THE SOLAR TACHOCLINE: WHERE DO WE STAND?

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ABSTRACT

This paper reviews some of the basic features of the tachocline of shear present at the base of the solar convective zone. We discuss some aspects of its dynamics and evaluate processes capable of stopping the spread of the shear deeper into the radiative interior. By taking into account the macroscopic mixing occuring within this thin layer, we can improve substantially the agreement between recent 1–D solar models and quantities inferred from observing the Sun, such as the radial sound speed profile or the photospheric abundances of light elements.

1. INTRODUCTION

The rotation profile exhibited by the Sun throughout its interior (Schou et al. 1998) is still puzzling theoretician even after many years of sustained effort. There are still several unanswered questions: Why does the solar core rotate so slowly (approximately at the rate of the mid-latitude external layers)? Why does the outer differential rotation of the convective zone doesn't exhibit cylindrical like rotation? Why does the transition between the differentially rotating convective zone and the almost uniformly rotating radiative interior, the tachocline, is so the thin? It is not our intention to address here all these difficult questions but rather to discuss some aspects of the properties of the tachocline and how they are related to the global dynamics and evolution of the Sun (see Brun & Toomre 2000 for a discussion on the solar differential rotation problem). The main reason for our interest in the tachocline is that in this thin region several important processes for the global dynamics and activity cycles of the Sun take place and interact:

- the solar dynamo is supposely taking place within this layer and the creation and storage of toroidal magnetic field depends on its thickness and radial shear profile
- the turbulent beating of the convective downflows (plumes) on the stable layer establish an overshoot region and produces gravity waves
- it is mainly located where the change of mode of transport of energy from convection to radiation occurs
- its proximity to the thermonuclear burning zone of lithium ^{7}Li and beryllium ^{9}Be influence their photospheric composition due to the extra macroscopic mixing it produces

Therefore understanding the role played by the tachocline on the solar structure and dynamic is really important, if one want to progress in our knowledge of the Sun. The characteristic of the tachocline are now well established by helioseismic inversions (Corbard et al. 1999) and one could also have an idea from up to date standard solar models of the thermodynamical properties of this layer (see Table 1).

Table 1. Solar Tachocline Parameters

location	$0.691 \pm 0.004\ R_\odot$
width	$< 0.05 R_\odot$
ρ range	$\sim$0.16-0.32 g/cm^3
T range	$\sim$2.0-2.8 10^6 K

Let us now review the basic physical principles governing this transition layer. The presence of latitudinal differential rotation at the base of the convection zone induces a latitudinal temperature gradient, $\Omega(\theta) \rightarrow \nabla T(\theta)$. Without any limiting process this temperature gradient will diffuse inwards on a thermal diffusion time scale, enforcing differential rotation deep into the radiative interior of the Sun. Yet helioseismic observations indicate a uniform rotation profile in the radiation zone.

So we have to invoke a process to hinder the spread of the tachocline deeper down in the radiative interior. There are several possibilities: the stable stratification of radiative zone, the presence of a μ gradient created by microscopic diffusion, an anisotropic turbulence and magnetic fields. The first effect, the stable stratification of the radiative zone, would indeed slow down the spread of the tachocline (changing the thermal diffusion (2^{nd} order spatial derivative) to a hyper diffusion (4^{th}

order)) but in spite of that, the layer would still extend to one-third of the radius in the present Sun as estimated by Spiegel and Zahn (1992, or SZ92), which is far too deep. We are thus left with three processes. The presence of a gradient of composition is often used to damp instabilities in the radiative interior of the Sun (Vauclair 1999). Unfortunately SZ92 have shown that instead of stopping the spread, the presence of a μ-gradient as built up at the base of the convection by the Sun during its evolution due to gravitational settling of chemical elements, will increase it leading to an even thicker tachocline. So we are left with just two processes to yield a narrow tachocline: namely magnetic fields or anisotropic turbulence.

Presently, several hydrodynamical or MHD model of this shear layer and its extent have been proposed using either of the last two processes. We can try to classified them in two categories, slow or fast motions tachocline:

In the first category, i.e slow tachocline, there are mainly two models which have been worked out in some details to explain the thiness of the tachocline: SZ92 using anisotropic turbulence and Gough & McIntyre (1998) using a weak secular magnetic field.

We know that the model of tachocline developped by SZ92 is giving satisfaying results on the extent of this layer thus confirming that an anisotropic turbulence could stop the diffusion of the tachocline deeper down. Since the publication of this work there have been a lot of comments on the validity of their asumptions regarding the instability of the solar latitudinal differential rotation and on the resulting angular momentum transport properties of such an instability. Arguments were given in favor of a linearly stable solar differential rotation if no magnetic fields were present to destabilized the layer (Charbonneau, Dikpati & Gilman 1999) or as in Gough & McIntyre (1998) that the angular momentum transport via anisotropic turbulence will lead to an increase rather than to a decrease of the differential rotation within the tachocline. However a more recent study by Dipkati & Gilman (2000), using a shallow water model to include the radial dependence of the tachocline (Pedloski 1990), have shown that the solar differential rotation profile could be instable to linear shear instabilities even without magnetic field, thus confirming the possibility to invoke anisotropic horizontal turbulence (due to the radial stiffness of the radiative zone) to hinder the spread of the tachocline. Also we would like here to note that most of the work done on the stability of the solar differential rotation profile have been through linear perturbation analysis. But as already shown by Richard & Zahn (1999), using results from a Couette-Taylor experiment, the intense level of turbulence present in the Sun is likely to make the latitudinal rotation profile instable to non-linear shear perturbations and thus is even more likely to generate an anisotropic horizontal turbulence which will act to reduce the latitudinal differential rotation and to stop the spread of the tachocline deeper down. So in regards of these new studies we could still consider SZ92 has a valid first order model of the tachocline. Perhaps the fact that SZ92 didn't take into account the action of magnetic fields assuming that the hydrodynamical anisotropic turbulence will dominate the dynamical influence of such fields is an unjustified hypothesis. This has not yet been verified and and need to be done. Finally in SZ92 the resulting meridional circulation due to the anisotropic turbulence present in the tachocline has an overturning time of the order of a million years. For this reason we call it a slow tachocline (see also Gilman 2000) and we will see in the next section what is the influence of such a macroscopic mixing on the solar phostospheric abundances.

In Gough & McIntyre model, the tachocline is confined close to the base of the convective zone due to the outward diffusion of a secular magnetic field balancing the inward thermal diffusion of the differential rotation. But no magnetic field is present within the tachocline itself. This result on a slow two cells structure meridional circulation within the tachocline with an overturning time of a million years. One positive aspect of this model is that it also propose a solution for the uniform rotation of the central part of the Sun using Ferraro's law of isorotation of the magnetic field (Cowling 1976). But their model is not clear on how they could avoid the secular magnetic field to shred through the tachocline at mid latitude where there is no opposing inward thermal diffusion (i.e convergence of the two cells circulation). Furthermore by excluding the presence of magnetic fields within the tachocline they omitted the action of any dynamo generated fields and the possible interaction of these fields with the central secular one.

We now turn on the second class of tachocline models, namely the fast tachocline ones. For this purpose we will briefly discuss the model developped by Gilman & Fox (1997) and subsequent works. In this model the tachocline is considered magnetized and the source of the anisotropic turbulence is a magnetic instability. The resulting meridional circulation has an overturning time of the order of months, which is substantially faster than the two previous circulation overturning time. However in this model only the latitude and longitude have been taking into account to describe the dynamics of the tachocline thus omitting its radial extent, which we think is an important aspect of this transition layer. In the recent shallow water model of Dipkati & Gilman (2000), the influence of the radial dimension has been introduced and has we already said earlier they indeed find new classes of instabilities even in the non magnetized case. They intend to develop soon a magnetic shallow water model of the tachocline. To conclude with this discussion on the properties of this transition layer, we think that it is still too early to decide whether or not it is turbulent, or if the magnetic field is frozen in it or acts only to oppose the inward diffusion.

We will now discuss recent 1–D solar models, using the description of Speigel and Zahn to characterize the motions present in the tachocline and their mixing properties. We first recall how we build solar models including a macroscopic diffusivity D_T. Then we compare our results to the most recent helioseismic data and surface abundance observations for ^{7}Li and ^{9}Be.

2. IMPLEMENTING TACHOCLINE 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 SZ92 where anisotropic turbulence serves to stop the spread of the layer. This anisotropic diffusion will also interfere with the advective transport of chemicals (Chaboyer & Zahn 1992). Using these results, Brun, Turck-Chièze and Zahn (1999) 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 and $\hat{\Omega}/\Omega$ the solar differential rotation of the convective zone. In our solar models, we treat h as an adjustable parameter, chosen to agree with the helioseismic determination of the tachocline thickness $h \leq 0.05 R_\odot$ (Corbard et al. 1999).

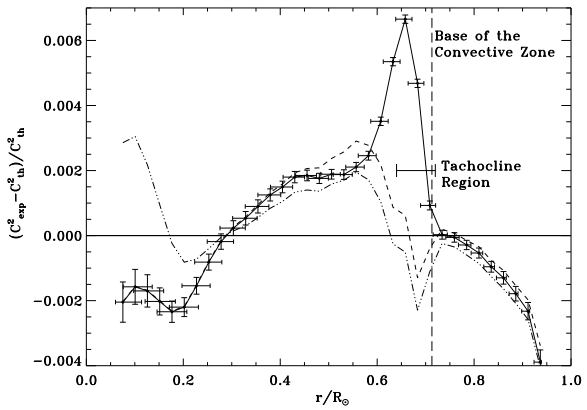

Figure 1. Squared sound speed difference between GOLF+MDI data (error bars) and the reference model (solid curve), model B_{tz} that incorporates time dependent macroscopic mixing in the tachocline region (dashed curve) and model B_{tpp} where the (pp) reaction rate S_{11} has been artificially increased by 5% (dash three dots curve). Also shown are the tachocline extent and the base of the convective zone (vertical long dashed line).

3. RESULTING SOUND SPEED PROFILE AND LIGHT ELEMENTS SURFACE ABUNDANCE

Starting from the reference model of Brun, Turck-Chièze and Zahn (1999, or BTZ99) built with the CESAM code, Morel (1997), we introduce our coefficient D_T in the diffusion equation of chemical species, and follow the time evolution of the solar model from the pre-main sequence (PMS) until 4.6 Gyr. In Figures 1 and 2 (see BTZ99 for a more detailed discussion), we compare the results of our reference model (which has only microscopic diffusion) with two models (namely B_{tz} and B_{tpp}) which includes the macroscopic mixing in the tachocline as explained above, taking into account its variation in time as the Sun is spun down, using Skumanich (1972).

As expected, with macroscopic mixing the composition profile below the convective zone is smoother and flatten over the depth of the tachocline. Since there is less settling of helium, its photospheric abundance $^4\mathrm{He}_s = 0.251$ 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 curve* with error bars), the squared sound speed difference reveals a peak just below the convective zone, 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 (if one does not change the opacities or the nuclear reaction rates for example). 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 (*dashed curve*). As well, if one increases the proton-proton (pp) nuclear reaction by less than 5% and allows for macroscopic mixing within the tachocline, the resulting sound speed profile (model B_{tpp}, *dash three dots curve*) is also in relative good agreement with the helioseismic inversion data at the base of the convective zone. Namely, the peak has disappeared, but the effect in the core indicated that an increase of 5% of S_{11} is exagerated. Therefore it is encouraging to see that by introducing macroscopic mixing in the tachocline and by varying the main microscopic processes within their theoretical and/or observational errors bars we could improve substantially the agrrement between the Sun and our models.

Another constraint come from the surface abundances of chemical species. 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

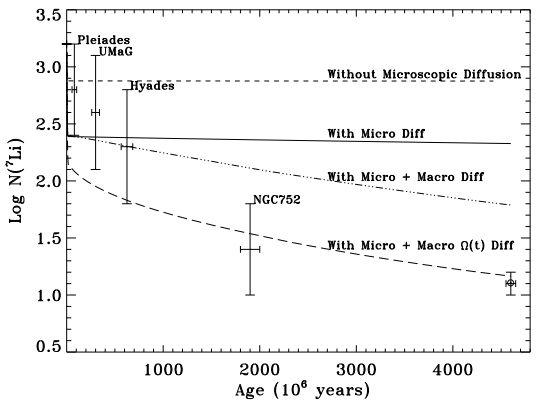

Figure 2. Depletion of ^7Li versus evolution time for several solar models: no microscopic diffusion (dash), with microscopic diffusion (solid curve) and with mixing within the tachocline: no time dependence (dash three dots), and with a time dependence (i.e model B_{tz}, with initial heavy element abundance $Z_0 = Z_0^{ref} = 0.01959$) (long dash). We superimpose on the theoretical curves the open cluster observations (see BTZ99 and references therein).

only be satisfied if those chemical species are mixed in a rather thin layer below the convective zone in order to preserve ^{9}Be, which is very little depleted according to Balachandran and Bell (1998). This is the case with our tachocline model, which extends only 5% below the base of the convective zone.

In Figure 2 we show the resulting lithium depletion occurring during the Sun's evolution with 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 error 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 BTZ99) 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 (see Piau & Turck-Chièze these proceedings for a detailed discussion on the PMS phases). 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 convective zone.

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