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Mixing in the Solar Tachocline

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Abstract. We conduct numerical simulations of updated solar models including a physical treatment of the tachocline [1], the rotational transition layer localized at the base of the solar convection zone. We first describe what is the current understanding of this thin shear layer. We then show that we improve substantially the agreement between the models and the observed Sun by taking into account the macroscopic mixing occuring within this region.

1. Introduction

The presence of a shear layer connecting the differential rotation of the convective zone (CZ) to the solid rotation of the radiative zone is now well established by helioseismic inversions ([2]). Both its location at $0.691 \pm 0.004\ R_\odot$ and its width of less than $0.05\ R_\odot$ are well constrained. There are several hydrodynamical or MHD descriptions of this shear layer and its extension but none is definitive. In these models the motions in the tachocline are either turbulent or laminar, involve magnetic fields or are purely hydrodynamical (see [3] and references therein). This layer is also presumably the region where the solar global dynamo takes place, making its complete description rather difficult. In our models, we have been using the description of Speigel and Zahn [1] in order to characterize the motions present in the tachocline and thus the amount of mixing. We first recall how we build solar models including a macroscopic diffusivity D_T. Then we com! pare our results to the most recent helioseismic data and surface abundance observations for ^{7}Li and ^{9}Be.

2. Implementing macroscopic mixing in solar models

Macroscopic mixing may be treated in solar models by adding an effective diffusivity D_T in the equation for the time evolution of the concentration of chemical species. To establish this coefficient for the tachocline, we use the description by Spiegel and Zahn [1] where anisotropic turbulence is responsible for stopping the spread of the layer. This anisotropic diffusion will also interfere with the advective transport of chemicals [4]. Using these results, Brun, Turck-Chièze and Zahn [5] have derived an expression for the macroscopic diffusivity D_T, taking into account the differential rotation profile and the tachocline thickness h:

$$D_T \propto \nu_H (h/r_{bcz})^2 (\hat{\Omega}/\Omega)^2,$$

where, ν_H is the horizontal effective viscosity, r_{bcz} the radius at the base of the convective zone (BCZ) and $\hat{\Omega}/\Omega$ the solar differential rotation of the CZ. In our solar models, we treat h as an adjustable parameter, chosen to agree with the helioseismic determination of the tachocline thickness $h \leq 0.05R_\odot$ [2].

3. Results: sound speed and abundance of light elements

Starting from the reference model of Brun, Turck-Chièze and Zahn [5] built with the CESAM code [7], we introduce our coefficient D_T in the diffusion equation of chemical species, and we follow the time evolution of the solar model from the pre-main sequence (PMS) until 4.6 Gyr.In Figures 1 and 2 (see Ref. [5] for a more detailed discussion), we compare the results of our reference model (which has only microscopic diffusion) with one (namely B_{tz}) which includes the macroscopic mixing in the tachocline as explained above, taking into account its variation in time as the Sun is spun down [6]).

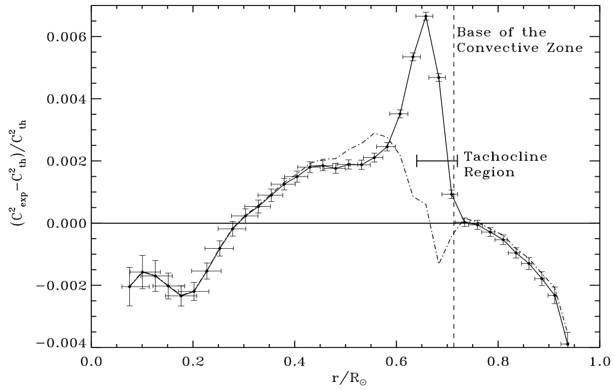

Figure 1. Squared sound speed difference between GOLF+MDI data (error bars) and the reference model (*solid curve*) and model B_{tz} that incorporates time dependent macroscopic mixing in the tachocline region (*dash dot*). Also shown are the tachocline extention and the BCZ (*vertical dashed line*).

As expected, with macroscopic mixing the composition profile below the convective zone is smoother and it flattens over the depth of the tachocline. Since there is less settling of helium, its photospheric abundance $^4\mathrm{He}_s = 0.2473$ is slightly higher, in better agreement with the helioseismic determined value. This indicates that the purely microscopic diffusive model is overestimating the effect of gravitational settling on chemical species during the Sun's evolution.

The effect on the sound speed is displayed in Figure 1. When the macroscopic transport is neglected (*solid curved with error bars*), the squared sound speed difference reveals a peak just below the CZ, coinciding with the tachocline. Macroscopic diffusion acts to reduce this peak, but when one recalibrates the model to yield the present abundance of heavy elements ($Z/X = 0.0245 \pm 0.002$), the effect is rather minor. On the other hand, if the heavy elements are left free to adjust within the observational uncertainties, the peak is completley removed, leaving only a broad bump positioned at 0.6 $R_\odot$, which presumably is due to another cause (*dash dotted curve*).

The two light elements ^{7}Li and ^{9}Be are extremely sensitive to mixing processes occuring in stars because their nuclear burning temperatures are rather low (respectively 2.5 10^6 and 3.2 10^6 K). The new observational constraints can only be satisfied if those chemical species are mixed in a rather thin layer below the CZ in order to preserve ^{9}Be, which is very little depleted according to Balachandran and Bell [8]. This is the case with our tachocline model, which extends only 5% below the base of the convective zone.

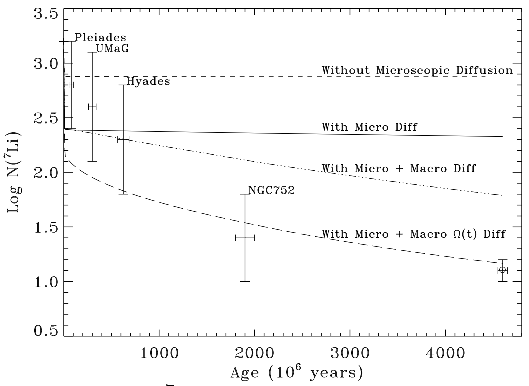

Figure 2. Depletion of ^{7}Li versus evolution time for several solar models: no microscopic diffusion (*dash*), with microscopic diffusion (*solid curve*) and with mixing within the tachocline: no time dependence (*dash three dots*), and with a time dependence (i.e model B_{tz}, with initial heavy element abundance $Z_0 = Z_0^{ref} = 0.01959$) (*long dash*). We superimposed on the theoretical curves the open cluster observations (see [5] and references therein).

In Figure 2 we show the resulting lithium depletion occurring during the Sun's evolution for different models, including one without any diffusive processes. Clearly only the diffusive models including macroscopic mixing in the tachocline yield a substantial depletion during main sequence evolution, in agreement with the observations (superimposed with their inherent dispersion on the theoretical curves). But it is important to note that the thickness of the tachocline and the strength of mixing have been larger in the past (see [5]), when the Sun was rotating faster. When this time dependence is included in the models (as in model B_{tz}), the lithium is burned more effectively and the models present a reasonable value of the solar ^{7}Li depletion (~ 100). However, the lithium depletion during PMS is probably overestimated due to the crude spin-down law we have adopted; we have also neglected the influence of the possibly strong magnetic field present in the early phases of the Sun.

In conclusion, our results show that it is important to assess the evolution of the photospheric abundance of the three elements ^{4}He, ^{7}Li, ^{9}Be, and to examine their sensitivity to microscopic as well as macroscopic processes. This study encourages the introduction of macroscopic processes in stellar evolution models, and demonstrates the crucial role of the thin tachocline layer below the CZ.

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