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How alien can alien worlds be?

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Abstract

In an attempt to select stars that can host planets with characteristics similar to our own, we selected seven solar-type stars known to host planets in the habitable zone and for which spectroscopic stellar parameters are available. For these stars we estimated 'empirical' abundances of O, C, Mg and Si, which in turn we used to derive the iron and water mass fraction of the planet building blocks with the use of the model presented in Santos *et al.* (2015). Our results show that if rocky planets orbit these stars they might have significantly different compositions between themselves and different from that of our Earth. However, for a meaningful comparison between the compositional properties of exoplanets in the habitable zone and our own planet, a far more sophisticated analysis (e.g. Dorn *et al.*, 2017) of a large number of systems with precise mass and radius of planets, and accurate chemical abundances of the host stars. The work presented here is merely the first humble step in this direction.

1 Introduction

Observations revealed a now well-known dependence between exoplanet formation and metallicity. Giant planets tend to form more frequently around metalic stars (e.g. Gonzalez, 1997; Santos *et al.*, 2001; Mortier *et al.*, 2013). This dependence, however, is less clear for low-mass/small-size planets (e.g. Sousa *et al.*, 2011; Buchhave & Latham, 2015; Zhu *et al.*, 2016). Interestingly, there are no planets observed around very metal poor stars e.g. [Fe/H] < -1 dex (exoplanet.eu), which probably means that there is a critical metallicity below which no planet can be formed (e.g. Johnson & Li, 2012). This critical metallicity is much higher than the metallicity of population III stars in our Galaxy, leading to the inference that planet formation started only after the first stars were formed and died, enriching the the interstellar gas with metals. However, this process did not take very long (in astronomical timescale) since many planets are found around thick disk stars that are typically older than 8 Gyr (e.g. Haywood *et al.*, 2013). Moreover, it was shown that planet formation was more efficient around thick disk stars when compared to the thin disk stars of the same (low) metallicity (Haywood, 2009; Adibekyan *et al.*, 2012a,b). This stems from the thick disk stars being enhanced in α-elements such as O, Mg, Si (e.g. Bensby *et al.*, 2003; Adibekyan *et al.*, 2013a) which seems to compensate the lack of iron, typically used as a proxy of overall metallicity (Adibekyan *et al.*, 2012a). Indeed a system of five sub-earth-size planets was detected around a 11.2 Gyr old star (Campante *et al.*, 2015), setting the limit for the earliest exoplanet system formed and opening a possibility for the existence of ancient life in our Galaxy.

During (at least) the 11.2 billion year-long history of exoplanet formation in the Milky Way, the interstellar gas has chemically evolved significantly. Some recent works detail how abundances of different chemical elements changes with time (e.g. Nissen *et al.*, 2017; Delgado Mena *et al.*, 2017a) and place in the Galaxy (e.g. Recio-Blanco *et al.*, 2014; Kordopatis *et al.*, 2015). Abundances of these different individual heavy elements and specific elemental ratios (e.g. Mg/Si and Fe/Si) are, in turn, very important for the formation (Santos *et al.*, 2001; Suárez-Andrés *et al.*, 2017; Santos *et al.*, 2017; Adibekyan *et al.*, 2015, 2017), orbital architecture (Adibekyan *et al.*, 2013b; Beaugé & Nesvorný, 2013; Mulders *et al.*, 2016), structure and composition (Santos *et al.*, 2015; Thiabaud *et al.*, 2014; Dorn *et al.*, 2015), and even maybe for 'habitability' of the exoplanets (Adibekyan *et al.*, 2016). This discussion leads to a conclusion that the chemical environment i.e., time and place in the Milky Way, play a crucial role for the formation of planets and their main characteristics (Adibekyan, 2017).

In a recent work, Adibekyan *et al.* (2016) proposed that planets in the habitable zone of solar-like stars may have different compositions from that of our Earth. In this work, we try to estimate the composition of the planet building blocks around stars that are known to host planets in the habitable zone (HZ)[1].

2 Planets in the habitable zone: sample selection

To select stars with HZ planets we used the the Habitable Exoplanet Catalog[2]. From the list of “Conservative” and “Optimistic Sample of Potentially Habitable Exoplanets” we selected planets that are hosted by solar-type stars with effective temperature higher than 4500 K. We note that the derivation of stellar parameters, including stellar metallicity, is very challenging for cooler stars and are typically less precise. For six (Kepler-1540, Kepler-1544, Kepler-1552, Kepler-1090, Kepler-1606 and Kepler-1638) out of 13 selected systems, the stellar metallicity (the most important parameter for the current study) was derived by Morton *et al.* (2016)

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[1] Do not mix with the Habeertable Zone defined in Turbo-King *et al.* (2017).

[2] http://phl.upr.edu/projects/habitable-exoplanets-catalog

Table 1: Stellar parameters and abundances of the sample stars. The index emp refer to the 'empirical' derivation of the abundances. The references for stellar parameters are in the last column.

star	$T_{\rm eff}$	log g	[Fe/H]	[O/H]	[C/H]	[Mg/H]	[Si/H]	$[O/H]_{emp}$	$[C/H]_{emp}$	$[Mg/H]_{emp}$	$[Si/H]_{emp}$	References
Kepler-22	5518±44	4.44±0.06	-0.29±0.06	-0.19±0.05	-0.24±0.05	-0.23±0.03	-0.24±0.02	-0.10±0.10	-0.28±0.06	-0.18±0.06	-0.21±0.05	Borucki *et al.* (2012)
HD40307	4774±77	4.42±0.16	-0.36±0.02		-0.36±0.10	-0.20±0.09	-0.19±0.08	-0.14±0.10	-0.40±0.05	-0.22±0.03	-0.27±0.05	Tsantaki *et al.* (2013)
HD10700	5310±17	4.46±0.03	-0.52±0.01	-0.26±0.10	-0.52±0.10	-0.30±0.06	-0.36±0.01	-0.18±0.10	-0.52±0.10	-0.29±0.08	-0.35±0.07	Sousa *et al.* (2008)
Kepler-452	5757±85	4.32±0.09	0.21±0.09					0.21±0.10	0.17±0.08	0.22±0.08	0.21±0.08	Jenkins *et al.* (2015)
Kepler-62	4925±70	4.68±0.04	-0.37±0.04					-0.14±0.10	-0.39±0.05	-0.21±0.05	-0.22±0.06	Borucki *et al.* (2013)
Kepler-174	4880±126	4.68±0.15	-0.43±0.10					-0.18±0.10	-0.59±0.10	-0.41±0.01	-0.40±0.04	Rowe *et al.* (2014)
Kepler-443	4723±100	4.62±0.10	-0.01±0.10					0.02±0.10	-0.11±0.09	-0.07±0.10	0.06±0.07	Torres *et al.* (2015)

using the *vespa*[3] package. The non-spectroscopic metallicities of these six stars seem to be too biased (probably because of the fitting priors and algorithm) towards the solar value. The mean metallicity and the standard deviation of the six stars is 0.000±0.058 dex. In fact, about 80% of the stars from the full sample of Morton *et al.* (2016) have metallicities from -0.1 to 0.1 dex. For comparison, only about 34% of stars from the volume-limited HARPS sample of Adibekyan *et al.* (2012c) lie within the aforementioned range of metallicity. Without making any judgment on the quality of this work, but nonetheless noting the clear discrepancy, we preferred to confine our analysis to spectroscopicly derived parameters. As such, we limited our analysis to seven stars (Kepler-22, HD40307, HD10700, Kepler-452, Kepler-62, Kepler-174, Kepler-443) with metallicities only derived by spectroscopic methods (see Table 1). It is interesting to see that six out of seven hosts have sub-solar metallicities, although the metallicity of Kepler-443 is compatible with the solar value within the error.

3 Abundances of the host stars

In order to derive composition of the planetary building blocks, as it was done in Santos *et al.* (2015) chemical abundances of O, C, Mg, and Si are necessary. Our intensive literature search for chemical abundances of the sample stars was not very productive. Only three stars have elemental abundances reported in the literature: Kepler-22 – (Schuler *et al.*, 2015), HD40307 – (Delgado Mena *et al.*, 2017b; Suárez-Andrés *et al.*, 2017), and HD10700 – (Bertran de Lis *et al.*, 2015; Delgado Mena *et al.*, 2017b; Suárez-Andrés *et al.*, 2017). To obtain the 'empirical' abundances of other stars we proceed as follows. We first searched for stellar analogs[4] for each star in these catalogs: Suárez-Andrés *et al.* (2017) for Carbon abundance and Delgado Mena *et al.* (2017b) for abundances of Mg and Si. The mean abundance of all the analogs was used as a proxy for the 'empirical' abundance for a given star, and the standard deviation (star-to-star scatter) of the abundances was used as an error of the empirical' abundance. Oxygen abundance was derived from the empirical formula between [O/H] and [Fe/H] provided in Suárez-Andrés *et al.* (2017) which is based on the Bertran de Lis *et al.* (2015) data. Original and 'empirical' abundances of the stars are presented in the Table 1. As can be seen from the table, the difference between 'empirical' and original abundances can be as large as 0.1 dex. Thus we stress that the 'empirical' abundances should be considered only as rough estimates.

4 Composition of the planet building blocks

The model presented in Santos *et al.* (2015) uses atomic abundances of O, C, Mg, Si and Fe, as input, and with simple stoichometric equations calculates the mass fraction of H_2O, CH_4, Fe, $MgSiO_3$, Mg_2SiO_4, the total mass percentage of all heavy elements (Z), the iron mass fraction (f_{iron} = $m_{Fe}/(m_{Fe} + m_{MgSiO_3} + m_{Mg_2SiO_4})$ and the water mass fraction ($w_f = m_{H_2O}/(m_{H_2O} + m_{Fe} + m_{MgSiO_3} + m_{Mg_2SiO_4})$). These values are derived for each star using the original spectroscopic and 'empirical' abundances. The results are presented in Table 2. From the table we can see that for the three stars for which together with the 'empirical' abundances spectroscopic abundances are available (HD40307, HD10700, and Kepler-22), the derived values are similar and agree within the error bars. However, it should be mention the uncertainties of some of the parameters are large, especially if they are derived from the 'empirical' abundances.

5 Results and Discussion

Our results summarized in Table 2 show that if small-size and low-mass planets are found in the HZ of the studied seven stars then they are expected to have significantly different iron-to-silicate and water mass fractions. In particular, the iron mass fraction in five out of seven cases is significantly lower (from ∼24 to ∼28%) than what this model would predict for solar-system planet building blocks (i.e. f_{iron} = 33% Santos et al. 2017, submitted). Water content would also vary from system to system between ∼56 to 72%. Here we should stress again the large uncertainties for this parameter that mostly come from the larger errors on the C and O abundances.

Very recently, Santos et al. (2017, submitted) compiled chemical abundances for large sample of solar-type stars from the solar vicinity and derived the expected composition of the planet building blocks. The authors found that stars belonging to different galactic stellar populations (thin disk, thick disk, halo, and high-α metal-rich - Adibekyan *et al.* (2011)) are expected to have rocky planets with significantly different iron mass and water mass fractions. Our results go well in line with the findings of Santos et al. (2017, submitted), since stars in our small sample having different metallicities and ages probably belong to different galactic populations. The results also somehow confirm the prediction of Adibekyan *et al.* (2016) that exoplanets in the HZ may have composition different from that of our Earth.

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[3] https://github.com/timothydmorton/vespa

[4] We defined stellar analogs as stars with [Fe/H]±0.1 dex, $T_{\rm eff}$±500K, and logg±0.3 dex.

Table 2: Mass fractions and total fraction (Z) of heavy elements, iron mass fraction among refractory species (f_{iron}), and the water mass fraction (w_f). All values are in %.

star	H_2O	CH_4	Fe	$MgSiO_3$	Mg_2SiO_4	Z	f_{iron}	w_f
HD40307$_{emp}$	0.39±0.11	0.15±0.01	0.06±0.00	0.08±0.03	0.07±0.02	0.74±0.12	27.89±1.72	65.00±11.58
HD40307	0.38±0.11	0.15±0.03	0.06±0.00	0.10±0.06	0.07±0.07	0.76±0.12	25.10±2.82	62.30±14.35
HD10700$_{emp}$	0.37±0.11	0.11±0.03	0.04±0.00	0.06±0.05	0.07±0.05	0.65±0.11	23.80±2.51	68.52±13.08
HD10700	0.38±0.10	0.12±0.03	0.04±0.00	0.06±0.02	0.06±0.03	0.66±0.10	24.36±1.36	70.37±10.63
Kepler-22$_{emp}$	0.45±0.13	0.20±0.02	0.07±0.01	0.10±0.05	0.08±0.05	0.90±0.14	29.85±3.24	64.29±14.83
Kepler-22	0.33±0.04	0.20±0.02	0.08±0.01	0.10±0.02	0.07±0.02	0.78±0.05	30.64±2.90	56.90±5.00
Kepler-62$_{emp}$	0.40±0.10	0.15±0.02	0.06±0.01	0.11±0.04	0.06±0.03	0.76±0.10	25.88±2.53	63.49±11.22
Kepler-174$_{emp}$	0.39±0.11	0.10±0.02	0.04±0.01	0.08±0.01	0.03±0.01	0.63±0.11	26.86±4.68	72.22±11.14
Kepler-443$_{emp}$	0.56±0.14	0.29±0.05	0.13±0.03	0.23±0.04	0.02±0.05	1.25±0.16	32.70±6.00	59.57±15.68
Kepler-452$_{emp}$	0.82±0.21	0.55±0.10	0.21±0.05	0.28±0.15	0.15±0.15	2.02±0.25	32.73±5.84	56.16±30.27
Sun	0.50±0.07	0.37±0.04	0.13±0.01	0.18±0.06	0.08±0.06	1.26±0.08	33.14±3.11	56.08±5.12

6 A laconic conclusion

We estimated the water and iron-to-silicate mass fraction of planet building blocks for seven solar-type stars with precise spectroscopic metallicities that are known to have planets in the HZ. Our very simplified analysis show that if rocky planets are found orbiting around these stars they might have different composition compared to our own planet. To confidently answer to the question postulated in the title of this manuscript a far more sophisticated analysis for each individual object is needed with an important requirement of having very precise masses and radius of the planets and very accurate chemical abundances of the host star (e.g. Dorn *et al.*, 2017).

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