Abstract. The solar interior has been scrutinized by two different and independent probes during the last twenty years with important revisions of the solar model, including a recent heavy element abundance revision. Today, we get a quantitatively coherent picture (even incomplete) of the solar (stellar) radiative zones. In this review, we recall the clues for solar gravitational settling definitively established by the seismic determination of the photospheric helium content. We comment also on the need for mixing in the transition region between radiation and convection in the case of the Sun and of population II stars. We finally list the open questions and the importance to continue more precise investigations of the solar (stellar) radiative zone in detecting gravity modes with the project DynaMICS.

1 Introduction

Gravitational settling of elements is a natural phenomenon in stars of long lifetime and is stimulated by abundance anomalies in very different stages of stellar evolution. It is also a very difficult ingredient to introduce in stellar modelling due to the very slow velocity of this process. In fact, it competes with turbulence and radiative pressure and the corresponding diffusivity coefficient is of the order of $10 \text{ cm}^2\text{s}^{-1}$ when the turbulent diffusivity could be locally $10^4$ greater. Figure 1 of Brun, Turck-Chièze and Zahn (1999) shows a comparison between the different orders of magnitude of the diffusivity coefficients in the transition region between the two regimes of energy transport: radiation and convection, called the tachocline (Kosovichev et al. 1997). Consequently, one needs to perform a very detailed calculation including a proper description of the ionized state of the different elements to estimate the final movements which result from the competing processes. G. Michaud and his collaborators (Proffitt & Michaud 1991, Michaud
Knowing this great challenge and investigate the problem with impressive success along years. Their calculations remain the references and most of the solar modelers use the simplified version of their detailed calculations (Michaud & Proffitt 1993) to introduce the gravitational settling of elements in their computations.

The difficulty to take the different processes properly into account pushes to find one or two cases where the result could be confronted to detailed observations and not only to only photospheric observations. In fact, the solar seismic investigation has represented a unique case to check the effect of such phenomenon and its richness largely compensates for the smallness of the expected effect.

In this review, we first recall how the seismic probe has imposed the need for microscopic diffusion in solar-like stars. Then we show the coherence of the two solar probes: acoustic modes and neutrinos and the present status of solar modelling, including new results on the CNO and neon abundances. Mixing probably partly inhibits this phenomenon and examples are given for the Sun and population II stars. We finally focus on the new space project DynaMICS which will investigate the solar radiative zone in more details to better constrain the slow and dynamical phenomena of this important region of stars.

2 The interest of gravitational settling of elements in the Sun

It has always appeared clear that gravitational settling must be a small effect in the Sun. So large photospheric anomalies are not expected in this case. Nevertheless, twenty years ago, standard solar models were burning about a factor 100 less lithium than observed and such anomalies were considered as a manifestation of something missing in stellar evolution. At the end of the eighties, helioseismology has known a strong development and represented a promise for a more dynamical picture of stars, extremely useful for very young stars, the ultimate stages of stellar evolution and the Sun-Earth relationship. The first step was the derivation of the thermodynamical properties of the internal Sun through the extraction of the sound speed profile. Two main characteristics have been extracted from ground acoustic mode measurements:

- the adiabatic exponent in the region where hydrogen and helium are partly ionized (above 0.95 \( R_\odot \)). It is possible to determine the photospheric helium abundance in adjusting the theoretical value to the observed \( \Gamma \). Vorontsov, Baturin & Pamyatnykh (1991) were the first to deduce a value of 0.25 ± 0.01 for the photospheric helium, much smaller than the value of about 0.27 deduced for standard model when the initial helium value is conserved in the convective zone. Such nearly primordial helium photospheric value, rapidly confirmed by Basu & Antia (1995), favors the idea that the present helium photospheric value is different from the initial one by more than 10-12% and that the gravitational settling acts in the Sun for explaining these two values.

- the limit of the base of the convective zone which has appeared lower than the one predicted by standard model at that time: 0.713 ± \( R_\odot \) instead of 0.73
Table 1. Time dependence of the boron neutrino prediction, central temperature and initial helium with updated physics.

| Year | Predicted Flux | Central Temperature | Initial Helium | Physics Notes |
|------|----------------|---------------------|----------------|---------------|
| 1988 | 3.8 ± 1.1      | 15.6                | 0.276          | CNO opacity, \(^7\text{Be}(p, \gamma)\) T-C,1988 |
| 1993 | 4.4 ± 1.1      | 15.43               | 0.271          | Fe opacity, screening T-C93b, Dzitko95 |
| 1998 | 4.82           | 15.67               | 0.273          | Microscopic diffusion C-D93, Brun98 |
| 1999 | 4.82           | 15.71               | 0.272          | Turbulence in tachocline Brun, 1999 |
| 2001 | 4.98 ± 0.73    | 15.74               | 0.276          | Seismic model (SM) T-C, 2001 |
| 2003 | 5.07 ± 0.76    | 15.75               | 0.277          | SM + magnetic field Couvidat, 2003 |
| 2004 | 3.98           | 15.54               | 0.262          | - 30% of CNO T-C, 2004 |
| 2004 | 5.31 ± 0.6     | 15.75               | 0.277          | SM + updated T-C, 2004 |
| 2005 | 5.17           | 15.52               | 0.273          | StM (Ne + 0.5 dex) this work |
| SNO  | 5.44 ± 0.99 (CC+ES 2001) | 5.09 ± 0.63 (NC 2002) | 5.27 ± 0.46 (2003) |

This point was favoring also the introduction of gravitational settling.

The SoHO observations of the rotation profile (Kosovichev et al 1997) and the lithium problem has led us to introduce not only the microscopic diffusion but also a turbulent term to take into account the shear of the layers at the base of the convective zone with enhanced horizontal motions which slightly inhibit the slow gravitational settling of elements by about 10%. Introducing the two processes, and some reasonable characteristics of the time dependence of the tachocline along the main sequence, have led us to demonstrate that most of the photospheric abundances (including lithium and beryllium) were understood in the solar case (Brun, Turck-Chieze & Zahn 1999). The profiles of the sound speed obtained by helioseismic measurements and the one deduced from solar models without and with microscopic diffusion showed the progress done in introducing the gravitational settling and turbulence to reproduce solar observables.

### 3 The coherence between helioseismology & neutrinos

The solar neutrino puzzle has been considered as a persistent problem for decades up to the recent detection with SNO of all the different species of neutrinos (Ahmed et al., 2004). During that period, the helioseismic probe has allowed an independent approach to the solar core which has stimulated extensive efforts in Astrophysics and a lot of improvements in the calculation of predicted neutrino fluxes (Turck-Chieze et al. 1993). Table 1 summarizes the time evolution of the predicted boron 8 neutrino flux (the most sensitive to the central temperature), corresponding to different updated of the solar models. Most of the models are standard model (StM), the most recent are seismic models (SM) which are models in total agreement with the observed sound speed profile of Turck-Chieze (2001). One has noticed that the most recent standard model including the updated photospheric composition of Asplund et al. (2005) disagrees with helioseismic profile and neutrino detections (Turck-Chieze et al., 2004). They take into account 3D
calculation of the atmosphere and deduce a reduction of 30% in CNO abundance. On the contrary the seismic model predicts neutrinos in excellent agreement with the detected values for all the experiments. But very recently after the update in composition, Antia and Basu (2005) have noticed that the observed sound speed difference clearly shown on Figure 1 could be highly reduced by modifying only the neon abundance. Figure 2 shows several heavy element contributors to the opacity in the radiative zone for the old composition (Grevesse & Noels 1993) and for the new one (Asplund et al. 2005). In fact by increasing only this element by 0.5 dex, one reconciles once more the two probes: acoustic modes and neutrinos (Table 1 and Figure 1). So one could notice that there is an excellent coherence between the two solar probes even some uncertainty persists on the composition or on some dynamical effect in the solar radiative zone.

4 The dynamics of the solar radiative zone and population II stars

In fact, it is not so easy to accept a neon composition problem as a lot of measurements of this element in solar X-ray flares, γ ray lines, or EUV regions or HII hot stars agree so a factor 1.5-2 error at the photosphere is difficult to suspect. Figure 8 of Meyer (1993) summarizes the situation. But recently Drake and
Testa (2005) show higher values in some specific more active stars. So the problem stays open and encourages further investigations on opacity measurements or neon reestimate. Independently, we have more and more indications of the complexity of the radiative zone, first the rigid rotation (Couvidat et al. 2003) supposes an angular momentum release by gravity modes or magnetic field. MHD calculations are developing nowadays to better understand how the kinetic energy is redistributed in the different motions: meridional circulation, differential rotation, magnetic energy... A lot of questions stay open on the stability of the magnetic configurations or the connection between different internal magnetic fields. It is not totally clear: 1) if the core rotation is quicker than the rotation of the rest of the radiative zone as suggested by the 2 gravity mode candidates detected with the GOLF instrument (Turck-Chieze et al. 2004) 2) and if there is a measurable effect of a relic magnetic field.

we are preparing a new space velocity Doppler instrument to detect some gravity modes which are the keys to answer to the preceding questions and to predict the variability of the solar activity on mean and long terms. The project DynaMICS (Turck-Chièze et al, 2005) is an European effort in discussion with CNES for a microsatellite mission.

It is evidently useful to pursue our search for microscopic and macroscopic manifestation in solar-like stars with lithium as the unique tool. Classical models of young stars lead to a too large depletion of lithium (Piau and Turck-Chièze 2002). In this case microscopic diffusion cannot act in this too rapid sequence and their modeling is probably more complex, magnetic field needs probably to be introduced to better describe the extension of the radiative zone. Population II stars are certainly extremely interesting to study as in this case there is no destruction in early stage, it seems that in this case the association of microscopic diffusion and turbulence are necessary to explain the data (Richard et al. 2004). Piau (2005) shows very promising results in treating simultaneously the gravitational settling of elements and the partial inhibition of this process by the presence of a tachocline in these stars.
In conclusion, the process explored by Georges Michaud and his collaborators a long time ago is remarkably verified in the solar case, despite different reestimate of the solar abundances and the present new puzzling situation. The idea to complete such a process by turbulence in the transition region between radiation and convection is largely supported by the seismic solar observations and the interpretation of the "Split Plateau" in population II stars. Such processes need more and more sophisticated estimate of the partial ionisation and of the magnetic perturbation due to the plasma motion (Alecian and Stift, 2004).

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