Sun-like stars unlike the Sun
Clues for chemical anomalies of cool stars

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We present a summary of the splinter session “Sun-like stars unlike the Sun” that was held on 09 June 2016 as part of the Cool Stars 19 conference (Uppsala, Sweden). We discussed the main limitations (in the theory and observations) in the derivation of very precise stellar parameters and chemical abundances of Sun-like stars. We outlined and discussed the most important and most debated processes that can produce chemical peculiarities in solar-type stars. Finally, in an open discussion between all the participants we tried to identify new pathways and prospects towards future solutions of the currently open questions.

1 Motivation

In stellar astronomy, we sometimes divide stars into two wide groups and colloquially refer to them as cool stars (late-type stars) and hot stars (early-type stars), although there is no sharp division between these two groups. These kinds of definitions are lexical and have only a descriptive, qualitative character. A more quantitative boundary between cool and hot stars was suggested by Gray (2005) based on the shape of the bisectors of the spectral lines. Main sequence stars with spectral types of later than about F0 have a bisectors with a so-called classical C shape, while hotter stars show reversed C shape. This boundary is called ”granulation boundary” (e.g. Gray & Nagel 1989; Gray & Toner 1986) and practically divides the Hertzsprung–Russell diagram into cool and hot stars (Gray 2005). In this work, adopting the definition of Gray we refer to stars later than F0 when saying ”cool stars”. These low-mass stars have long lifetimes and their envelopes contain information about their stellar evolution and the history of the evolution of chemical abundances in the Galaxy.

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During the last decade, noticeable advances were made in the characterization of atmospheric properties (e.g. effective temperature, metallicity, surface gravity) and chemical abundances of cool stars. The high precision in stellar atmospheric parameters is crucial for precise characterization of physical properties of stars such as their mass and age.

The extremely high precision in chemical abundance derivations allowed observers to study subtle chemical peculiarities in Sun-like stars. Given the nature of the detailed chemical abundance derivations, it is likely that many physical processes determine the chemical characteristics of the stars. Understanding the origin of these anomalies is very important for the further advancement of Galactic and stellar astronomy, as well as the very fast advancing field of exoplanetary research.

In June 2016, we organized a Splinter Session at the Cool Stars 19 workshop with the goal to bring together experts of stellar, Galactic and planetary astrophysics to highlight the latest results and discuss what may make Sun-like stars unlike the Sun. We had six invited review talks and four contributed talks, which were followed by an open discussion between speakers and participants. The main scientific questions discussed during the session were:

I. Abundances of the Sun and Sun-like stars. What is the highest precision and accuracy we actually can expect current analysis methods to deliver? What are the limitations in the theory (e.g. model of atmospheres, 1D, hydrostatic, LTE) and observations (e.g. spectral resolution, signal-to-noise ratio, atmospheric observational conditions)?

II. Abundance characteristics of stars. How is the inhomogeneous Galactic chemical evolution, the star- and planetary formation history, and the stellar evolution reflected in the surface abundances of Sun-like stars? How can we study these different aspects by analyzing the elemental abundances in stellar spectra?

In this paper we summarize the presentations and the discussions of this splinter session.

2 Solar twins, analogs and solar-type stars

Classifying a star as solar-type, solar analog, or solar twin depends on the degree of similarity between the star and the Sun. The categorization also reflects the evolution of astronomical instrumentation and observational techniques. Cayrel de Strobel (1996) defined a solar twin as a star that has the same atmospheric and physical properties as the Sun within the observational errors. This definition obviously depends on the uncertainties of the derived parameters. Soderblom & King (1998) provided a more practical definition of these three categories of stars. While the literature is full of quantitatively different definitions of solar twins, analogs and sun-like (solar type) stars, these definitions are qualitatively similar (e.g. Adibekyan et al. 2014; Datson et al. 2015; do Nascimento et al. 2014; González Hernández et al. 2010; Meléndez et al. 2009; Porto de Mello et al. 2014; Ramírez et al. 2009). For more discussion on different definitions we refer the reader to Datson (2014).

In the splinter session the following definitions for solar twins, analogs and Sun-like stars in terms of stellar parameters were presented and used. Solar twins: \( T_{\text{eff}} = 5777 \pm 100 \text{ K} \), \( \log g = 4.44 \pm 0.10 \text{ dex} \), \([\text{Fe/H}] = 0.00 \pm 0.10 \text{ dex} \) (e.g. Adibekyan et al. 2014; Ramírez et al. 2009), solar analogs: \( T_{\text{eff}} = 5777 \pm 200 \text{ K} \), \( \log g = 4.44 \pm 0.20 \text{ dex} \), \([\text{Fe/H}] = 0.00 \pm 0.20 \text{ dex} \) (e.g. Adibekyan et al. 2014), and solar-type: main sequence or subgiant stars with \( 5000 < T_{\text{eff}} < 6500 \text{ K} \).

With the recent advances of asteroseismology, thanks to Kepler (Borucki et al. 2010) and CoRoT (Convection, Rotation, and planetary Transits – Baglin et al. 2006) missions, parameters determined by asteroseismology have also been included in the definition of solar analogues and twins. In particular, the presence of solar-like oscillations can be used to consider a star as a solar analog, or a seismic solar analog (e.g. Beck et al. 2016b; do Nascimento et al. 2013; Metcalfe et al. 2012; Salabert et al. 2016a).

2.1 Accuracy and precision in stellar parameters and chemical abundances

High-precision and high-accuracy stellar abundances are crucial for many fields of stellar, planetary and galactic astrophysics. However, precise and accurate derivation of stellar atmospheric abundances is a difficult challenge which is obvious when comparing different techniques and measurements (Hinkel et al. 2016; Jofre et al. 2017).

2.1.1 High-resolution spectroscopy

If past analyses of large, homogeneous and high-quality data reached abundance precisions of \( 0.03-0.07 \text{ dex} \) (e.g. Adibekyan et al. 2015b, 2012c; Bensby et al. 2003, 2014; Gilli et al. 2006; Nissen & Schuster 2010; Reddy et al. 2006; Takeda 2007; Valenti & Fischer 2005), the latest works on solar twins that are based on differential line-by-line analysis report even higher precision of \(< 0.01 \text{ dex} \) (e.g. Adibekyan et al. 2016a,b; Bedell et al. 2014; González Hernández et al. 2013, 2010; Meléndez et al. 2009, 2012; Nissen 2015, 2016; Ramírez et al. 2010; Saffe et al. 2016; Spina et al. 2016a,b; Tucci Maia et al. 2014). Consequently, the precision in atmospheric parameters reported for the solar twins is very high: \( \sim 10 \text{ K} \) for \( T_{\text{eff}} \), \( \sim 0.02 \text{ dex} \) for \( \log g \), and \( \sim 0.01 \text{ dex} \) for \([\text{Fe/H}] \) (e.g. Adibekyan et al. 2016a; Bedell et al. 2014; Ramírez et al. 2014; Spina et al. 2016a,b; Tucci Maia et al. 2014).

Recently, Bedell et al. (2014) analyzed solar spectra observed with different instruments, from different asteroids, and at different times, i.e. conditions. The authors reached a conclusion that a major effect on differential relative abundances is caused by the use of different instruments (up to

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\( \text{We note that the value of the nominal solar effective temperature recommended by IAU 2015 resolution B3 is } 5772 \pm 0.8 \text{ K} (\text{Prša et al. 2016}). \)
0.04 dex). They found that the choice of asteroids to obtain the solar reflected spectra and time-dependent effects (observations at different epochs) are smaller than 0.01 dex. Bensby et al. (2014) have also analyzed (applying exactly the same analysis techniques) different spectra of the Sun (scattered solar light from the afternoon sky, the Moon, Jupiter’s moon Ganymede, and the asteroids Vesta and Ceres) obtained during a period of six years with different instruments. The maximum observed differences for solar parameters were 49 K for $T_{\text{eff}}$, 0.03 dex for $\log g$, and 0.03 dex for solar metallicity. In turn, Adibekyan et al. (2016a) showed that the average difference in chemical abundances observed for two different high-quality (signal-to-noise ratio of about 400) spectra obtained during the same night for the same star is usually small $\lesssim 0.01 \pm 0.03$ dex, but can reach up to 0.06 dex depending on the element.

Most of the reported uncertainties are in fact precision, or internal (random) errors (e.g., uncertainties in the continuum setting, in the $\log gf$ values). Systematic errors, due to the model atmospheres and atomic data are more difficult to estimate and can be much larger than the random errors. Recently, Bensby et al. (2014) evaluated the external precision of their abundance derivation by comparing their results for solar-type stars with those from the literature (Adibekyan et al. 2012c; Reddy et al. 2006, 2003; Valenti & Fischer 2005). The authors found that the differences (average for all stars in common) in stellar parameters and abundances of individual elements observed between different works range from -10K to +120 K for $T_{\text{eff}}$, from -0.05 to -0.07 dex for $\log g$, from -0.02 to +0.03 dex for [Fe/H], and from -0.09 to 0.10 dex for different elements. For more complete and extensive comparison of more than 80 data sets we refer the reader to Hinkel et al. (2014). They found that the variation between studies per element has a mean of 0.14 dex for all elements in all stars in their compiled catalog, called the Hypatia Catalog.

The comparison between different studies of solar twin stars shows higher agreement. In particular, Nissen (2015) when comparing his results with those of Ramírez et al. (2014) for 14 stars in common obtained an average difference and rms deviation of: $\Delta T_{\text{eff}} = 0 \pm 10$ K, $\Delta \log g = 0.002 \pm 0.020$ dex, and $\Delta [\text{Fe/H}] = 0.000 \pm 0.014$ dex. The same author, when comparing his results with that of Sousa et al. (2008) for the 21 solar twins in common found the following average differences and rms deviations: $\Delta T_{\text{eff}} = -1 \pm 8$ K, $\Delta \log g = 0.018 \pm 0.033$ dex, and $\Delta [\text{Fe/H}] = -0.003 \pm 0.009$ dex. Comparison of chemical abundances of individual elements, and abundance ratios is also usually small. For example, the average offset and rms deviation in [Y/Mg] abundance ratio observed between Nissen (2016) and Tucci Maia et al. (2016) is 0.012±0.016 dex (see Fig. 1).

![Fig. 1](image)

Fig. 1 Comparison of [Y/Mg] abundance ratios derived by Nissen (2016) and Tucci Maia et al. (2016) for 14 solar twin stars. (Courtesy of Poul Erik Nissen).

### 2.1.2 3D and non-LTE effects

Most of the studies, when deriving stellar parameters and elemental abundances used classical 1D hydrostatic models with an assumption of local thermodynamic equilibrium (LTE). Thanks to the exponentially increasing level of computational power, huge progress has been made in the last decade in developing 3D hydrodynamical model atmospheres (e.g. Beeck et al. 2013; Freytag et al. 2012; Magic et al. 2013; Trampedach et al. 2013). Furthermore, non-LTE calculations and corrections are now available for more than 20 elements (e.g. Li, O, Na, Mg, Si, Ca, Ti, Fe, Sr, Ba) (e.g. Amarsi et al. 2015, 2016; Bergemann 2011; Korotin et al. 2015; Lind et al. 2009, 2012; Merle et al. 2011; Osorio et al. 2015; Prakapavičius et al. 2013; Shi et al. 2011; Spite et al. 2012). For a detailed discussion of non-LTE effects in the lines of different elements we refer the reader to Mashonkina (2014).

For most elements with complex atoms, non-LTE effects are not very strong in solar-twins. The amplitude of these effects are different for different species (species sensitive to over-ionisation or collision-dominated species) and depends on atmospheric parameters of the stars. For example in the case of iron (see Fig. 2) and other neutral Fe-peak atoms, the non-LTE effects increase as temperature increases, surface gravity decreases, and the metallicity decreases (e.g. Bergemann & Nordlander 2014). Obviously, when comparing stars with very similar parameters, such as solar twins, the differential non-LTE effects are very small (e.g. Nissen 2015; Spina et al. 2016a). They become non-negligible for high-precision work on solar analogs and should be considered when solar-type stars are intercompared.

### 2.1.3 Asteroseismology

Comparison of physical parameters derived with different, independent methods help us to understand and estimate the accuracy of the derivations. A combination of different astronomical tools and methods also helps to improve the accuracy of the determinations. In particular, asteroseismology combined with high-resolution spectroscopy allows us to substantially improve the accuracy of the stellar parameters (e.g. Chaplin et al. 2014; Creevey et al. 2016; Lebreton...
Fig. 2 The dependence of typical NLTE corrections for high-excitation ($E_{\text{exc}} > 2.5$ eV), unsaturated ($W_\lambda < 50$ mÅ) Fe I lines on stellar parameters. All models have $\xi_t = 2.0$ km s$^{-1}$. The figure is from Lind et al. (2012).

Galactic chemical evolution and nucleosynthesis with solar twins

Important information about the formation and evolution of galaxies are locked into the chemical compositions of stars. All the metals, or elements heavier than Boron, originate
from stars that enrich the interstellar medium with their own unique pattern of elements depending on their mass and initial metallicity. In fact, each specific element has been produced by different sites of nucleosynthesis that contribute to the chemical evolution of galaxies with different timescales (e.g. Pagel 2009).

The chemical abundances, measured as $[\text{X}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ for solar-type stars are traditionally used to study the Galactic chemical evolution because iron has been assumed to be a good chronological indicator of nucleosynthesis (e.g. Adibekyan et al. 2012c; Bensby et al. 2003; Chiappini et al. 1997; Edvardsson et al. 1993; Romano et al. 2010; Smiljanic et al. 2014, 2016). Obviously, the studies of the relations between the abundance ratios and age would provide more direct information about the nucleosynthetic history of elements and chemical evolution of our Galaxy.

Recently, Nissen (2015, 2016) used relatively high-precision ages (derived from evolutionary tracks) and chemical abundances of 18 elements (from O to Ba) determined for 21 solar twins to study the correlations between these two parameters. For stars younger than 6 Gyr, Nissen found that some elements show very tight correlation with stellar age. Nissen showed that this linear correlation breaks down at 6 Gyr and the stars with ages between 6 and 9 Gyr split up into two groups with high and low values of $[\text{X}/\text{Fe}]$ for the odd-Z elements Na, Al, Sc, and Cu. Nissen (2016) concluded that the younger stars were formed from a well-mixed interstellar gas while older stars formed in regions that were enriched by supernovae with different neutron excesses. He also showed that due to very tight linear correlation with age, $[\text{Y}/\text{Mg}]$ and $[\text{Y}/\text{Al}]$ abundance ratios can be used to derive stellar ages with a precision reaching 1 Gyr (see Fig. 3). This result on solar twins was later confirmed by other authors (Spina et al. 2016a; Tucci Maia et al. 2016) and was extended to solar analogs (Adibekyan et al. 2016b). Interestingly, Feltzing et al. (2016) recently showed that the correlation between $[\text{Y}/\text{Mg}]$ and age is a function of metallicity and gets flat at metallicities below -0.5 dex.

More recently, Spina et al. (2016a) studied a sample of 41 thin disk and four thick disk stars for which superb abundances with 0.01 dex precision and accurate stellar ages have been obtained through a line-by-line differential analysis of the EWs relative to the solar spectrum (see Bedell et al. 2014; Spina et al. 2016b). Based on this data set, Spina et al. (2016a) outlined the $[\text{X}/\text{Fe}]$-age relations over a time interval of 10 Gyr (see Fig. 4). They presented the $[\text{X}/\text{Fe}]$-age relations for 23 elements (C, O, Na, Mg, Al, Si, S, Ca, Sc, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Y, Ba, La, Ce, Nd, and Eu). Their main results revealed that each different class of elements showed distinct evolution with time that relies on the different characteristics, rates and timescales of the nucleosynthesis sites from which they are produced. The $\alpha$-elements are characterized by a $[\text{X}/\text{Fe}]$ decrement as time goes on. Strikingly, an opposite behavior is observed for Ca. The iron-peak elements show an early $[\text{X}/\text{Fe}]$ increase followed by a decrease towards the youngest stars. The $[\text{X}/\text{Fe}]$ for the $n$-capture elements decrease with age.

Knowledge of the $[\text{X}/\text{Fe}]$-age relations is a gold mine from which we can achieve considerable understanding about the processes that governed the formation and evolution of the Milky Way: the nature of the star formation history, the supernovae (SNe) rates, the stellar yields, and the variety of the SNe progenitors, etc. This approach has already successfully applied before to low(er) precision data (e.g. Edvardsson et al. 1993) and demonstrated its power. These types of studies are of fundamental significance in efforts to reconstruct the nucleosynthetic history of the Galactic disk through chemical evolution models.

4 Chemical abundances of Sun-like stars with and without planets

The connection (probably bi-directional) between stellar and planetary properties has been widely explored. In particular, the very first correlation observed in the field of exoplanetary research was the correlation between the giant-planet occurrence and stellar metallicity (usually iron content was used as a proxy for overall metallicity) (e.g. Fischer & Valenti 2005; Gonzalez 1997; Santos et al. 2001, 2004;
After the first planets were discovered, astronomers tried to search for chemical signatures of planet formation and planet engulfment on the planet-host stars. Several studies, starting from Gonzalez (1997) and Smith et al. (2001), explored a possible trend between the abundances of chemical elements and the condensation temperature ($T_c$) of the elements. This trend is usually called “$T_c$ trend,” and the slope of the correlation (slope of the linear fit) of [X/Fe] vs. condensation temperature is usually named “$T_c$ slope”.

Meléndez et al. (2009) were the first to report a statistically significant deficit of refractory elements (high-$T_c$) with respect to volatiles (low-$T_c$) in the Sun compared to solar twin stars (see Fig. 5). The authors suggested that these missing elements were trapped in the terrestrial planets in our solar system. The same conclusion was also reached by Ramírez et al. (2009), who analyzed a larger number of solar twins and analogs with and without detected planets. However, these results and explanations were strongly contested by González Hernández et al. (2010) and González Hernández et al. (2013), who did not find a statistically significant and consistent $T_c$ trend when comparing stars with and without planets, even when evaluating these $T_c$ trends for stars with detected super-Earth like planets (see Fig. 6). This very exciting possible connection between chemical peculiarities of parent stars and formation of planets has also been examined in other works (e.g. Biazzo et al. 2015; Ecuvillon et al. 2006; Hinkel & Kane 2013; Maldonado et al. 2015; Mishenina et al. 2016; Nissen 2015; Sañé et al. 2015, 2016; Schuler et al. 2011b; Sozzetti et al. 2006; Spina et al. 2016a,b; Takeda et al. 2001), but contradictory conclusions were reached.

Together with the rocky material accretion (e.g. Schuler et al. 2011b; Spina et al. 2015) and/or rocky material trap (e.g. Meléndez et al. 2009) in terrestrial planets, several explanations are proposed to explain the $T_c$ trend. Adibekyan et al. (2014) suggested that the $T_c$ trend strongly depends on the stellar age (see Fig. 7) and they found a tentative dependence on the galactocentric distances of the stars. The correlation with stellar age was later confirmed by several authors (e.g. Nissen 2015; Spina et al. 2016b), while the possible relation with the galactocentric distances is more challenging (see Adibekyan et al. 2016b; Maldonado et al. 2015) probably because of its very complex nature or because the galactocentric distances were estimated indirectly. Maldonado et al. (2015) and Maldonado & Villaver (2016) further suggested a significant correlation with the stellar radius and mass. Ønehag et al. (2014) in turn showed that while the Sun shows a different $T_c$ trend when compared to the solar-field twins, it shows a very similar abundance trend with $T_c$ when compared to the stars from the open cluster M67. They suggested that the Sun, unlike most stars,
was formed in a dense stellar environment where the protostellar disk was already depleted in refractory elements by radiative pressure on dust grains from bright stars before the Sun formed (see Gustafsson et al. 2016, for further discussion). Gustafsson, at this meeting and in a forthcoming paper, has demonstrated that it is difficult in this way to cleanse enough material for forming a full cluster with such abundance characteristics – the photoionization of the gas limits the amount of cleansed gas that is cool enough for star formation severely. Gaidos (2015) also suggested that gas-dust segregation in the disk can produce the $T_c$ trend, although only a qualitative analysis and discussion was made.

To separate the possible chemical signatures of planet formation from the effects of Galactic chemical evolution, several authors tried to correct the $T_c$ slope by using the [X/Fe]–age relation (e.g. Spina et al. 2016b; Yana Galarza et al. 2016). However, such kind of corrections are not easy to perform because of the intrinsic scatter in the [X/Fe]–age distributions due, for instance, to migration processes in the Galaxy (e.g. Haywood 2008; Haywood et al. 2013; Minchev et al. 2013; Sellwood & Binney 2002) and possible intercorrelation between different parameters.

However, the comparison of binary systems of twin stars should not be affected by the above mentioned processes and effects (e.g. formation time and place) and the only complications can be related to stellar evolution (if the stars do not have exactly the same physical properties e.g. mass). Several authors studied the $T_c$ trend in binary stars with and without planetary companions (e.g. Liu et al. 2014; Mack et al. 2016; Saffe et al. 2015) or in binary stars where both components host planets (e.g. Bizzarro et al. 2015; Ramírez et al. 2015; Teske et al. 2015, 2016). Although some significant differences between the twin pairs in some systems were reported, in general the results and conclusions of these studies point in different directions. Thus, as a whole, it is difficult to conclude that there are systematic differences in the chemical abundances of stars with and without planets in the binary systems. Moreover, there are discrepancies in the results even for the same individual systems such as 16 Cyg AB (e.g. Laws & Gonzalez 2001; Schuler et al. 2011a; Takeda 2005; Tucci Maia et al. 2014). It should be noted also that there are not many high-precision abundance values derived from the analysis of planet-hosting binary systems.

Fig. 6 Abundance differences, $\Delta[X/Fe]_{\text{SUN-\text{STARS}}}$, between the Sun and 10 stars hosting super-Earth-like planets (circles). Diamonds show the average abundances in bins of $\Delta T_c = 150$ K. Linear fits to the data points (solid line) and to the mean data points (dashed-dotted line) weighted with the error bars are also displayed. The figure is from González Hernández et al. (2013).
Fig. 5 Differences between [X/Fe] of the Sun and the mean values in the solar twins (with no detected planets) as a function of $T_{\text{cond}}$. The abundance pattern shows a break at $T_{\text{cond}} \sim 1200$ K. The solid lines are fits to the abundance pattern, while the dashed lines represent the standard deviation from the fits. The figure is from Meléndez et al. (2009).

Fig. 7 $T_c$ slopes versus ages for the full sample (top) and for the solar analogs (bottom). Gray solid lines provide linear fits to the data points. The figure is from Adibekyan et al. (2014).

4.2 Li abundance

Lithium, being a light element, can be easily destroyed in the inner layers of solar-type stars, extending to the outer layers if an efficient mixing process is at work. The Li abundance is very sensitive to different processes such as rotation-induced and overshooting mixing (e.g. Pinsonneault et al. 1992; Xiong & Deng 2009; Zhang 2012). It also strongly depends on many parameters such as effective temperature, metallicity and age (e.g. Baumann et al. 2010; Carlos et al. 2016; Delgado Mena et al. 2015, 2014; Pinsonneault et al. 1992; Takeda et al. 2010). The presence of stellar companion can also affect the lithium abundance through interactions of the components (e.g. Zahn 1994). Even the possibility of the Li production by stellar flares have been discussed in the literature (Canal 1974; Montes & Ramsey 1998), although the recent observations by Honda et al. (2015) does not provide any evidence of Li production by superflares.

Together with the aforementioned processes, it was suggested that the presence of planets and/or formation of planet can also affect the Li content. In particular, several works, starting from King et al. (1997), showed that solar analogs (in the temperature range of $T_{\text{eff}} = T_\odot \pm 80$K but a relatively large range of metallicities) with detected planets are systematically more depleted in Li than their 'single' counterparts (e.g. Castro et al. 2009; Chen & Zhao 2006; Delgado Mena et al. 2014; Figueira et al. 2014; Gonzalez 2008, 2015; Gonzalez et al. 2010; Israelian et al. 2009, 2004; Takeda et al. 2010). This relation, however, was contested by several authors (e.g. Baumann et al. 2010; Carlos et al. 2016; Ghezzi et al. 2010; Luck & Heiter 2006; Ramirez et al. 2012; Ryan 2000) arguing that the reported Li depletion in planet hosts relative to the non-hosts can be related to the bias in age, mass and metallicity. Figueira et al. (2014) applied a multivariable regression to simultaneously consider the impact of different parameters (age, metallicity, $T_{\text{eff}}$) on Li abundances. The authors reached the conclusion that planet-hosting stars display a depletion in lithium.

As in the case of $T_c$ trend, studying stellar twins in binary systems can help to understand the origin of Li depletion. Probably the most suitable system for this kind of studies is the 16 Cyg binary system. The 16 Cyg system is composed of two solar-type stars which are two of the best observed Kepler targets. A red dwarf is in orbit around 16 Cyg A, and 16 Cyg B hosts a giant planet. The Li abundance is much more depleted in 16 Cyg B than in 16 Cyg A, by a factor of at least 4.7 (King et al. 1997). The interesting aspect of studying the 16 Cyg system is that the two stars have

\[ \sigma(\text{volatiles}) = 0.011 \text{ dex}, \]
\[ \sigma(\text{refractories}) = 0.007 \text{ dex}. \]

\[ [\text{Fe}/\text{H}] = [\text{Fe}/\text{H}]_{\odot} + 0.1 \text{ dex}, \]

\[ [\text{Mg}/\text{Fe}] = [\text{Mg}/\text{Fe}]_{\odot} + 0.1 \text{ dex}. \]
the same age and may be assumed to have the same chemical composition. Since the observable parameter difference between the two stars is very small (e.g. $\lesssim 0.05 M_\odot$ in mass, $\lesssim 80 K$ in temperature), the currently observed differences in Li abundance is likely to be due to their different evolution, related to the fact that one of them hosts a giant planet while the other does not.

The fact that 16 Cyg B has a planet suggests that a disk may have been in interaction with the star at the beginning of its evolution. Recently Deal et al. (2015) studied the impact of the accretion of metal rich planetary matter onto this star. The accretion modifies the surface chemical composition of the star and may trigger an instability called fingering (or thermohaline) convection (Deal et al. 2013; Garaud 2011; Théado & Vauclair 2012; Vauclair 2004). This instability occurs in the case of a stable temperature gradient and an unstable mean molecular weight gradient when the thermal diffusivity is larger than the molecular one. This mixing process dilutes the accreted matter and may transport light elements down to their nuclear destruction layers and lead to an extra depletion at the surface. The authors used the Brown et al. (2013) 1D prescription (determined from 3D simulations) to compute the effect of fingering convection.

![Fig. 8](Image) Li abundance profiles after the accretion of different masses at the beginning of the main sequence in the model of 16 Cyg B (Courtesy of Morgan Deal). An accreted mass lower than 0.6$\odot$ practically does not affect the lithium abundance, while an accretion of Earth-like chemical composition matter of 0.66$\odot$ mass is enough to explain the lithium abundance difference observed between the two stars.

5 Summary

Determining both precise and accurate stellar abundances is a truly difficult task. There are many different choices to make: telescopes and instruments, atomic and molecular data, 1D or 3D model atmospheres that incorporate either LTE or NLTE line formation, and techniques that determine abundances with respect to the Sun or in a (line-by-line) differential approach with respect to another star. The results from these varying methods produce abundances that can be highly precise, approaching $\lesssim 0.01$ dex, with exciting new findings as discussed above.

Deal et al. (2015) used the TGEC, which includes complete atomic diffusion (including radiative accelerations). By testing the accretion of planetary matter with the same chemical composition as the bulk Earth (Allègre et al. 1995), they found that the more massive the accreted mass, the more Li depletion occurs at the surface (see Fig. 8) i.e. opposite to a common expectation that the accretion of planetary material should increase the Li abundance. The accretion of a fraction of an Earth mass is enough to explain a Li ratio of 4.7 in the 16 Cyg system. The authors concluded that such a process may be frequent in planet-hosting stars and should be studied in other cases in the future.

It is difficult to determine the highest achievable accuracy in stellar abundance determinations due to the fact that different models and analyses are not always in agreement. Additionally, it is complicated to calculate the associated error budget including systematics. Going beyond 0.01 dex will likely require modelling of stellar (magnetic) activity (e.g. Fabbian & Moreno-Insertis 2015) in some cases even time-dependent phenomena like diffusion (e.g. Önehag et al. 2014). Employing these techniques requires meticulous work and will be limited to relatively small data sets in order to enable extremely high accuracy. It is important, for the sake of measuring the true surface abundances of stars, that we continue to work on high precision spectroscopy while developing the modelling techniques to a higher degree of self-consistency.

Studying stellar abundances allows a deep insight into the formation and evolution of stars and stellar systems. Namely, [X/Fe]-age correlations can relate whether stars were formed from well-mixed molecular clouds or within areas that were enriched to varying degrees by supernovae (Nissen 2016). By looking at the abundances with age, it is possible to get a clearer picture of the nucleosynthetic enrichment timescales for different element classes (Spina et al. 2016a). However, studying how stellar abundances vary when a star hosts planets is not straightforward. There is an on-going controversy as to whether refractory elements are locked up inside of planets as they form, as shown by the $T_c$ trend from some studies, but not from others. The solution may be correlated with stellar age, Galactic distance, or due to a molecular cloud already depleted in refractory elements prior to star formation. The Li content, in particular, may be depleted in planetary hosts compared to non-hosts. These questions are intriguing because the solutions offer a wide range of stellar and planetary evolution scenarios. With a coordination between accurate observed stellar abundances and detailed models for both stars and planets, we are optimistic that the mysteries underlying the varying abundance characteristics of Sun-like stars unlike the Sun may be revealed in the future.

4 See Dupree et al. (2016) for an extreme case.
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