Volatile and refractory abundances of solar analogs with planets

J. I. González Hernández, ^{1,2} E. Delgado-Mena, ³ S. G. Sousa, ³, G. Israelian, ^{1,2} N. C. Santos, 3,4 and S. Udry⁵

¹ Instituto de Astrofísica de Canarias (IAC), E-38205 La Laguna, Tenerife, *Spain: jonay@iac.es*

²*Depto. Astrof´ısica, Universidad de La Laguna (ULL), E-38206 La Laguna, Tenerife, Spain*

³*Centro de Astrof´ısica, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal*

⁴Departamento de Física e Astronomia, Faculdade de Ciências, Universidade *do Porto, Portugal*

⁵*Observatoire Astronomique de l'Universit´e de Gen`eve, 51 Ch. des Maillettes, -Sauverny- Ch1290, Versoix, Switzerland*

Abstract.

We present a detailed abundance analysis of high-quality HARPS, UVES and UES spectra of 95 solar analogs, 33 with and 62 without detected planets. These spectra have $S/N > 350$. We investigate the possibility that the possible presence of terrestrial planets could affect the volatile-to-refratory abundance ratios.

We do not see clear differences between stars with and without planets, either in the only seven solar twins or even when considering the whole sample of 95 solar analogs in the metallicity range $-0.3 < [Fe/H] < 0.5$. We demonstrate that after removing the Galactic chemical evolution effects the possible differences between stars with and without planets in these samples practically disappear and the volatile-torefractory abundance ratios are very similar to solar values.

We investigate the abundance ratios of volatile and refractory elements versus the condensation temperature of this sample of solar analogs, in particular, paying a special attention to those stars harbouring super-Earth-like planets.

1. Introduction

The last 10 years of spectroscopic observations dedicated to the search of extrasolar planets have provided an unprecedented set of high-quality spectra. Indeed, the HARPS GTO program [\(Mayor et al. 2003\)](#page-5-0) have produced a spectroscopic database containing a substantial amount of high-resolution and high signal-to-noise spectra of G-type stars. These high-quality data have been used to produce detailed abundance analysis [\(Neves et al. 2009](#page-5-1); [Adibekyan et al. 2012a](#page-4-0)[,b\)](#page-4-1). In particular, a subsample of very highquality spectra of solar analogs were analyzed to derive very accurate abundances of 24 chemical elements (González Hernández et al. 2010). Previously, Meléndez et al. [\(2009](#page-5-2)) noticed that the abundance pattern of the Sun reveals a deficiency in refractory elements with respect to the volatile content when comparing with the mean abundance pattern of 11 solar twins. They found a clear decreasing trend of the mean abundance differences, Δ [X/Fe]_{SUN-STARS}, versus the condensation temperature, T_C , and suggested that this issue was connected with the presence of terrestrial planets in the solar planetary system. Ramírez et al. [\(2009](#page-5-3)) found a similar behaviour than that of Meléndez et al. [\(2009](#page-5-2)) when considering a larger sample of solar analogs.

Later, González Hernández et al. (2010) studied in detail the chemical abundances of a subsample of solar analogs in the HARPS program with and without planets with very high-quality HARPS, UVES and UES spectroscopic data. These authors demonstrated that the abundance ratios, [X/Fe], of solar analogs with and without planets exhibit very similar Galactic chemical evolution trends. They also found a decreasing trend of the mean abundance differences, $\Delta[X/Fe]_{\text{SUN–STARS}}$, versus the condensation temperature, T_C , of the small subsample of seven solar twins in the HARPS data, two with and five without known planets. However, despite the higher quality of the HARPS data, the scatter of the data points around the linear fits was larger than that of the results presented by Meléndez et al. (2009). Also, the mean abundance differences of all Gtype dwarfs with and without planets versus the condensation temperature also present similar behaviours.

The mean abundance trends of their sample of solar analogs with and without planets get null when taking into account the impact of the Galactic trends (González Hernández et al. [2011a\)](#page-4-3). In addition, two stars hosting super-Earth-like planets, HD 1461 and HD 160691, also show practically zero values of volatile-to-refractory abundance ratios compared to solar when subtracting the effects of the Galactic chemical evolution (González Hernández et al. [2011b](#page-4-4)). Here, we revisit the chemical analysis of solar analogs with and without planets taking into account the discovery of new low-mass exoplanets (e.g. [Mayor et al. 2011\)](#page-5-4).

2. Observations

The spectroscopic data used in this work were taken with the HARPS, UVES, and UES spectrographs at the 3.6-m ESO, 8-m VLT, and 4.2-m WHT telescopes, installed in the La Silla Paranal Observatory, ESO (Chile), and in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrof´ısica de Canarias, in the island of La Palma, respectively. The selected spectra of solar analogs were observed with HARPS and UVES spectrographs at resolving power of *R* ∼ 110, 000 and for some UVES and UES spectra, at $R \sim 85,000$ and $\sim 65,000$, respectively. All the spectra used in this work have $S/N > 350$. These very high-quality data have on average a S/N ratio of roughly 850.

3. Stellar parameters and abundance analysis

The stellar parameters and metallicities of the whole sample of stars were computed by applying the equivalent width method, described in [Sousa et](#page-5-5) al. [\(2008](#page-5-5)), to a set of FeI-II lines measured with the code ARES [\(Sousa et al. 2007\)](#page-5-6), and evaluating the excitation and ionization equilibria. The chemical abundance derived for each spectral line was computed using the 2002 version of the LTE code MOOG [\(Sneden 1973](#page-5-7)), and a grid of Kurucz ATLAS9 plane-parallel model atmospheres [\(Kurucz 1993](#page-4-5)).

We determine the mean abundance of each element relative to its solar abundance by computing the line-by-line mean difference. Our fully differential analysis is, at least, internally consistent. We use the HARPS spectrum of *Ganymede*, a Jupiter's satellite, as solar reference, which has a $S/N \sim 400$ (see González Hernández et al. [2010](#page-4-2), for further details).

4. Discussion

4.1. Solar analogs with and without planets

The sample of solar analogs have 62 stars without known planets and 33 stars with planets. The mean abundance ratios of the whole sample are displayed in Fig. [1,](#page-2-0) and they seem to behave in a similar way for both stars with and without planets. These abundance differences exhibit a decreasing trend towards increasing condensation temperature although some scatter around the linear fits to the data points is appreciable. We consider that the Galactic chemical effects have an impact on these results even if the metallicity range is relatively narrow. Thus, we fit a linear function to the Galactic trends of the abundance ratios, [X/Fe], of solar analogs without detected planets (see Fig. 3 in González Hernández et al. 2010), and we subtract the value of these trends to each element abundance at the metallicity of each star. The result is depicted in right panel of Fig. [1.](#page-2-0) There one can see that the slopes of the previous linear fits to the data points tend to adopt values very close to zero. The scatter around the fits also decreases significantly. The fact that we find very similar behaviour in the mean abundance pattern of stars with and without planets, irrespective of the number of planets, and mass and orbital period of the planets, suggest that there is no clear signature of terrestrial planets in these mean patterns.

Figure 1. *Left panel:* Mean abundance differences, Δ [X/Fe]_{SUN-STARS}, between the Sun, and 33 planet-host stars (blue filled circles) and 62 "single" stars (red open circles) of the whole sample of solar analogs. Error bars are the standard deviation from the mean divided by the square root of the number of stars. Linear fits to the data points weighted with the error bars are also displayed for planet hosts (blue dashed line) and "single" stars (red solid line). An arbitrary shift of -0.15 dex has been applied to the abundances of the planet-host stars, for the sake of clarity. *Right panel:* Same as left panel but after correcting each element abundance ratio of each star using a linear fit to the Galactic chemical trend of the corresponding element at the metallicity of each star.

4.2. Solar analogs with very low-mass planets

Eight of the solar analogs host super-Earth-like planets and four stars harbour Neptunelike planets. We try to investigate the individual patterns of these stars (with respect to the Sun) to search for a signature of terrestrial planets. In Fig. [2](#page-3-0) we display the abundance pattern of four stars hosting super-Earth-like planets. We have removed the

Galactic chemical effects from the individual abundance ratios of these stars. The linear fits depicted as solid lines give the same weight to each element abundance but there are much more refractory elements than volatiles. Therefore, we think a linear fit that attach the same importance to all condensation temperature values would have more significance. Thus, we compute the mean value of the element abundances in bins of $\Delta T_C = 150$ K, using all the element abundances available in each T_C bin. The result is also shown in Fig. [2.](#page-3-0) The slope given by these mean fits change sometimes with respect to the linear fit of all the element abundance ratios taken separately. The solar analogs HD 45184 and HD 189567 host only one super-Earth-like planet each with a minimum mass $m_p \sin i \sim 12.7$ and 10.0 M_{\oplus} , respectively. The stars HD 1461 and HD 96700 harbour only two super-Earth-like planets each with $m_p \sin i \sim 5.9$ and 7.6 M_{\oplus} , and $m_p \sin i \sim 9.0$ and 12.7 M_{\oplus} , respectively. If one assumes that the super-Earth-like planets mostly contain rocky material and therefore are abundant in refractory elements, then according to the line of reasoning in Meléndez et al. (2009), these stars should exhibit mean abundance trends with positive slopes. This is not the case for the star HD 45184. The star HD 1461 shows a flat abundance pattern that it is also not expected since the amount of rocks in the two super-Earth-like planets should be significantly greater than in the solar system. The solar analogs HD 189567 and HD 96700 hosting one and two super-Earth-like planets, respectively, show increasing abundance trends versus increasing condensation temperature. Although for these two stars we find the expected positive slopes, the absolute value of this slope is larger for the star hosting only one planet, which is *a priori* not expected.

Figure 2. *Left panel:* Abundance differences, Δ [X/Fe]_{SUN-STARS}, between the Sun and two solar analogs hosting only one super-Earth-like planet each (circles). Error bars are the uncertainties of the element abundance measurements, corresponding to the line-by-line scatter. Diamonds show the average abundances in bins of ΔT_C = 150 K. Error bars are the standard deviation from the mean abundance of the elements in each *T^C* bin. Linear fits to the data points (solid line) and to the mean data points (dashed-dotted line) weighted with the error bars are also displayed. An arbitrary shift of -0.25 dex has been applied to the abundances of one planet host, for the sake of clarity. *Right panel:* Same as left panel but these two stars harbour only two super-Earth-like planets each.

The stars whose less massive planet is a Neptune-like planet, which we assume *ad hoc* to have a minimum mass in the range $m_p \sin i \sim 14–30$ M_{\oplus} , also exhibit different behaviours. On the one hand, two of them show high (positive) values of the slopes of their abundances trends versus *TC*. Hence this would mean that they should contain a substantial amount of rocky material forming low-mass planets, maybe pointing to these Neptune-like planets. On the other hand, the other two stars, with possibly similar Neptune-like planets, show negative slopes, which is not consistent with the previous line of reasoning.

5. Conclusions

We have carefully inspected the abundance patterns as a function of condensation temperature of solar analogs trying to identify any clear signature of terrestrial planets. The result is not conclusive enough. The mean abundance ratios versus condensation of stars with and without detected planets exhibit similar behaviours which may indicate that if there is any signal, should be the same for all stars, irrespective of whether these stars host planets or not. We note that most of the stars with planets are indeed stars with known giant planets.

However, some stars harbour already detected low-mass planets. In particular, in this sample of solar analogs, there are eight stars hosting super-Earth-like planets, and four with Neptune-like planets, which present different volatile-to-refractory abundance ratios. One would expect that the amount of rocky material (and hence the content of refractory elements) in low-mass planets is significant. Only some of these stars show positive trends versus condensation temperature, which is what one would expect if these trends hide information related to the presence of rocks in their planetary systems. The other stars display flat or negative trends which is in disagreement with the previous statement. There might be a connection between the abundance patterns of stars, in particular, solar analogs, and the presence of terrestrial planets but this work reveals that there is still no clear evidence.

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