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Searching for solar siblings among the HARPS data*
(Research Note)

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ABSTRACT

The search for solar siblings has been particularly fruitful in the past few years. At present, there are four plausible candidates reported in the literature: HIP21158, HIP87382, HIP47399, and HIP92831. In this study we conduct a search for solar siblings among the HARPS high-resolution FGK dwarfs sample, which includes precise chemical abundances and kinematics for 1111 stars. Using a new approach based on chemical abundance trends with condensation temperature, kinematics, and ages we found one (additional) potential solar sibling candidate: HIP97507.

Key words. stars: abundances – stars: kinematics and dynamics – solar neighborhood

1. Introduction

Today, it is accepted that most stars are born in clusters (Lada & Lada 2003), which is also believed to be the case of our Sun. According to Wielen et al. (1996), the Sun was born in the inner part of the Milky Way, perhaps 1.9 kpc closer to the Galactic center than its current location. The stars that have born in the same cluster as the Sun, called solar siblings, were spread away from their initial orbits across the Galaxy. In this scenario, mechanisms such as spiral density waves may play an important role (e.g. Lépine et al. 2003).

Portegies Zwart (2009) quoted that if the parental cluster of our Sun had 10^3 stars, at least 1% of the solar siblings (about 10−60) should still be located within 100 pc and that more than 10% should be within a region of 1 kpc around the present location of our Sun. On the other hand, Mishurov & Acharova (2011) showed that this result is only true in the most optimistic case.

Identifying the Sun's siblings would put constraints on the number of stars in the original cluster. Moreover, reconstructing the orbits of the siblings in the Galaxy would help us to understand the Sun's accurate birth location.

The search for solar siblings is an ambitious task, strongly restricted by their ages, metallicities, and kinematics. The latter has been particularly fruitful during the past few years. A search for solar siblings conducted in the Hipparcos catalog, provided a list of six potential candidates (Brown et al. 2010): HIP21158, HIP30344, HIP51581, HIP80124, HIP90122, and HIP99689. Because of the relatively low age estimates, low metallicity values, or high radial velocities, only the star HIP21158 was thought to be a real potential candidate. The same work, also discussed five more stars, which were found close to the solar isochrones: HIP56287, HIP57791, HIP89825, HIP92381, and HIP101911. However, all of these stars were discarded either because of their radial velocities, or due to the lack of age estimates or metallicity values. Bobylev et al. (2011) introduced a new kinematic approach to search for solar siblings. They found two potential candidates: HIP87382 and HIP47399. More recently, the first giant, HIP175740, was pointed out as a potential solar-sibling candidate (Batista & Fernandes 2012). In addition, the authors also discussed a potential candidate, which has known orbiting planets (HIP115100). However, the latter star was discarded because of its supersolar metallicity.

Very recently, Adibekyan et al. (2014) used a sample of 148 solar-type stars from González Hernández et al. (2010, 2013) to explore the main factors responsible for the abundance trends with condensation temperature (T_c hereafter). The authors found that the slope of this trend (T_c slope hereafter) significantly correlates (at more than 4σ) with the stellar age. They also found evidence that the T_c slope correlates with the mean Galactocentric distance of the stars (R_{mean}), indicating that stars that originated in the inner Galaxy have fewer refractory elements than volatiles. Therefore the authors concluded that age and Galactic birth place are determinant for the chemical structure of stars and they also determine the T_c slopes. This means that stars that were born in the same cluster probably have the similar metallicity and show similar abundance trends with the T_c.

The search for solar siblings is strongly dependent on the ability of finding compatible metallicities between surveys (Batista & Fernandes 2012). In this work, we conducted a search for solar siblings among the HARPS high-resolution FGK dwarfs sample (Adibekyan et al. 2012c) using a new approach based on the observed chemical abundance trends with the T_c. The paper is organized as follows: in Sect. 2, we present the sample. Section 3 presents the criteria we considered in conducting this search and the potential candidates. Finally, in Sect. 4, we summarize the results.

* Based on observations collected at the La Silla Paranal Observatory, ESO (Chile) with the HARPS spectrograph at the 3.6-m telescope (ESO runs ID 72.C-0488, 082.C-0212, and 085.C-0063).

2. Sample

Our initial sample comprises 1111 FGK dwarfs with high-resolution spectra observed with the HARPS spectrograph (Mayor et al. 2003) at the ESO 3.6 m telescope (La Silla, Chile). The sample was built to study the chemical properties of exoplanet-hosting stars (e.g. Adibekyan et al. 2012b,a) and was then used to study chemical properties and kinematics of stellar populations in the solar neighborhood (e.g. Adibekyan et al. 2011, 2013).

Precise stellar parameters ($T_{\rm eff}$, log g, [Fe/H], and $\xi_{\rm t}$) and elemental abundances for 12 elements (namely Na, Mg, Al, Si, Ca, Ti, Cr, Ni, Co, Sc, Mn, and V) for all the stars were determined in a homogeneous way. The atmospheric parameters and elemental abundances were determined using a local thermodynamic equilibrium analysis relative to the Sun with the 2010 revised version of the spectral synthesis code MOOG (Sneden 1973) and a grid of Kurucz ATLAS9 plane-parallel model atmospheres (Kurucz 1993). The reference abundances used in the abundance analysis were taken from Anders & Grevesse (1989). Since all the analysis is differential with respect to the Sun, the reference abundances are not a major concern. We refer to Sousa et al. (2008) and Adibekyan et al. (2012c) for more details.

The stars in the initial sample had effective temperatures ranging between 4487 and 7212 K, but only a few stars in the sample have temperatures that are very different from the solar one. Recently, Tsantaki et al. (2013) showed that the parameters of the stars in this sample are most precise if the $T_{\rm eff}$ is higher than 5000 K. To have the most reliable stellar parameters and abundances (see also Adibekyan et al. 2013) we decided to establish a cutoff in temperature at 5000 K. This lead to a sample of 881 FGK stars (mostly dwarfs, with only 23 having log g < 4 dex). The metallicites of the stars range from −1.39 to 0.55 dex.

For all the stars in the sample, Adibekyan et al. (2012c) derived the space velocity components (U, V, W) with respect to the local standard of rest, adopting the standard solar motion $(U_\odot, V_\odot, W_\odot) = (11.1, 12.24, 7.25)$ km s^{-1} from Schönrich et al. (2010).

2.1. $T_{\rm c}$ slope derivation

As mentioned in the introduction, we wished to use the abundance trends ([X/H]) with $T_{\rm c}$ to select the solar sibling candidates. For this purpose we made a plot of [X/H] versus $T_{\rm c}$ for each individual star from our sample and then applied a liner regression to fit the trend. We used the slopes of the linear fits ($T_{\rm c}$ slopes) for our analysis. The 50% equilibrium condensation temperatures ($T_{\rm c}$) of the elements were taken from Lodders (2003), which varies between 958 K (for Na) and 1659 K (for Ca and Sc). The distribution of the $T_{\rm c}$ slopes for the stars in the sample is shown in Fig. 1.

3. Selection of potential candidates

Stars that have born in the same cluster are predicted to share similar features, such as chemical abundances and ages. Our search is based on the criteria discussed in the literature (e.g. Brown et al. 2010; Bobylev et al. 2011; Batista & Fernandes 2012) and a new criterion based on the $T_{\rm c}$ slopes.

3.1. Chemical tagging: metallicities and $T_{\rm c}$ slope

In all the previous studies aimed to track the solar siblings, the authors only focused on the iron abundance, which is commonly used as a proxy for the overall metallicity of a star. In this study we first constrained our selection to stars with metallicity close to the Sun by ±0.1 dex, that is, |[Fe/H]| < 0.1 dex. This allowed us to select 339 stars out of 881.

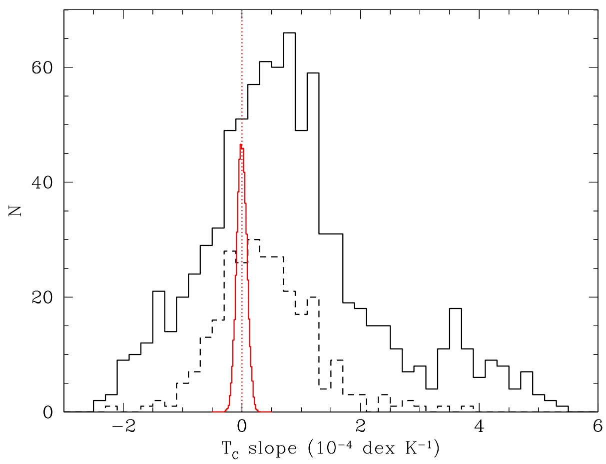

Fig. 1. Distribution of the $T_{\rm c}$ slopes for the full sample (black solid line) and for the stars with |[Fe/H]| < 0.1 dex (black dashed line). The position of the Sun is shown by the red dotted line. The expected distribution of the $T_{\rm c}$ slopes for 500 solar composition stars accepting the average abundance errors from Adibekyan et al. (2012c) is plotted with a red solid line.

Then in the second step we selected the stars with $T_{\rm c}$ slopes (in absolute value) and an error of the slopes smaller than 0.71×10^{-4} dex K^{-1}. This value corresponds to the 0.1 dex difference in [X/H] (Δ[X/H]) when the difference in the $T_{\rm c}$ ($\Delta T_{\rm c}$) is 701 K[1]. This step left us with 101 stars with chemical properties most similar to our Sun. We note that the limiting values used in this section are quite conservative, taking into account the uncertainties of the individual element abundances (Adibekyan et al. 2012c; Sousa et al. 2011).

The distribution of the $T_{\rm c}$ slopes of the selected stars are presented in Fig. 1. In the same figure we also overplot the expected (simulated) distribution of the $T_{\rm c}$ slopes for stars with solar chemical composition ([X/Fe] = 0 dex) and error of the abundances as in Adibekyan et al. (2012c). The simulated distribution of the slopes is Gaussian and picked at zero, while the distribution for the stars in our sample is skewed towards positive slopes. This is probably because age and $R_{\rm mean}$ distributions of our sample stars are not symmetric around the solar age and $R_{\rm mean}$ (see Adibekyan et al., in prep.). It is also interesting to note that the bimodality of the $T_{\rm c}$ slope distribution for the full sample arises because there are two disk populations in the solar vicinity: thin and thick. The second peak, at a higher value of the $T_{\rm c}$ slope, corresponds to the thick-disk stars (see Adibekyan et al., in prep.).

3.2. Stellar kinematics and ages

Numerical simulations conducted by Brown et al. (2010) showed that solar siblings may have approximately the following values of parallax (π) and proper motion (μ): $\pi \geq 10$ mas; $\Delta\pi/\pi \leq 0.1$; $\mu \leq 6.5$ mas yr^{-1}. They also quoted that stars with these kinematic features may have radial velocities (RV) lower than $\sim$10 km s^{-1} in absolute value. In their simulations they used the observationally established value of $(V_{\rm LSR} + V_\odot)/R_\odot$ constrained

[1] The whole range of the $T_{\rm c}$ for the elements used in this study is 701 K, i.e., 1659−958 K.

Table 1. Main parameters of HIP97507 and HIP61173.

Star	[Fe/H]* dex	T_{eff}* K	log g* dex	T_c slope dex K^{-1}	π mas	μRA mas/yr	μDec mas/yr	RV	U	V – km s^{-1} –	W	Age Gyr
HIP97507	−0.03 ± 0.05	5662 ± 62	4.44 ± 0.10	5.1 ± 3.2 (×10^{-5})	18.56	−23.81	−39.37	−1.3	−3.1	−9.2	6.7	3.5 ± 3.2
HIP61173	0.06 ± 0.05	5888 ± 63	4.14 ± 0.10	−0.4 ± 4.6 (×10^{-5})	18.74	−26.05	39.09	−1.4	−10.1	2.7	5.7	5.4 ± 1.2

Notes. (*) The errors are the quadratic sum of the precision and systematic errors.

by McMillan & Binney (2010) to avoid introducing biases related to inadequacies in the simulated phase-space distribution of the siblings.

Bobylev et al. (2011) searched to answer this problem from another perspective. They constrained their search for solar siblings to stars with a magnitude of the total stellar space velocity (henceforth V_{pec} for short) relative to the Sun: $V_{pec} = (U^2 + V^2 + W^2)^{1/2} \lesssim 8$ km s^{-1}. This limiting value was indeed estimated from a typical random error, which for each (U, V, W) component is about 22 km s^{-1}. Then, the authors analyzed the parameters of their encounters with the solar orbit in the past in a time interval similar to the lifetime of stars and selected the best candidates.

Following the criteria introduced by Brown et al. (2010) and also the first criteria of Bobylev et al. (2011), that is, $V_{pec} \lesssim$ 8 km s^{-1}, we did not find any solar sibling candidate within the 101 solar-metallicity stars seleted in the Sect. 3.1. Indeed, the above mentioned criteria strongly depend on many assumption and are not very strict. Changes in the model parameters would also change the final criteria. Therefore, we chose to slightly extend the kinematic criteria to search stars close to the Sun ($\pi \geq 10$ mas and $\Delta\pi/\pi \leq 0.1$) and to have $V_{pec} < 12$ km s^{-1}. Now, we found two stars, HIP97507 and HIP61173, which have V_{pec} of 11.8 and 11.9 k s^{-1} (see Table 1) and a very low radial velocity of −1.3 and 1.4 km s^{-1} (Gontcharov 2006), respectively. Taking into account the errors in the velocity components, we decided to consider these stars as plausible solar sibling potential targets. Here we note that we did not compute the past- encounter parameters with the solar orbit for these stars in more detail as was done in Bobylev et al. (2011). The main parameters of these stars are listed in Table 1.

In the search for solar siblings, one must also consider stellar ages. However, deriving the age of a star is quite an arduous task and the errors are often on the order of Gyr. For these two candidate we estimated an age of 3.5 ± 3.2 (HIP97507) and 5.4 ± 1.2 (HIP61173) Gyr by using the PARAM database (da Silva et al. 2006), which is similar to the age of our Sun when one takes into account the error in age derivation. Casagrande et al. (2011) obtained 3.91 and 4.38 Gyr for the age of HIP97507 and 5.16 and 5.9 Gyr using the Padova and BASTI isochrones, respectively. Our candidate stars have a low level of activity, log $R'_{HK} = -4.907 \pm 0.036$ (HIP97507) and log $R'_{HK} = -5.119 \pm 0.031$ (HIP61173), which means that the stars are not younger than two Gyr (Pace 2013). However, as suggested by Pace (2013), there is no decay of chromospheric activity after 2 Gyr, and it is not possible to estimate the exact and precise age for stars older than the mentioned age.

4. Results and discussion

Although it is not the most abundant element, iron is commonly used as a proxy of the overall metallicity of a star because of its high number of available spectral lines to measure in solar-type stars. Indeed, the metallicity criterion, used in many studies, can be improved by using additional chemical abundances of other elements.

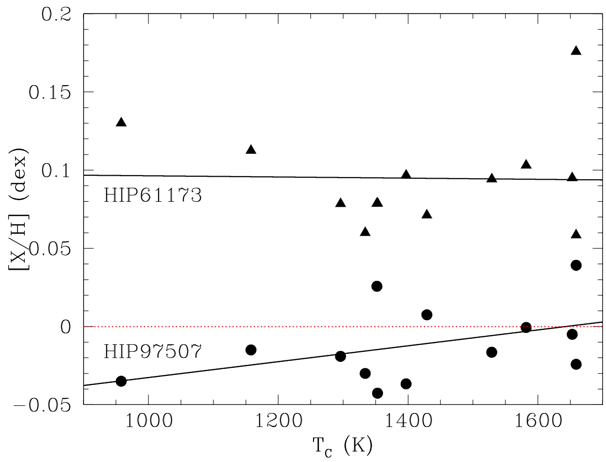

Fig. 2. [X/H] versus T_c for the solar sibling candidates HIP97507 (black circles) and HIP61173 (black triangles). The black solid line provides the linear fit to the data points. The red dotted line shows the position of the Sun.

For the first time, this study provides a search for solar siblings in a very homogeneous sample in terms of the metallicity and chemical abundances in general. We constrained our search for solar siblings among the HARPS FGK dwarfs sample (Adibekyan et al. 2012c) based on the trends observed between the chemical abundances of the stars and condensation temperature. Furthermore, applying the kinematics criteria, we found two solar sibling candidates, HIP97507 and HIP61173, which have a peculiar velocity of about 12 km s^{-1}. Our estimates of the ages of these stars are very close to the age of our Sun (within the errors).

The [X/H] versus T_c for the solar sibling candidates are shown in Fig. 2. Although HIP61173 shows a practically negligible slope, the abundances of all the individual elements are higher than 0.05 dex. Since this star is a "solar analog", the derived stellar parameters and chemical abundances are very precise (see Sousa et al. 2008; Adibekyan et al. 2012c), which forces us to conclude that HIP61173 does not have a solar composition and hence cannot be a solar sibling candidate.

While our paper was submitted, Ramírez et al. (2014) made a detailed analysis of the chemical composition of 30 solar sibling candidates listed in the literature with the goal to select the most probable candidate(s). The authors also showed that several key elements, such as Na, Al, V, B, and Y, can be used for a chemical tagging of solar siblings. Following the referees suggestion, we derived abundances of several heavy elements including Ba and Y for our candidate star (HIP97507): [Cu/H] = 0.02, [Zn/H] = 0.04, [Ba/H] = 0.07 dex, and [Y/H] = 0.00 dex (see González Hernández et al. 2010, for details on the derivation of these elements). These values are quite compatible with the composition of the Sun, probably expect for Ba. However, several studies showed that the dispersion in Ba abundance within open clusters can be higher than 0.1 dex (e.g. Jacobson & Friel 2013; Mishenina et al. 2013). Chemical abundances for these elements also suggest a slightly enhanced metallicity for HIP61173: [Cu/H] = 0.14, [Zn/H] = 0.07, [Ba/H] = 0.05 dex, and [Y/H] = 0.00 dex.

Summarizing, in the sample of 1111 FGK dwarfs from the HARPS GTO subsample (Adibekyan et al. 2012c) there is only one promising potential candidate: HIP97507 (HD186302). We note that the simulations by Portegies Zwart (2009) predict only very few solar siblings within 100 pc from the Sun, and probably with masses lower than that of the Sun (mostly M dwarfs). With the new astrometric measurements that will be conducted with *Gaia*, the knowledge of the star kinematics of the solar neighborhood will be improved. Consequently, the kinematics and age criteria necessary to search for solar siblings will also be improved.

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