CONSISTENT SOLAR MODELS INCLUDING THE $^7$Li AND $^3$He CONSTRAINTS

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ABSTRACT

Improvements induced by helioseismology show that microscopic diffusion cannot be neglected in solar models. Helium and metal diffusion is now generally introduced in the computations. They cannot however explain the observed lithium depletion. Macroscopic motions are needed to bring up to the convection zone the nuclearly depleted matter. Such motions also lead to a better agreement between the sound velocity in the model and that deduced from the inversion of seismic modes. On the other hand, they must not bring up too much $^3$He, as we now know that the $^3$He/$^4$He ratio cannot have changed by more than 10 percent during these last 3 Gyr. Here we present new consistent solar models in which the $^3$He constraint is satisfied. The fact that $^3$He must remain constant while $^7$Li must be depleted leads to strong constraints on the effective macroscopic diffusion coefficient allowed below the solar convection zone.

Key words: Sun : abundances; helioseismology, diffusion processes

1. SETTLING AND MIXING

The importance of helium and heavy element settling inside the Sun is now widely recognized. Solar models computed in the old “standard” way, in which the element settling is totally neglected, do not agree with the inversion of the seismic modes. The discrepancy is much reduced when element settling is introduced. This result has been obtained by many authors, in different ways (see Gough et al. (1996) and references therein).

For the first time, Turcotte et al. (1998) have consistently computed the radiative accelerations on the elements included in the OPAL opacities. They have found that, contrary to current belief, the effect of radiation can, in some cases, be as large as $\approx 40\%$ that of gravity below the solar convective zone. This is important only for metals however, and not for helium. When the radiative accelerations are neglected, the abundances of most metals change by about $\approx 7.5\%$ if complete ionization is assumed below the convective zone, and by $\approx 8.5\%$ if detailed ionization rates are computed. When the radiative accelerations are introduced, with detailed ionization, the results lie in-between.

Although the introduction of pure element settling in the solar models considerably improve the consistency with the seismic Sun, some discrepancies do remain, particularly below the convective zone where a “spike” appears in the sound velocity (Guzik 1998, Turck-Chièze et al. 1998). It has been shown that this behavior may be due to the helium gradient which would be too strong in case of pure settling. Mild macroscopic motions below the convection zone slightly decrease this gradient and helps reducing the discrepancy (Richard et al. 1996 - RVCD, Corbard et al. 1998). The helium profiles directly obtained from helioseismology (Basu 1997, Antia and Chitre 1997) show indeed a helium gradient smoother than the gradient obtained with pure settling.

2. LIGHT ELEMENT ABUNDANCES

The abundance determinations in the solar photosphere show that lithium has been depleted by a factor of about 140 compared to the protosolar value while beryllium is generally believed to be depleted by a factor 2. These values have widely been used to constrain the solar models (e.g. RVCD). However, while the lithium depletion factor seems well established, the beryllium value is still being discussed. Balachandran and Bell (1998) argue that the beryllium depletion is not real because of insufficient inclusion of continuous opacity in the abundance determination. Their new treatment leads to a solar value identical to the meteoritic value.

Observations of the $^3$He/$^4$He ratio in the solar wind and in the lunar rocks (Geiss 1993, Gloecker and Geiss 1996, Geiss and Gloecker 1998) show that this ratio may not have increased by more than $\approx 10\%$ since 3 Gyr in the Sun, which is in contradiction with the results of RVCD.

While the occurrence of some mild mixing below the solar convection zone is needed to explain the lithium depletion and helps for the conciliation of the models with helioseismological constraints, the $^3$He/$^4$He observations put a strict constraint on its efficiency. The solar chemical composition appears as a powerful tool in order to produce consistent solar models.
In RVCD, a mild mixing below the convection zone, attributed to rotation-induced shears (Zahn 1992), was introduced. This mixing was supposed to be stopped at some depth due to a stabilizing mu-gradient. Such an assumption is necessary to prevent mixing in the nuclear core regions, otherwise we do not obtain the right sound velocity (Richard and Vauclair, 1997; Bahcall et al., 1997; Degl’Innocenti and Ricci, 1998). The best model presented in RVCD was obtained assuming a critical mu-gradient of \( 4 \times 10^{-13} \) cm\(^{-1}\), compatible with the order of magnitude deduced from Huppert and Spiegel 1977. In this model, lithium was depleted by a factor 140 and beryllium by about 2. On the other hand the \(^3\)He abundance increased too much in the convection zone compared to the recent determinations.

We now know that there may be a lithium depletion by a factor 3 in the pre-main sequence evolution, and that beryllium may not be depleted at all, which relaxes the constraints. The most stringent constraint is now given by the \(^3\)He determinations.

We have tried several parametrizations of mixing below the solar convection zone, which could reproduce both the \(^7\)Li and the \(^3\)He constraints. The only way to obtain such a result is to postulate a mild mixing, which would be efficient down to the lithium nuclear burning region but not too far below, to preserve the original \(^3\)He abundance. A mixing effect decreasing with time, as obtained with the rotation-induced shear hypothesis, helps satisfying the constraints, as the \(^3\)He peak itself builds up during the solar life.

Here we present results obtained with a similar prescription as in RVCD (rotation-induced mixing) in which the critical mu-gradient (\( \nabla \mu_c \)) was allowed to vary between \( 1.10^{-13} \) and \( 5.10^{-13} \) cm\(^{-1}\).
4. COMPARISON WITH OTHER STARS

The lithium abundance in the Sun may be compared to that observed in galactic clusters of known ages (aPer: Balachandran et al., 1996; Pleiades: Soderblom et al., 1993a; UMaG: Soderblom et al., 1993b; Hyades: Thorburn et al., 1993; NGC752: Balachandran, 1995). Following the solar evolutionary track we may attribute an effective temperature and, from the observations, a lithium abundance for each age. Figure 4 displays the observed lithium variations with age and the theoretical ones obtained with $\nabla \mu_c = 1$ and $2.10^{-13}\text{cm}^{-1}$. We can see that the parametrization of the mixing below the convection zone, which best accounts for the solar light element abundances and helioseismology, also correctly reproduce the lithium abundance evolution with time.

![Figure 4](image_url)

**Figure 4.** Lithium depletion with time in $1M_\odot$ stars obtained from the observations of galactic clusters and comparison with the two theoretical models

5. SUMMARY

In summary the best solar models must include the effect of element settling, which represents an improvement on the physics, without any free parameter added. These models can be considered as the new “standard” models. They cannot however reproduce the $^7\text{Li}$ depletion and they lead to a spike in the sound velocity, compared to the seismic Sun, just below the convective zone. These two observations suggest the presence of some mild mixing in this region of the internal Sun. Adding the constraint on the abundance of $^3\text{He}$ as given by Geiss and Gloecker (1998) leads to a precise description of the allowed profile of the macroscopic diffusion coefficient below the convective zone. The result is consistent with the mixing needed to smooth out the spike in the sound velocity and it leads to a lithium abundance variation with time consistent with the observations of galactic clusters. This parametrized description can be taken as a challenge for the hydrodynamics.

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