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ORIGINAL ARTICLE

The chemical composition of solar-type stars in comparison with that of the Sun

Bengt Gustafsson · Jorge Meléndez · Martin Asplund · David Yong

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Abstract The question whether the solar chemical composition is typical for solar-type stars is analysed by comparing the Sun with different stellar samples, including a sample of stars with very similar parameters, solar twins. Although typical in terms of overall metallicity for stars of solar age and galactic orbit, the solar atmosphere is found to have abundances, as compared with solar twins, that indicate that its gas has once been affected by dust formation and dust separation. It is concluded that this may be related to the formation of the solar planetary system and its special properties.

Keywords Sun: abundances · Stars: abundances · Solar system: formation · Planetary systems

1 Introduction

In her ground-braking PhD thesis and monograph *Stellar Atmospheres* Cecilia Payne (1925) concluded that "the uniformity of the composition of stellar atmospheres appears to be an established fact". At times and in some circles this uniformity was almost developed into a dogma (cf., e.g., Unsöld 1969), which however was gradually relaxed with the understanding that carbon stars (Russell 1934), Ap and Am stars (Aller 1947) and Population II dwarfs (Chamberlain and Aller 1951) had chemical compositions that departed from the standard one, for which the Sun with the solar system provided the most reliable source. Later it was demonstrated, e.g. by Edvardsson et al. (1993), Fuhrmann (1999) and Bensby et al. (2003) that even solar-type stars in the galactic disk show different composition patterns, depending on whether they belong to the thick-disk or the thin-disk population. The possibility that even within these disk populations there might be a significant scatter in relative abundances among the heavy elements, e.g. in [Mg/Fe] for a given [Fe/H], was explored, e.g. by Edvardsson et al. (1993), however with inconclusive results. Yet, the question whether the Sun in such a case would turn out to be special in terms of its composition, or whether it would still be normal enough to represent "a cosmic composition" was asked.

In several studies, e.g. Gustafsson (1998), Robles et al. (2008), Gustafsson (2008), and Allende Prieto (2008), the issue whether the Sun departs chemically from the majority of similar stars has been explored. On the basis of the Geneva–Copenhagen Survey of 14,000 nearby F and G dwarfs, one may from photometric estimates of overall metallicity trace a tendency for the Sun to be more metal-rich by typically 0.2 dex than most stars at its age and galactic orbit (Holmberg et al. 2009), and this might then be understood as a result of the general tendency for metal-rich stars to have a higher probability being planetary hosts (Gonzalez 1997). However, if one restricts the sample of comparison stars in the Geneva–Copenhagen survey to the stars within a distance of 40 pc from the Sun, the evidence is much less clear. Also, spectroscopically Valenti and Fischer (2005) in their admittedly biassed survey of F, G and K stars

B. Gustafsson (✉)
Institutionen för Fysik och Astronomi, Uppsala Universitet, Uppsala, Sweden
e-mail: bg@astro.uu.se

J. Meléndez
Centro de Astrofísica da Universidade do Porto, Porto, Portugal

M. Asplund
Max-Planck-Institut für Astrophysik, Garching, Germany

D. Yong
Research School of Astronomy & Astrophysics, Australian National University, Canberra, Australia

found a mean [Fe/H] of −0.01, and Fuhrmann (2004) found a sample of 118 thin-disk stars with a mean age of 4.5 Gyr to have a mean [Fe/H] of −0.04, while 60 older thin-disk stars with a mean age of 6.9 Gyr had a mean [Fe/H] of −0.07. So, we conclude that while there may be a marginal effect for the Sun to depart in overall metallicity, it is then probably less than 0.10 dex.

As regards abundances relative to iron for other heavy elements, a number of spectroscopic surveys of solar-type stars have been conducted in recent years (see, e.g. Chen et al. 2000; Fuhrmann 2004; Reddy et al. 2003; Mishenina et al. 2004; Gilli et al. 2006; Bensby et al. 2005; Allende Prieto 2008; Neves et al. 2009), partially with the aim of mapping the galactic disk evolution, and partially as part of investigating the characteristics of planetary hosts. Although some of these studies seem to imply mean values of [X/Fe], with X being e.g. Mg or Ca, deviating by up to 0.10 dex from the solar value of 0.00, the effects are usually not significant and also contrary in some cases. We conclude that no clear tendencies for the Sun to stand out chemically from other similar stars have been found until now.

In order to proceed further on this issue it is necessary to reduce the systematic as well as more spurious errors in the abundance analyses to significantly below 0.10 dex. How would that be possible? There are essentially several important necessary requirements in order to make this possible: (1) the spectra should have very high quality, with high S/N (of several hundreds) and high resolution ($R > 50{,}000$), in order for the errors in equivalent widths and in the definition of the spectral continuum to be minimised and (2) the choice of lines used as abundance criteria should be very selective, in order to avoid misidentifications and blends. The systematic errors, reflecting remaining errors and oversimplifications in the modelling of stellar atmospheres and spectra are the most difficult to compensate for. One way of circumventing those problems is to (3) make the study rigorously differential. This means that the solar spectrum should be observed under "star-like conditions", e.g. as represented by the reflection spectrum of an asteroid, the effective-temperature scale should be accurate and return the proper solar effective temperature, and the comparison stars should be as solar-like as possible, in order for the systematic model errors to cancel to a high degree. The study to be presented below (see Meléndez et al. 2009a for a more complete description) is designed to fulfil these requirements.

2 Abundances of a solar-twin sample

A suitable sample of stars for comparison with the solar spectrum has been selected, following Meléndez et al. (2006) and Meléndez and Ramírez (2007). From 10^5 stars in the Hipparcos catalogue, about one hundred solar-twin candidates were found on the basis of trigonometric parallaxes, photometry and colour-effective-temperature relations, and to some extent age indicators. Then, high-quality spectra of 30 solar-twin candidates observable in April 2007 were obtained at the Magellan 6.5 m Clay Telescope at Las Campanas, Chile, with the Mike spectrometer at a resolution of $R = \Delta\lambda/\lambda = 65{,}000$, $S/N = 450$ per pixel, and $340\ \text{nm} < \lambda < 1000\ \text{nm}$. The minor planet Vesta was observed to represent the solar spectrum. Using a spectroscopic analysis of the Fe I line strengths and variations of these strengths with excitation energy that were most similar to the corresponding measures in the solar spectrum (for more details on the method, see Meléndez and Ramírez 2007), resulted in the selection of 11 stars with spectra almost indistinguishable from solar. We call these stars solar twins. Our method is hardly model dependent at all.

These spectra were analysed on a line-by-line basis relative to the Sun, using standard 1D model atmospheres with the solar atmosphere represented by models from the same grid. The results were independent of whether Castelli and Kurucz (2004) models or MARCS models (Gustafsson et al. 2008) were used, which is to be expected since these different model grids are quite similar for solar-type stars, and the analysis is designed to be as little model dependent as possible. T_{eff}, $\log g$ and [Fe/H] were now finally fixed by matching FeI and FeII lines. The effective temperatures were found to agree with the solar one to within 75 K, $\log g$ to within 0.10 dex and [Fe/H] to within 0.07 dex for the selected twins.

The resulting relative abundances are illustrated in Fig. 1. It is seen that for many elements the mean abundances of the twins depart from the solar values. For individual elements the covariation between the specific element abundance and the iron abundance is very tight; e.g. the mean value of [Cr/Fe] is 0.010 with a standard deviation of 0.009. This, and our error estimates as given in Fig. 1, suggest that we have succeeded in our ambition to achieve a very high accuracy in our differential abundance determinations.

It should also be noted that the solar Li abundance, when comparing to those of the unbiassed sample of twins, is found to be normal for a star with solar mass, metallicity and age (see Meléndez et al. 2009b).

3 The connection to dust condensation

From Fig. 1 it seems that the Sun, as compared with the twins, is rich in certain elements and in particular in the relatively light ones, and more relatively normal or even somewhat poor in the more heavy ones. We note then that the twins were selected to have [Fe/H] close to solar so the similarity for the iron-peak elements is expected. There is however not a clear-cut correlation between the difference between solar vs. twin abundances and atomic number. In Fig. 2 we have instead plotted these differences

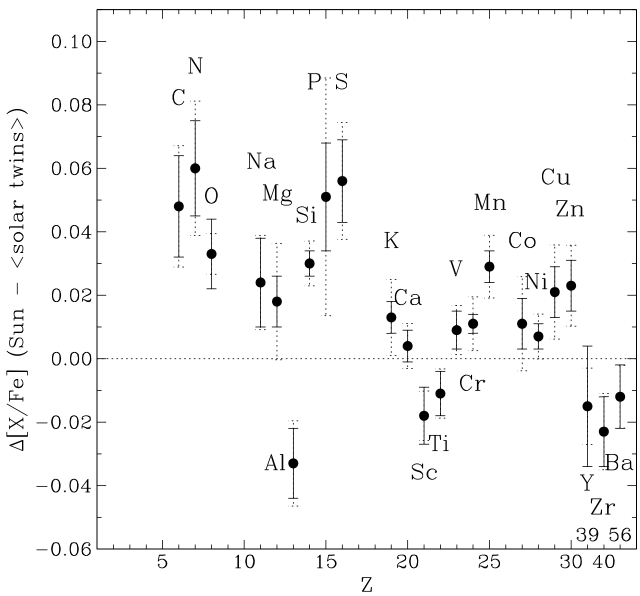

Fig. 1 Differences between the solar logarithmic elemental abundances relative to iron and the corresponding mean values observed in the solar twins as a function of atomic number Z. For sake of clarity the elements Y (Z = 39), Zr (Z = 40) and Ba (Z = 56) have been included after Zn. Observational 1σ errors in the relative abundances (including observational errors in both the Sun and solar twins) are shown with *dotted error bars*, while the 1σ errors in the mean abundance of the solar twins are shown with *solid error bars*. The figure is from Meléndez et al. (2009a)

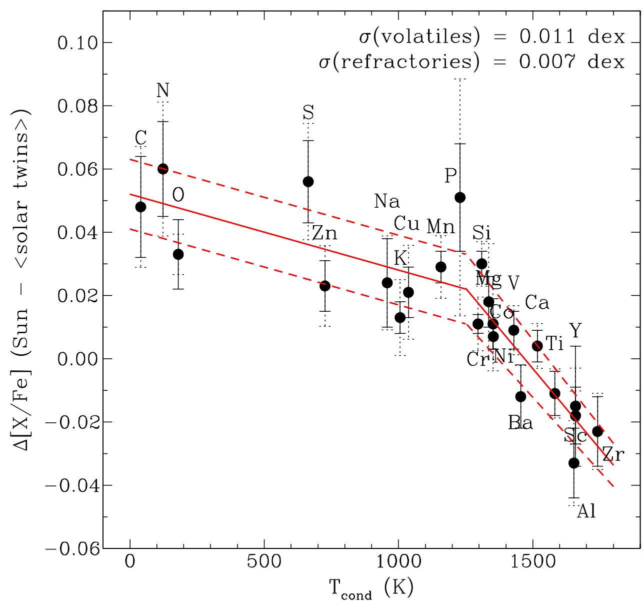

Fig. 2 Differences between [X/Fe] of the Sun and the mean values for the solar twins for different chemical elements X as a function of T_{cond}. The abundance pattern shows a break at $T_{\mathrm{cond}} \sim 1200$ K. The *solid lines* are fits to the abundance pattern, while the *dashed lines* represent the standard deviation from the fits. Note in particular that S and Zn, which have relatively low T_{cond}, are overabundant in the solar atmosphere relative to the comparison stars, while Al and Zr, with their high T_{cond}, show the largest underabundance. The low element-to-element scatter from the fits for the refractory ($\sigma = 0.007$ dex) and volatile ($\sigma = 0.011$ dex) elements confirms the high precision of our work. The zero point for the differences in relative chemical abundances depends on the adopted reference element, which here is Fe; the volatiles would appear normal while the refractory elements more depleted had we instead normalised on C. *Error bars* are as in Fig. 1. The figure is from Meléndez et al. (2009a)

relative to the 50% dust-condensation temperature for a solar-composition gas, following Lodders (2003). We obviously obtain an excellent correlation. This correlation is statistically highly significant—an arrangement of this type has a probability of occurring by mere chance that is less than $\sim 10^{-9}$. The scatter from the mean trend in Fig. 2 is only 0.01 dex. So, the Sun seems to be overabundant by $\sim$0.05 dex in the volatile elements (low T_{cond}) while elements that easily form dust (i.e. refractories, high T_{cond}) are underabundant by typically $\sim$0.02 dex. We note in particular that the refractory element aluminum with its relatively low atomic number, and the high-atomic number Zn, which has a relatively low T_{cond}, nicely follow the trend in Fig. 2. The pattern is quite similar to that observed (with a larger amplitude) in the interstellar medium (Savage and Sembach 1996) and in that case generally regarded an effect of dust condensation. Also λ Bootis stars and some highly evolved stars show similar though more pronounced effects, and this again is usually ascribed to accretion of dust-cleansed gas (Venn and Lambert 1990; Heiter 2002). It should be noted that this pattern found for the twins is not just a statistical phenomenon. All twins, except for one (HD 167060), which is more solar-like than the others, show a similar pattern, although more or less pronounced (see Fig. 3).

The phenomenon found is so astonishing, and may lead to so far-reaching conclusions, that it is very important to try to find independent evidence for it. However, a problem is then that the differential accuracy in existing studies generally does not permit any firm conclusions. For example, Ecuvillon et al. (2006) have looked for abundance-difference correlations with T_{cond} in comparisons between stars that are known to host planetary systems, with stars with no planets discovered, but they found no significant effect. Recently, however, Ramírez et al. (2009) traced effects similar to ours in their independent sample of 22 twins, observed with high resolution and S/N with the McDonald 2.7 m telescope. We have also checked our spectroscopic results by comparing one of our twins, HIP 79672 to the Sun using HIRES/Keck spectra of very high quality for the star and the asteroid Ceres. The results of this analysis agree very satisfactorily with the results of our MIKE/Clay data.

Stellar chemical analysis is known to be plagued by systematic errors of considerable magnitude (see, e.g., Asplund 2005). Could our results be caused by some such errors? A survey through the possible errors, in model atmospheres, in line-forming theory, in basic atomic data, and in fundamental parameters for the stars, does not give much evi-

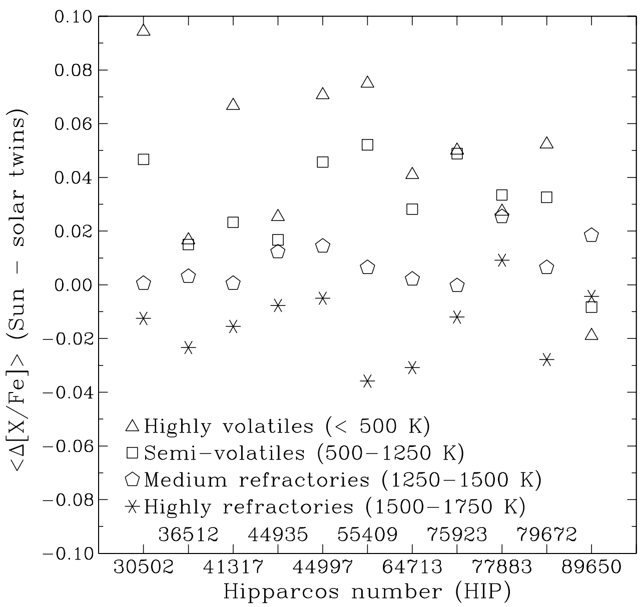

Fig. 3 Mean [X/Fe] ratios observed in the solar twins for highly volatile (*triangles*), semi-volatile (*squares*), medium refractory (*pentagons*) and highly refractory (*stars*) elements, for the solar twins. Most solar twins show similar trends with $T_{\rm cond}$ with the highly refractory elements ($1500 < T_{\rm cond} < 1750$ K) well separated from the highly volatile elements ($T_{\rm cond} < 500$ K) and in between the semi-volatile ($500 < T_{\rm cond} < 1250$ K) and medium refractory ($1250 < T_{\rm cond} < 1500$ K) elements. This separation between the refractories and volatiles on a star-by-star basis further emphasises that the observed chemical abundance differences are indeed real. The figure is from Meléndez et al. (2009a)

dence for this possibility. Indeed, an error in the temperature scale could lead to even greater departures in abundances than those observed, but it would not generate the consistent pattern of Figs. 2 and 3. We consider the explanation of the phenomenon as a result of errors in the analysis as improbable.

One special circumstance might cause systematic effects when the Sun is compared to the stars: the Sun is almost inevitably seen from a point in its equatorial plane, while the stars have more or less randomly oriented rotation axes relatively to the lines of sight. Could it be that the solar flux spectrum would look differently if we could observe it from a point at higher latitudes? Waiting for a near passage by a suitable comet at a high latitude—the corresponding few asteroids are too faint to admit high-resolution spectroscopy—one could observe the centre-to-limb variation of different abundance criteria along a meridian and compare with the corresponding variation along the equator, and then go through the complicated modelling needed in order to convert the observations to flux differences. Such observations are being planned, but there is little hope that the effects are large enough, and systematic enough, to give rise to a pattern similar to that in Fig. 2.

4 The origin of the effect

4.1 Early dust separation

One possible explanation of the effect found could be that the Sun was formed out of a cloud where dust had been blown away early on, e.g. by radiation pressure from luminous massive stars. Although this possibility cannot be ruled out, it does not explain why just the proto-solar cloud but not the corresponding solar-twin clouds would have been affected. In spite of that, this scenario is not easy to disprove or verify—other traces of massive-star activity in the composition of the solar system, and the absence of similar traces for the twins might be conceived as indications to look for. Another alternative, that the Sun early in its evolution was bright enough for its radiation to cleanse its proto-planetary disk, suffers even more from this type of critique—if the Sun was able to do so, why were the solar twins not?

4.2 Dust separation during planetary formation

It is natural to associate the reduced content of refractories in the solar atmosphere as compared with volatiles to the planetary formation in the solar proto-planetary nebula since the inner planets and meteorites of the Solar system are converse in this respect: richer in refractories than in volatiles (Palme 2000). In fact, the abundance pattern of these bodies reminds one of a mirror image of that shown in Figs. 1 and 2 (Alexander et al. 2001; Ciesla 2008). Also, the total mass of refractories in Mercury, Venus, Earth and Mars is about 8×10^{27} g, which means that if these planets were suddenly added to the present solar convective envelope of about $0.02 M_\odot$, already roughly half of the difference in [X/Fe] for each element X relative to the twins would be compensated away. Another suggestive circumstance is the break in the correlation of Δ[X/Fe] in Fig. 2 at $T_{\rm cond} \approx 1200$ K, a temperature which is thought to occur only in the inner parts of the proto-planetary disk ($R < 3$ AU, cf. Ciesla 2008).

The challenging suggestion is thus that the terrestrial planets formed in the proto-planetary disk after which the remains of the inner disk, depleted in refractories, were accreted onto the Sun. In order for this mechanism to lead to the observed abundance pattern, the solar convection zone at accretion and thereafter should not have contained much more mass than it does presently. Also, there must have been a difference as regards planetary formation and disk accretion between the Sun and the twins, which would explain the observed abundance differences between them. None of these requirements is non-trivial. First, the standard picture of pre-main-sequence evolution shows an early phase, along the Hayashi track in the HR diagram, when the model proto-sun was fully convective. After some time, as the Sun would be approaching the main sequence, the convection zone is found to gradually get shallower and reach its present size after about 30 Myr (D'Antona and Mazzitelli 1994). However, observations of proto-planetary disks in young stellar regions suggest that the disks have life times of typically less than 10 Myrs (Calvet et al. 2000; Sicilia-Aguilar et al. 2006), a time when the convection zone is still predicted to contain more than about 40% of the solar mass. True enough, gas accretion onto older stars have been detected but that is rare—only 1% of stars at an age of 13 Myr were found to show signs of accretion by Currie et al. (2007) and White and Hillenbrand (2005). However, if we now conjecture that the Sun was one of these rare cases when the inner proto-planetary disk was accreted quite late, while most twins behaved more normally in this respect, both requirements would be satisfied.

Other explanations which also involve planetary formation are worth exploring as well. One modification of the scenario above would be that the disk has been importantly depleted in refractories as well as volatiles also by the formation of the giant planets. Since both Jupiter and Saturn are believed to have rocky cores with masses of several earth masses and are also known to be richer in heavy elements (or poorer in H and He) than the Sun (de Pater and Lissauer 2001; Guillot and Hueso 2006) their cleansing of the solar disk may well have contributed significantly to the abundance pattern observed. In this case, greater masses are affected by planetary formation so that the requirement that the final accretion onto the Sun should occur quite late may be somewhat relaxed: it would still be possible to pollute a deeper convection zone.

Yet another interesting possibility, brought forward by Nordlund (2009), and which does not require any late infall of the disk, is that the early Sun did not develop through a state with a very deep convective zone at all. The dynamical accretion and convection calculations of the PMS evolution of the Sun by Wuchterl and Tscharnuter (2003) and Wuchterl and Klessen (2001) do in fact suggest this scenario, although these authors do not bring the calculations beyond 2 Myr. Their solar models do not become fully convective; instead, they have convective zones of similar relative thickness as the present Sun. If this occurred in reality, new possibilities in terms of a chemically inhomogeneous Sun open up, with surface layers severely affected by chemical fractionation in the proto-planetary disk. The effects may perhaps be large enough to explain the discrepancy between chemical analyses of the solar atmosphere and the solar seismology results concerning the mean molecular weight in the solar interior gas. This requires that the formation of the giant planets has contributed significantly to the depletion of heavy elements in the proto-planetary disk. This possibility is interesting enough to motivate renewed and more detailed calculations extended to longer times of the solar early evolution with dynamical convection.

Still another possibility could be that the disks of the Sun and the twins early formed terrestrial planets but that the twins engulfed them at later stages (again after ∼30 Myr), which led to a chemical composition of their outermost layers being enriched in heavy elements. This engulfing might be due to disturbances by inwards migrating giant planets or close stellar passages in clusters where the stars were formed (cf. Davies et al. 2008). This explanation may, however, be ruled out, since the μ-gradient would generate thermohaline convection below the hydrogen convection zone, which would have rapidly erased the higher metallicity of the outer layers (Vauclair 2004).

4.3 Test by planetary hosts

None of our solar twins are known to have planets, but few of them have been monitored long enough to make any safe statements on whether they are planetary hosts or not. However, we have access to observations similar to those of the twins but of 10 *solar analogues*, i.e. stars with fundamental parameters somewhat more departing from the solar ones such that larger systematic errors must be expected in the differential abundance analysis. Among these, four are known to be planetary hosts, while for the remaining six no planets have been discovered until now. The planetary hosts carry known planets in the range from 0.17 to 10 Jupiter masses within 1.6 A.U. from the star. One star (HD 160691) is known to host a system with at least 4 planets.

Contrary to our naïve expectation, when analysing our spectra of these solar analogues we found that the stars known to be planetary hosts all closely resemble the solar twins in chemical composition. Conversely, four of those for which no planets as yet have been found showed a solar-like pattern, while two of these stars were more similar to the twins. Thus, it seems that the existence of a planetary system as such does not lead to a solar-like abundance pattern. One may guess, however, that a *solar-like* planetary system may be connected to solar-like abundances—evidently, the Sun, if explored at a distance and with methods like those used for searching for planets around the analogues, would not be seen as a planetary host.

4.4 Explanations on galactic scales

The differences in chemical composition between the Sun and the solar twins might also be thought to result from systematically different origins in the Galaxy. If for instance the Sun is really more iron-rich than its typical contemporaries (see above), its chemical composition pattern should perhaps rather be compared with more metal-poor stars than stars with [Fe/H] close to 0.0. Such more metal-poor stars are known to have abundance patterns different from that of the Sun (see, e.g. Bensby and Feltzing 2006;

Chen et al. 2002), with non-solar ratios of α-elements relative to iron. However, the metallicity of the Sun is not *so* different from its contemporaries that this explanation could work, and, moreover, elements like C, Al and Zn do not seem to fit this hypothesis at all. Furthermore, age estimates for the twins lead to a median age of 4.1 Gyr (cf. Meléndez et al. 2009a), which is not significantly different from the age of the Sun.

Another possibility could be that the Sun originated in some other region in the Galaxy than the twins. Indeed, Wielen et al. (1996) suggested that the Sun has migrated from an inner Galactic orbit. Assuming that there are radial gradients in the abundance ratios, a difference between the Sun and the twins might result. However, observed gradients in [O/Fe] for young thin-disk objects are not steep enough (Przybilla et al. 2008) and galactic chemical evolution models do not suggest that the gradients were much steeper 5 Gyrs ago (Chiappini et al. 2001).

Still a possibility might be that the pre-solar cloud just happened to be polluted by an individual supernova in a special way, as compared with the twins. However, it is not possible to reproduce the solar pattern by any mixture of the yields of SNe II and SNe Ia, as calculated by Woosley and Weaver (1995) and Thielemann et al. (2002), respectively.

4.5 Long-lived planetary disk or shallow convection zone?

Among the various possibilities discussed above to explain the special solar abundance pattern two alternatives seem most attractive:

(1) The infall of the solar disk occurred later (after more than 20 Myrs) for the Sun than for the twins, or
(2) The solar convection zone never became very massive, so that the remains of the proto-planetary disk, depleted by planetary formation, could mark the solar convection zone chemically, independently of when it was accreted

In the first case it remains to understand why the solar proto-planetary disk was so long-lived, as compared with most observed disks as well as the presumed disks of the twins and of the solar analogs with planets. In the latter case, it remains to explain why only one or possibly two of the twins show the solar pattern.

The second hypothesis above is yet to be verified by detailed calculations for the early solar evolution extending into times beyond a few Myr, and such calculations must clearly be carried out. It is interesting, however, that it may open a way to also explain the inconsistency between the solar atmospheric composition and solar seismology results.

A particularly interesting question is now if these explanations are linked to a connection between the solar pattern and the existence of rocky planets in the inner parts of the planetary system. In case (1), the late infall makes it possible for the solar convection zone to be polluted by just the modification of the disk composition from the formation of the terrestrial planets. A somewhat earlier infall, say at 20 Myrs when the convection zone is much more massive, then requires that also a depletion of refractories due to giant planet cores has to be invoked. However, the absence of a solar pattern does not necessarily imply the absence of rocky planets, it may just reflect the still earlier disk infall. Thus, within this framework, a solar pattern found for a suspected planetary host would seem to be a satisfactory indication, but not a necessary one, for a planetary system with rocky planets like that of the Sun. In case (2) the connection to the terrestrial planets is more uncertain, since the mass of the convection zone as a function of time is presently not known with any certainty.

We have, however, already hinted at some other indications that the solar pattern is really related to the existence of terrestrial planets: the gradient in the abundance ratio of refractories relative to volatiles in the inner solar system with this ratio decreasing outwards, in combination with the break in the relation in Fig. 2 at $T_{\rm cond} \sim 1200$ K. In combination, these circumstances suggest on not only intuitive grounds that the existence of the terrestrial planets is directly reflected in the solar-composition pattern. The possibility to look for similar patterns in solar-type stars in order to trace candidates for solar-like planetary systems in general is interesting.

5 General conclusions

The study of chemical abundances of stars was summarised almost 30 years ago by Bernard Pagel at an ESO workshop, where he distinguished between two different types of scientists: “the broad sweepers” and “the ultimate refiners”. The need to improve the stellar abundances to accuracies better than 0.2 dex or so was then stressed by the latter group. Their project had its virtues, not only to make new interesting results in stellar astronomy possible, like tracing intricate differences in abundance ratios between different galactic populations, but also to arrive at physically reasonably consistent analysis methods in order to master the then unknown systematic errors that notoriously plagued the analyses.

Today, due to systematic efforts by several dedicated groups and ingenious individuals, the physical realism is being increased drastically in the modelling of stellar atmospheres and spectra, and for the first time we can claim that the systematic errors in chemical analysis of stars are under reasonable control. However, important systematic errors still remain on the 0.1 dex level (cf. Asplund 2005). An issue is then whether it is worthwhile to try to circumvent these errors and improve the analysis beyond that accuracy level. Are there important results, and in particular new discoveries to be made if we, by using various tricks like a rigorous differential approach, make efforts to reach much higher accuracies? Speaking in general terms, one could claim that science has repeatedly proven that order-of-magnitude increases in the accuracy of measurements tend to generate new interesting science. We think that the present study of the solar abundances relative to solar twins has again demonstrated this fact. Although the results of our study are astonishing, the finding that there *are* new things to be discovered when following this track is not. It was realised already more than 400 years ago and certainly was a basic drive for founders of modern empirical science like Tycho Brahe and Galileo Galilei. It was also expressed in a provoking way in the famous recommendation ascribed to Galilei: "*Measure what is measurable, and make measurable what is not so.*" In spite of the fact that this quote is probably a product of the imagination of French 19th century scholars, and was first spread efficiently in the scientific community in its English form by Hermann Weyl in the 1940s (see Kleinert 2009), the attitude expressed in it has fruitful applications, not the least in stellar abundance analysis.

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References

Alexander, C.M.O., Boss, A.P., Carlson, R.W.: Science **293**, 64 (2001)
Allende Prieto, C.: In: Israelian, G., Meynet, G. (eds.) The Metal-Rich Universe, p. 30. Cambridge University Press, Cambridge (2008)
Aller, L.H.: Astrophys. J. **106**, 76 (1947)
Asplund, M.: Annu. Rev. Astron. Astrophys. **43**, 481 (2005)
Bensby, T., Feltzing, S., Lundström, I.: Astron. Astrophys. **410**, 527 (2003)
Bensby, T., Feltzing, S., Lundström, I., Ilyin, I.: Astron. Astrophys. **433**, 185 (2005)
Bensby, T., Feltzing, S.: Mon. Not. R. Astron. Soc. **367**, 1181 (2006)
Calvet, N., Hartmann, L., Strom, S.E.: In: Protostars and Planets, IV, p. 377 (2000)
Castelli, F., Kurucz, R.F.: arXiv:astro-ph/0405087 (2004)
Chamberlain, J.W., Aller, L.H.: Astrophys. J. **114**, 52 (1951)
Chen, Y.Q., Nissen, P.E., Zhao, G., et al.: Astron. Astrophys. Suppl. Ser. **141**, 491 (2000)
Chen, Y.Q., Nissen, P.E., Zhao, G., Asplund, M.: Astron. Astrophys. **390**, 225 (2002)
Chiappini, C., Matteucci, F., Romano, D.: Astrophys. J. **554**, 1044 (2001)
Ciesla, F.J.: Meteorit. Planet. Sci. **43**, 639 (2008)
Currie, T., Kenyon, S.J., Balog, Z., Bragg, A., Tokarz, S.: Astrophys. J. **669**, L33 (2007)
D'Antona, F., Mazzitelli, I.: Astrophys. J. Suppl. Ser. **90**, 467 (1994)
Davies, M., Malmberg, D., Chambers, J.E., et al.: Phys. Scr. T **130a**, 4030 (2008)
de Pater, I., Lissauer, J.K.: Planetary Sciences. Cambridge University Press, Cambridge (2001)
Ecuvillon, A., Israelian, G., Santos, N.C., Mayor, M., Gilli, G.: Astron. Astrophys. **449**, 809 (2006)
Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D.L., Nissen, P.E., Tomkin, J.: Astron. Astrophys. **275**, 101 (1993)
Fuhrmann, K.: Astrophys. Space Sci. **265**, 265 (1999)
Fuhrmann, K.: Astron. Nachr. **325**, 3 (2004)
Gilli, G., Israelian, G., Ecuvillon, A., Santos, N.C., Mayor, M.: Astron. Astrophys. **449**, 723 (2006)
Gonzalez, G.: Mon. Not. R. Astron. Soc. **285**, 403 (1997)
Guillot, T., Hueso, R.: Mon. Not. R. Astron. Soc. **367**, L47 (2006)
Gustafsson, B.: Space Sci. Rev. **85**, 419 (1998)
Gustafsson, B.: Phys. Scr. T **130a**, 4036 (2008)
Gustafsson, B., Edvardsson, B., Eriksson, K., et al.: Phys. Scr. T **130a**, 4036 (2008)
Heiter, U.: Astron. Astrophys. **381**, 959 (2002)
Holmberg, J., Nordström, B., Andersen, J.: Astron. Astrophys. **501**, 941 (2009)
Kleinert, A.: N.T.M. Z. Gesch. Wiss. Techn. Med. **17**, 199 (2009)
Lodders, K.: Astrophys. J. **591**, 1220 (2003)
Meléndez, J., Dodds-Eden, K., Robles, J.A.: Astrophys. J. **641**, L133 (2006)
Meléndez, J., Ramírez, I.: Astrophys. J. **669**, L89 (2007)
Meléndez, J., Ramírez, I., Casagrande, L., et al.: Astrophys. Space Sci. (2009a). doi:10.1007/s10509-009-0187-3
Meléndez, J., Asplund, M., Gustafsson, B., Yong, D.: Astrophys. J. Lett. **704**, L66 (2009b)
Mishenina, T.V., Soubiran, C., Kovtyukh, V.V., Korotin, S.A.: Astron. Astrophys. **418**, 551 (2004)
Neves, V., Santos, N.C., Sousa, S.G., et al.: Astron. Astrophys. **497**, 563 (2009)
Nordlund, Å.: Astrophys. J. Lett. arXiv:0908.3479 (2009, submitted)
Palme, H.: Space Sci. Rev. **92**, 237 (2000)
Payne, C.: Stellar Atmospheres. Harvard Observatory Monographs, No. 1 (1925)
Przybilla, N., Nieva, M.-F., Butler, K.A.: Astrophys. J. **688**, L103 (2008)
Ramírez, I., Melendez, J., Asplund, M.: Astron. Astrophys. **508**, L17 (2009)
Reddy, B.E., Tomkin, J., Lambert, D.L., Allende Prieto, C.: Mon. Not. R. Astron. Soc. **340**, 304 (2003)
Robles, J.A., Linewater, C.H., Grether, D., et al.: Astrophys. J. **684**, 691 (2008)
Russell, H.N.: Astrophys. J. **79**, 317 (1934)
Savage, B.D., Sembach, K.R.: Annu. Rev. Astron. Astrophys. **34**, 279 (1996)
Sicilia-Aguilar, A., Hartman, L.W., Füréz, G., et al.: Astron. J. **132**, 2135 (2006)
Thielemann, F.-K., Argast, D., Brachwitz, F., et al.: Astrophys. Space Sci. **281**, 25 (2002)
Unsöld, A.: Science **163**, 3871 (1969)
Valenti, J., Fischer, D.A.: Astrophys. J. Suppl. Ser. **159**, 141 (2005)
Vauclair, S.: Astrophys. J. **605**, 874 (2004)
Venn, K.A., Lambert, D.L.: Astrophys. J. **363**, 234 (1990)
White, R.J., Hillenbrand, L.A.: Astrophys. J. **621**, L65 (2005)
Wielen, R., Fuchs, B., Dettbarn, C.: Astron. Astrophys. **314**, 438 (1996)
Woosley, S.E., Weaver, T.A.: Astrophys. J. Suppl. Ser. **101**, 181 (1995)
Wuchterl, G., Klessen, R.S.: Astrophys. J. Lett. **560**, L185 (2001)
Wuchterl, G., Tscharnuter, W.M.: Astron. Astrophys. **398**, 1081 (2003)