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SMALL AND INTERMEDIATE MASS STELLAR EVOLUTION - MAIN SEQUENCE AND CLOSE TO IT

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ABSTRACT We present the standard models for small and intermediate main sequence stars and we discuss some of the problems arising with semiconvection and overshooting. The surface abundance of Li serves as a test for other physical mechanisms, including microscopic and turbulent diffusion, rotation and mass loss.

INTRODUCTION

The evolution of stars less massive than about 9 $M_\odot$ has been extensively studied during the last three decades. Recent reviews (Iben, 1991; Chiosi, 1990 and references therein) describe the physics input and the main results and problems in this mass range. Numerous tables and evolutionary tracks have been published since the pioneering works of Henyey, Iben, Kippenhahn, Weigert, Demarque... In the evolutionary tracks of Iben (1964), most of the prominent features near the main sequence, MS, still remain valid. This can be seen in the results of Becker (1981), Vandenberg (1985), Lattanzio (1986), Castellani et al. (1990)... . A complete set of evolutionary tracks has been published by Maeder and Meynet (1989) with enlightning discussions of the problems still present in the confrontation between theoretical predictions and observations.

SEMICONVECTION

The convective core reaches its maximum extent soon after the hydrostatic ajustement to nuclear reactions. The opacity coefficient can be written in a simplified way as

$$\kappa = (1+X)[0.2 + C\rho^m T^{-n}] \qquad (1)$$

where X is the mass abundance of hydrogen and C, a constant. The large sensitivity to temperature of the CNO cycle keeps the density and the temperature nearly constant with time in the nuclear burning region so, as X decreases, the opacity decreases and the convective core must shrink. In all models of mass

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greater than about 2 $M_\odot$ reaching the maximum extent of their convective core, there is a discontinuity of the hydrogen abundance, smaller in the convective core than in the outer layers, and of the radiative temperature gradient, ∇_{rad}, which is larger than the adiabatic value, ∇_a, on the external side of the convective core limit. Imposing the continuity of T and of ρ/μ at the inner side, i, and at the outer side, o, of the convective core limit, one can write, from equation (1)

$$\frac{\kappa_o - \kappa_i}{\kappa} = \frac{\Delta\kappa}{\kappa} = \frac{\Delta X}{1+X} + m\frac{\kappa_{tot} - \kappa_s}{\kappa_{tot}}\frac{\Delta\rho}{\rho} \tag{2}$$

where κ_s is the contribution due to scattering to the total opacity coefficient, κ_{tot}. This relation becomes

$$\frac{\Delta\kappa}{\kappa} = \Delta X\left[\frac{1}{1+X} - m\frac{\kappa_{tot} - \kappa_s}{\kappa_{tot}}1.25\mu\right] \tag{3}$$

and, taking m equal to 1, a positive value of ΔX implies a positive $\Delta\kappa$ if

$$\frac{\kappa_s}{\kappa_{tot}} > 0.24 \tag{4}$$

which is the case for models with $M \geq 2M_\odot$. This means that the outer side of the convective core limit is unstable to convection, according to the Schwarzschild criterion

$$\nabla_{rad} = \nabla_a. \tag{5}$$

When the criterion for convective instability is written from density requirements, its expression becomes the so-called Ledoux criterion

$$\nabla_{rad} = \nabla_a + \nabla_\mu \tag{6}$$

where ∇_μ is different from zero in a region of varying mean molecular weight. Ledoux (1947) has actually suggested that a μ-discontinuity is likely to be replaced by a partially mixed region. This process is known as semiconvection.

The problem is not too serious in stars of about 3 $M_\odot$ since the radiative gradient becomes smaller with time, the decrease in κ due to the smaller density and that of P/T^4 being more pronounced than the increase in L/m. As the radiation pressure is negligible, the adiabatic temperature gradient remains constant and stability towards convection is quickly restored at the outer edge of the convective core. For more massive stars, the problem becomes more serious, not because of the initial discontinuities in X and ∇_{rad}, which have similar values, but because of the increasing contribution of the radiation pressure to the total pressure. As time goes on, the radiative gradient slowly decreases as in smaller masses but the adiabatic temperature gradient decreases more rapidly. This means that a semiconvective region must take place.

It has been a long standing problem to decide which criterion (5) or (6) had to be fulfilled in the semiconvective region (Simpson, 1971; Ziolkowski, 1972; Barbaro et al., 1972; Varshawsky and Tutukov, 1973;...). Schwarzschild and Härm

(1958) already proposed a partial mixing with the convective core matter which stopped when relation (5) is satisfied while Sakashita and Hayashi (1961) discussed a processes involving relation (6). Although it seemed at first that both processes would lead to similar results for massive stars, $M > 15\ M_{\odot}$ (Stothers and Chin, 1968), Iben (1966 a,b) had drawn the attention on the drastic effects of modifying the μ-distribution during MS on the post MS phases. Chiosi and Summa (1970) found that a partial mixing cannot be maintained all the way to He burning and a fully convective intermediate zone sets in, when Schwarzschild criterion is adopted to mix the semiconvective region. More sophisticated scenarios were proposed by Stothers (1970) while Stothers and Chin (1973) showed the extreme sensititivity of the post MS phases to the μ-profiles. Other sequences of models have been computed by Stothers and Chin (1975), based on the Ledoux criterion and by Stothers and Chin (1976), with the Schwarzschild criterion for masses ranging from 5 to 60 $M_{\odot}$. They found that adopting either the Schwarzschild or the Ledoux criterion, He burning starts on the blue side of the H-R diagram for masses higher than about 17 $M_{\odot}$ while for smaller masses, results are very sensitive to the initial chemical composition, blue loops appearing more easily with the Ledoux criterion. They tried to decide between those criterions from observational tests but these appeared not to be very conclusive with a predicted excess of red supergiants with both criteria. Following a suggestion by Kato (1966), Gabriel and Noels (1976) have shown that g^+ modes trapped in the varying μ-region are vibrationally unstable and the semiconvective mixing should be performed according to relation (5).

Chiosi and Maeder (1986) proposed a limit of 13 $M_{\odot}$ above which all stars start burning helium on the blue side of the H-R diagram when semiconvection is treated according to relation (5). For lower mass stars, the differences between relations (5) and (6) are not significant in their results.

Interesting discussions can be found in Massevich and Tutukov (1973), Iben (1974), de Loore (1980), Chiosi (1990) and references therein.

OVERSHOOTING

Another difficulty in fixing the limit of the convective region arises from a possible overshooting above or below the layer where relation (5) is satisfied. This comes from the non-vanishing kinetic energy of the convective elements at the boundary of the convective region. Relation (5) implies the annulation of the acceleration but a more correct criterion should be based on the kinetic energy of the elements. The distance to which these elements can move above the classical boundary is not known, but is probably of the order of the pressure scale height (Chiosi, 1986) although a better choice would be a fraction of the convective core radius (Zahn, 1992). Such an overshooting leads to a larger fully mixed convective core which means a longer MS duration and, in the H-R diagram, a wider MS width, especially for massive stars.

Should some overshooting be present, the discontinuities in X and ∇_{rad}

would take place in a region where ∇_{rad} is appreciably smaller than ∇_a. It is reasonable to admit that a sufficient amount of overshooting solves the semiconvection problem or, at least, makes it important for much higher masses (Langer, 1992).

The problem of core overshooting has been very recently extensively studied by Maeder and Meynet (1989) and by Stothers (1991). They take a distance of overshooting, $d = \alpha H_p$, where H_p is the pressure scale height at the convective core boundary and α is a parameter smaller than 1. Several observational tests serve as guides to derive the value of α. The conclusion of Maeder and Meynet (1989) is in favour of $\alpha = 0.25$ while Stothers (1991), regards that value as an upper limit, most of his tests being satisfied with $\alpha = 0$. It is to be expected that if α is found to be very small, semiconvection must be taken into account because of its effects on later stages of evolution. Therefore observational tests of α should be restricted to the vicinity of the MS and those involving evolved stars are likely to bias the derived value. The models used in these analyses were computed with the opacities from the Los Alamos Opacity Library (Huebner et al., 1977; LAOL) in Maeder and Meynet (1989), as in Claret and Giménez (1991a) or the Cox and Stewart (1970) opacities in Stothers (1991). The latter author argues that the best fit to the observations is, preferably to overshooting, an increase in metallicity, up to $Z \sim 0.04$. This high value of Z is to be interpreted as a need for larger opacities in the envelopes of MS stars.

Such enhancements in the opacities have recently been found by Rogers and Iglesias (1991; OPAL). New grids of models have been computed (Stothers and Chin, 1991, Schaller et al., 1992) with an overshooting parameter chosen to match the observations. One of the best test for overshooting is the MS width (Napiwotzki et al., 1991). In Stothers and Chin (1991), the agreement is excellent with the observations, taking the OPAL opacities and Z between 0.02 and 0.03. There is no special need for overshooting here. Similar results are obtained for O- and B-type stars. From these results, Stothers and Chin favour a solar-like metal abundance and no significant overshooting. The absence of any treatment of the semiconvective region is not important as long as the models are located on the MS as was shown by Stothers and Chin (1968) and Chiosi and Summa (1970). The evolved models, being very sensitive to the μ-profile during the MS, require a semiconvective mixing starting from the zero age main sequence, ZAMS, if no overshooting is present. In Schaller et al. (1992), similar results are obtained with OPAL opacities, in the sense that the ZAMS and the terminal age main sequence, TAMS, are displaced towards the red. However the displacement is greater for the TAMS which means that a smaller distance of overshooting is needed to reproduce the observed width of the MS. Instead of $\alpha = 0.25$ with the LAOL opacities, these authors find a value of about 0.2 and conclude that differences due to opacities are not likely to suppress the overshooting. With these results, Meynet (1992) obtains very nice isochrone fittings with galactic clusters.

Another important test for overshooting is the apsidal motion test (Claret and Giménez, 1991a,b).

Li PROBLEM

We have seen that, in order to explain such an evident feature as the MS width, it was necessary to add some mixing to the convective core which is a possible solution to the problem of semiconvection. Undershooting from the convective envelope or other processes of mixing might be present in MS stars of lower masses. Recently, Alongi et al. (1991) have shown that isochrone fitting in globular clusters as well as in galactic clusters needed core overshooting and envelope undershooting. To test such processes, one of the most powerful tool is the photospheric Li abundance.

Li in Galactic Clusters

It is well known, since 1986 (Boesgaard and Tripicco, 1986a) that a gap exists in the Li abundances of the Hyades cluster in a very narrow effective temperature range, around 6400-6900 K. Figure 2.1, in Michaud and Charbonneau (1991) shows a succession of galactic clusters of increasing ages, from 0.05 Gyr for α Persei to 6.5 Gyr for NGC 188. One can see that the spectacular Li dip found in the Hyades is not unique but seems to be present in clusters older than $\sim$ 0.1 Gyr and absent in younger clusters, except for a slight tendency already showing up in the Pleiades.

Li and Be are light elements easily destroyed by (p,α) reactions at temperatures of 2.5 10^6 K and 3 10^6 K respectively.

In MS stars, a convective envelope is present at low Te, its extension increasing as Te decreases. If the lower limit of this envelope includes such high temperature layers, burning of Li at the bottom of the envelope might be at work. It has however been shown that classical convection only is not sufficient to produce the observed trend in the cool end of the Hyades (Baglin and Morel, 1984). These authors had to introduce overshooting and turbulent diffusion, each process by itself being unable to explain the shape of the abundance curve. Pinsonneault et al. (1992b) have recently shown that, with the new OPAL opacities in standard models, Li burns at the base of the convective zone and is depleted by the observed amounts in stars of masses lower than 0.9 $M_\odot$ and Te smaller than 5300 K.

To explain the Li dip and its wings in the Hyades, many physical processes have been advanced.

1. *Microscopic diffusion* (Michaud, 1986; Vauclair, 1987)

A diffusion equation is added to the problem, with a diffusion coefficient D_{12} given by Paquette et al. (1986). Other expressions of D_{12} can be found in Noerdlinger (1977) and Cox et al. (1989). This process is more efficient when the convective envelope is thin and it can be inhibited by mixing. It can lead to a depletion or to an enhancement of the surface Li abundance according to the relative values of the gravitational acceleration, g, versus the radiative acceleration, g_R, at the base of the convection zone. The diffusion timescale at

6400 K is of the order of 10^9 yr, which can explain the slight depletion in this portion of the Hyades curve (Balachandran, 1990).

2. *Meridional circulation* (Charbonneau and Michaud, 1988)

This calculation originates from a model developed by Tassoul and Tassoul (1982) who showed that meridional circulation can occur in a radiative zone surrounding the μ-gradient region. It is assumed that this circulation penetrates the convective envelope. Its effect is double. First, it may inhibit or reduce the microscopic diffusion if the rotational velocity is greater than a critical value. This can show up in reducing a possible overabundance of Li, if $g_R > g$, or underabundance, if $g > g_R$. The other aspect is an increase of the mixed region whose base can reach sufficiently hot layers where Li is destroyed. This leads to a systematic depletion of the surface abundance of Li.

3. *Turbulent diffusion* (Schatzman, 1969)

A fast rotating star with a convective envelope is likely to be spun down through winds and magnetic fields, the envelope being more affected by the braking than the core. This results in differential rotation which is known to induce turbulent mixing (Zahn, 1974). As it is still not possible to fully model the physics involved, two different approaches have been used. The first one (Schatzman, 1977; Schatzman and Maeder, 1981; Baglin et al., 1985; Vauclair, 1988; Michaud et Charbonneau, 1991) adopts a diffusion equation in which the expression of the turbulent diffusion coefficient, starting from a constant value to more sophisticated expressions introducing space and time dependencies, is parametrized to reproduce the observations. Schatzman and Baglin (1991) have recently revisited this problem and have shown that it is not possible to explain the depletion in late spectral type stars as well as in the Li dip with a process depending only on rotation.

The second approach is based on the pioneering works of Endal and Sofia (1976, 1978), introduced later in the Yale code, YREC, by Sofia et al. (1991). These authors compute rotating models in which the transport of angular momentum and the associated mixing is treated through coupled diffusion equations, with a diffusion coefficient obtained from the physics involved in the different instability mechanisms. They have however to adjust the ratio between the diffusion coefficient of matter and that of the angular momentum, to obtain coherent results for different trace elements and stars of various ages and chemical composition. Using the new OPAL opacities, Pinsonneault et al. (1992b) have found an increase of the convective envelope in standard models, which is compensated by a new lower Li (p,α) reaction rate. Rotating models are able to explain the cool part of the Li curve in the Hyades by adjusting the initial value as well as the diffusion velocity of the angular momentum.

4. *Mass loss* (Schramm et al., 1990)

The extension of the instability strip crosses the ZAMS in the mass range of 1 to 2.5 $M_\odot$. Willson et al. (1987) have suggested that pulsations could lead to mass loss for such stars during their early MS evolution. A small amount of mass loss is able to suppress the overabundance predicted by diffusion processes on the hot part of the Li dip. The work of Schramm et al. (1990) involves models computed with mass loss as the only "non standard" mechanism. It puts tight constraints on the amount of mass loss rates for MS stars around 1.3 $M_\odot$, $7\ 10^{-11} \leq \dot{M} \leq 10^{-10}\ M_\odot/yr$, in agreement with recent observations by Brown et al. (1990). The lower value is necessary to find a Li dip and the upper one, to explain the presence of Be. This light element does not seem to be depleted in stars, located in the Li dip although a slight decrease by a factor 2-4 might be present (Boesgaard and Budge, 1989).

5. *Internal gravity waves* (Garcia Lopez and Spruit, 1991)

Press(1981) suggested that an alternative way for transporting angular momentum was by internal gravity waves generated at the base of the convective zone by the convective cells acting on the radiative layers (Schatzman, 1991). Garcia Lopez and Spruit (1991) could reproduce the Li dip but only at the expense of an artificial increase in the wave flux by a factor of about 15.

Each process by itself is able to reproduce, at least parts of the Li curve in the Hyades although they probably all contribute to the depletion of Li. The reddest portion of the Li curve is mostly due to Li burning in the convective envelope with probably some additional mixing. The shoulder needs Li diffusion while the dip requires either fast diffusion or rotational mixing. The hot shoulder seems to be locked at a stable value of Li. If upward diffusion is acting, rotational mixing or mass loss should be present to inhibit the overabundance or nothing non standard happens in these stars.

Li in F-Stars

It was of course extremely tempting to try to find similar features in field F stars. Extensive work has been done by Balachandran (1990). The Li abundance in terms of rotational velocity, $v \sin i$, for about 200 F stars, shows an extremely large dispersion at low $v \sin i$ and that undepleted Li stars are found for a very wide range of $v \sin i$. In the H-R diagram, for masses between 1.0 and 1.85 $M_\odot$, the decrease in $v \sin i$ at low Te can be explained by the more important slowing down role played by the deepening of the convective envelope, although one finds slow rotators at the hot side of the sample. A clustering of Li depleted stars in the Te range of the Li dip is present, but in the same region, a number of hardly depleted stars is also visible. At the hottest side of the sample, there is no Li depletion, whatever the rotational velocity is. Similar results have been obtained by Boesgaard and Tripicco (1986b, 1987).

In all processes discussed before, only those that can lead to a spread in the Li abundance in the Li dip and to a nearly constant higher value on both wings, the largest ones being found for the hottest stars, can be retained.

Turbulent diffusion, if at work, depends on the initial value of $v \sin i$ and on the mass of the convective envelope. For early F stars, no braking should occur due to their very thin convective envelope. If one adopts a maxwellian initial velocity distribution, the present spread in $v \sin i$ reflects the initial values but whatever $v \sin i$ was and still is, no Li depletion should have occured. This can explain the observed spread in $v \sin i$ and the nearly constant value of Li, close to the meteoritic value. The spread in Li abundance inside the Li dip is explained by the wide range in initial velocities. Small initial $v \sin i$'s give small depletion whereas large inital $v \sin i$'s, because of the strong spun down, lead to high Li depletion. This means that, in the Li dip, a dispersion of the Li abundance essentially reflects a dispersion in the initial $v \sin i$'s although the present $v \sin i$'s are similar.

Li in Halo Stars

For pop II stars, constraints are different :

1. For a given Te, the lower value of Z implies a much smaller convective envelope.

2. The initial Li abundance is not necessarily that observed in undepleted pop I stars. It should be constrained by the standard Big Bang yield but uncertainties remain.

3. In the range 5500 K < Te < 6300 K, Spite and Spite (1982) have shown that the surface Li abundance is nearly constant, within a factor 2 at most. This value is about an order of magnitude smaller than the cosmic abundance. This is true as well for extreme halo stars (Hobbs and Thorburn, 1991). There seems to be no correlation with metallicity, in constrast with Be coming exclusively from spallation reactions and showing an increase with metallicity.

4. The ages are every large, greater than 10 Gyr. Masses involved are small, ranging from 0.6 to 0.8 $M_\odot$, which means that they are still on the MS, burning hydrogen essentially through the p-p chain. This is very important as, contrary to pop I F stars, the evolution proceeds along the MS towards higher Te's instead of leaving the MS towards smaller Te's.

The Yale and the Montreal groups have recently attempted to fit the observations with standard, diffusive and rotational models.

1. *Standard models*

The Spite plateau is quite well fitted by standard models (Demarque et al., 1991; Proffitt and Michaud, 1991a) starting with an initial, i.e. presumably primordial, abundance of Li given by $A_{Li} = 12 + \log(N_{Li}/N_H) = 2.2$ which is the value observed at the hot end of the Spite plateau. The slope at low temperatures may be adjusted by varying the Z value (Deliyannis and Demarque, 1991a).

2. *Diffusive models*

Diffusion in halo stars consists mainly of gravitational settling at the base of the convection zone which becomes very thin as Te reaches 6300 K. This shallow convection zone enhances the effect of diffusion and Li isochrones show a downward curvature at high Te. The main bulk of observations, plateau and decrease at low Te, is still quite well fitted. The initial Li abundance is larger, of the order of 2.4 (Demarque et al., 1991; Proffitt and Michaud, 1991a; Chaboyer et al., 1991). The theoretical downward curvature at high Te is a strong constraint on He diffusion. This He diffusion acts in two ways. Firstly, it reduces the hydrogen content in central regions (Stringfellow et al., 1983) and secondly, it increases the hydrogen content in the envelope thus reducing the effective temperature (Deliyannis et al., 1990). This leads to a reduction in the ages of globular clusters obtained by isochrone fittings by about 10 % (Deliyannis and Demarque, 1991b) to 15 % (Proffitt and Michaud, 1991a).

3. *Rotational models*

In the approach adopted in YREC (Pinsonneault et al., 1992a), the emphasis is put on the interaction between diffusion of angular momentum and mixing. Starting from an initial value of the Li abundance of the order of 3.1, much higher than the so-called primordial value, and equal to the value observed in early F stars, it is possible to get a curve close to the Spite plateau by adjusting some parameters, among which the initial angular momentum and the rate of spun down taken from the observations of T Tauri stars and young clusters. This could possibly account for the slight dispersion among the observations. Such a high value of the primordial Li abundance seems to be in disagreement with other elements used to test the standard Big Bang model.

The other approach of the mixing due to rotation, turbulent diffusion, has been recently applied to halo star models including gravitational settling of He and Li (Proffitt and Michaud, 1991a). The initial Li abundance is taken to be 2.5 or 2.4. The effect of turbulent diffusion is to reduce the extent of the Spite plateau without changing much the maximum at high temperature. Turbulent diffusion acts as a Li depleter at low temperature by increasing Li burning and acts against microscopic diffusion at high temperature. The very existence of the Spite plateau implies a limited amount of turbulent diffusion which is not sufficient to inhibit completely He diffusion. This should lead to a reduction in the ages of globular clusters of the order of 12 % to 15 %, down to 12 Gyr. A value near 15 Gyr would require a slightly larger value of the initial Li abundance.

Li in the Sun

Up to now, we have been dealing with different Li depletion mechanisms which could explain the observations, provided the initial abundance of Li is known. Either in halo stars, where this value should be the primordial Li abundance, or in galactic clusters, where it is taken from supposedly undepleted early F stars, this cho is questionable. The only star for which we have direct indicator of the Li abundance in the original nebula is the Sun, from the meteoritic abundance, $A_{Li,met} = 3.31 \pm 0.04$ (Anders and Grevesse, 1989). As the photospheric Li abundance is $A_{Li,\odot} = 1.16 \pm 0.1$, the depletion factor is of the order of 140. Note that in the Sun, Be is also slightly depleted by a factor of about 2 ($A_{Be,met}$= 1.42, $A_{Be,\odot} = 1.15$).

1. A small amount of Li can be burned during the pre MS phase (Bodenheimer, 1965). Even by adding overshooting, D'Antona and Mazzitelli (1984) failed to destroy much Li. New modelling of overshooting during MS by Skaley and Stix (1991) suggests that with a good choice of parameters, temperatures (2.8 10^6 K) higher than in standard models can be reached at the base of the mixed region.

2. Microscopic diffusion by itself cannot account for such a high Li depletion. Proffitt and Michaud (1991b) have recently shown that some turbulent mixing must be added. Furthermore, gravitational settling reduces the surface He abundance by about 10 %. The change in metallicity is smaller and somewhat more uncertain. Similar decreases for Y and Z at the surface were obtained by Cox et al. (1989).

3. Turbulent diffusion has been modelized by Lebreton and Maeder (1987). Although they succeeded to fit the solar Li abundance, they had problems with the ν flux and the oscillation periods. Baglin et al. (1985) showed that a similar turbulent diffusion coefficient could not fit at the same time the Hyades and the Sun. Thévenin et al. (1987) pointed out that such a fit to the solar value would lead to a Be depletion larger than the observed one. Very recently, Proffitt and Michaud (1991b) fitted the observed Li and Be abundances with models including microscopic and turbulent diffusion.

4. Using evolutionary rotating models, Pinsonneault et al. (1989) succeeded in depleting Li and Be by the proper amounts at the age of the Sun. The method is that of YREC with coupled equations describing the transport of angular momentum and isotopes and a parametrized relation giving the variation with time of the angular momentum. Five free parameters are then adjusted to fit the observations, namely the Li and Be surface abundances, starting with a reference solar model. The difference found in the diffusion coefficients could mean that mixing and transport of angular momentum are not coupled or that some other process accounts for most of the angular momentum transport. The velocity curve and the Li and Be surface abundances as functions of age can be found in Pinsonneault et al. (1989) and Demarque (1991) for different values of the initial angular momentum. The velocity curve agrees with the empiral law of Skumanich (1972). It shows the expected increase of equatorial velocity during pre MS contraction and the subsequent braking by stellar wind and magnetic field. It has to be pointed out that the velocity curve on the MS is independent of the initial conditions, which gives an upper limit to the rotational velocity on the MS. The present solar model has outer layers (r $> 0.6\ R_{\odot}$) rotating nearly rigidly, together with a rapidly rotating core (r $< 0.2\ R_{\odot}$).

5. Boothroyd et al. (1991) have recently investigated the effects of a reasonable mass loss, $\dot{M} \sim 10^{-10}\ M_{\odot}/yr$, in agreement with Brown et al. (1990), on the solar Li depletion, with no other mechanism taken into account. They succeed to explain the observed solar Li and Be depletions with models losing about 10 % of their initial mass during the early MS evolution. This result is nearly independant of the mass loss time scale and leads to a Y value of 0.276 only slightly smaller than their standard value. However, Swenson and Faulkner (1990) showed that mass loss was an unlikely mechanism to explain the Li depletion in the Hyades G dwarfs because these stars should have nearly similar initial masses with different mass loss rates to lead to the observed wide range of Li abundances and effective temperatures.

STANDARD SOLAR MODELS

Since the fundamental review by Bahcall and Ulrich (1988), three recent papers (Sackmann et al., 1990; Ulrich and Cox, 1991; Guenther et al., 1992) discuss the present state of the art in standard solar models and present tables with numerous solar models obtained by different groups. Uncertainties in the basic data, like the age, the Z/X ratio, the luminosity, radius and mass are discussed together with their influence on the results. All models agree to predict a Y value of $\sim 0.28 \pm 0.01$, for a Z value of $\sim 0.019 \pm 0.001$, and a chlorine neutrino flux, F_ν, of the order of 8 SNU. Only non standard solar models (Maeder, 1990) can substantially reduce this high value of F_ν, such as the mixed model recently proposed by Sienkiewicz et al. (1990) and references therein.

A correct calibration of the Sun should be based on the ratio Z/X, which is the only observed constraint on the chemical composition (Bahcall et al., 1982). Most of the standard models however are obtained with a fixed value of Z and values of Y and of the mixing length parameter α adjusted to give the luminosity and radius of the Sun at the solar age. The best value of Z/X is now 0.027 ± 0.003, obtained with the meteoritic abundance of iron.

1. It is now well known that the Y value strongly depends on the interior opacities. Values as low as 0.24 were obtained with the Cox and Stewart (1970) opacities while the present values come from the LAOL opacities (Huebner et al., 1977). The low temperature opacities, $T \leq 10\ 000$ K, have a negligible effect on Y; it only changes the mixing length parameter, α, the largest values of α being obtained for the largest low temperature opacities. With the new OPAL opacities (Rogers and Iglesias, 1991), computed for the mixture recommended by Anders and Grevesse (1989), calibration of the Sun leads to a slight increase in Y, of about 0.01 (Guenther et al., 1992; Schaller et al., 1992 ; Morel et al., 1992; Neuforge, 1992).

The major change between OPAL and LAOL opacities is an increase due to metals, essentially iron, around $3\ 10^5$ K (Iglesias et al., 1992). This peak in opacity is located in the adiabatic part of the convective envelope and decreases strongly when the density increases.

Recently however, new photospheric iron abundance determinations (Holweger et al., 1990, 1991; Biémont et al., 1991; Hannaford et al., 1992) have led to an agreement with the meteoritic value. In their new opacity computations, including intermediate coupling, Iglesias et al. (1992) have adopted this new solar iron abundance, lower than the previously used value by about 40 %. The intermediate coupling results are substantially higher around $3\ 10^5$ K than the previous ones, for a given mixture. However, reducing the iron abundance somehow annihilates this increase. Nevertheless, their results clearly show the importance of iron as a substantial contributor to the opacity at high temperatures. At the solar center, $T_6 \sim 15$, $\rho \sim 150$, one finds a reduction in the opacity of about 7 %. The importance of iron had already been emphasized by Courtaud et al. (1990). We have calibrated the Sun, using the OPAL opacities with the meteoritic iron abundance and LS coupling and we find Y = 0.280 and Z = 0.02, which shows the decrease in Y, by about 0.01, for models obtained with similar physics, except for the iron abundance (Morel et al., 1992).

The ratio of the opacity computed with intermediate coupling to the opacity computed with LS coupling for the two values of the iron abundance shows that, except for the peak region, differences are extremely small and as the peak itself has little influence on the solar model, these new OPAL opacities do not affect our Y value given hereabove.

2. The equation of state (EOS) has received much attention these last years in an effort to include as correctly as possible partition functions and interactions between the components of the mixture. The chemical picture has led to the equation of state of Fontaine et al. (1977) and more recently to the so-called MHD equation of state (Hummer and Mihalas, 1988; Mihalas et al., 1988; Däppen et al., 1988) while the physical picture is used by the Livermore group (Rogers, 1986; Iglesias et al., 1987). A discussion of these approaches has been published recently by Däppen et al. (1991). Chabrier (1992) recently compared the various results obtained by Fontaine et al. (1977), Magni and Mazzitelli (1979), Mihalas et al. (1988) and his own computations (Saumon and Chabrier, 1991) for a fluid composed of pure hydrogen. Large differences occur at low temperature and medium to large densities. Under solar conditions, the physics involved in these computations lead to similar results. Differences are more striking in the adiabatic gradient at low temperature. There is a divergence of MHD for $\log \rho$ larger than about -2 and a peak in Saumon and Chabrier (1991) near $\log \rho \sim 0.25$ due to a thermodynamic inconsistency. Again, in the solar regime, the differences are small.

Lebreton and Däppen (1988) and more recently Guenther et al. (1992) have investigated the effect of adopting a new EOS. With better partition functions and better interactions, they obtain a decrease of Y by about 0.01.

3. Most standard solar models predict an extension of the convective envelope, d_c, given by $d_c/R \sim 0.27$ and a temperature at the base of the order of $T_b \sim 2\,10^6 K$.

The inversion of helioseismic data (Christensen-Dalsgaard et al., 1991) allows the determination of the sound speed inside the Sun. The transition from adiabatic layers to subadiabatic ones leads to a discontinuity in the derivative of the sound speed. The location of this feature indicates very precisely the lower limit of the mixed adiabatic region, d_a, which is $d_a/R = 0.287 \pm 0.003$. This value is somewhat larger than the predicted value given hereabove. Solar models computed with the OPAL opacities, the MHD equation of state and the high solar abundance of iron (Guenther et al., 1992; Morel et al., 1992) lead to a slightly better agreement with the helioseismic value.

4. All standard models are computed with the mixing length theory, MLT. Attempts have been made to refine the treatment of convection. Some of these have recently been proposed by Pedersen et al. (1990), Forestini (1991), Canuto and Mazzitelli (1991) and Lydon et al. (1992).

CONCLUSIONS

Observational tests seem to reveal some weakness in the physics adopted in the so-called standard models. It is our opinion that in the near future, a new generation of standard models should include many of the physical phenomena discussed here, i.e. semiconvection, overshooting, microscopic and turbulent diffusion, rotation and mass loss.

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