

Solar twins in the ELODIE archive^{★,★★}

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ABSTRACT

A large dataset of ~2800 spectra extracted from the ELODIE archive was analysed in order to find solar twins. Stellar spectra closely resembling the spectrum of the Sun were selected by applying a purely differential method, directly on the fluxes. As solar reference, 18 spectra of asteroids, Moon, and blue sky were used. Atmospheric parameters and differential abundances of eight chemical elements were determined for the solar twin candidates after a careful selection of appropriate lines. The Li feature of the targets was investigated and additional information on absolute magnitude and age was gathered from the literature. HIP 076114 (HD 138573) is our best twin candidate; it looks exactly like the Sun in all these properties.

Key words. stars: atmospheres – stars: abundances – stars: fundamental parameters – stars: solar-type

1. Introduction

The definition of solar twin was first introduced by Cayrel de Strobel et al. (1981). Solar twins are stars which have the same physical properties as those of the Sun: mass, radius, luminosity, chemical composition, rotation, and activity. Consequently, the spectrum of a solar twin should be identical to that of the Sun. One way to find solar twins is thus to compare stellar spectra to solar spectra, and to identify those that are the most similar. There are several motivations for searching for solar twins. The Sun, as the best-known star, is used as the fundamental standard in many astronomical calibrations. A first motivation for identifying stars that replicate the solar astrophysical properties is the need to have other reference stars that are observable during the night under the same conditions as any other target. For example, Casagrande et al. (2010) used a set of solar twins to calibrate the effective temperature scale from the infrared flux method, and showed that this model-independent technique is not affected by systematics (Casagrande et al. 2014). Sun-like stars can also help us to understand whether the chemical composition of the Sun compared to other stars is unusual (Ramírez et al. 2009; Nissen 2015) and to explore the connections between planet formation and stellar chemical composition (Ramírez et al. 2014). Solar twins are natural candidates for harbouring planetary systems similar to ours. Finally, solar twins may also give some clues to where and how the Sun formed in our Galaxy. Such stars may have formed under the same conditions as the Sun and from the same molecular cloud. In that case, these stars are known as solar siblings and they are expected to share the same kinematical properties as the Sun (Liu et al. 2015).

Since the pioneering work by Hardorp (1978), the hunt for the closest solar twins has been very active. Giusa Cayrel de Strobel and her collaborators made a huge

contribution to the subject with a detailed spectroscopic analysis of many candidates (Cayrel de Strobel et al. 1981; Cayrel de Strobel & Bentolila 1989; Friel et al. 1993) and a review of the state of the art (Cayrel de Strobel 1996). More recently, a large-scale search of solar twins has been performed, and 17 twins identified, by Datson et al. (2012, 2014, 2015) using the ESO FEROS and HARPS archives. Porto de Mello et al. (2014) conducted a spectroscopic survey of solar twin stars within 50 parsecs of the Sun and identified some candidates on the basis of photometric colours and atmospheric parameters determined from high resolution spectra. Several other studies have used the differential analysis of high resolution spectra to identify solar twins, but very few stars similar to the Sun have been found. HIP 079672 (HD 146233 – 18 Sco) is the most studied star, and often claimed to be the best example (Porto de Mello & da Silva 1997; Soubiran & Triaud 2004; Meléndez et al. 2006; Takeda & Tajitsu 2009). It was finally found not to be a perfect twin because it has a slightly higher effective temperature and surface gravity, different chemical pattern (Meléndez et al. 2014a), higher mass, and younger age (Bazot et al. 2011; Li et al. 2012). Despite a lower Li content and indications that it is older, HIP 114328 (HD 218544) is considered by Meléndez et al. (2014b) to be an excellent solar twin to host a rocky planet owing to its abundance pattern, which is very similar to that of the Sun. Monroe et al. (2013) claim that the abundance pattern of HIP 102152 (HD 197027) is the most similar to solar of any known solar twin; others consider HIP 056948 (HD 101346) to be the prime target in the quest for other Earths owing to its similarity to the Sun (Meléndez et al. 2012; Takeda & Tajitsu 2009; Meléndez & Ramírez 2007). In fact, most of the solar twins are found to have chemical compositions different from that of the Sun when submitted to high precision differential analysis, suggesting that the Sun has an unusual abundance pattern (Nissen 2015). Interestingly, Önehag et al. (2011) claims that M67-1194 is the first solar twin known to belong to a stellar association. The chemical similarity between the Sun and M67-1194 suggests that the Sun formed in a cluster like M67. However Pichardo et al. (2012) have demonstrated with dynamical arguments that M67 could not have been the birth cluster

* Based on data extracted from the ELODIE archive at Observatoire de Haute-Provence (OHP), <http://atlas.obs-hp.fr/elodie/>

** Tables 2 and 4–8 are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/587/A131>

of the Sun and have also excluded the possibility that the Sun and M67 were born in the same molecular cloud.

In this paper we searched for new solar twins in a large sample of spectra selected from the ELODIE archive (Moultaka et al. 2004), using eighteen spectra of asteroids, of the Moon, and of the day sky as solar reference. This observational material is described in Sect. 2. We proceeded in several steps. First, as described in Sect. 3, twin candidates were identified with a minimum distance method already used and validated for that task by Soubiran & Triaud (2004). Then their atmospheric parameters (effective temperature T_{eff} , surface gravity $\log g$, metallicity $[M/H]$) were derived and compared to those of the Sun (Sect. 4). We inspected the spectral range around the Li lines at 670.78 nm to find twin candidates showing the same Li depletion as the Sun (Sect. 5). In Sect. 6 we explain how we selected the good lines from which abundances were determined differentially to the solar spectra. Finally, we searched for extra information on the targets (Sect. 7) and discuss our findings in Sect. 8.

2. ELODIE spectra

All the spectra used in this paper were retrieved from the archive of the ELODIE echelle spectrograph (Moultaka et al. 2004). ELODIE was on the 1.93 m telescope at Observatoire de Haute-Provence (OHP) between late 1993 and mid 2006. It was designed for very precise radial velocity measurements (the discovery of the first extrasolar planet 51 Peg B by Mayor & Queloz 1995, was made with this instrument), but it has also been used for many other programs in stellar physics and galactic structure. The spectra cover the interval from 389.5 to 681.5 nm and are recorded as 67 orders with a resolution of $R \approx 42\,000$ (Baranne et al. 1996). The archive provides the spectra in two formats. In the *S2D* format the spectra are recorded as 67×1024 pixels; the coefficients of the pixel-to-wavelength relation of each order are stored in the FITS header; the orders are deblazed (the blaze function being stored in a FITS extension). In the *spec* format the orders are reconnected and resampled in wavelength with a constant step of 0.05 Å, covering the range 400–680 nm (the first three blue orders are not included as their signal-to-noise ratio (S/N) is usually very low). There are several modes of observation related to the two sets of optical twin-fibres, direct and scrambled: one fibre is assigned to the object, while the second can be masked, can be on the sky, or can be illuminated by a thorium-argon lamp. The ELODIE archive also releases the radial velocities calculated at the telescope by cross-correlation of the spectra with numerical masks of spectral type F0 or K0. The Gaussian fit of a cross-correlation function (CCF) provides the fitted radial velocity, the full width at half maximum (FWHM), and the amplitude of the correlation peak. In the case of spectroscopic binaries, a double Gaussian is fitted. The CCFs are provided as FITS files, with the parameters of the Gaussian fit in the header. More detailed information on the ELODIE archive data products is available in the online user's guide¹.

The ELODIE archive contains more than 35 000 public spectra and there are ~8000 distinct object names (with possible duplication due to unresolved aliases). For this work on solar twins, only spectra with a S/N at 550 nm greater than 70, a measured radial velocity, and an identification resolved by Simbad were selected. Spectra showing an enlarged CCF with FWHM greater than 12 km s⁻¹ or a double-peaked CCF were rejected. No other selection based on colour or spectral type was made. Large series of observations of a single star were shortened by retrieving

Table 1. Solar spectra available in the ELODIE archive.

| Name | Date /Imanum | S/N 550 nm | FWHM km s ⁻¹ | Exposure type |
|----------|-----------------|---------------|----------------------------|------------------|
| CERES | 19950206 /0021 | 107.3 | 11.13 | OBTH |
| CERES | 20000327 /0023 | 117.3 | 11.01 | OBJOd |
| CERES | 20040209 /0007 | 130.8 | 11.03 | OBJOd |
| Sky | 19960629 /0007 | 335.6 | 11.07 | OBJO |
| Sky | 20060613 /0010 | 190.9 | 10.96 | OBJOs |
| Sky | 20060613 /0011 | 286.3 | 10.98 | OBJOs |
| Sky | 20021127 /0009 | 430.1 | 10.95 | OBJOd |
| Sky | 20060601 /0027 | 142.4 | 11.04 | OBJOd |
| MOON | 19980114 /0008 | 381.4 | 11.06 | OBJOd |
| MOON | 19981001 /0012 | 110.8 | 10.99 | OBTHs |
| MOON | 19991222 /0013 | 139.6 | 11.05 | OBJOd |
| MOON | 19991222 /0014 | 156.5 | 11.06 | OBJOd |
| MOON | 20000124 /0028 | 200.0 | 11.0 5 | OBJOd |
| MOON | 20000124 /0029 | 224.9 | 11.05 | OBJOd |
| MOON | 20000609 /0008 | 350.8 | 11.08 | OBJOd |
| MOON | 20000609 /0009 | 246.4 | 11.08 | OBJOd |
| VESTA | 19950110 /0020 | 98.7 | 11.11 | OBTH |
| CALLISTO | 19990813 / 0037 | 218.2 | 11.10 | OBJOd |

Notes. The spectra can easily be retrieved from the archive using the date of observation and the exposure serial number (imanum). The S/N is provided in the header of the spectrum, for the order 46 centred on 550 nm. The FWHM is that of the CCF retrieved from the archive. The exposure type indicates whether the observation was made with a simultaneous thorium calibration (OBTH) or not (OBJO) and with direct or scrambled fibres (d and s, respectively, after 1997).

from the archive only one observation per night and five observations in total (the ones with the highest S/N, favouring exposures without simultaneous thorium-argon). Repeated observations of the same stars were used to test the consistency of our methods and to provide more robust results, as explained in Sects. 4 and 6. The selection corresponds to 2784 spectra of 1165 different stars which were downloaded as FITS files in *S2D* and *spec* formats, together with the CCF files. In addition, 18 spectra of solar system bodies and day sky light were retrieved to be used as reference solar spectra. These solar spectra were obtained at different dates and with various S/N and fibre modes giving a representative range of observing conditions for the other stars. The list of solar spectra is presented in Table 1.

3. Minimum distance between spectra

To measure the degree of similarity between two spectra, of a target and of the Sun, we applied the TGMET code developed by Katz et al. (1998), a purely differential method implementing a minimum distance criterion. TGMET was already applied by Soubiran & Triaud (2004) on a selection of ~200 ELODIE G dwarf spectra in order to identify solar twins.

The method was applied to *S2D* spectra, on orders 21 to 67, corresponding to the wavelength range 440–680 Å, with rejection of the under-illuminated edges of the orders. Order 63 (~648–652.5 nm) was rejected because it is highly affected by telluric lines. We briefly recall the principle of the TGMET method. Two spectra to be compared need to be put on the same scale, in wavelength and in flux. The wavelength alignment is performed by shifting the compared spectrum to the radial velocity of the solar spectrum and by resampling it to the same wavelength points. This operation implies an interpolation between wavelengths for the compared spectrum, which is performed with the quadratic Bessel formula. Once the horizontal adjustment is made, the vertical adjustment is performed by

¹ <http://atlas.obs-hp.fr/elodie/intro.html>

fitting the flux of the compared spectrum to the solar spectrum. To do so, a simple factor is determined by least-squares (since the two stars have roughly the same temperature it is not necessary to introduce a slope). The reduced χ^2 of that fit, computed order-by-order over nearly 40 000 wavelengths in total, is thus a distance quantifying the similarity between the two spectra. However, following [Katz et al. \(1998\)](#), we did not adopt the real reduced χ^2 for the distance between two spectra, which would imply taking into account the noise on each pixel. Instead, we computed an averaged and normalized instrumental response curve that we used as the weighting function of the fit. This smooth function reflects the global variation of S/N over each order (the edges of an order are underexposed compared to its central part). It gives a similar weight to the continuum and to the wings and bottom of absorption lines, contrary to a weighting function based on the photon noise. Several tests made in [Katz et al. \(1998\)](#) demonstrated its higher performance, especially at high S/N.

TGMET was applied to compute the distance of each solar spectrum to each of the other spectra. The TGMET output for a given solar spectrum resulted in 2801 distances (for 2784 target spectra plus the 17 other solar spectra) that were sorted by increasing value. Since solar spectra were processed like the other targets, they were used to verify the results: the nearest neighbours of a given solar spectrum are expected to always be the other solar spectra. This is verified in most cases, but sometimes some stars are found closer to a given solar spectrum than other solar spectra, demonstrating that the observing conditions affect the results. This also means that such stars have spectra that are very similar to that of the Sun, and thus they are good candidates for solar twins. TGMET was also run with spectra convolved to a common broadening of $FWHM = 12 \text{ km s}^{-1}$ in order to minimize the possible effect of a different rotation and macroturbulence in the targets and in the Sun; however, this did not produce significantly different results. Other TGMET runs were performed on a smaller number of orders. TGMET was run on \sim half of the orders which carry the most information due to a larger number of absorption lines. In another run we removed ten orders that systematically yielded the worst results among the solar spectra. Another run was performed using only the order 39 centred on the Mg triplet at \sim 520 nm, which is sensitive to effective temperature, surface gravity, and metallicity and thus a good region for testing the spectroscopic similarity of stars. The best twin candidates were identified by mixing these results obtained with TGMET runs in different configurations. In total 108 TGMET output files were obtained, corresponding to 18 solar spectra \times 2 (convolved and non-convolved spectra) \times 3 (all orders, selected orders, order 39). The list of solar twin candidates was built by selecting all stars ranked at a smaller distance than the last solar spectrum in these different result files. This gives 56 stars (225 spectra) among which remarkable stars are to be noted. HIP 079672 (HD 146233, 18 Sco) is by far the most frequent first neighbour. HIP 018413 (HD 024409), HIP 076114 (HD 138573), and HIP 089474 (HD 168009) appear in the five nearest neighbours in more than 70% of the result files, followed by HIP 118162 (HD 224465) and HIP 041484 (HD 071148). The status of these stars as solar twins will be discussed in Sect. 8.

4. Atmospheric parameters

The atmospheric parameters and abundances of the solar and target spectra were derived with iSpec ([Blanco-Cuaresma et al. 2014](#)) following the recipes described in [Blanco-Cuaresma et al. \(2015\)](#). For that task we used the ELODIE spectra in *spec* format

(i.e. with the orders reconnected and the wavelengths resampled at a constant step) in the range 480–670 nm where iSpec was extensively tested and validated. As model atmospheres we used MARCS ([Gustafsson et al. 2008](#)).

For the atmospheric parameters, the line list established for the *Gaia* ESO survey ([Heiter et al. 2015a](#)) was used. It consists of \sim 140 000 atomic lines extracted from the VALD database among which \sim 2000 lines of 35 elements have been revisited and evaluated on the basis of the quality of the atomic data and of the spectral synthesis for the Sun and Arcturus. For our use the recommended lines were selected, those flagged as being the most reliable ones. The parameters T_{eff} , $\log g$, and $[M/H]$ were determined automatically and iteratively. The different steps are (1) the normalization of the spectra by two-degree splines at every nanometer on pre-selected points; (2) a first guess of atmospheric parameters by comparing the wings of the H α and H β lines and the Mg triplet to a small pre-computed synthetic grid; (3) the Gaussian fit of lines with rejection of badly fitted lines (blended lines, gaps, cosmoics, too faint lines, etc.); and (4) the synthesis of the remaining lines allowing the determination of the atmospheric parameters by least-squares. V_{mic} and V_{mac} were set as free parameters while $v \sin i$ was set to 2 km s^{-1} for all the targets. These three parameters are possibly degenerated, but the selection of spectra with $FWHM \leq 12 \text{ km s}^{-1}$ prevented us from dealing with stars rotating much faster than the Sun or with higher macroturbulent velocity. In practice, from 615 to 805 lines of 28 elements were used to determine the atmospheric parameters, depending on the spectrum.

In order to evaluate systematic errors and correct them, we investigated in detail the results obtained for the 18 solar spectra. A very high consistency was obtained. For T_{eff} and $\log g$, the averaged values are 5773K and 4.32 with standard deviations of 9 K and 0.02 dex, respectively. The T_{eff} difference with the fundamental value, 5777 K, is negligible. It is worth noting that the fundamental T_{eff} of the Sun was recently revised by [Heiter et al. \(2015b\)](#) to be $T_{\text{eff}\odot} = 5771 \pm 1 \text{ K}$, putting our determination even closer to that fundamental value. We found a systematic shift of -0.12 dex for gravity with respect to the fundamental value of $\log g_{\odot} = 4.44$. This bias was found in previous works based on iSpec ([Blanco-Cuaresma et al. 2015](#)). A correction of $+0.12$ dex was thus applied for the rest of the analysed targets, establishing a global zero point centred on the solar reference parameters. Similarly, we found an average metallicity $[M/H] = -0.15$ dex for the solar spectra, determined from lines of various elements. The global metallicities of the targets, determined from the same lines, were thus corrected by this value to be relative to the Sun.

As stated in the ELODIE user's manual, it is suspected that for image types OBTH, the presence of the thorium-argon orders interleaved with the stellar orders may lead to pollution of the stellar spectrum by highly saturated Argon lines which can contaminate the adjacent stellar orders. So, in principle, this kind of spectra should not be used to determine atmospheric parameters and abundances. However, we obtained similar atmospheric parameters for the Sun when we averaged them from the 15 OBJ and 3 OBTH spectra separately: negligible differences of 8K, 0.02 dex, and 0.01 dex were measured in T_{eff} , $\log g$, and $[M/H]$, respectively. There is thus apparently no impact of the image type on the atmospheric parameters, probably owing to the selection of well-fitted lines and to the synthesis method.

In the target sample, 48 stars have duplicate observations from which we estimated the internal consistency of the derived atmospheric parameters. For these stars the standard deviation

around the mean T_{eff} ranges from 1 K to 20 K with a median of 9 K. For $\log g$ the median standard deviation is 0.02 dex with no higher value than 0.04. For $[M/H]$ all the stars have a median standard deviation of 0.01 dex except HIP 097336, which has a standard deviation of 0.02 dex for five spectra. Although these values show the excellent consistency of the iSpec determinations of atmospheric parameters from one spectrum to another, we still verified that the 16 stars observed with both modes OBJ and OBTH have derived parameters in good agreement from both types of exposures.

HIP 079672 (18 Sco) is one of the *Gaia* benchmark stars recently studied by Heiter et al. (2015b) who determined fundamental $T_{\text{eff}} = 5810$ K and $\log g = 4.44$ from the defining relations, independently of spectroscopy. The *Gaia* benchmark stars are intended to serve as calibrators for spectroscopy and thus can be used to evaluate our determinations. Only one spectrum is available for HIP 079672 in the ELODIE archive from which we determined $T_{\text{eff}} = 5793 \pm 9$ K and $\log g = 4.43 \pm 0.015$, in good agreement with the fundamental values. We thus confirm that HIP 079672 is slightly hotter than the Sun.

Atmospheric parameters are presented in Table 2. The histograms of the differences with the solar values are presented in Fig. 1. There are 22 stars that fall into the category of solar twins according to the criteria adopted by Meléndez et al. (2014b): they differ by less than 100 K in T_{eff} , 0.1 dex in $\log g$, and 0.1 dex in metallicity from the Sun values. We flag these stars as atmospheric parameter (AP) category B in Table 2. Three remarkable stars have to be noted as they have the same atmospheric parameters as the Sun, within 25 K in T_{eff} , 0.05 dex in $\log g$, and $[M/H]$ (flagged as AP category A in Table 2): HIP 076114, HIP 085244, and HIP 088194. The status of these stars as solar twins will be discussed in Sect. 8.

Interestingly some stars have quite different parameters from the Sun (flagged as AP category C in Table 2). For instance HIP 065721 is a subgiant cooler than the Sun and slightly more metal-poor. This example illustrates the degeneracy of atmospheric parameters at the resolution of 42 000 when the overall spectrum is considered. This suggests that the spectroscopic comparison between spectra should be performed differentially, on a line-by-line basis.

5. Li content

It is known that the lithium abundances of solar-type stars show a large dispersion (see e.g. the comprehensive study by Takeda et al. 2007). This is subject to various interpretations. The Sun is depleted in Li and it is expected that solar twins show the same deficiency. We have classified our target stars into three categories after a visual inspection of the wavelength range including the Li lines at ~ 670.78 nm in comparison to one of the ELODIE solar spectra. We classified the stars that show a similar Li deficiency to the Sun as category A (see Table 2), those with a slightly higher Li abundance as category B, and those that exhibit a pronounced Li feature as category C. There are 24, 11, and 21 stars in category A, B, and C, respectively. Figure 2 shows two examples of stars in each category. It is worth noting that HIP 076114 and HIP 088194 are classified as A for their similarity to the Sun in both atmospheric parameters and lithium content.

Stellar rotation and activity are strongly correlated with the surface Li content of solar-type stars (Takeda et al. 2007). The stars examined here are considered slow rotators according to our initial constraint $FWHM \leq 12$ km s $^{-1}$. It is thus interesting to find such a wide range of Li content.

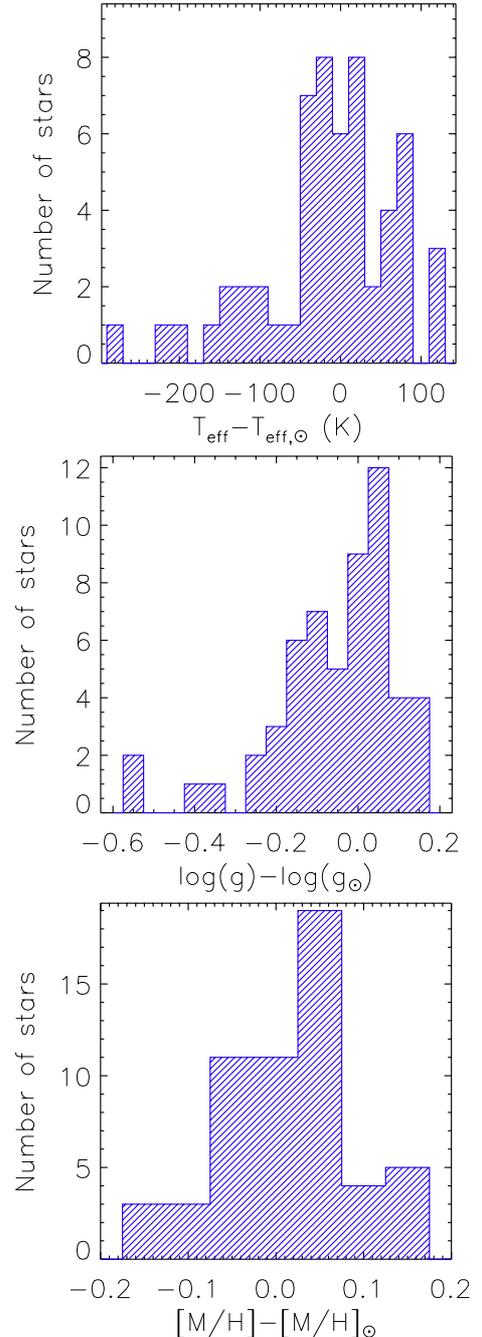


Fig. 1. Histograms of the differences between the atmospheric parameters of the twin candidates and of the Sun, as obtained by iSpec.

6. Abundances

The chemical abundances were derived with iSpec and the line list of the *Gaia* ESO survey, this time also including the lines that were labelled less reliable owing to uncertain atomic data or possible blends. However the 18 solar spectra allowed us to keep only the lines that gave consistent abundances from one spectrum to another. Moreover, since we are dealing with solar twins, a differential analysis with respect to solar spectra was possible, which reduced the uncertainty in relative abundances due to bad atomic data. In this way we were able to obtain a high precision, which is so important when identifying solar twins (Meléndez et al. 2012).

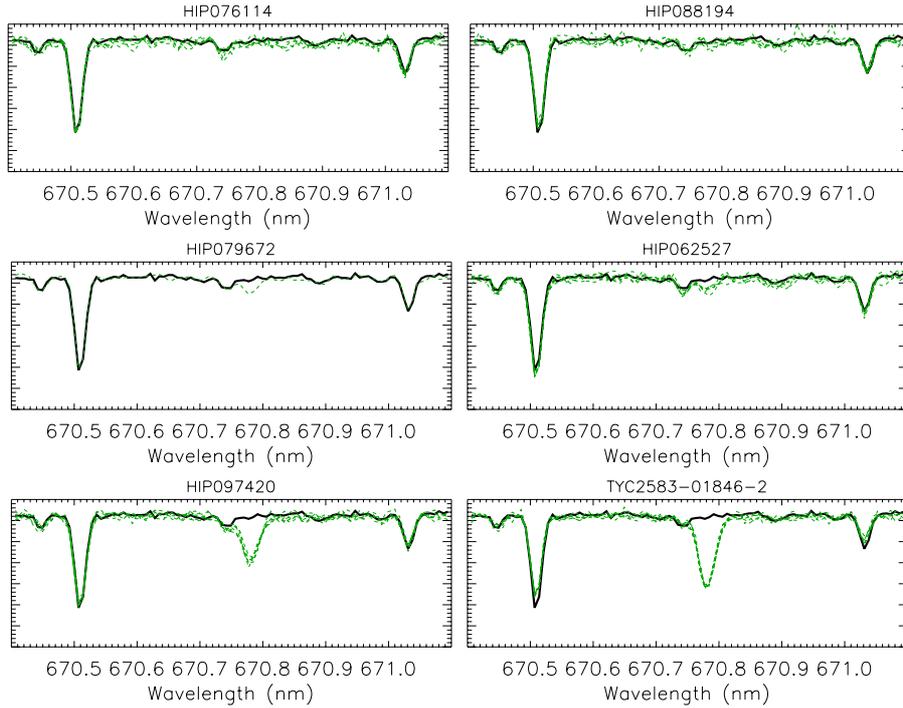


Fig. 2. Comparison of the spectral range centred on the 670.78 nm Li feature in one of the Sun spectra (black thick line) and a target (green dashed line) with up to five spectra available for some stars. *The upper panels* show two stars classified as A (the same Li deficiency as the Sun), *the middle panels* show two stars classified as B (slightly more abundant in Li than the Sun), *the bottom panels* show two stars classified as C (pronounced Li feature).

A total of 1865 lines were measurable in the ELODIE spectra out of which we kept only those measured in at least 17 out of 18 solar spectra with a weighted standard deviation lower than 0.02. Then we selected the chemical elements for which at least three such lines were measured. This left us with 189 Fe lines, 23 Ni lines, 15 Si and Ca lines, 8 Cr lines, 5 Mn and Ti lines, and 4 Na lines, all of which were neutral, plus 3 FeII lines. Table 7 lists these 267 lines which were found to be suitable for spectral synthesis of solar-type stars. For each of these lines, we took as reference abundance the weighted mean obtained on the 17 or 18 solar spectra. The line-by-line abundances of the 225 spectra were then measured differentially for this set. As the total error for a line abundance relative to the Sun, we quadratically summed the weighted standard deviation obtained for the solar spectra and the rms of the fit obtained for the target spectrum. Then the weighted average and standard deviation were computed for each element and each star (see Tables 4–6). With up to five spectra available for a large fraction of the targets, the determination of $[\text{FeI}/\text{H}]$ was often based on the measurement of 945 individual lines. In total we obtained 59 707 individual line measurements with errors between 0.01 and 0.111 and a median error of 0.02. As a verification, we checked the agreement of the $[\text{FeI}/\text{H}]$ and $[\text{FeII}/\text{H}]$ determinations (Fig. 3). The mean difference is 0.008, which demonstrates the excellent agreement of the two estimates of the iron abundance, with a standard deviation of 0.019, which agrees perfectly with the median error of 0.02 of all the individual line measurements.

Figure 3 also shows that there is a concentration of stars slightly more metal-rich than the Sun, which is a possible bias in the content of the ELODIE archive in favour of stars followed up for the search of extrasolar planets.

HIP079672 (18 Sco) has been studied at very high resolution ($R \sim 110\,000$) and S/N (800–1000) by Meléndez et al. (2014a) who obtained abundances differentially to the Sun with

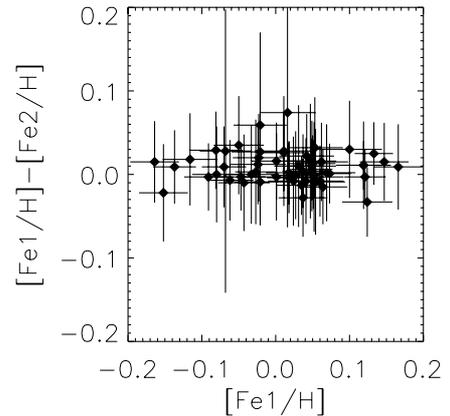


Fig. 3. Difference in iron abundances obtained with neutral and ionized lines for the 56 twin candidates. The mean difference is 0.008 dex with a standard deviation of 0.019 dex.

an unprecedented level of precision. We compare their determinations to ours in Table 3: they agree within 0.03 for Ti and Cr, within 0.008 for Na and Ca, and within 0.004 for Fe, Si, Mn, and Ni. Thus the agreement is largely better than expected from our quoted errors. For comparison we also show the abundances from Jofré et al. (2015) who made an extensive study of the *Gaia* benchmark stars. They are also in excellent agreement.

Seven solar analogs have all the tested elements agreeing with the solar abundances within 0.05: HIP 021436, HIP 035265, HIP 076114, HIP 085244, HIP 089474, HIP 100963, TYC2694-00364-1.

Figure A.1 shows the iron abundances of the 56 targets from neutral and ionized lines and Fig. A.2 displays the abundances of the other elements. The stars are numbered from 1 to 56 for the sake of clarity. The abundances of the tested elements are well centred on the solar value with a small spread. This suggests that

Table 3. Comparison of abundances determined in this work for HIP 079672 (18 Sco) to those obtained by Meléndez et al. (2014a) and by Jofré et al. (2015).

| [X/H] | This work | Meléndez et al. (2014a) | Jofré et al. (2015) |
|-------|---------------|-------------------------|---------------------|
| Fe | 0.051 ± 0.026 | 0.054 ± 0.005 | 0.03 ± 0.01 (a) |
| Na | 0.017 ± 0.045 | 0.025 ± 0.004 | |
| Si | 0.043 ± 0.014 | 0.047 ± 0.003 | 0.048 ± 0.018 |
| Ca | 0.065 ± 0.016 | 0.057 ± 0.006 | 0.058 ± 0.036 |
| Ti | 0.022 ± 0.045 | 0.051 ± 0.007 | 0.046 ± 0.026 |
| Cr | 0.034 ± 0.026 | 0.056 ± 0.006 | 0.049 ± 0.023 |
| Mn | 0.037 ± 0.012 | 0.041 ± 0.006 | 0.040 ± 0.018 |
| Ni | 0.038 ± 0.027 | 0.041 ± 0.004 | 0.039 ± 0.017 |

Notes. (a) NLTE determination from Jofré et al. (2014).

the solar abundance pattern is not unusual as has been suggested by some studies (Nissen 2015); however, this point needs further confirmation with other elements that are not part of this study because of our strict selection of very well measured lines in the ELODIE solar spectra, which has guaranteed a high level of precision.

7. Additional information

The 56 twin candidates are either Hipparcos or Tycho stars. We obtained their information from the XHIP catalogue (Anderson & Francis 2012) and from Simbad (see Table 8). All the stars are within 60 pc of the Sun, their spectral types vary from F8 to G6.5. Their $B - V$ colours and M_v absolute magnitudes span a wide range of values. Ages are provided in the form of a probable range, which are sometimes very large owing to the lack of constraints on this fundamental property.

We proceeded as in the previous sections and classified the stars into two categories depending on the similarity of their M_v absolute magnitude and age with the solar values. Stars with M_v in the range [4.6–5.0] are potentially similar to the Sun ($M_{v_{\odot}} \approx 4.80$). If their age interval also includes the age of the Sun (~ 4.5 Gyr), then these stars are good twin candidates. Fifteen stars were found to be similar to the Sun based on their absolute magnitude and age range.

We also searched in Simbad whether the twin candidates have a detected extrasolar planet and found four such stars: HIP 053721, HIP 065721, HIP 096901, and HIP 097336, none of which is a good solar twin.

8. Discussion

In each of the previous sections, we classify 56 twin candidates according to their similarity with the Sun using different properties: global spectrum, atmospheric parameters, Li content, abundances of eight chemical elements, absolute magnitude, age, and the presence of a planet. According to the TGMET method, six stars were found to have a spectrum very similar to that of the Sun: HIP 079672, HIP 018413, HIP 076114, HIP 089474, HIP 118162, and HIP 041484. Three stars were found to have solar atmospheric parameters: HIP 076114, HIP 085244, and HIP 088194, two of which also have the same Li deficiency: HIP 076114 and HIP 088194. Seven stars were found to have a solar abundance pattern for eight chemical elements: HIP 021436, HIP 035265, HIP 076114, HIP 085244, HIP 089474, HIP 100963, and TYC2694-00364-1. Table 9 summarizes the categories A, B, and C for each target according to its similarity to the Sun in atmospheric parameters, abundances, Li content, absolute magnitude, and age.

It is remarkable to find a star similar to the Sun in all these properties, HIP 076114 (HD 138573). This star is also in the list of best twins of Datson et al. (2012), although they classify it after HIP 079672 (18 Sco) (see also Datson et al. 2015). HIP 076114 is also part of the survey of solar twin stars within 50 parsecs of the Sun by Porto de Mello et al. (2014), as well as in the Solar Twin Planet Search by Ramírez et al. (2014), but not mentioned as a remarkable twin in these two papers. It is worth noting that the galactic velocity of that star differs by ~ 40 km s⁻¹ from that of the Sun, suggesting that it is not a solar sibling. It is, however, an excellent star to use for calibrations or to search for exoplanets.

HIP 085244 is our second best twin candidate; it has solar atmospheric parameters and chemical pattern, but it is classified as B for Li and has a slightly more enhanced content. According to XHIP, this star is supposed to be older than the Sun. HIP 085244 is also part of the survey of solar twin stars within 50 parsecs of the Sun by Porto de Mello et al. (2014).

HIP 088194 has solar atmospheric parameters and is deficient in Li, but it is slightly more metal-poor than the Sun. This is clearly visible in Figs. A.1 and A.2 (star 40). It is older than the Sun according to XHIP, but is the same age according to Porto de Mello et al. (2014). It is one of the new candidates considered as excellent in that work.

HIP 021436 has a solar chemical pattern and also the same Li content, but its effective temperature is lower by ~ 60 K than that of the Sun. Although we classify it as B for the atmospheric parameters, it still falls into the solar twin category according to the criterion defined by Meléndez et al. (2014b). Our T_{eff} determination (5715 ± 10 K) is in very good agreement with the seven values listed in the PASTEL catalog (Soubiran et al. 2010) ranging from 5675 to 5748 K. It is worth noting that this star has a galactic velocity compatible with that of the Sun within 10 km s⁻¹. Its age reported in XHIP is not well constrained, so possibly compatible with that of the Sun. It is thus also a very good solar sibling candidate.

HIP 035265 has the solar chemical pattern, absolute magnitude, and age compatible with the Sun, but it is hotter by ~ 80 K and with a strong Li feature. It also has a galactic velocity different from the Sun. This is therefore not a perfect solar twin or sibling.

HIP 100963 has a solar chemical pattern, but it is hotter than the Sun ($T_{\text{eff}} = 5821 \pm 6$ K) and has a pronounced Li feature. It was previously identified as a solar twin by Ramírez et al. (2009) who determined $T_{\text{eff}} = 5815$ K and $[\text{Fe}/\text{H}] = +0.018 \pm 0.019$ in very good agreement with our determinations (i.e. $[\text{Fe}/\text{H}] = +0.011 \pm 0.034$). Considering this star as an excellent solar twin, Takeda & Tajitsu (2009) made an extensive study at very high resolution ($R = 90\,000$) and high S/N (500–1000) and found it hotter than the Sun by 23 K with a difference in iron abundance of 0.004 and a higher Li content—by a factor of ~ 56 —than the Sun, also in good agreement with our findings.

TYC2694-00364-1 has been poorly studied as an individual star until now. It essentially differs from the Sun by its hotter temperature ($T_{\text{eff}} = 5842 \pm 1$ K) and a strong Li feature.

HIP 042575, HIP 056832, and HIP 118162 are our next good solar twins, never identified as such before. Although slightly metal-rich, their abundances differ by less than 0.1 dex from those of the Sun. They exhibit a solar Li deficiency and have an age and absolute magnitude compatible with those of the Sun. Next is HIP 011728, also more metal-rich but previously identified as a solar twin by Porto de Mello et al. (2014) and Datson et al. (2015). Its absolute magnitude is reported as $M_v = 5.03$ in XHIP, higher than that of the Sun. Then we

Table 9. Summary of the classification of solar twin candidates after comparison to the Sun based on atmospheric parameters, abundances of eight elements, Li content, absolute magnitude, and age.

| HIP/TYC | HD | AP | Ab. | Li | Mv+age | Previous studies |
|-----------------|-----------|----|-----|----|--------|--|
| solar twins | | | | | | |
| HIP 076114 | HD 138573 | A | A | A | A | [5], [6], [7] |
| HIP 085244 | HD 158222 | A | A | B | C | [6] |
| HIP 088194 | HD 164595 | A | B | A | C | [6] |
| HIP 021436 | HD 029150 | B | A | A | C | [8] |
| HIP 035265 | HD 056124 | B | A | C | A | [2] |
| HIP 100963 | HD 195034 | B | A | C | A | [3], [4] |
| TYC2694-00364-1 | HD 197310 | B | A | C | B | |
| HIP 042575 | HD 073393 | B | B | A | A | |
| HIP 056832 | HD 101242 | B | B | A | A | |
| HIP 118162 | HD 224465 | B | B | A | A | |
| HIP 011728 | HD 015632 | B | B | A | C | [6], [8] |
| HIP 018413 | HD 024409 | B | B | A | C | |
| HIP 049756 | HD 088072 | B | B | B | A | [1], [6], [7], [8] |
| HIP 079672 | HD 146233 | B | B | B | A | [1], [2], [3], [4], [5], [6], [7], [8] |
| HIP 043557 | HD 075767 | B | B | B | C | [8] |
| HIP 007585 | HD 009986 | B | B | C | A | [2], [6], [7], [8] |
| HIP 097420 | HD 187237 | B | B | C | A | [6] |
| HIP 041484 | HD 071148 | B | B | C | C | [1], [2] |
| HIP 094981 | HD 181655 | B | B | C | C | |
| other stars | | | | | | |
| HIP 011253 | HD 014874 | B | C | B | C | |
| HIP 029432 | HD 042618 | B | C | B | C | |
| HIP 102040 | HD 197076 | B | C | C | A | |
| HIP 007339 | HD 009407 | C | A | A | B | |
| HIP 089474 | HD 168009 | C | A | A | C | |
| HIP 001813 | HD 001832 | C | B | A | C | |
| HIP 031965 | HD 047309 | C | B | A | C | |
| HIP 044089 | HD 076752 | C | B | A | C | |
| HIP 064150 | HD 114174 | C | B | A | C | |
| HIP 072043 | HD 129814 | C | B | A | C | |
| HIP 086193 | HD 159909 | C | B | A | C | |
| HIP 041844 | HD 071881 | C | B | B | C | |
| HIP 077052 | HD 140538 | C | B | B | C | |
| HIP 096901 | HD 186427 | C | B | B | C | star with planet |
| HIP 007918 | HD 010307 | C | B | C | C | |
| HIP 050316 | HD 088986 | C | B | C | C | |
| HIP 053721 | HD 095128 | C | B | C | C | star with planet |
| HIP 007902 | HD 010145 | C | C | A | A | |
| HIP 036874 | HD 060298 | C | C | A | C | |
| HIP 050505 | HD 089269 | C | C | A | C | |
| HIP 090355 | HD 169822 | C | C | A | C | |
| HIP 096402 | HD 184768 | C | C | A | C | |
| HIP 096895 | HD 186408 | C | C | A | C | |
| HIP 097336 | HD 187123 | C | C | A | C | star with planet |
| HIP 097767 | HD 187923 | C | C | A | C | |
| HIP 062527 | HD 111513 | C | C | B | C | |
| HIP 096948 | HD 186104 | C | C | B | C | |
| HIP 043726 | HD 076151 | C | C | C | A | |
| HIP 085810 | HD 159222 | C | C | C | A | |
| HIP 116613 | HD 222143 | C | C | C | A | |
| TYC2583-01846-2 | HD 146362 | C | C | C | B | |
| HIP 004290 | HD 005294 | C | C | C | C | |
| HIP 021010 | HD 028447 | C | C | C | C | |
| HIP 024813 | HD 034411 | C | C | C | C | |
| HIP 029525 | HD 042807 | C | C | C | C | |
| HIP 063636 | HD 113319 | C | C | C | C | |
| HIP 065721 | HD 117176 | C | C | C | C | star with planet |

Notes. The best solar twins are sorted at the top of the table. The columns AP (atmospheric parameters), Li, and Mv+age report the classification (A, B, C) from Tables 2 and 8. The column Ab. indicates whether the differential abundances in Tables 4–6 agree with the solar value within 0.05 dex (A) or within 0.10 dex (B), or whether they differ (C). For the 19 stars considered good solar twins (AP and Ab. equal A or B), the last column indicates studies where that star was previously identified as a solar twin: [1] = [Soubiran & Triaud \(2004\)](#); [2] = [Meléndez et al. \(2006\)](#); [3] = [Ramírez et al. \(2009\)](#); [4] = [Takeda & Tajitsu \(2009\)](#); [5] = [Datson et al. \(2012\)](#); [6] = [Porto de Mello et al. \(2014\)](#); [7] = [Ramírez et al. \(2014\)](#); [8] = [Datson et al. \(2015\)](#).

have HIP 018413, a new solar twin, slightly colder, more metal-poor, and older than the Sun, which is one of the closest twins according to TGMET. HIP 049756 has already been identified as a solar twin in several previous studies. We classified it as

B owing to the atmospheric parameters and abundances because $[M/H]$ and $[Ca/H]$ are slightly higher than our limits, 0.05 dex and 0.058 dex, respectively, while all the other values are solar. Its main difference to the Sun is a higher lithium content.

The most studied HIP 079672 (18 Sco) is definitively not a perfect solar twin according to our ranking at the 14th position in Table 9. We find a hotter temperature and enhanced abundances relative to the Sun, including lithium, thus confirming the findings of Meléndez et al. (2014a).

The next four solar twins are already known. They all have a higher lithium content. The last one in the list, HIP 094981, is unknown. It is colder and more metal-rich, but is still a solar twin according to the criterion of Meléndez et al. (2014b). It is also more luminous ($M_V = 4.27$) and much older than the Sun (10.4 Gyr) with a strong Li feature.

The second part of Table 9 lists the other stars that were found to differ from the Sun, either in their atmospheric parameters or in their abundances. It is, however, worth noting HIP 007339 and HIP 089474, which have solar chemical patterns and lithium deficiencies. HIP 007339 is one of the coldest stars in our sample ($T_{\text{eff}} = 5630 \pm 12$ K), while HIP 089474 differs from the Sun by its lower surface gravity ($\log g = 4.29 \pm 0.01$). However, the two stars are not good solar sibling candidates; they have galactic velocity values that are significantly different from the Sun's, with a radial velocity component $U = 50.8$ km s⁻¹ for HIP 007339 and a rotational component $V = -62.1$ km s⁻¹ for HIP 089474. HIP 089474 is also old (9.1 Gyr), which interestingly makes it a possible member of the thick disk.

9. Conclusion

In this work, we have selected 56 solar twin candidates from among 1165 tested stars based on the similarity of their spectrum to that of the Sun. We have determined their atmospheric parameters and abundances, and examined their Li content to further study their similarity to the Sun.

One strength of our study is that we used a large number of solar spectra (18) as references, representative of the range of observing conditions, and from which we selected the best lines to be analysed for abundance measurements by synthesis. Several spectra were available for the majority of the selected targets, up to 5 (225 spectra in total). The analysis was performed differentially to the solar spectra, on a line-by-line basis for the selected set of lines. This led to a very good internal precision. Our atmospheric parameters and abundances also proved to be accurate, in excellent agreement with other studies made at higher resolution and S/N. This demonstrates that the ELODIE archive is a very good resource for making comprehensive studies of solar-type stars.

We found that the best solar twin in our sample is HIP 076114 (HD 138573), dethroning previous candidates (HIP 079672/18 Sco, HIP 100963). All the other stars slightly differ from the Sun in one or another property. We list 19 solar twins that have T_{eff} , $\log g$, and abundances that differ from those of the Sun by less than 100 K and 0.1 dex.

We found a good solar sibling candidate, HIP 021436, which would be worth studying further.

Acknowledgements. C.S. would like to dedicate this paper to the memory of Giusa Cayrel de Strobel, an inspiration for a younger generation of astronomers

in the quest for solar twins and many other topics. D.M. acknowledges financial support from the Irakian ministry of higher education and research. We acknowledge constructive comments and suggestions from the anonymous referee. We used the CDS-SIMBAD and NASA-ADS databases, and the VizieR service at CDS.

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Appendix A: Additional figures

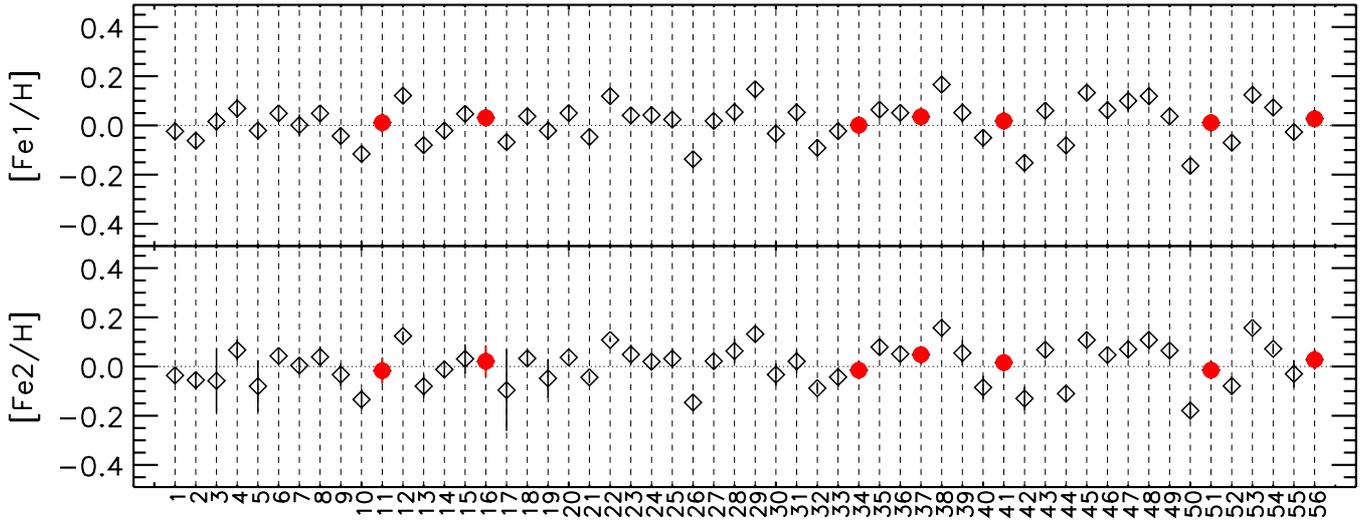


Fig. A.1. Iron abundance of the 56 solar twin candidates obtained from neutral and ionized lines. Red dots represent the seven stars found to have the same abundances as the Sun, within 0.05 dex, for all the tested elements.

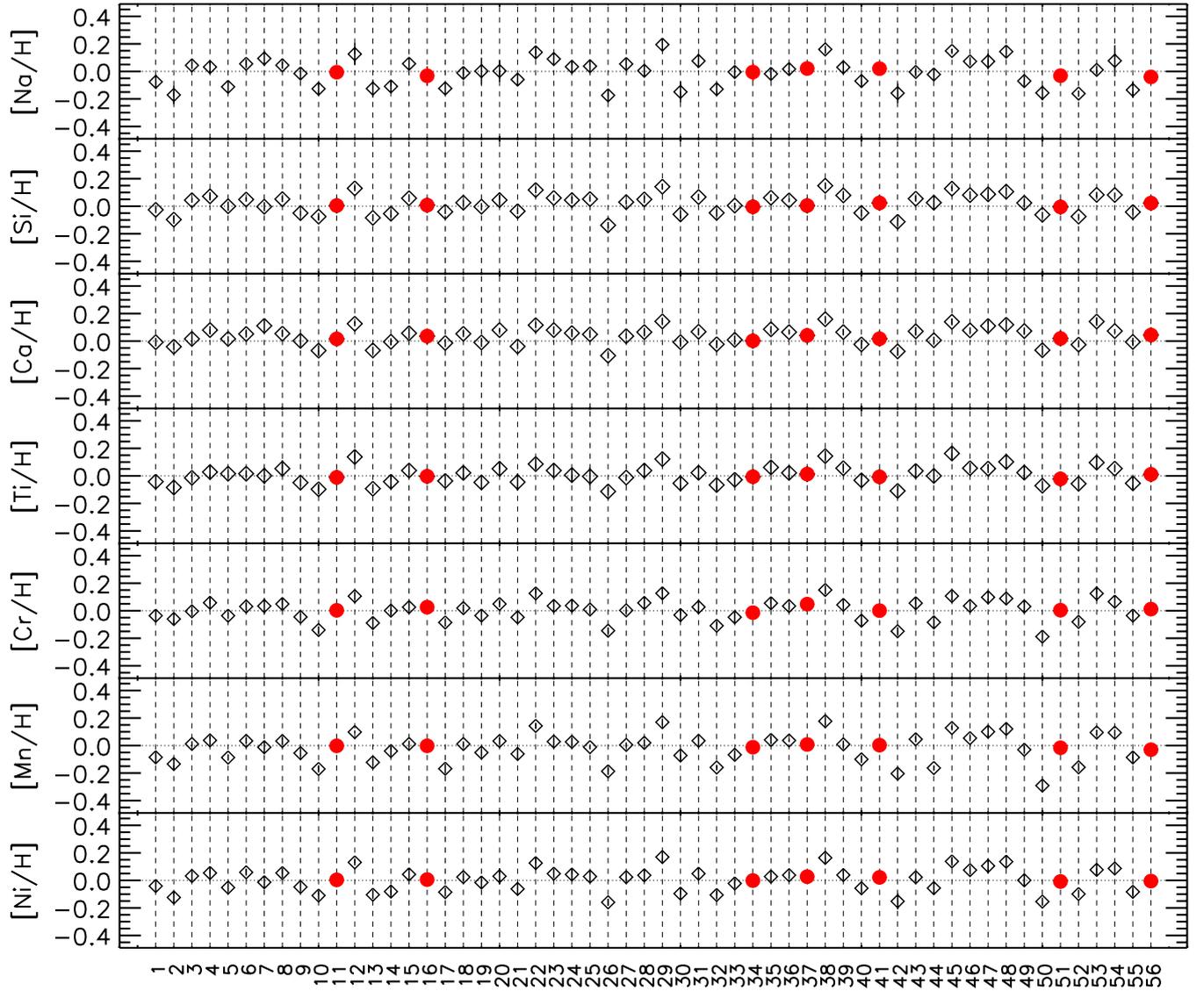


Fig. A.2. Like Fig. A.1 for the other elements.