SOLAR TWINS AND POSSIBLE SOLUTIONS OF THE SOLAR AND JUPITER ABUNDANCE PROBLEMS

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ABSTRACT

Implications of the recently discovered systematic abundance difference between the Sun and two collections of ‘solar twins’ are discussed. The differences can be understood as an imprint on the abundances of the solar convection zone caused by the lock-up of heavy elements in the planets. Such a scenario also leads naturally to possible solutions of two other abundance peculiarities; 1) the discrepancy between photospheric abundances derived from accurate 3-D models of the solar photosphere and the abundance of heavy elements in the solar interior deduced from helioseismology, and 2) the abundance pattern of Jupiter, which can either—with great difficulty—be interpreted as a general and similar overabundance of both common elements such as carbon, nitrogen and sulphur and rare inert gases such as argon, krypton and xenon, or—much more simply—as an under-abundance of hydrogen.

Subject headings: Sun: abundances – Jupiter: abundances – solar system: formation – convection

1. INTRODUCTION

Melendez et al. (2009) have recently found systematic differences between the abundances of heavy elements in the Sun and a number of nearby ‘solar twins’, selected from the Hipparcos catalogue. The differences are tightly correlated with the condensation temperatures of the elements (Lodders 2003), and are very well established, with formal probabilites of occurring in a random sample of the order of 10^-9. Ramirez et al. (2009) have found similar differences for a selection of northern hemisphere solar twins. Melendez et al. (2009) propose that the abundance difference patterns could possibly be related to the presence of planets.

One purpose of this Letter is to discuss this issue in some detail, and to bring forward into the discussion some aspects that may not yet be generally appreciated. Among these is the fact that, when taking into account realistic accretion histories from gravo-turbulent models of star formation Wuchterl & Klessen (2001) find that, contrary to conclusions from models based on a quasi-static picture (e.g. D’Antona & Mazzitelli 1994), the early Sun was not fully convective but had a structure more or less homologous to the current Sun, with a convection zone depth of only about one third of the radius (Wuchterl & Tscharnuter 2003).

Another aspect that, on closer inspection, is almost unavoidably related to this issue is the so-called ‘solar abundance problem’ (aka ‘the solar oxygen crisis’: Ayres 2008). Recent re-analyses of photospheric abundances of heavy elements (Asplund 2005; Caffau et al. 2008; see also Asplund et al. 2009) and Nordlund et al. (2009), lead to values of $Z_{CZ}$, the mass fraction of elements heavier than helium in the convection zone, between 0.012 and 0.015, while the best fit of models of the solar interior to measurements of solar oscillations generally suggest $Z \approx 0.017$ (e.g. Antia & Basu 2006). These latter model fits are mainly sensitive to the abundances below the solar convection zone (CZ), while the photospheric measurements of course pertain to the well-mixed solar CZ. In principle these abundances could differ, with the CZ value being smaller than the interior value. Since the present solar CZ contains about 2.5% of the solar mass, the ‘missing’ amount of heavy elements in the CZ is only about 10–40 Earth masses — the exact amount depending on if one adopts the Asplund (2005) or the Caffau et al. (2008) value of $Z_{CZ}$. This is comparable to the mass of heavy elements locked up in the planets. Thus, even allowing for a somewhat more massive CZ in the early Sun, one would expect to see a difference in CZ and interior heavy element abundance, of the order of the one that is implied by the solar abundance problem. This connection has been pointed out previously by Haxton & Serenelli (2008).

A third issue that may very well also be related is the peculiar abundance pattern of Jupiter (Owen et al. 1999).

In the following sections of this Letter I discuss, in turn, the likely initial conditions for the collapse of the solar nebula (Section 2), the resulting structure and early evolution of the Sun (Section 3), and the conclusions one can draw with respect to the solar and solar twin abundances on the background of the previous sections (Section 4). Finally (Section 5) I discuss the abundance pattern of Jupiter in the light of the previous conclusions. The final Section summarizes the discussions and presents the overall conclusions in compact form.

2. INITIAL CONDITIONS FOR SOLAR COLLAPSE

A lot of experience has been accumulated over the last few years concerning the conditions under which stars form in turbulent molecular clouds. Numerical simulations have been performed with both soft particle hydrodynamics methods (e.g. Klessen et al. 2005; Bate 2003) and grid methods (e.g. Li et al. 2004; Padoan et al. 2007). A rather consistent picture has emerged, where it is understood that the spectrum of initial masses of stars — the initial mass function (IMF) — is the results of the interaction of turbulent fragmentation with self-gravity, where supersonic and super-Alfvénic turbulence chops up the medium into a state with a very intermittent mass distribution (Padoan & Nordlund 2002). A small fraction of the mass reaches, in localized regions, sufficiently high densities to become gravitationally unstable, and these regions then collapse to form stars.

In light of this highly dynamic picture of star formation one might well question if the assumption of the near hydrostatic Bonnor-Ebert (B-E) like initial state for solar collapse adopted by Wuchterl & Klessen (2001) is realistic. For reasons that
are best explained with reference to what can be gleaned from looking explicitly at how pre-stellar cores approach collapse in simulations aimed at understanding star formation rates \cite{Padoan2009}, it is apparent that B-E like initial states are indeed reasonable approximations.

The power law part of the IMF distribution is a power law exactly because essentially all local density maxima with that amount of mass reach densities large enough for collapse. In such cases the collapse typically starts well before all mass that will eventually converge has arrived; the collapse starts as soon as enough mass has arrived for the local region to become gravitationally unstable, and additional mass that arrives later on then just adds to an already established collapse.

The initial mass function starts to deviate significantly from the high mass power law asymptote at masses of around 1–2 solar masses, because some of these cores are unable to reach sufficient density for collapse. Indeed, the point where the IMF has a slope of -1, rather than a value close to the Salpeter power law slope of -1.35, is near one solar mass, in empirical as well as theoretical initial mass functions \cite{Padoan2002,Chabrier2003}. A slope of -1 corresponds to a maximum in the contribution per unit logarithmic mass interval from the IMF, so in this sense the Sun is a ‘typical star’: parcels of gas in star forming regions are more likely to end up in solar-like stars than in more massive or less massive stars.

Irrespective of the differences in fractions of cores that collapse, and in how early or late the collapse commences, the situations just before the collapse are quite similar; mass is accumulating, with a density maximum at some point in space, with nearby motions on the average converging relative to the density maximum, thus systematically adding to the mass of the growing core. Eventually the core reaches a point in time where it becomes gravitationally unstable, but just before that point in time it is a near-isothermal structure, close to hydrostatic equilibrium, with self-gravity balanced by gas (and magnetic) pressure \cite{Ballesteros2007}. Such structures are necessarily similar to — while not identical to — B-E spheres \cite{Bonnor1958}. Indeed, the similarity in structure between pre-stellar cores and BE-spheres is well established observationally \cite{Baecmann2000}.

The choice by \cite{Wuchterl2003} to take BE-spheres as initial conditions for models of stellar collapse is thus very well motivated, and even though the detailed structure of pre-stellar cores — in particular in the outer parts — may deviate somewhat from BE-spheres, the inner and denser parts are likely to be well approximated by BE-spheres.

The assumption of one-dimensional accretion made by \cite{Wuchterl2001} and \cite{Wuchterl2003} is a weakness. The importance of this weakness is hard to estimate at the current time, since there are no 2-D or 3-D simulation that also include an accurate representation of the central star. Most works that study the collapse of pre-stellar cores in two- or three-dimensional focus on the question of fragmentation, and do not attempt to study the interior structure of the resulting star. The recent 2-D model by \cite{Tscharnnute2009} gives some hints, in that it shows that a major part of the stellar mass rather quickly ends up in the stellar embryo, after being processed in a relatively thick accretion structure that surrounds the growing stellar embryo. This indicates that the accretion history and thermal evolution of the stellar embryo may turn out not to be that different when the full three-dimensional structure is included.

3. STRUCTURE OF THE EARLY SUN

While many earlier models of the collapse of pre-stellar cores to stellar densities have been presented \cite{Wuchterl2001} and \cite{Wuchterl2003} appear to be the first to adopt a realistic initial structure, and the first who have attempted to predict the accretion history characteristic of the collapse of a solar mass core to stellar densities, rather than just adopt some ad hoc accretion rate prescription.

Subsequently \cite{Froebrich2006} have gone a step further, predicting the typical distribution of luminosity and effective temperature of Class 0 and Class I sources in star forming regions by using accretion statistics derived from simulations of gravo-turbulent star formation in molecular clouds. The results are encouraging and provide much better fits to observed distributions than models that assume parameterized, constant accretion rates. Similar efforts have been undertaken by \cite{Baraffe2009}.

One of the most striking and significant differences between the \cite{Wuchterl2001} models and other models of the early Sun is the internal structure. While earlier models predict an extended period of time where the early Sun is fully convective, the \cite{Wuchterl2001} and \cite{Wuchterl2003} models start out being essentially homologous to the present Sun with, according to \cite{Wuchterl2003}, a convection zone depth of only about one third of the radius.

This result has profound consequences for the interpretation of the abundance pattern differences between the Sun and the solar twins, as well as for the possible interpretation of the solar abundance problem in terms of an abundance difference between the solar CZ and the solar interior \cite{Haxton2008}. It would thus be of great importance to have independent confirmation and / or a more detailed analysis of the reasons for these fundamental differences in internal structure. For now, we take the results at face value, and go on to discuss the implications.

4. THE SUN / SOLAR TWINS ABUNDANCE DIFFERENCES

The abundance difference pattern between the Sun and most of the solar twins reported by \cite{Melendez2009} and \cite{Ramirez2009} is intriguing and invites a search for an explanation. \cite{Melendez2009} systematically examine several possibilities — galactic evolution, supernova pollution, and early dust separation — but they conclude that none of them offer a compelling route to an explanation, and instead they settle for element separation processes related to planet formation as the most likely explanation. In short, the hypothesis is that the abundance difference pattern between the Sun and most of the solar twins could find an explanation in the more efficient ‘lock-up’ of refractories in planets, as compared to volatiles.

The one major difficulty that \cite{Melendez2009} find with this explanation is that, given the traditional models where the early Sun was fully convective \cite{DAntona1994}, one would have to place the separation processes at such a late time that it would require an unusually prolonged dissipation time for the protoplanetary disk in the solar system. However, according to the discussion above, when taking the results of \cite{Wuchterl2001} and \cite{Wuchterl2003} into account, the assumption of a delayed evolution of the solar system is no longer needed.
4.1. Heavy elements in the planets and in the solar CZ

With the problem of full mixing no longer on the table it is certainly worthwhile to continue to examine the possibility that the elements locked up in planets have left an observable imprint on solar abundances. Indeed, with even just a reasonably shallow convection zone in the early Sun, the situation is turned completely up-side-down, in that — as illustrated by the following discussion — it would then be surprising to not find such an effect.

The mass budgets are as follows: The currently favored total heavy element contents of Jupiter and Saturn are approximately 35 and 23 Earth masses, respectively (Saumon & Guillot 2004). The major reservoirs of hydrogen in the ice giants Uranus and Neptune are probably their contents of water and ammonia, which means that by mass the hydrogen content is rather negligible. The helium content is harder to estimate, but helium is never mentioned as a major constituent candidate of the ice giants, so a reasonable estimate of the total mass of heavy elements in the planets lands around 80 Earth masses (figures from 50 to 90 are mentioned in the literature).

On the other hand the total mass of heavy elements in the current solar convection zone is, assuming $Z=0.012$ (Asplund 2005) and $M_{\text{CZ}} = 0.025M_\odot$, approximately 100 Earth masses. With similar amounts of heavy elements locked up in planets, the only possibility to not see an effect in solar convection zone abundances would be either 1) if the Sun was, after all, fully convective (or nearly so) at the time of element separation by the planets and accretion of the remnant gas, or 2) if the hydrogen that corresponded to the heavy elements was more or less completely ejected from the solar system. The first possibility requires that a major mistake exists in the works of Wuchterl & Klessen (2001) and Wuchterl & Tscharnuter (2003). The possibility to eject large amounts of primordial gas from the solar system through intense external illumination has been examined by Adams et al. (2006), who find that it is unlikely with typical cluster conditions that such an effect penetrates inside radii of about 30 AU.

We thus conclude that the heavy elements locked up in the planets are very likely to have caused a significant abundance difference between the solar convection zone and the solar interior, and since the existence of such a difference could explain the apparent inconsistency between the observed photospheric solar abundances and the solar interior ones deduced from helioseismology, a hypothesis that such an abundance difference actually exists and is the main cause of the solar abundance problem indeed is a very attractive one, as advocated also by Haxton & Serenelli (2008).

4.2. The Sun / solar twins abundance difference pattern

As per the discussion above it appears quite likely that the heavy elements locked up in planets have left an imprint even on the total abundances of heavy elements in the solar photosphere and convection zone. But if that is the case, we certainly should also expect to see differential effects, since it is quite unlikely that all elements heavier than helium are present in solar proportions in the planets.

The rocky planets are of course an illustration of this point, since they are heavily overabundant in refractories relative to volatiles. The fact that meteorites (and hence asteroids) show a differential abundance pattern very similar to the Sun / solar twin pattern (Alexander et al. 2001) is tantalizing as well, even though asteroids represent a totally ignorable fraction of the solar system mass.

The situation with respect to refractories and volatiles in the giant planets is not known empirically, and in principle the differential effect of the rocky planets could be neutralized by (or at least drowned in) the much larger contributions from the giant planets. It appears unlikely, however, that this is the case, given for example the apparently diverse conditions under which the gas and ice giant planets formed. So, from a consideration of the rather special circumstances that would be required to not have a differential effect due the lock-up of heavy elements in planets, the presence of differential effects between volatiles and refractories is not surprising.

Against this background the occurrence of relative abundance differences between the Sun and solar twins is also not surprising by itself, since the lock-up of heavy elements in planets would otherwise have to be very nearly the same in the solar twins and in the Sun, to keep the differential effects below the limits set by the abundance accuracies reached by Melendez et al. (2009) and Ramirez et al. (2009). The hypothesis advocated by Melendez et al. (2009), that the abundance differences are somehow related to the occurrence of planets, thus indeed seems very attractive.

It is difficult to judge from the relatively small number of cases investigated until now if the differential abundance pattern is likely to be one between on the one hand systems like the Sun (there are 2-3 such systems in the 11 star sample used by Melendez et al. 2009) and systems without planets, or if it is one between systems that all have planets, but with differences in the profiles of volatile and refractory element depletions. Melendez et al. (2009) attempt to elucidate this question by comparing solar analogues with and without known planets, but find the initially surprising result that it is the solar analogues that do not have known planets that are more similar to the Sun, while the ones that are known to have planets are more similar to the majority of the solar twins. Such a result can easily be explained, however, if the (rather different) close-in gas giants typical of currently detected exo-planets have a relatively more ‘flat’ profile of volatile to refractory element abundances. As with the solar twins, a pattern similar to the Sun may be taken to signal the presence of, as-of-yet undetected, more solar system like planets.

Even though other conclusions cannot be excluded, it appears likely that the observed abundance difference pattern, with its clear dependence on the condensation temperature of particularly the refractory elements, is in fact characteristic of the Sun’s heavy element depletion due to the planets. If this is indeed the case it is quite remarkable, in that the refractory over-abundance pattern that is known to apply to just a very small fraction of the solar system mass — the meteorites and hence the asteroids — would then actually apply in essentially the same form to the whole collection of planets.

5. THE JUPITER ABUNDANCE PROBLEM

Jupiter has an abundance pattern that is from one point of view very peculiar. Jupiter is the only planet in the solar system where hydrogen is the most common chemical element (by number), and in that respect Jupiter is more akin to the Sun than the other planets. However, relative to the Sun Jupiter is still overabundant in heavy elements. In fact, a number of chemically very diverse elements are overabundant with respect to the Sun by about the same factor of three. These elements include the volatile elements carbon, nitrogen and sulphur, but also several of the inert gases; e.g., argon,
krypton and xenon (Owen et al. 1999). While a number of other chemical elements (such as oxygen among the volatiles and helium and neon among the inert gases) deviate from the pattern, these deviations may well be due to specific interior processes in Jupiter, as discussed by Owen et al. (1999).

The fact that several rare and inert gases are enhanced by essentially the same factor as some of the most common volatile elements is indeed a curious circumstance, which is hard to explain in terms of enrichment of Jupiter’s atmosphere by accretion and capture of planetesimals, in that it is very difficult to bind inert gases efficiently to planetesimals. But, lacking a better explanation (Owen et al. 1999) nevertheless conclude that "It seems to us that the only explanation ... is that these elements came to the planet in very cold (T < 30 K) icy planetesimals", and a number of subsequent and related papers have gone to great length to explain that such bindings are possible via ‘clathration’ at very low temperatures.

However, this entire line of explanations has a severe problem, irrespective of how likely (or not) one finds a construction where inert gases are bound to icy planetesimals at temperatures that probably occurred in the early solar system only at very large distances from the Sun. Even if the process is in principle possible, it would have been totally unrelated to the processes that are assumed to have enhanced the much more common elements. Given that the processes are independent, it would be a coincidence of some proportions to have these processes produce virtually the same overabundance (it may be unlikely even to have a population of more ordinary planetesimals produce the same overabundance of carbon, nitrogen and sulphur).

On the other hand, in the context of a discussion where lock-up of elements in planets appears to be an attractive possibility, another and much simpler explanation offers itself: Jupiter’s abundance pattern would be a natural outcome of a situation where about 2/3 of the hydrogen that initially ‘belonged to’ Jupiter’s heavy elements was lost into the Sun and never settled into Jupiter. Rather than regarding Jupiter’s abundance pattern as the result of an enhancement of several heavy elements, one could also see it as the result of a depletion of a single element; hydrogen. Since all other planets are depleted in hydrogen to a much more complete extent, such an explanation seems a priori not at all unlikely. A similar explanation has been advanced by Guillot & Hueso (2006).

6. CONCLUSIONS

The newly discovered abundance pattern differences between the Sun and stars (solar twins) that are in other respects virtually identical to the Sun (Melendez et al. 2009, Ramirez et al. 2009) can possibly be understood as an imprint on the abundances of the solar convection zone by the lock-up of heavy elements in the planets. Models of the formation of the Sun that start out from pre-stellar core structures similar to those actually observed result in early solar structures that are not fully convective (Wuchterl & Klessen 2001, Wuchterl & Tscharnuter 2003), and this removes the need for peculiar assumptions such as delayed formation of the solar planets. The credence of such a line of explanations is further strengthened by the possibility to explain two other abundance related problems; 1) the apparent discrepancy between increasingly accurate photospheric abundance determinations (Asplund et al. 2009), and 2) the apparent overabundance of a number of chemically very different element in Jupiters atmosphere, which can instead be interpreted as an under-abundance of hydrogen, presumably stemming from the very same process that, in the case of the other planets, was able to separate hydrogen even more efficiently from the heavier elements.

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