

The Astrophysics of Planetary Systems: Formation, Structure, and Dynamical Evolution

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Chemical clues on the formation of planetary systems

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Abstract. Theoretical studies suggest that C/O and Mg/Si are the most important elemental ratios in determining the mineralogy of terrestrial planets. The C/O ratio controls the distribution of Si among carbide and oxide species, while Mg/Si gives information about the silicate mineralogy. We find mineralogical ratios quite different from those of the Sun, showing that there is a wide variety of planetary systems which are not similar to Solar System. Many of planetary host stars present a Mg/Si value lower than 1, so their planets will have a high Si content to form species such as MgSiO₃. This type of composition can have important implications for planetary processes like plate tectonics, atmospheric composition or volcanism. Moreover, the information given by these ratios can guide us in the search of stars more probable to form terrestrial planets.

Keywords. stars: abundances, stars: atmospheres, stars: fundamental parameters, planetary systems, planetary systems: formation

1. Introduction

The study of the photospheric stellar abundances of planet host stars is the key to understand how and which of the protoplanetary clouds form planets and which do not. These studies also help us to investigate the internal and atmospheric structure and composition of extrasolar planets.

One remarkable characteristic of planet host stars is that they are considerably metal rich when compared with single field dwarfs (Gonzalez 1998, Gonzalez *et al.* 2001, Santos *et al.* 2000, 2001, 2004, Fischer & Valenti 2005). Two main explanations have been suggested to clarify this difference. The first of these is that the origin of this metallicity excess is primordial, so the more metals you have in the proto-planetary disk, the higher should be the probability of forming a planet. On the other hand, this excess might be produced by accretion of rocky material by the star some time after it reached the main-sequence. Recent studies on chemical abundances in stars with and without planets showed no important differences in [X/Fe] vs. [Fe/H] trends between both groups of stars (Takeda 2007, Bond *et al.* 2008, Neves *et al.* 2009, González Hernández *et al.* 2010). However, other works have reported less statistically significant enrichments in other species such as C, Na, Si, Ni, Ti, V, Co, Mg and Al (Santos *et al.* 2000, Gonzalez

et al. 2001, Sadakane *et al.* 2002, Bodaghee *et al.* 2003, Fischer & Valenti 2005, Beirão *et al.* 2005, Gilli *et al.* 2006, Bond *et al.* 2006, Gonzalez & Laws 2007).

These results have important implications for models of giant planet formation and evolution. There are two major planet formation models: the core accretion model (Pollack *et al.* 1996), more likely to form planets in the inner disk, and the disk instability model (Boss 1997), which is in better agreement with the conditions in the extended disk. In the core accretion model, planet formation is dependent on the dust content of the disk (Pollack *et al.* 1996) while in the disk instability model it is not so clear (Boss 2002, Cai *et al.* 2006). Present observations are thus more compatible with core accretion model although they do not exclude disk instability.

Theoretical studies suggest that C/O and Mg/Si are the most important elemental ratios in determining the mineralogy of terrestrial planets and they can give us information about the composition of these planets. The C/O ratio controls the distribution of Si among carbide and oxide species, while Mg/Si gives information about the silicate mineralogy (Bond *et al.* 2010a, Bond *et al.* 2010b). Bond *et al.* (2010b) carried out simulations of planet formation where the chemical composition of the protoplanetary cloud was taken as an input parameter. Terrestrial planets were found to form in all the simulations with a wide variety of chemical compositions so these planets might be very different from the Earth. In order to investigate the mineralogical characteristics of those systems we will present C/O and Mg/Si ratios in a sample of 71 and 380 stars with and without detected planets, respectively, using new high quality spectra from the HARPS GTO sample (Mayor *et al.* 2003) and very precise stellar parameters (Sousa *et al.* 2008). In addition we use high quality spectroscopic observations for 42 stars hosting planets from the CORALIE survey, using the same spectral tools to determine their stellar parameters (Santos *et al.* 2004, 2005), and thus ensuring that the final sample is homogeneous.

2. Abundances

For all the elements we performed a standard LTE analysis with the 2002 revised version of the spectral synthesis code MOOG (Snedden 1973) and a grid of Kurucz ATLAS9 atmospheres with overshooting (Kurucz 1993), by measuring the equivalent width (EW) of the different lines with the ARES program[†] (Sousa *et al.* 2007).

Mg and Si abundances were calculated using the line list of Neves *et al.* (2009), adding a Mg line at λ 6318.72 Å. On the other hand, C and O abundances were determined by measuring the equivalent widths of *CI* lines at λ 5380.3 Å and λ 5052.2 Å and *OI* forbidden line at λ 6300 Å. We removed from the sample stars with $T_{\text{eff}} < 5100$ K since C abundance is not reliable for those stars. In addition, the spectral region around the forbidden line has telluric lines which can be blended with the *OI* line in some stars. So we made a detailed observation of the spectra to remove these objects from the sample in order to avoid wrong values of the O abundance. This, together with the limitation on T_{eff} , makes a final sample of 69 and 270 stars with and without detected planets from HARPS, and 31 stars with planets from other surveys.

In Fig. 1 [X/Fe] ratios as a function of metallicity are plotted. There is an average overabundance in the total planet-host stars with respect to the comparison sample stars for all the elements. Since targets with planets are on average more metal-rich than the stars of comparison sample, their abundance distributions correspond to the extensions of the comparison sample trends at high metallicity. Such a trend supports the primordial

[†] The ARES code can be downloaded at <http://www.astro.up.pt/~sousasag/ares/>

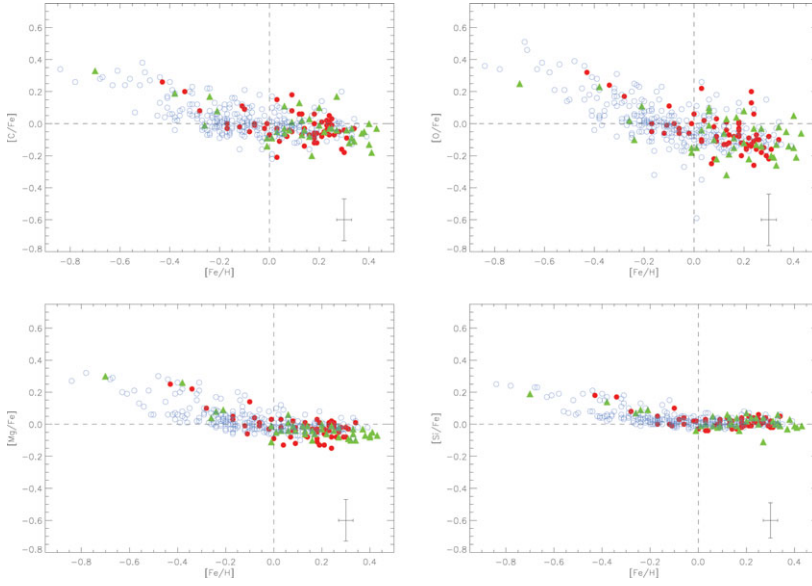


Figure 1. $[X/Fe]$ ratios as a function of metallicity for C, O, Mg and Si.

scenario as an explanation of the overmetallicity of planet-host stars. The samples of stars both with and without detected planets behave quite similarly except for Mg. At subsolar metallicities all stars present high Mg abundances irrespective of T_{eff} . However, this is not the case for $[Fe/H] \geq 0$, where stars without detected planets have higher Mg abundances. Nevertheless, this effect disappears when we take into account only solar analogs, with $5600 < T_{\text{eff}} < 5950$ K, perhaps due to the low number of stars with planets in this group. Therefore, it might be an effect in Mg abundances due to the presence of planetary companions.

3. C/O vs Mg/Si

In Fig. 2, C/O ratios as a function of Mg/Si are presented for different temperature ranges. These ratios are calculated as:

$$A/B = N_A/N_B = 10^{\log \epsilon(A)} / 10^{\log \epsilon(B)} \quad (3.1)$$

where $\log \epsilon(A)$ and $\log \epsilon(B)$ are the absolute abundances, so they are not dependent on solar reference abundances.

In our sample, 34% of stars with known planets have C/O values greater than 0.8 (see Table 1), which means that under the assumption of equilibrium those systems will contain carbide-rich phases (such as graphite, SiC and TiC) in the innermost regions of the disk. Metallic Fe and Mg-silicates such as olivine (Mg_2SiO_4) and pyroxene ($MgSiO_3$) are also present and are located further from the host star. Terrestrial planets forming in these planetary systems are expected to be C-rich, containing significant amounts of C in addition to Si, Fe, Mg and O. Those systems may possess an alternative mass distribution profile for solid material, potentially making it easier either for giant planets to form closer to the host star than previously expected or for terrestrial planets to form in the inner regions of the disk (Bond *et al.* 2010b). However, we find no evidence of any trends with C/O values for either planetary period, semi-major axis or mass. As such, it appears that any effects of an alternative solid mass distribution due to high

concentrations of refractory C-rich material are not preserved in the architecture of the system. This is believed to be due to the fact that Bond *et al.* (2010b) only considered equilibrium-driven condensation and did not include the effects of disequilibrium or the migration and radial mixing of material within the disk. Simulations addressing this issue are in progress. It should be noted, however, that we are still only able to detect giant planets. This conclusion may be not hold for extrasolar terrestrial planets which require significantly smaller amounts of solid material.

Table 1. C/O and Mg/Si distributions for stars with planets.

Ratio	Percentage	Principal Composition
C/O > 0.8	34%	graphite, TiC and solid Si as SiC
C/O < 0.8	66%	solid Si as SiO ₄ ^{4−} or SiO ₂
Mg/Si < 1	56%	pyroxene, metallic Fe and excess Si as feldspars
1 < Mg/Si < 2	44%	equal pyroxene and olivine
Mg/Si > 2	0%	olivine and excess Mg as MgO

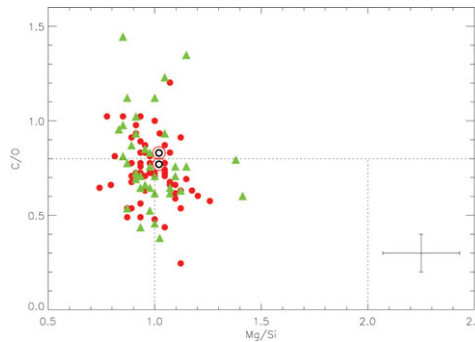


Figure 2. C/O vs Mg/Si for stars with planets from the HARPS GTO sample (red filled circles). Green triangles are stars with planets from other surveys. Solar abundances are calculated with the Kurucz Solar Atlas and the Harps daytime spectrum.

On the other hand, 66% of stars with known planets have C/O values lower than 0.8 and Si will be present in the solid form as SiO₄^{4−} or SiO₂, predominantly forming Mg-silicates. Silicate mineralogy will be controlled by Mg/Si ratio. For systems with a Mg/Si value between 1 and 2, the silicates present are predominately olivine and pyroxene in a condensation sequence closely resembling Solar. This is expected to result in the production of terrestrial planets similar in composition to that of Earth (in that their composition will be dominated by O, Fe, Mg and Si, with small amounts of Ca and Al also present). However, 56% of all planetary host stars in this study have a Mg/Si value less than 1. For such a composition, the solid component of the disk is dominated by approximately equal amounts of pyroxene and metallic Fe with minimal amounts of olivine present. Feldspars are also likely to be present as all available Mg is partitioned into pyroxene, leaving excess Si available to form other silicate species.

Such an excess of Si content is predicted to produce a quartz-feldspar rich terrestrial planet with a composition more like that of Earth's continental crust material than

that of Earth's olivine-dominated mantle. A composition such as this can have drastic implications for planetary processes such as plate tectonics and atmospheric composition. For example, volcanism on a Si-rich planet is expected to be intermediate to felsic in composition (i.e. >52% silica by weight) due to the potentially high SiO₂ content of the planet itself, producing igneous species such as andesite, rhyolite and granite. Eruptions may also be more explosive in nature due to the high viscosity of SiO₂-rich magma trapping volatiles within the magma.

Although we also found stars very similar to our Sun, it is clear that a wide variety of planets will probably exist within extrasolar planetary systems. These results can give us hints of what type of terrestrial planets we could find in different stars and help to guide the future surveys of low-mass planets.

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