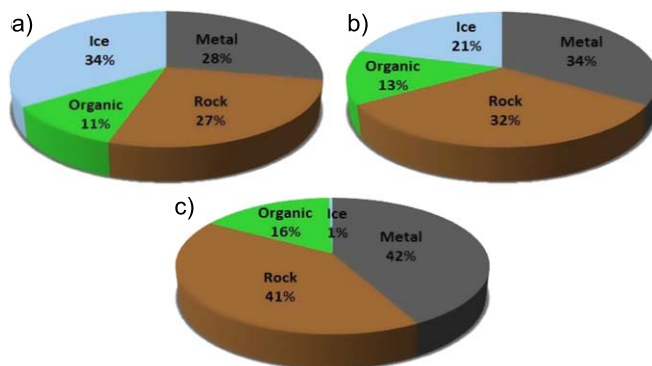


Figure 11. Planetesimal compositions in the stellar disk of HD 205353 with C/O: 0.81 calculated for (a) reducing (bulk density: 1.74 g cm^{-3}); (b) neutral (bulk density: 2.11 g cm^{-3}); and (c) oxidizing (bulk density: 3.10 g cm^{-3}) conditions.

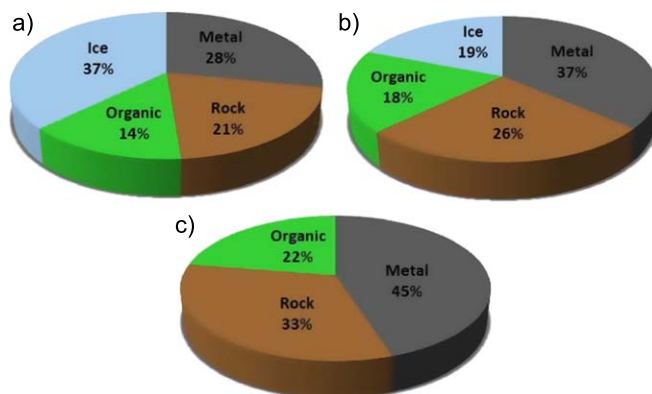


Figure 12. Planetesimal compositions in the stellar disk of HD 11506 with C/O: 1.07 calculated for (a) reducing (bulk density: 1.64 g cm^{-3}); (b) neutral (bulk density: 2.09 g cm^{-3}); and (c) oxidizing (bulk density: 2.94 g cm^{-3}) conditions.

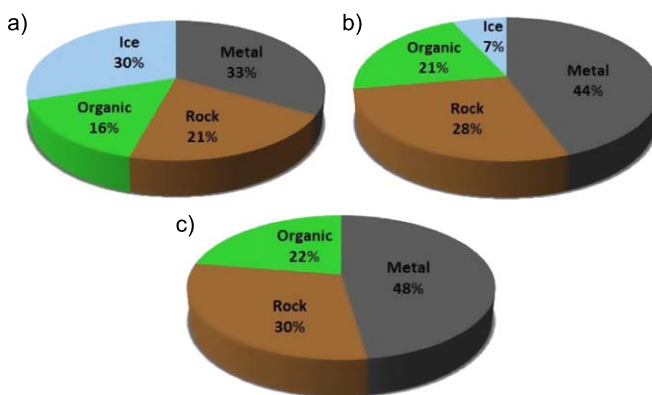


Figure 13. The planetesimal compositions in the stellar disk of HD 45652 with C/O: 1.35 calculated for (a) reducing (bulk density: 1.80 g cm^{-3}); (b) neutral (bulk density: 2.58 g cm^{-3}); and (c) oxidizing (bulk density: 2.96 g cm^{-3}) conditions.

HD 11506, whose C/O ratio is unity, loses its 37% of ice ratio totally toward the oxidizing case, because all of the oxygen is already consumed by CO. As can be seen in Figure 12, organic content increases from 14% to 22%, while metal and rock fractions increase about 1.5 times. Density is also doubled toward oxidizing case, from 1.64 to 2.94 g cm^{-3} .

Finally, the proportions for HD 45652, which represents the case where C/O is greater than 1, are displayed in Figure 13.

Once again, the 30% of ice fraction under reducing conditions is totally lost under oxidizing conditions. Organic content increases for 6%, and total refractory content increases from 44% to 78%. Density increases from 1.80 to 2.96 g cm⁻³.

If the outcomes of the C/O ratio and redox state are evaluated at the same time, it seems no longer possible for water formation under oxidizing circumstances when C/O exceeds 0.8. Reducing conditions however, allow abundant ice formation in the disks, whatever the C/O ratio is. It is also apparent that contributors other than water ice are also sensitive to the changes in the CO/CH₄ ratio. Therefore, planetesimal compositions may exhibit dramatic variations, from highly reducing to highly oxidizing circumstances, such that bulk densities can be doubled or halved from one extreme case to another.

5. Conclusions

In this study, a rough bulk distribution model is introduced for planetesimal diversities. Chemical composition of a star is assumed to correspond to the composition of its protostellar disk, and metallic, refractory, organic, and icy fractionation for its planets are estimated accordingly. Special attention is paid to the carbon-to-oxygen ratio, because it is one of the essential chemical drivers of circumstellar and planetary chemistry. About 500 stars were studied to trace a statistical trend between stellar C/O ratios and planetesimal compositions.

It should be kept in mind, however, that this work presents a straightforward approach by which the disks are assumed to share the same compositional distribution as their parent stars. Many factors such as galactic position, temperature, pressure, mass distribution, elemental distribution, redox state, and dynamic factors like formation and migration of giant planets can perturb the conditions in a protoplanetary disk on a general and regional basis. It is therefore expected that the C/O and solid carbon ratios experience changes with time and distance to the parent star, providing diversity to the protostellar composition and differentiating the planetesimal formation. Accordingly, a variety of planets may come out depending on these influences.

In light of the findings in this paper, it is seen that a higher C/O ratio in a protostellar disk will lead to the formation of denser, more refractory planetesimals, in agreement with previous studies. Low C/O ratios in contrary will result in the formation of more volatiles and ices. Depending on disk composition and formation distance to the host star, it is possible to generate various types of planets in any stellar system, from ice or ocean planets, to totally arid ones. It is also possible to expect extrasolar systems to contain planets similar to the ones already found in the solar system, or very unusual ones from our point of view.

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