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Characterization of exoplanet hosting stars within the GAPS program

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Abstract. Properties of exoplanets strongly depend on properties of their hosting stars. In the context of the Global Architecture of Planetary System program we aim at characterizing planet hosting stars in terms of several astrophysical properties and elemental abundances. Here, we report some results of a homogeneous and accurate determination of stellar properties, abundances of many elements, and kinematic parameters of a sample of transiting planet-hosting stars. In particular, we discuss the distribution of C/O, Mg/Si, and Fe/Mg as mineralogical diagnostics, the trend of higher stellar oxygen abundance for lower-mass planets, and the tendency for higher-density planets to be around metal-rich stars. We also find a preference for giant planets around stars with subsolar [C/Fe] ratio. We discuss our results in the context of planetary formation, taking into account that part of our results could be also related to the location of the stars within the Galactic disk. This kind of accurate investigation will be useful as benchmark for current and upcoming space missions dealing with large samples of targets to get more insights into the planet formation–migration mechanisms.

Key words. Stars: abundances – Stars: fundamental parameters – Techniques: spectroscopic – Planetary systems

1. Introduction

Stars and planets are perpetually interwined, so in planetary systems one cannot be studied without accounting for the other. Planetary properties are critically dependent on the properties of the hosting stars, and therefore accurate estimates of planetary parameters rely on precise determination of the hosting star parameters. Moreover, since fundamental parameters of large samples of planet-hosting stars are often found in the literature as the result of analysis performed by different methodologies, resulting in an inhomogeneous census of stars with planets, the requirement for homogeneity, together with precision, for the determination of stellar parameters and elemental abundances becomes crucial (see, e.g.,

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Torres et al. 2012; Santos et al. 2013; Sousa et al. 2015; Brucalassi et al. 2022; Danielski et al. 2022; Magrini et al. 2022, and references therein). Several studies have indeed pointed out the existence of correlations between the characteristics of the host stars and the properties and frequencies of their planetary systems, together with the important information on the hosting star's chemical composition with the aim to separate the signatures left on the planet during its formation and migration from those due to the star (see, e.g., Biazzo et al. 2022; Wang et al. 2022, and references therein).

Within the Global Architecture of Planetary Systems (GAPS; Covino et al. 2013) project, one of the aims is to obtain homogeneous and precise fundamental parameters of different samples of planet-hosting stars: from young objects (Baratella et al. 2020) to open cluster members (Malavolta et al. 2016), from late-type stars (Maldonado et al. 2020) to early-type (Borsa et al. 2019), from metal-poor targets (Barbato et al. 2019) to transiting planet host stars (Biazzo et al. 2015), to cite some. In the present work, we will report some results on a sample of 28 FGK stars hosting transiting planets with masses between 0.06 to $\sim 7.3\,M_{\rm Jup}$ recently analyzed by Biazzo et al. (2022) in the context of the GAPS project. In particular, we applied an accurate and homogeneous procedure to derive stellar parameters, global properties, abundances of multiple elements, and kinematic properties of transiting planet host stars using high-quality data. Our aim was investigating possible relationships between astrophysical, kinematic, and chemical parameters of exoplanet host stars and the properties of their transiting planets, thus providing necessary information for next-coming studies of their exoplanets with current and new facilities. Our procedure is based on non-automatic tools and it is indeed time consuming. We are aware that such kind of work cannot be applied to big sample of data but we suggest it can be used as a benchmark analysis for interpreting the composition, the origin, and evolution of planets through current and future statistical studies with new facilities, like *JWST* and *Ariel*.

We refer to Biazzo et al. (2022) for the detailed description of methods, analysis, and interpretation of the data. Here, we report some results within the latter work recently published on the use of stellar abundances as mineralogic diagnostics (Sect. 2), on the possible relationships between stellar abundances and planetary properties (Sect. 3).

2. Stellar abundances as mineralogic diagnostics

We derived stellar parameters and abundances of 26 elements (Li, C, N, O, Na, Mg, Al, Si, S, Ca, Sc, Ti, V, Cr, Fe, Mn, Co, Ni, Cu, Zn, Y, Zr, Ba, La, Nd, Eu) from high-resolution HARPS-N@TNG data ($R \sim 115\,000$, $\lambda \sim 3\,900 - 6\,900$ Å; Cosentino et al. 2012) obtained between 2012 and 2016. We used co-added spectra to increase the signal-to-noise ratio and applied a line-by-line homogeneous and accurate method. In the end of our analysis, the effective temperature of our stars resulted to be in the range of ~4400-6700 K, the surface gravity around $3.90 < \log g < 4.55$, the projected rotational velocity $v \sin i$ within 10 km/s, while the iron abundance [Fe/H] was within −0.3 and 0.4 dex (see Biazzo et al. 2022 for more in-depth details).

Elemental abundances ([X/H][1]) and elemental ratios (X/Y[2]) are important because they govern the distribution and formation of chemical species in the protoplanetary disk, and hence they are useful to get information about the mineralogy of planets. For instance, the abundance ratio of volatile elements like carbon-to-oxygen (C/O) in a planet host star is useful to indicate to first order if a planet around it would be dominated by silicates or by carbides, while refractory elements like Mg/Si is critical to modulate the dominant mineral assemblages (olivine vs pyroxene) in the mantle of a silicate planet. Further, Fe/Mg is an in-

[1] The abundance of the X element is given as $[X/H]=\log \frac{\epsilon(X)}{\epsilon(H)} + 12$, where $\log \epsilon(X)$ is the absolute abundance.

[2] The X/Y ratio is the elemental number ratio, namely $X/Y=10^{\log \epsilon(X)}/10^{\log \epsilon(Y)}$, with $\log \epsilon(X)$ and $\log \epsilon(Y)$ absolute abundances.

dicator of the degree of core-mantle fractionation (see, e.g., Wang et al. 2022, and references therein). In Fig. 1 we show the distribution of our stars in the C/O vs Mg/Si and Fe/Mg vs Mg/Si diagrams with respect to the sample of planet-hosting stars in Suárez-Andrés et al. (2018) and Adibekyan et al. (2012a), respectively. Our stars are mainly concentrated around a mean C/O value of ∼ 0.5, while Fe/Mg and Mg/Si show wider distributions, with the target hosting the lower-mass planet (namley, HAT-P-26) showing the higher value of Mg/Si. The peak of the Mg/Si-C/O distribution for our targets is consistent with Si which will take solid form as SiO_4^{4-} and SiO_2 and Mg equally distributed between pyroxene and olivine. The peak of the Mg/Si-Fe/Mg distribution is close to the region where cores start to be bigger (see also Wang et al. 2022).

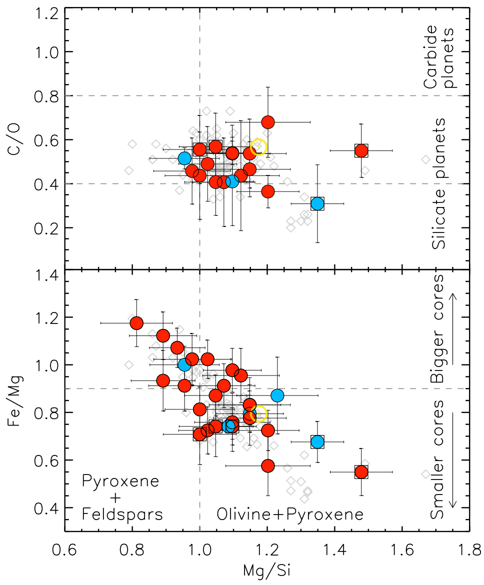

Fig. 1. C/O (*upper panel*) and Fe/Mg (*lower panel*) vs Mg/Si. Red circles refer to stars with [Fe/H]> 0.0, while blue dots are those with [Fe/H]≤ 0.0. Squares represent targets with thick-to-thin disk probability ratios (TD/D) greater than 0.5 (see Biazzo et al. 2022 to know how this parameter and kinematic properties were derived). Overplotted in gray are the results by Suárez-Andrés et al. (2018) and by Adibekyan et al. (2012a), respectively for C/O and Fe/Mg ratios. Vertical line represents Mg/Si=1.0, while horizontal lines are plotted for C/O=0.4, 0.8 and for Fe/Mg=0.9 as defined by Suárez-Andrés et al. (2018) and by Wang et al. (2022), respectively. Our solar values of $(C/O)_\odot$=0.57, $(Fe/Mg)_\odot$=0.79, and $(Mg/Si)_\odot$=1.17 are also represented with a solar symbol (in yellow).

3. Stellar abundances and planetary properties

3.1. Stellar carbon and oxygen abundance vs planetary mass

With the aim of looking for possible relations between stellar abundances and planetary properties, we show in Fig. 2 the abundance of two of the volatile elements we analyzed (i.e. carbon and oxygen) versus the planetary mass. As mentioned, the masses of the planets (M_p) around our stars range between ∼0.06 and ∼7.3 M_{Jup}. We see a possible decreasing trend of [O/Fe] with increasing M_p with a Spearman associated statistical significance (ρ) of $\sim 9 \times 10^{-6}$. For the carbon abundance, we find a weak statistical significance of ∼ 0.07. A flat tendency was found for C by Suárez-Andrés et al. (2017). This means that a more significant correlation is present for the [O/Fe] ratio versus M_p when compared to the [C/Fe] ratio, with an evident decreasing step toward lower [O/Fe] values for $M_p > 0.5\, M_{Jup}$. This could imply that the formation of low-mass planets is favored at the highest values of stellar volatile elements. This interpretation could be justified in the framework of the pebble accretion scenario. Higher mass planets are expected to form early in the circumstellar disks, when the accretion rate is high and capable of supporting the rapid growth of their cores. They can therefore form in disks poor in the abundance of volatile elements like oxygen (and carbon). Lower mass planets are expected to form over longer timescales, in circumstellar disks characterized by lower accretion rate (see Hartmann et al. 1998; Johansen et al. 2019; Tanaka et al. 2020). These planets can therefore form around volatile-rich stars. This means that the trend of the [O/Fe] ratio could be explained by the larger contribution of oxygen to the mass fraction of heavy elements in the stars and their circumstellar disks and its lower volatility compared to carbon (see Turrini et al. 2021, and references therein). Any increase in the oxygen abundance would have a larger impact on the availability of solid material of planet-forming disks than equal increases in the carbon abundance, thus resulting more effective in promoting the formation of low-mass planets. However, we are cautious about definitive conclusions because we note that some of the targets hosting low-mass planets and showing higher [O/Fe] (and [C/Fe]) are also those resulting chemically old and possibly belonging to the thin-to-thick disk transition (i.e. with TD/D greater than 0.5). Moreover, looking at the mean position of their stellar Galactic orbits, they indeed seem to have migrating from the Galactic inner disk, with higher content of α-elements, like the oxygen (and carbon; see Biazzo et al. 2022 for details on how Galactic-dynamics calculations and age estimations were done). Finally, it is interesting to note that we find a preference for giant planets to be around stars with sub-solar [C/Fe] ratio, as also reported by Unni et al. (2022) for LAMOST-Kepler field stars.

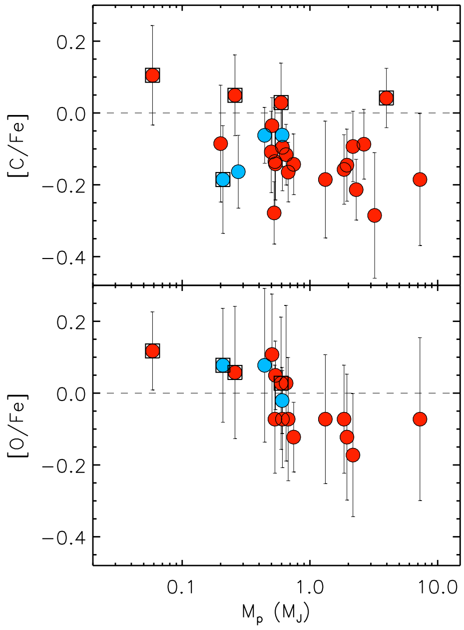

Fig. 2. Stellar [C/Fe] (*upper panel*) and [O/Fe] (*lower panel*) versus M_p. The dashed lines represent the solar value. Symbols as in Fig. 1.

3.2. Stellar iron abundance vs planetary orbit eccentricity

In Fig. 3 we show the distribution of the iron abundance of our stellar sample in terms of the planetary orbit eccentricity. We find a tendency for high-eccentricity planets to be around more metal-rich stars. Similar findings were reported by Dawson & Murray-Clay (2013) and Mills et al. (2019). Since we are aware that our sample is statistically small, we try to assign a confidence level of our result using a one-side 2×2 Fisher's exact test (Agresti 1992; Langsrud et al. 2007). Choosing the divisions at $e = 0.1$ for high- and low-eccentricity orbits and [Fe/H]=0.00 dex for metal-poor and metal-rich stars, we find a p-value of 0.29 as the chance that random data would yield this trend, indicating a probability of correlation of 71%. Moreover, if we consider the literature values from the NASA Exoplanet Archive of the planetary density of our sample, we find some evidence that denser planets (mean planetary density $\rho_P \sim 1.7$ g/cm^3) are around stars with greater [Fe/H] (and therefore in more eccentric orbits) when compared with planets around more metal-poor stars with $e < 0.1$ (mean $\rho_P \sim 1.1$ g/cm^3). This result seems to give support the recent findings by Magrini et al. (2022) according to which at a given stellar mass larger planets are found around more metal-poor stars. The authors claim that a natural explanation to this could be that the larger amount of heavy elements that can be accreted by the giant planets during their formation and migration around higher metallicity stars translates into more compact radii and higher densities than those of similar planets formed in lower metallicity environments (Thorngren et al. 2016; Shibata et al. 2020; Turrini et al. 2022).

4. Conclusions

Thanks to the homogeneous and accurate analysis of exoplanet hosting stars based on high-

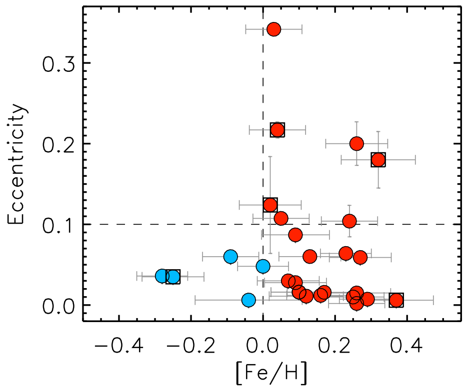

Fig. 3. Orbital eccentricity from the NASA Exoplanet Archive versus our stellar [Fe/H]. The horizontal line is plotted for $e = 0.1$, while the vertical dashed line indicates [Fe/H]=0.0. Symbols as in Fig. 1.

resolution HARPS-N@TNG spectra we obtained atmospheric parameters and elemental abundances of 26 elements from lithium to europium, together with their kinematic and global properties (see Biazzo et al. 2022 for details). Herewith, some of our results:

- From the analysis of the Mg/Si ratios, we find that most of the targets show values consistent with a distribution of Mg between olivine and pyroxene, while the C/O ratio for all targets is compatible with Si present in rock-forming minerals. The peak of the Fe/Si distribution is compatible with cores starting to be bigger.
- We find a tendency for the oxygen to be lower for higher-mass planets. Similar but very weak statistically significant correlation is found for carbon.
- We find some evidence for high-eccentricity planets to be around more metal-rich stars, and also for denser planets to be around stars with higher [Fe/H].

The detailed knowledge of chemical abundances of planet hosting stars is important to trace the formation and evolution of their planets. Thanks to this kind of approach, we were able to suggest the formation and migration scenario for those four targets for which abundances of planets hosted by stars analyzed in the present work were obtained. In particular, thanks to the analysis of the planetary-to-stellar elemental ratios, we were able to suggest a formation outside the CO_2 showline for two targets, and a farther out formation (between the CO_2 and CH_4 showlines and between the N_2 and CO_2 showlines) for the other two targets (see Biazzo et al. 2022 for details).

Analyses like that one performed in this work are necessary for studies on planetary composition that take into account host star composition, in particular for transiting planet host stars, for which more information about the system formation, migration, and evolution can be retrieved. Metallicity and ratios of several elements (like Mg/Si, C/O, C/N, S/N, N/O) are important indicators of planet formation; therefore, future high-precision observations are essential to further explore the trend between stellar and planetary properties toward the understanding of the formation mechanisms of planets. For instance, *JWST* observations and other upcoming infrared spectroscopic missions (like *Ariel*) will allow us to draw more robust conclusions, in particular regarding the level of precision for planetary abundances, useful to provide definitive conclusions for planetary formation, migration, and evolution.

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