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Is the Sun unique as a star—and if so, why?

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Abstract
The question whether the Sun is peculiar as compared with other stars in its neigbourhood is revisited. It is concluded that although the Sun is rather normal from many points of view, it departs in several respects from most stars of similar age and galactic orbit. Thus, it is more massive, and the amplitude of the micro-variability of the Sun at visual wavelengths seems unusually small. It also departs from most stars in being a single star, and it may have an unusual planetary system. There are some tentative indications that its chemical composition departs from those of most solar-type stars of similar age. This is discussed and the departures are found not to be significant. I discuss here to what extent these peculiarities may be understood in terms of it being a planet host.

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1. Introduction

Ever since it was realized that the stars are suns, as was earlier pictured in Otto von Guerickes classical *Experimenta nova Magdeburgia de vacuo spatio* from A D 1671 (see the picture on the cover of this volume), the issue *how* characteristic a star the Sun could be has been on the agenda, although means to discuss it scientifically had to await advances in astrophysics in late centuries. The discovery during the last decade of many extra-solar planetary systems has, in addition to demonstrating that the central star in our planetary system is not unique in being a planet host, also rendered the issue of its possible peculiarities more significant. Thus, the question is now to what extent the properties and details of the solar planetary system can be taken as representative when modelling systems seen around other stars. Further, the discovery of giant gaseous planets close to many solar-type stars raises the question whether the solar system—with Jupiter and Saturn at considerable distances from the Sun—is really abnormal in this respect, and if so, if this is just circumstantial, or whether it could be linked to our own existence. The latter issue touches upon the dubious but not uninteresting Anthropic-Principle discourse—to what extent and in which respects should scientific explanations of why the Universe happens to be the way it is be given in terms of the existence of observers. A check in the Smithsonian/NASA ADS shows that the Principle has been referred to frequently in the last decade, and in hundreds of these references the possible peculiarities of our solar system have been discussed. So, if we would find that the Sun really were special, e.g. in terms of chemical composition or variability compared with most ‘solar-type’ stars, one might ask whether this peculiarity would be needed for Earth-like planets to form within a habitable zone, or even for life to form in general. A reasoning along these lines might also lead to the suggestion that life could be more sparse in the Universe than one would assume if the Sun were just normal.

A decade ago, I made an attempt to discuss the question, ‘Is the Sun a Sun-like Star?’ at an ISSI workshop (Gustafsson 1998). In the present paper, I shall revisit this issue. In the 1998 review, the question of the normality of the Sun was discussed as regards the following properties: *mass, age, chemical composition, angular momentum, differential rotation, granulation and turbulence, activity and binarity*. Our star was suggested to be *abnormal* in certain respects, namely concerning mass, chemical composition, activity and binarity. Here, I shall in particular return to these aspects and consider them in the light of more recent empirical results.

2. The large solar mass

As is well known, most stars have masses below one solar mass. In fact, the percentage of single stars that have masses below that of the Sun in the immediate solar neigbourhood is as high as about 84% and this may well be typical for general Galactic fields, cf e.g. Ninkovic and Trajkovska (2006). It has been speculated that this unusually great mass of the Sun could be explained in anthropic terms: if our central star were more massive than about 1.3 solar masses, its luminosity would increase by a factor of two or more in 4×10^9 years, and life could probably not have survived long enough on a planet in its neigbourhood to develop conscious observers of the universe. Thus, the famous 'faint-sun problem' (Sagan and Mullen 1972) which refers to the fact that the corresponding increase of the solar luminosity with its present mass is about 30% (cf e.g. VandenBerg *et al* 2008), a figure great enough to require considerable adjustment mechanisms in the heat balance of the Earth for life to survive, would have been much more severe with a somewhat higher solar mass. If, on the other hand, the solar mass and luminosity L would have been much smaller than that at present, the radial extension Δr of the habitable zone around it would be smaller too, since $\Delta r \sim L^{0.5}$ (cf Kasting *et al* 1993). This luminosity dependence would overcompensate for the slope in the mass distribution, and make the probability of finding life on planets peak for stars with about one solar mass. The reasoning is, however, built on the speculation that the orbit distribution in planetary systems is not systematically dependent on the mass of the central star, and in particular that orbits do not scale down in size for diminishing stellar mass.

However, another more astronomical reason for the high solar mass cannot be excluded. A glance through the Catalogue of Schneider (2007) of planets discovered until 31 October 2007 discloses that only about 30% of all 215 planetary systems detected with the radial-velocity method have central stars with masses smaller than solar mass. For the 32 systems detected photometrically by the transit method, at least half of the central stars are still estimated to be more massive than the Sun. True enough, these numbers suffer from considerable selection effects, and systematic statistically unbiased studies must be made to explore whether the fraction of stars with planetary systems is reduced for stars with the lowest masses. We note that Heiter and Luck (2003) in their comparison of stars with and without giant planets list a greater fraction of stars with sub-solar masses in the latter category. However, Valenti and Fischer (2005) have explored the properties of the FGK planet-search sample of 1040 stars and found a median mass of 1.1 solar masses. In figure 10 in Fischer and Valenti (2005), we find a tendency for a mass dependence of the fraction of stars with discovered planets, but as the authors point out, this may be due to an underlying correlation between stellar magnitude and metallicity. It is not clear today whether the selection effects in the present planet searches, favouring stars similar to the Sun, are sufficiently strong to raise the fraction of 30% of lower-mass host stars to more than 80%. Thus, perhaps, it cannot be excluded that the Sun, while being extraordinarily massive as a star, is not so as a planet-system host. Indeed, this in the end might also suggest an anthropic background to its mass, but then directly related to the central topic of this conference.

3. The chemical composition

We have previously suggested (Gustafsson 1998) that (i) the Sun might be unusally metal-rich for its present age and orbit by about 0.1–0.2 dex in [Fe/H]. Also, (ii) a tendency for the Sun to be somewhat poor in light elements relative to Fe, $\Delta[\mathrm{X/Fe}] \approx -0.04$, where X = C, Na–Ti (but excluding Ca), has been traced. These results were very much founded on the study by Edvardsson *et al* (1993) of 193 solar-type stars in the solar neighbourhood. Since then, the spectroscopy of stars has developed considerably, and a number of recent accurate and extensive surveys of abundances in Galactic disc stars relative to the Sun have been conducted. Also, the solar absolute abundances have been scrutinized.

3.1. The solar metallicity

Although the first of these tendencies, (i), is supported by a number of more recent studies, the situation is not clear. Reddy *et al* (2003) in their spectroscopic study of Galactic disc stars obtain a mean metallicity, for stars of solar age, of [Fe/H] near −0.3 dex with an S.D. of about 0.1 dex. However, these authors may have a sample of Thin Disc stars biased towards low metallicities. Holmberg *et al* (2007) in their photometric and statistical study of about 10^4 Galactic stars find a mean metallicity of stars of solar age for a volume-limited sample within 40 pc of $[\mathrm{Fe/H}] \approx -0.1$ to −0.2, depending on the calibration of the photometry, with an S.D. of 0.2, a scatter that is claimed to be dominated by real 'cosmic' scatter. Although these studies might suggest that the Sun is unusually metal-rich for its age, there are similar stars around, but they would then constitute a minor part of the total number of stars in the same age group and with similar galactic orbits. However, the mean [Fe/H] value in the large sample of F, G and K stars that have been observed by the Keck, Lick and AAT planet-search programmes is −0.01, which is essentially identical to that of the Sun (Valenti and Fischer 2005), but this could be due to an age effect since most of the FGK stars may be younger than the Sun and the age–metallicity relation of Holmberg *et al* (2007) may suggest a rather steep upturn during the last 5 billion years—note that this, however, is dependent on the particular calibration used for their *uvby* photometry! Also note that few stars in the age interval 4–5 Gyr in Holmberg *et al* (2007; their figure 24) may suggest mean metallicities very close to solar. Fuhrmann (2004; and references therein) in his detailed spectroscopic study of many nearby stars finds a mean [Fe/H] of −0.041 for 118 Thin Disc stars with a mean age of 4.5 Gyr. Similarly, he finds a mean [Fe/H] of −0.074 for 60 old Disc stars with a mean age of 6.9 Gyr. So, if the Sun is unusually metal-rich for its age, it may be a rather marginal effect. And it is conceivable that the solar metallicity is just normal.

It is tempting to discuss the solar metallicity in the light of the strong tendency for metal-rich stars to be overrepresented among the host stars of planetary systems (e.g. Santos *et al* 2005; see also Valenti's review in the present volume). According to Santos *et al* only about 10% of the stars with planetary systems detected have $[\mathrm{Fe/H}] \leqslant -0.15$, whereas about 50% of all the stars in the same fields are found to be metal-poor. This tendency has been confirmed by several other authors (see e.g. Bond *et al* 2006) although Fuhrmann (2004) again suggests a considerably less-pronounced overrepresentation. If we assume that the probability to detect whether any planetary system exists around a star is independent of metallicity—a very questionable assumption since e.g. the masses of giant planets or their migration might well be enhanced in metal-rich environments—we estimate from figure 1 in Santos *et al* (2005) that the probability that a planetary system exists around a given star with [Fe/H] in the range −0.1–0.1 is about a factor of 4 times greater than that for a more metal-poor star. Such a bias would then make the Sun a fairly normal planetary-system-carrying star of its age even if it were more metal-rich than most contemporary stars. If instead, the observed metallicity distribution of host stars would be ascribed to a tendency for higher metallicities to promote the formation of planetary systems with gaseous giants close to the stars, while systems with smaller planets or giants at greater distances (like our solar system) are assumed to be characteristic of more metal-poor stars (a hypothesis with some support from the meagre statistics of the stars with Neptune-sized planets, cf Bonfils *et al* 2007), a possibly high metallicity of the Sun must still be considered peculiar for a star of this age.

3.2. Abundances relative to iron

The second tendency (ii), some enhancements of light elements relative to Fe in solar-type stars relative to the Sun, can also be explored further with the recent excellent spectroscopic data, but again we find the situation to be unclear. From the Chen *et al* (2000) results for 90 F and G disc dwarfs, one may trace a tendency for stars around the Sun [Fe/H] to have enrichments of Mg, Al, Si, K and Ca by 0.03–0.10 dex, although not in Ti. We note that the detailed study by Fuhrmann (2004; and references therein) of Mg and Fe does not strongly support such an enrichment. Reddy *et al* (2003) trace positive offsets in Mg, Al, Si and S of 0.03–0.05 dex relative to Fe at solar metallicities in their study of 181 F and G dwarfs. They also find a possibly greater offset for C, but with considerable uncertainty. The Sun is, however, in the outskirts of their parameter domain (most stars being hotter and more metal-poor) and they warn that systematic errors in the analysis and model atmospheres might cause the tendencies. They find no significant offsets for Mg, Si and S relative to Fe if iron abundances are not determined from Fe I lines but from Fe II lines alone, a fact suggesting that over-ionization of Fe may play a role in their local thermodynamic equilibrium (LTE) results. Mishenina *et al* (2004) analyse spectra of 174 F, G and K dwarfs to determine Mg, Si, Fe and Ni abundances and find some similar effects for Mg, in a non-LTE analysis, and a pronounced effect for Si. Gilli *et al* (2006), in their study of 101 planetary hosts and a comparison sample of 98 stars with no planets identified as yet, find no significant departures in solar abundances ratios for [Na/Fe] and [Si/Fe] and negative values for [Ca/Fe], but trace positive, though hardly significant departures from 0.0 for [Mg/Fe] and [Al/Fe]. Bensby *et al* (2005) selected samples of stars with Thin and Thick Disk characteristics, respectively, and discovered systematic differences between different samples in Alpha element abundances (O, Mg, Si, Ca and Ti) relative to Fe from low metallicities all the way to [Fe/H] $\approx$ 0.0. If one restricts the discussion to the Thin Disk stars, the offsets get smaller or negligible at solar metallicity with Ca and possibly Mg being exceptions. Allende Prieto (2006) finds no significant departures from solar abundances of Si, Ti or Ni for a sample of 80 solar analogues with solar Fe. Meléndez and Ramírez (2007) similarly find very good agreement in the chemical composition between the Sun and four proposed solar twins, and in particular for HIP 56948, which has fundamental parameters very close to those of the Sun. These results together suggest that the tendency (ii) is, *if existing at all*, not pronounced, but a detailed study of it with a careful review of the reasons for different results obtained by different authors and with consideration of departures from LTE, effects of atmospheric inhomogeneities, uncertainties in the temperature scale (still a notorious problem when stars are compared with the Sun), as well as kinematic population characteristics and ages of the stars to compare with, is necessary before one may firmly say whether the Sun, in terms of light element abundances relative to Fe, is at all deviant. If it were, the difference will be, at the most, of the order of 10%.

It is interesting to note in this connection that the question whether stars hosting giant planets in general depart in chemical composition from stars that have not been found to carry planets has been much discussed and extensively explored recently, still, however with no consensus except for an overall high metallicity of planet hosts already mentioned above. For the lighter elements we note that Beirão *et al* (2005), in their comparison of [Na/Fe], [Mg/Fe] and [Al/Fe] in 98 stars with known giant planets and 41 ‘single’ stars, do not trace any systematic differences between the two samples. Nor do Ecuvillon *et al* (2006) trace any clear tendencies for the planet hosts to depart in [O/Fe], or Gilli *et al* (2006) and Bond *et al* (2006) in their comprehensive comparisons of abundances of 12 and 7 different elements, respectively. This is in contrast to Robinson *et al* (2006) who, on the basis of the catalogue by Valenti and Fischer (2005), trace a tendency for the planet hosts to be overabundant in Si and Ni. These findings are, however, not confirmed by Gonzalez and Laws (2007) in their study of 18 elements in 31 planet hosts and other datasets who, however, yet see some indications of differences in [Al/Fe], [Si/Fe] and [Ti/Fe] and suggest even more subtle differences in [Na/Fe], [Mg/Fe], [Sc/Fe and [Ni/Fe]. For further discussion, see Valenti’s paper in the present proceedings.

Finally we note that the data of Reddy *et al* (2003) also may suggest offsets of about −0.05 dex for [V/Fe] and [Mn/Fe] at [Fe/H] $\approx$ 0.0. One might possibly also trace a similar tendency for Cu from the results of Ecuvillon *et al* (2004), although, in that case, the offset would change sign directly when [Fe/H] gets positive. One might speculate that these results could indicate that the Sun is somewhat rich in these heavier elements. For various reasons, however, these results must be considered even more uncertain than those for the lighter elements. Gilli *et al* (2006) also do not confirm such tendencies for V.

3.3. The Lithium abundance

The scatter in the Li abundances for stars similar to the Sun (the so-called solar analogues) is known to be considerable, varying from $\log A(\mathrm{Li}) \approx 3$ to 1, i.e. by about a factor of 100. The solar abundance ($\log A(\mathrm{Li})_\odot = 0.92$) is in the lower end of this interval, however not very peculiarly low. Thus, recently, Meléndez and Ramírez (2007) identified a solar twin, HIP

56948, which has fundamental stellar parameters including age similar to the solar ones and a similarly low lithium abundance. What might be of special interest is that it has been argued that planet-host stars tend to show systematically low Li abundances (Gonzales and Laws 2000, Israelian *et al* 2004), which, however, has been suggested by Ryan (2000) to be caused by an irrelevant comparison sample in the study of Gonzales and Laws, while Luck and Heiter (2006) referred their negative confirmation of the effect of Israelian *et al* to systematic errors in the effective-temperature scale.

Takeda *et al* (2007) have recently explored the Li abundances and other spectroscopic characteristics of 118 solar analogues, and demonstrated that the lithium abundances closely correlate with the broadening of the line widths by large-scale motions (i.e. the sum of the so-called macroturbulence and rotational broadening). They suggest that the angular momentum is the key factor determining the Li abundance by affecting the possibilities for Li destruction by mixing it into deeper and hotter layers, and as well as slowing down for objects forming planetary systems. We note that there are considerable difficulties in understanding the relatively small angular momentum gradients in the Sun, which are derived by helio-seismology. Instead, steep gradients as well as efficient in-mixing and destruction of Li to much lower values than observed is expected. It has, however, recently been shown that internal waves generated by convection in solar-type stars produce oscillations that should lead to efficient angular redistribution from the stellar core to the envelope. Charbonnel and Talon (2005; see also Talon 2008 for a comprehensive review) have demonstrated that models including this mechanism are not only able to match the observed solar angular momentum distribution, but also reproduce its Li abundance. The differences in Li among the solar analogues would, with this background, presumably be a consequence of differences in initial angular momentum and in magnetic braking by an early wind, in addition to a spread in ages and some spread in mass. The suggested systematically small Li abundances for planet-host stars would then, however, not be easily explained.

3.4. Absolute solar abundances

Recently, M Asplund, N Grevesse and collaborators derived new chemical abundances for the solar atmosphere, taking granulation effects, departures from LTE and new atomic and molecular data into consideration (see Grevesse *et al* 2007, and references cited therein). They have found considerable revisions necessary, notably for the CNO abundances, which have been revised downwards relative to previous established values by about 0.2 dex. These revisions lead to significant reductions of the overall metallicity (the mass fraction of elements heavier than He, dropping from $Z = 0.018$ to 0.012) and thereby also of the opacities in the stars. This seriously challenges the interpretation of solar seismological data (which suggest a higher Z). We also note in passing that the existence of a 'hook' in the colour-magnitude diagram of the rich open cluster M67, which is found to have a close to solar composition from spectroscopy and an age somewhat smaller than solar, suggests higher absolute CNO abundances. This is because the 'hook' indicates a restructuring of the star when hydrogen is exhausted from the core, and this only occurs if CNO burning in a convective core has taken place, which at the turn-off mass of this cluster requires high CNO abundances (VandenBerg *et al* 2007). A way out of this dilemma may be to advocate effects of diffusion of the CNO elements inwards in solar-type stars, which however does not resolve the problem with the indications from solar seismology. Anyhow, in certain respects, the reduced CNO abundances make the Sun 'more normal' in that they now agree better with what has been obtained for more massive Pop I stars and galactic gaseous nebulae.

With these new and considerable revisions of the solar abundances, it may seem astonishing that we have shown interest in proposed abundance differences between the Sun and other solar-type stars of only 1/4 of the revisions. Should we not learn from the work of Asplund *et al* that the abundances are so uncertain that minor differences between stars should be considered insignificant?

True enough, the possibly significant abundance differences between the Sun and other stars are differential ones, while the discourse on solar absolute abundances is something else since those are much more subject to systematic errors. Yet, this is only partly reassuring. The key issue here is *how similar* the comparison stars have to be relative to the Sun and *how similar* the methods have to be in order for systematic errors to be reduced to an insignificant level. We shall return to this issue at the end of this paper.

4. Stellar activity and variability

Since the discovery of cyclic activity variations for stars from F- to M-spectral-type on or near the main sequence by Wilson (1978), the activity diagnostics at different wavelengths have been monitored for different stars and not the least for stars of solar type. The general result of these studies is that, although the sample of comparison stars is still limited, the Sun seems relatively normal for its age, at least as regards its period of the activity cycle (for references, see Gustafsson 1998). The mean S index, measuring the summed relative strengths of the Ca II and H line cores, at the Solar Disk centre seems to be at the lower limit of the distribution for 57 solar-type stars of Hall and Lockwood (2004), according to Livingston *et al* (2007). Also, the mean HK index of the Solar Disk centre is less than the seasonal mean values for even the most quiet solar-type stars in M67 (Giampapa *et al* 2006). When it comes to the integrated Solar Disk HK index, it seems however normal, e.g. as compared with the M67 stars, even if about 7% of those have a higher HK emission than found even at solar maxima, and 17% have lower HK emission than the Sun at solar minima. Giampapa *et al* suggest that these latter stars may be in a prolonged state of quiescence analogous to that of the Sun during the Maunder minimum. This fraction of stars indicates somewhat fewer Maunder-minima-like episodes than the proposal by Damon (1977), based on the evidence from ^{14}C records that the Sun should have had low magnetic activity for about 1/3 of the time during the past millennia.

In one particular respect, a deviation has been suggested, namely, in the degreee of photometric variations at visual wavelengths from the integrated solar disc, which is 0.1% or less, and therefore seems to be at least two times smaller than similar comparison stars (Lockwood *et al* 1997). The programme of Lockwood *et al*, carried out in the Strömgren *b* and *y* bands for 32 stars with a number of carefully selected comparion stars, has been pursued since 1984. The results were reported recently and related to other activity measures by Lockwood *et al* (2007). A clear correlation between chromospheric variability and brightness variability in the visual is found. Young active stars show gradually fainter visual brightness when the Ca II emission increases, whereas older and less-active stars like the Sun show the converse: a covariation between visual and Ca II emissions. Obviously, the compensation balance between faculae and star spots is age-dependent. The earlier result that the Sun shows less brightness variations than almost all other stars in the sample remains, this in spite of the fact that the Sun tends to belong to the stars at its given chromospheric mean activity as measured by the emission in the H and K lines, which have relatively large variation in this latter emission. The authors warn that this apparently outstanding property of the Sun might be due to small-number statistics. otherwise, one could speculate that the fact that our solar measures are special in that they are made close to the solar equatorial plane while the observations for the stars are more randomly made relative to their rotation axes could be of significance. A still more speculative thought could be that the solar spot–faculae compensation is special for the Sun, and this could possibly suggest an anthropic 'explanation'. Note, however, the suggestion that the solar flux has varied much more in historical times, e.g. been reduced by about 0.24% during the Maunder minimum (Lean *et al* 1995).

5. Binarity

The Sun is somewhat peculiar in that it is single, while most of the solar-type stars appear in binary or multiple systems (Duquennoy and Mayor 1991). The works by Halbwachs *et al* (2003) and Eggenberger *et al* (2004) suggest that 56% of the stars with spectra in the interval F7-K are binaries with periods $\leqslant 5.5 \times 10^3$ years or multiple stars. Since long, it has been argued that this property of the Sun might be due to difficulties in forming or maintaining a planetary system in the varying gravitation potential of a stellar system (see e.g Cameron 1962), an argument which more or less explicitly may suggest an anthropic reasoning. The recent discoveries of planets also in binary systems give a different picture. Presently, more than 40 planets are known in binaries or multiple systems. It is not quite clear how biased this number is by selection effects, but it is possible that the probability of finding planets around a binary star is indeed comparable with that of finding planets around a single star. However, planets with masses smaller than that of Jupiter in short-period orbits ($P \leqslant 40$ days) seem to be less likely in tight binaries (with separations smaller than 100–300 AU), while the mass distribution and other properties of planets around wide binaries seem more similar to that of planets around single stars except for possibly the eccentricity distribution (Desidera and Barbieri 2007). The numerical simulations of Marzari *et al* (2007) suggest that planetary systems may form efficiently around individual components in binaries (the so-called S-type orbits) if the major axes of the binary orbits are large (at least several ten times the size of the planetary orbit) and their eccentricities relatively small. In such cases, the planet may also survive for more than 10^4 binary revolutions, according to the integrations of Holman and Wiegert (1999). We note that for half of the nearby binary systems that contain solar-type stars listed by Dvorak *et al* (1989; their table 1) and with periods in the range from 1.72–172 days, a planet with a mean distance from any of the stellar components of 1 AU would remain in the system. Also, trial simulations of Holman and Wiegert with a solar system model, augmented with a solar-mass companion with an orbit eccentricity of 0.4, showed that the planetary system could survive for 10^9 years, provided the semi-major axis of the binary was 400 or 500 AU. If the binary orbit had a considerable inclination relative to the planetary orbits, an even larger separation would be needed for the system to survive.

If the system instead contains a close binary (P-type orbit), planetary formation only occurs efficiently at distances several times the semi-major axis and primarily for small eccentricities and relatively equal stellar masses (Marzari *et al* 2007) and only in that case the planetary orbits may also be stable enough to survive, according to Holman and Wiegert (1999).

These theoretical results suggest that the fraction of binaries in stars that have surviving planetary systems may be considerably reduced relative to single stars. It is not known in which kind of binaries planetary systems like ours, with fairly distant giant planets and terrestrial planets in the habitable zone, may emerge. However, a hypothetical solar companion beyond several hundred AU and with an almost circular orbit would probably not have been disastrous for the stability of our planetary system.

6. Conclusions

We have found the Sun to be peculiar in certain respects, as regards its relatively large mass (compared with most stars), a probably low amplitude of its brightness variability, and in being a non-binary. In spite of several suggestions for specific departures in chemical composition of the Sun, e.g. that it possibly has a somewhat higher metal abundance (compared with stars of solar age and with similar orbits in the Galaxy), and further departures in abundances relative to Fe (e.g. in Li, Mg or Al), we do not consider these effects to be well established, as they may well reflect various systematic errors in the analyses or spurious scatter in the comparison-star samples. Further work on these abundance effects should build on detailed treatment of the different effects of non-LTE and three-dimensional (3D) convection in the atmospheric analyses, and/or on a very rigorous method in selecting comparison stars in order to ascertain that all their relevant fundamental parameters are well known and on the same scale as the solar parameters (including the elements of their galactic orbits), and have values very similar to the solar ones. In a number of other respects, we have found the Sun to show normal characteristics (cf Gustafsson 1998). In one respect, we have not discussed the peculiarity of the Sun—its possibly unusual planetary system with, e.g., near circular orbits also for the long-period gas giants. As has been stressed by Jeff Valenti (private communication), the low eccentricity of Jupiter's orbit allows an interior planet to reside continuously within the habitable zone, which has obvious anthropic implications.

Before worrying further about the peculiarities and their significance, we note that if the different properties under consideration are not statistically dependent (an assumption which in itself is an oversimplification) and also assuming each of the properties to be characterized by parameters that are normally distributed, one would expect about 3 out of 10 parameters to deviate by more than 1 S.D. (1σ) from the mean sample, and 1 out of 10 may well depart by 2σ. So, even if the Sun were drawn just randomly from a set of 'normal' stars, one expects it to be abnormal in some respects. However, it does not seem very probable that the peculiarities noted above can be entirely explained that way, even though it might be the case for a couple of them (say small variability and non-binarity).

It is seen from the sections above that the peculiarities of our star are instead repeatedly discussed in terms of its planetary system. Maybe the relatively large mass is typical for stars with planets (although extended planet searches with known biases are needed to prove that), maybe the suggested high metallicity of the Sun for its age and orbit reflects the increased probability of forming planets in high-metallicity environments (although this remains to be shown for lower-mass planetary systems), and maybe planetary systems like ours have a significantly greater chance to survive in a single-star potential (in spite of the recent discoveries of planets in binary systems). This strengthening tendency to refer to the planetary system when explanations are searched for for the properties of the Sun naturally reflects the progress in the study of extra-solar planets. Although in proceeding further along this way of explanation, one finds anthropic arguments—the Sun needs a planetary system for us to exist and ask these questions—it seems to be a more general and satisfactory procedure than to construct more special anthropic 'just-so stories' for each peculiarity of the Sun. Thus, a reasonably simple working hypothesis in answering the question in the title of this paper is: 'The Sun is odd in certain respects since a habitable planetary system has to be there too'. It is, however, quite possible that the further study of extra-solar planets will close this simple route. One example here is already given by the non-binarity issue, where the recent discovery of binaries with planets might make this explanation less attractive.

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Note added in proof: A comparison of the Sun to other stars was recently carried out by Robles *et al* (2008) astro-ph/0805.2962, ApJ in press. There, a quantitative statistical analysis, allowing for cosmic and observational spreads in various parameters, was attempted with the result consistent with the idea that the Sun is a normal star. Micro-variability and binarity were, however, not explicitly included in the analysis.