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The Sun. A typical star in the solar neighborhood?

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Abstract. The Sun is used as the fundamental standard in chemical abundance studies, thus it is important to know whether the solar abundance pattern is representative of the solar neighborhood. Albeit at low precision (0.05 – 0.10 dex) the Sun seems to be a typical solar-metallicity disk star, at high precision (0.01 dex) its abundance pattern seems abnormal when compared to solar twins. The Sun shows a deficiency of refractory elements that could be due to the formation of terrestrial planets. The formation of giant planets may also introduce a signature in the chemical composition of stars. We discuss both planet signatures and also the enhancement of neutron-capture elements in the solar twin 18 Sco.

Keywords. Sun: abundances, stars: abundances, stars: fundamental parameters, solar system: formation, Earth, planetary systems: formation

1. Introduction

In previous studies the question of whether the Sun has a normal composition has been discussed in detail (Gustafsson 1998, 2008; Gustafsson *et al.* 2010; Allende Prieto 2008, 2010). It has been recognized that earlier studies obtained discrepant results regarding possible chemical abundance anomalies in the Sun, probably due to relatively large (0.05 – 0.10 dex) abundance uncertainties. An illustrative example is the conflicting results found for the [O/Fe] ratio in solar-metallicity thin disk dwarfs. In the seminal study by Edvardsson *et al.* (1993), the [O/Fe] ratio around [Fe/H] = 0 in disk stars was found to be somewhat subsolar, meaning that the Sun could be either somewhat oxygen-rich or somewhat iron-poor, relative to disk stars. Different results were obtained by Bensby *et al.* (2004) and Ramírez *et al.* (2007), who found that solar-metallicity disk stars have [O/Fe] ~ 0 and [O/Fe] $\sim +0.1$ dex, respectively. These three different studies show that depending on how the analysis is made, worrisome differences of up to 0.15–0.20 dex could be found in the [O/Fe] ratios of disk stars. Even the consistent analysis of three different oxygen abundance indicators by Ecuvillon *et al.* (2006), resulted in discrepant oxygen abundances (solar, sub-solar and super-solar) regarding the [O/Fe] ratios of disk stars.

A serious issue when comparing the Sun to other solar-type stars is the effective temperature scale, as different photometric $T_{\rm eff}$ scales (e.g., Alonso *et al.* 1996; Ramírez & Meléndez 2005; Casagrande *et al.* 2010; Boyajian *et al.* 2013) may have different zero-points. On this regard, it is important to check the zero-points of a given temperature scale using solar colors as those derived recently by Meléndez *et al.* (2010), Ramírez *et al.* (2012) and Casagrande *et al.* (2012), using a large sample of solar twins and solar analogs. The same concern applies to photometric metallicities, i.e., their zero-point must be tested before they are used to compare the Sun to other stars (e.g., Árnadóttir *et al.* 2010; Meléndez *et al.* 2010; Datson *et al.* 2012).

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Another problem that may arise when comparing the Sun to other stars is the adopted line list and atomic data, and how that data is used to obtain spectroscopic stellar parameters ($T_{\rm eff}, \log g, v_t$). Sometimes gf-values are "calibrated" using very high resolution solar atlases, and then applied to stars that have been observed using a spectrograph with a much lower resolution, where the line profiles are not as well defined as in the solar atlas. Even worse would be to use solar gf-values determined by a different group using a different set of model atmospheres. The use of absolute (laboratory or theoretical) gf-values is also problematic, as their large uncertainties could imply relatively large errors (low precision) in the obtained stellar parameters. Also, although naively we would expect that absolute gf-values would result in accurate spectroscopic stellar parameters, this is not necessarily the case due to problems in model atmospheres (Asplund 2005) and the simplifications made for the treatment of line formation (LTE vs. NLTE; e.g., Lind, Bergemann & Asplund 2012). Also, precise absolute gf-values exist only for a minority of the lines, meaning that to obtain spectroscopic equilibrium using FeI and FeII lines we may have to use some imprecise absolute gf-values. The same applies to the determination of chemical abundances for elements other than iron. It is also dangerous to use different sets of lines for the Sun and for the stars, because due to the large errors in the absolute gf-values, a different set of lines could lead to a different solution, resulting in inaccurate and imprecise stellar parameters and stellar abundances.

Blends are also a serious issue, as the dependence of a given line to both stellar parameters and abundance of the main component could be affected by the minor component of the blend. This problem could be minimized by selecting clean lines or lines with weak blends, or also by deblending or spectrum synthesis. Another issue is both continuum determination during the data reduction and continuum placement in the measurements. The Sun and the sample stars must have a similar determination of the continuum. The way the measurements are done is also very important. It is increasingly common in the literature to use automatic tools such as ARES (Sousa *et al.* 2007) to measure the equivalent widths, yet the measurements done for a given sample star may not be identical to the way the measurement is done for the Sun. Even solar twins that may look almost identical to the Sun can show small variations in their spectra relative to the solar spectrum, due to somewhat different stellar parameters (Teff, log g, vt), different rotation velocities, different chemical compositions and different levels of telluric contamination. For a given line, ARES does a continuum normalization in a small spectral window, and due to the small variations mentioned above, the continuum fit done by ARES may not be necessarily the same for the stars and the Sun. Also, ARES may use a different number of components (lines) to model a given spectral window, and that number may vary from star to star. Although the automatic measurements are good enough for a typical abundance analysis, they may not be adequate to distinguish tiny variations (0.01 dex) between the chemical compositions of stars and the Sun.

In summary, systematic differences between the stars and the Sun could arise due to the (i) analysis techniques (equivalent widths vs. spectrum synthesis), (ii) stellar parameters, (iii) adopted grid of model atmospheres, (iv) treatment of line formation (LTE vs. NLTE), (v) adopted gf-values, (vi) adopted line lists, (vii) spectral resolution, (viii) signal-to-noise ratio, (ix) problems with the spectrograph, (x) adopted solar spectrum (sky, Moon, moons of other planets, asteroids, solar atlas), (xi) data reduction, (xii) determination of the continuum, (xiii) blends, (xiv) equivalent width measurements, and (xv) adopted solar abundances (e.g., Asplund *et al.* 2009), when solar abundances are not determined in the same analysis.

Many of the above problems could be eliminated or largely minimized by planning the observations of the stars and the Sun using the same spectrograph and the same

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setup. Even better would be to observe the Sun in the same observing run as the stars, to guarantee that there were no significant changes in the instrument configuration. The solar spectrum could be obtained using asteroids, which are almost point sources, so that the data reduction is performed in the same way as for the stars. Continuum normalization should be performed homogeneously in the stars and the Sun. Having obtained the stellar and solar spectra in the same way, we can now perform a strictly line-by-line differential analysis, so that we make sure that every line in the spectrum is measured in the same way in the stars and the Sun, using the same continuum regions and using exactly the same part of the line profile. Then, the abundances can be determined line-by-line, so that uncertainties in the gf-values will cancel out. It would be even better to perform this kind of analysis using solar twins, stars with spectra very similar to the Sun (e.g., Meléndez *et al.* 2006, 2009; Ramírez *et al.* 2009; Takeda & Tajitsu 2009; Datson *et al.* 2012). In this way, many of the modeling uncertainties mentioned above are minimized, resulting in extremely precise abundances at the 0.01–0.02 dex level, provided very high resolution ($R \geqslant 60000$) very high S/N ($\geqslant$200) spectra are employed. This is the approach first adopted by Meléndez *et al.* (2009) and Ramírez *et al.* (2009), that led to the discovery of abundances anomalies in the chemical composition of the Sun. The Sun seems chemically anomalous when compared to nearby solar twins in the thin disk, perhaps due to the formation of terrestrial planets in the Sun. The abundances anomalies that may be caused by planet formation are discussed in more detail below.

2. The stellar chemical abundance - planet connection

The processes of star and planet formation are far from fully understood, but we know that they occur nearly at the same time. Thus, it is likely that the formation of both terrestrial and gas giant planets has imprinted signatures in the chemical composition of their host stars. During the final phases of gas accretion by the star, when the proto-planetary nebula cools, dust grain condensates and later coagulates to form planetesimals and finally terrestrial planets in the inner region, while in the outer region rocky-ice embryos will accrete hydrogen and helium to form the gas giant planets (Morbidelli *et al.* 2012), although giant planets could also form by gravitational disk instability. The chemical fingerprints left by these processes are key to constrain different models of planet formation. The classical example of the star-planet connection is the well-known planet-metallicity correlation in solar type stars, indicating that a higher abundance of metals increases the probability of forming giant planets (Gonzalez 1997). This signature has been confirmed by further works (e.g. Fischer & Valenti 2005; Udry & Santos 2007; Ghezzi *et al.* 2010) and may favor the theory of core-accretion for giant planet formation.

Although the correlation between giant planet frequency and overall stellar metallicity has been important in the context of planet formation, it is probably only the tip of the iceberg regarding the connection between stars and planets. In the subsequent decade after the seminal work by Gonzalez (1997), there have been many attempts to explore other relations between planets and the abundance of specific chemical elements, but no clear result was obtained (Udry & Santos 2007), probably due to the relatively large uncertainties (about 0.05 dex) in the determination of chemical abundances (Asplund 2005), or in same cases due to a bias in the comparison between stars with and without planets, as shown for example for lithium, for which a fair comparison found no difference in the Li abundances of the two samples (Baumann *et al.* 2010).

As mentioned above, errors as low as 0.01 dex could be obtained in a strictly differential analysis of a sample of stars that are very similar to each other (due to the cancellation of systematic errors), opening thus new windows on the planet-star connection. Below we

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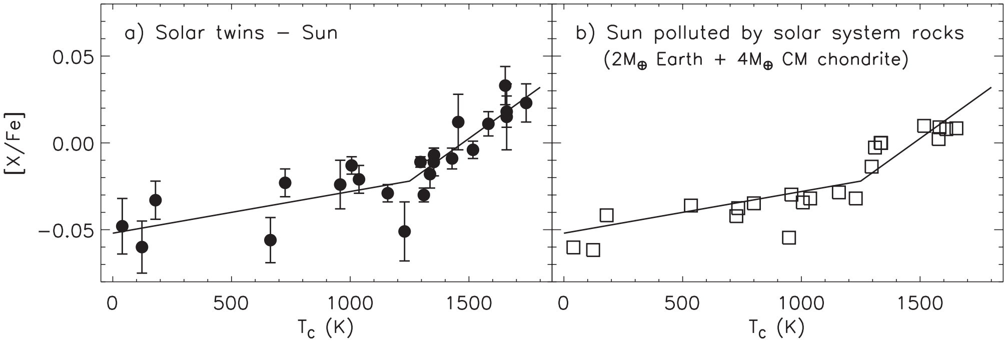

Figure 1. a) Average elemental abundance ratios (relative to Fe) as a function of condensation temperature for 11 solar twin stars from Meléndez *et al.* (2009). This clear correlation between [X/Fe] and T_C was not detected before due to the large errors in standard chemical composition analysis (~ ±0.05 dex). In Meléndez *et al.* (2009), the [X/Fe] values have errors of about 0.01 dex. The solid line is a linear fit to the data, but broken at T_C = 1250 K. **b)** Variation of the solar photospheric abundances, relative to Fe, if the Sun's present-day convective envelope were polluted by 2 Earth masses of Earth-like material and 4 Earth masses of CM chondrite rocks. Note the excellent agreement with the linear fit to the solar twin chemical abundance data (the solid line in this panel is the same as in panel a). Adapted from Meléndez *et al.* (2012).

will discuss recent works on high precision chemical abundances that are giving further clues on the formation of rocky (Meléndez *et al.* 2009) and giant (Ramírez *et al.* 2011) planets.

3. Signatures of terrestrial planet formation

A new era on precise chemical abundance determinations started with the analysis of 11 solar twins by Meléndez *et al.* (2009). As these stars have both stellar parameters and spectra nearly indistinguishable from the Sun, many systematic errors that plague stellar abundance analyses are canceled in a strictly line-by-line differential analysis of the solar twins relative to the Sun, being possible to achieve an unprecedented precision of 0.01 dex (Meléndez *et al.* 2009; Meléndez *et al.* 2012), about a factor of 5 smaller than standard abundance analyses. This dramatic improvement is critical to explore the small effects that planet formation may imprint on the chemical composition of stars.

Meléndez *et al.* (2009) found that the Sun is peculiar when compared to a sample of 11 solar twins (Fig. 1a). The abundance of refractory elements (those that condensed at high temperatures in the inner solar nebula) is systematically smaller in the Sun relative to the solar twins. The amount of material missing is compatible with the amount needed to form the terrestrial planets (Meléndez *et al.* 2009; Gustafsson *et al.* 2010; Chambers 2010), meaning that the deficiency of refractory elements in the solar photosphere would disappear if the rocky material formed in the solar system were diluted into the present-day solar convective envelope (Chambers 2010; Meléndez *et al.* 2012), as shown in Fig. 1b. This opens the exciting possibility of discovering stars that could potentially host terrestrial planets based on a careful chemical abundance analysis, but certainly further work is needed to consider this as a firm signature of rocky planets.

If the above signature is confirmed, then stars with chemical composition similar to solar could potentially host terrestrial planets. So far the stars that have their chemical composition most similar to the Sun are the solar twins HIP 56948 (Meléndez & Ramírez 2007; Meléndez *et al.* 2012) and HIP 102152 (Monroe *et al.* 2013). Interestingly, the precise radial velocity observations obtained for HIP 56948 at the McDonald and Keck

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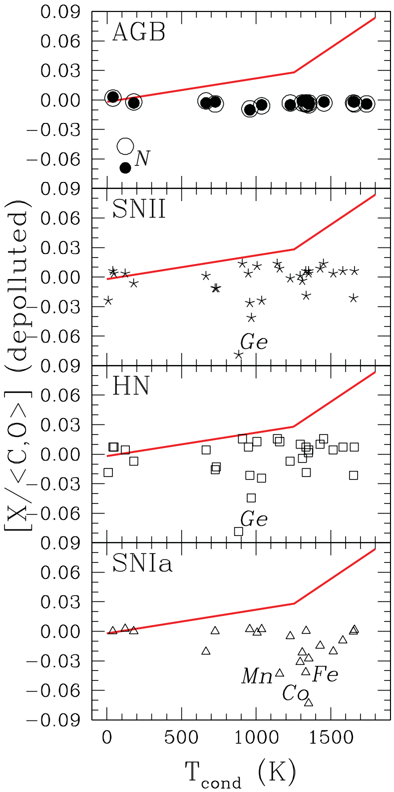

Figure 2. Abundance ratios obtained after de-polluting the solar nebula from contamination by an AGB star (circles), SNII (stars), hypernova (squares) and SNIa (triangles). In the top panel the effect of adopting different solar abundances (open circles: Anders & Grevesse 1989; filled circles: Asplund *et al.* 2009) is shown. The solid line represents the mean abundance pattern of 11 solar twins relative to the Sun (Meléndez *et al.* 2009). None of the pollution scenarios can explain the trend with condensation temperature. The chemical elements that change the most are labeled. Figure taken from Meléndez *et al.* (2012).

observatories, and for HIP 102152 at La Silla, show no signs of giant planets within and in the habitable zone, making these stars excellent candidates for hosting habitable rocky planets.

4. Is there any other explanation for the Sun's abundance anomalies?

As discussed extensively in Meléndez *et al.* (2009, 2012), the abundances anomalies cannot be explained by other causes such as contamination from AGB stars, SNIa, SNII or HN (Fig. 2), or by Galactic chemical evolution processes or age effects. Kiselman *et al.* (2011) have shown that the peculiar abundance pattern cannot be attributed to line-of-sight inclination effects. Also, the abundance trend does not arise due to the particular reflection properties of asteroids. Although the abundance peculiarities may indicate that the Sun was born in a massive open cluster like M67 (Önehag *et al.* 2011), this explanation is based on the analysis of only one solar twin.

So far the best explanation for the abundance trend seems to be the formation of terrestrial planets. The Kepler mission should detect the first Earth-sized planets in the habitable zones of solar type stars. We look forward to using 8–10 m telescopes to perform

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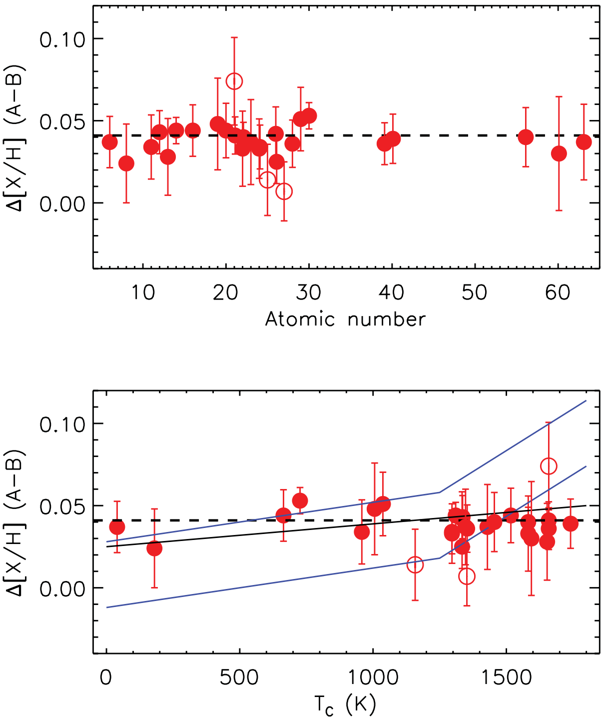

Figure 3. Top panel: elemental abundance difference between 16 Cyg A and B as a function of atomic number. Open symbols show the three species more discrepant from the mean: Sc I (21), Mn (25), and Co (27). Bottom panel: as in the top panel for the abundance differences versus dust condensation temperature. The dashed line is at +0.041 while the solid lines represent the mean trend of solar twins by Meléndez *et al.* (2009) with two arbitrary offsets. The dot-dashed line corresponds to a slope of 1.4×10^{-5} dex K^{-1}, as derived by Laws & Gonzalez (2001).

careful differential abundance analyses of those stars, in order to verify if our chemical signatures indeed imply rocky planets.

5. New signatures of giant planet formation

Regarding the formation of giant planets, we have recently studied the pair of solar analogs 16 Cyg A and B. This pair is very important to understand more about giant planet formation, because the star 16 Cyg B hosts a gas giant planet at 1.7 A.U. (Cochran *et al.* 1997), while no planets have been detected yet around 16 Cyg A. The binary pair is supposed to have the same chemical composition, as it was formed from the same natal cloud, unless the formation of the giant planet around 16 Cyg B altered its chemical abundances.

Our careful differential abundance analysis between 16 Cyg A and B showed that the component B is systematically more metal-poor, by about 10% (~0.04 dex), in the two dozen chemical elements analyzed (Ramírez *et al.* 2011), as shown in Fig. 3. Thus, it seems that the formation of the gas giant around 16 Cyg B robbed a fraction of the metals present in its parent nebula (Ramírez *et al.* 2011). Nevertheless, another abundance analysis (at somewhat lower precision) published nearly at the same date, showed no difference between the abundance pattern of components A and B (Schuler *et al.* 2011). Although the spectra used by Ramírez *et al.* (2011) have a higher resolving

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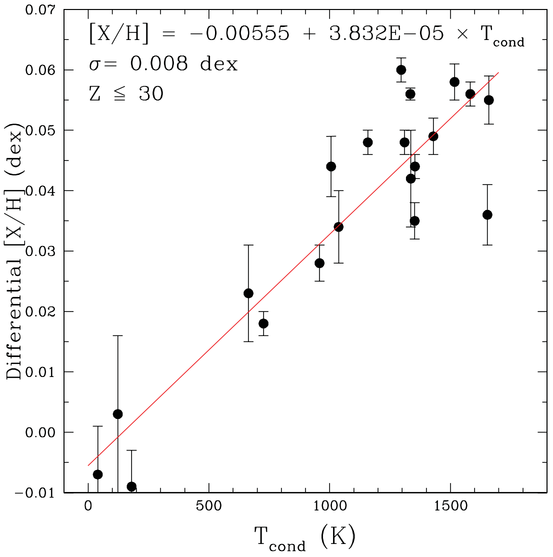

Figure 4. Trend with dust condensation temperature for the solar twin 18 Sco (Meléndez *et al.,* in preparation). The element-to-element scatter is only 0.008 dex.

power and a higher precision was achieved, it would be important to perform a new abundance analysis of the pair to confirm the signature of giant planet formation.

6. Planet search around solar twins

This discussion of signatures of terrestrial and giant planets are telling us that there could be a close connection between stellar chemical composition and planet architecture. Solar twins are ideal to obtain very precise stellar abundances but unfortunately planet information is lacking for most of them, so currently we cannot study in detail the relation between chemical abundance anomalies and different type of planets.

The synergy between the high precision (0.01 dex) chemical abundances obtained in solar twins (Fig. 4) and high precision (1m s^{-1}) radial velocities that can be obtained with HARPS, can give us new insights into the planet-star connection. In order to study with unprecedented detail the connection between chemical abundances and planet architecture, we have been granted 88 nights with HARPS for a Large ESO Programme that started in October 2011 and should continue until 2015. This in an international collaboration involving astronomers from Brazil, Germany, USA and Australia.

Around 70 solar twins are being observed at the ESO La Silla observatory and already some of them are showing radial velocity variations compatible with planets. For all the sample stars we have acquired high resolution high S/N spectra using the MIKE spectrograph at the 6.5 m Magellan telescope in Las Campanas, in order to obtain a homogeneous set of high precision (0.01 dex) chemical abundances. Also, some stars have spectra of even better quality acquired with UVES at the VLT.

Our initial chemical abundance analyses show that on a star-by-star basis we can obtain chemical abundances with a precision at the 0.004 – 0.008 dex level, i.e., even better than initially anticipated (0.01 dex). For the solar twin HIP 56948, the element-to-element scatter is only 0.004 dex for the volatile elements and 0.008 dex for the refractories (Meléndez *et al.* 2012), and our on-going work on the solar twin 18 Sco shows also an

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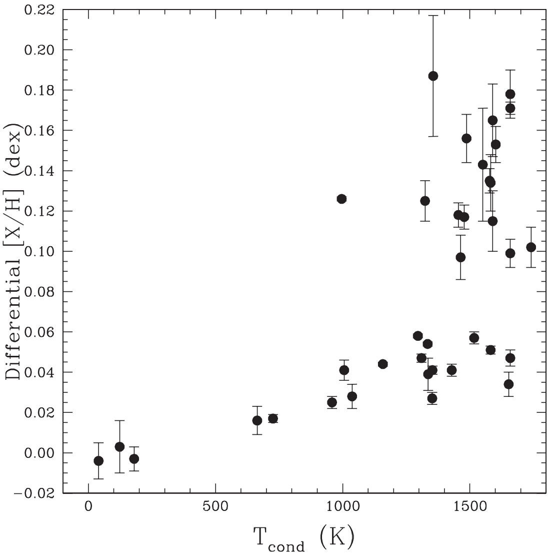

Figure 5. Complex abundance pattern of light and heavy elements in the solar twin 18 Sco (Meléndez *et al.*, in preparation). Besides the trend with condensation temperature shown in Fig. 4, all n-capture elements show a further enhancement ([X/H] > 0.09 dex)

element-to-element scatter of only 0.008 dex (Fig 4). Similar results are being obtained for other solar twins (Monroe *et al.* 2013).

7. Signatures of neutron-capture elements in the solar twin 18 Sco

The solar twin 18 Sco presents a complex abundance pattern (see Fig. 5). On top of the typical trend with condensation temperature seen in other solar twins (Meléndez *et al.* 2013; Monroe *et al.* 2013), this star also shows a large enhancement of the neutron-capture elements. Using yields of AGB stars computed by Amanda Karakas, we can verify if the observed enhancement is due to AGB pollution. After subtracting both the trend with condensation temperature and the s-process contribution from AGB stars, we are left with an abundance signature identical to the r-process in the solar system (Figure 6). This specific abundance pattern can only be obtained thanks to the high precision (0.01–0.02 dex) we achieved for these heavy elements.

8. Conclusions

Our work has shown that it is possible to obtain chemical abundances with a precision of about 0.01 dex or even better (∼0.005 dex) in some cases (Meléndez *et al.* 2012). This abundance precision can be achieved in a strictly differential line-by-line analysis. Our approach minimizes systematic errors due to deficiencies in the adopted model atmospheres. This is shown in Fig. 7, where the difference in differential abundances obtained using two dissimilar grids of model atmospheres (MAFAGS models vs. Kurucz overshooting models; see Meléndez *et al.* 2012) is shown. The average difference is only 0.001 dex, with an element-to-element scatter of only 0.00075 dex. The unprecedented precision that we achieve (∼0.01 dex) was key to discover that the Sun is not a typical star. The abundance anomalies in the Sun may be connected to the formation of terrestrial planets (Meléndez *et al.* 2009; Ramírez *et al.* 2009, 2010). Also, giant planet formation

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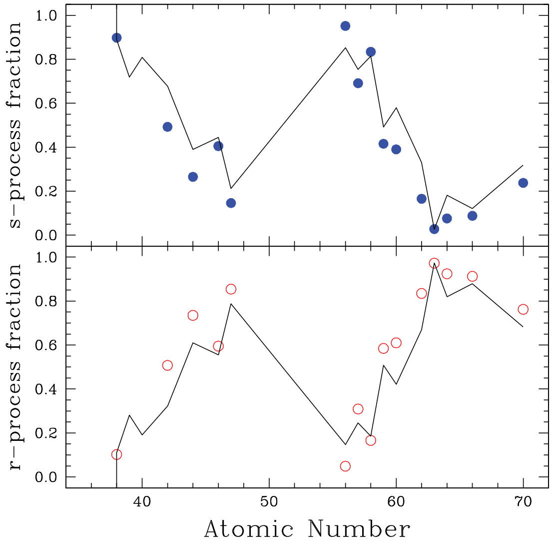

Figure 6. Abundance pattern of the n-capture elements in 18 Sco. In the upper panel the abundance pattern due to the AGB contribution (filled circles) is compared to the s-process in the solar system (line). The residual abundances in 18 Sco after subtracting the trend with condensation temperature and the s-process from AGB stars, are shown by open circles in the lower panel. This abundance pattern is in excellent agreement with the r-process in the solar system (line).

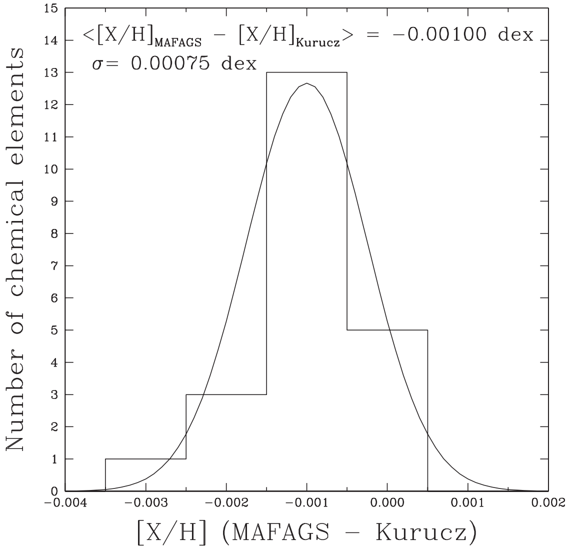

Figure 7. Histogram of the differences between differential chemical abundances obtained with MAFAGS models and Kurucz models. The element-to-element scatter is only $\sigma = 0.00075$ dex, i.e., 0.17%.

may imprint a signature in the chemical composition of stars (Ramírez *et al.* 2011). Our on-going planet search around solar twins will allow us to study at unparalleled precision any connection that may exist between planet architecture and chemical abundance peculiarities. Finally, our high precision abundances can give us better insights on the neutron-capture elements, which could be important for chemical tagging in our Galaxy.

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Discussion

Xiaowei Liu: (1) With the current radial velocity measurement accuracy, I assume it would be extremely difficult to rule out the presence of rocky planets in stars of your solar twin sample. (2) Assuming 50% of solar-type stars harbor rocky planets, do you see some of your solar twin stars showing exactly the same abundance pattern? (3) Would the abundance pattern amongst solar twins actually tell us more about planetary systems in those stars?

Jorge Meléndez: (1) Yes, rocky planets similar to the Earth cannot be detected with current instruments. However, we can use planets detected using the transit method by the Kepler mission. There is a large number of Kepler planet candidates with a radius as small as the Earth, and presumably a good fraction of them may be rocky planets. We plan to obtain chemical abundances of the host stars of those potential rocky planets, to verify our terrestrial planet hypothesis. (2) Yes, a fraction of the solar twins shows an abundance pattern similar to the Sun. We have found that about 15–20% of solar twins have the same chemistry as the Sun within the abundance errors. (3) This is exactly the goal of our 4-year (2011–2015) planet survey around solar twins with HARPS, to see if different planetary architectures could be associated to different abundance patterns. The analysis of the first star in our HARPS sample (Monroe, Meléndez, Ramírez *et al.* 2013), HIP 102152, shows that this star has a solar abundance pattern. Interestingly, the HARPS observations performed so far shows that this star does not have giant planets in its inner region. Therefore, so far it is similar to the Sun both in its abundance pattern and in the lack of inner giant planets.

Livia Origlia: In order to get such level of accuracy in the abundance estimates and high S/N you also used very precise flat-fielding of the observed spectra. Can you please comment on that?

Jorge Meléndez: The main problem related to flat-fielding was the fringing seen in the UVES spectra that were reduced by its pipeline. So, to improve the results the data was fully reduced by hand. Notice that the spectra falls on different pixels, so we do not need to achieve very high S/N in a given pixel of the combined flat field. Also, in some cases multiple exposures were combined to achieve a higher S/N. This is the case of the Li region, for which we combined a standard with a non-standard setup, so that we could have some overlap between both setups around the LiI 670.8nm line.

Xiaoting Fu: You mentioned that the Sun abundance is peculiar because it uses the material to form the dust and planets. Have you checked the abundance of the planet-host stars in Kepler.

Jorge Meléndez: We intend to verify the abundance pattern of the host stars of Kepler planet candidates with radius similar to Earth's, i.e., potential rocky planets. We have an observing run with Keck/HIRES in August 2013 to perform this work.

Hans-Walter Rix: You called the Sun "peculiar" in the comparison to the 11 solar twins. Is any star's abundance pattern "normal" when looked at with this precision? I.e., does the Sun's abundance pattern really deviate much more from the other stars than any of the other 11 stars deviate from the average?

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JORGE MELÉNDEZ: It is hard to define a “normal” abundance pattern. It could be defined either by the mean (in Meléndez *et al.* 2009 the trimean was adopted) chemical composition of the solar twins, or by the most refractory-rich stars (i.e. those stars who have the least depletion of refractory elements, as defined recently by Ramírez *et al.* 2013). In both definitions the Sun seems abnormal at a significant level. In Meléndez *et al.* (2013) we found two solar twins with large deviations from the mean abundance pattern of the twins, i.e., with chemical compositions similar to the Sun. We are analyzing larger samples of solar twins to better quantify the fraction of stars with chemical compositions similar to the Sun.

CHIAKI KOBAYASHI: For 18 Sco, what a beautiful agreement with the solar s- and r-process! How did you subtract the AGB contribution.

JORGE MELÉNDEZ: We used AGB yields computed by Amanda Karakas and diluted those yields into a one-solar-mass nebula, then the results were subtracted from the observed pattern of the neutron-capture elements in 18 Sco. Amanda please could you give us more details about it?

AMANDA KARAKAS: Comment: I took a model of a 3 $M_\odot$ AGB stars of $Z = 0.01$ and diluted the yields (1% of mass of material injected) into a 1 $M_\odot$ proto-solar cloud of solar composition. The nucleosynthesis model includes the s-process elements.

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