Astron. Astrophys. 341, 174–180 (1999)

ASTRONOMY AND ASTROPHYSICS

Theoretical models of low-mass, pre-main sequence rotating stars

I. The effects on lithium depletion

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Received 9 January 1998 / Accepted 29 July 1998

Abstract. Rotating stellar models of 1.2 $M_\odot$ down to 0.6 $M_\odot$ have been computed to investigate the effects of rotation on the lithium depletion of low-mass, pre-main sequence stars. The models were generated under three different rotation laws (rigid body rotation, local conservation of angular momentum over the whole star, and local conservation of angular momentum in radiative zones and rigid body rotation in convective ones), no angular momentum loss and redistribution, and under two prescriptions for convection, namely the mixing length theory [MLT] and the turbulent convection introduced by Canuto & Mazzitelli (1991) [CM]. The general features of the rotating models are compatible with previous results by other authors. As for the lithium depletion, our results show that rotation decreases lithium depletion while the star is fully convective but *increases* it as soon as the star develops a radiative core, a result which is expected from the theory since rotating stars behave as non-rotating stars of lower mass and so must experience greater lithium depletion. The results hold for all three rotation laws assumed, but are specifically presented here for the case of rigid body rotation. This result shows that other physical mechanisms must play a role on the lithium depletion in the pre-main sequence, in order to explain the observational data on low-mass, pre-main sequence stars such as those from the Pleiades (García López et al. 1994) and the α-Persei clusters (Balachandran et al. 1988, 1996).

Key words: stars: rotation – stars: pre-main sequence – stars: interiors – stars: evolution

1. Introduction

It has long been known that rotation is an important physical parameter in the theory of stellar structure and evolution, due to the changes it brings to the internal structure of stars. Besides, rotation is linked to a number of important physical processes in stars such as magnetic fields and the burning of light elements to name just a few. The subject of stellar rotation is discussed in greater detail, e.g., in Tassoul (1978).

Of all non-standard physical processes that could significantly influence the stellar depletion of lithium, rotation is undoubtedly the most quoted, since it is a natural agent for chemical mixing inside the stars (e.g. Charbonnel & Vauclair 1991; Pinsonneault 1991; Zahn 1992, 1993, 1994; Charbonnel et al. 1994; Strom 1994). Nevertheless, so far very few attempts have been made to include rotation in evolutionary codes, and even less to check the effects of rotation on lithium depletion.

As part of an ongoing project to improve the macro- and micro-physics of the ATON stellar structure code (Mazzitelli 1989 and references therein), we have then modified it to incorporate the hydrostatic structural effects (i.e. the changes in the internal structure of the star) due to presence of rotation.

Despite the great effort that has been conducted towards a better understanding of the depletion of light elements such as beryllium and lithium in young, low mass stars (as these elements can be used as tracers of the stellar evolution), the current picture is still subject to many uncertainties. Lithium depletion is related to a number of physical parameters such as stellar mass (Cayrel et al. 1984), metallicity (Hobbs & Duncan 1987) and rotation (Marcy et al. 1985; Soderblom 1993; Martín et al. 1994; Randich et al. 1998). Rotating models have been built up by the Yale group (Pinsonneault et al. 1990, and recently Chaboyer et al. 1995). The resulting pre-main sequence lithium depletion is modestly dependent on the stellar rotation rate. In fact during the pre-main sequence phase, rotating models deplete just a bit *more* lithium than the non-rotating models due to the hydrostatic properties of the rotating models. The main importance of rotation resides in the subsequent redistribution of angular momentum – and the chemical mixing associated to this process – which occurs during the main sequence evolution: this leads to a large spread in the *main sequence* lithium abundances of stars.

Comparing these models with the observations, however, we have to notice the following:

1. a spread in the lithium abundances is created *early* in the life of stars, as it is present in young clusters such as α Persei and

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the Pleiades (~ 100Myr). On the contrary, the mixing due to the redistribution of angular momentum, which causes the lithium spread in rotating models, occurs mostly *later* during the stellar life.

2. the spread is in the sense that, statistically at least, the stars having the largest rotational velocities seem to deplete *less* lithium. In fact García López et al. (1994), and later Jones et al. (1996), found that the observed spread in lithium abundances of the Pleiades low-mass stars is related to rotation in such a way that fast rotators have less lithium depletion than slow rotators. Evidence for such a rotation-lithium depletion relation has also been found by Cunha et al. (1995), who have studied the lithium abundance over a sample of late F to early G young stars in the Orion association. Binaries in the Hyades present a lower scatter in abundances than single stars in the same cluster, and close binaries show conspicuous overabundances (Barrado y Navascués & Stauffer 1996).

Consequently, the observational indications are opposite to the predictions of rotating models. The quest for a mechanism inhibiting lithium depletion in pre–main sequence motivated Martín & Claret (1996) to a new exploration of the effect of rotation. At variance with Pinsonneault et al. (1990), they found indeed that rigid body rotating models depleted less lithium than the non–rotating models. They attributed the differences of their results, with respect to those of Pinsonneault et al. (1990), mainly to the adopted opacities, as the latter authors used the older Cox & Stewart (1970) libraries. Therefore, the theoretical models by the Yale group are in conflict with the Martín & Claret results. On the other hand, the result by Martín & Claret (1996) would help in solving the problem of lithium, also in view of the fact that modern computations of pre–main sequence lithium depletion in non–rotating models provide *too much depletion* with respect to what the observations in open clusters demand (D'Antona and Mazzitelli 1997, Martín 1997, Ventura et al. 1998), and a *reduction* of this depletion is needed.

It is important to sort out whether the structural (hydrostatic) differences between the rotating and non-rotating models work towards confirming the observational constraints or not. If there is no substantial difference between the rotating and non rotating models, as predicted by Pinsonneault et al. (1990), the differences in lithium depletion found among open clusters stars must be entirely attributed to the phases of angular momentum transport and associated chemical mixing, which is less important in fast rotating stars due to the lower degree of differential rotation between the radiative interior and the external convective envelope, but the early spread in abundances remains not understood.

In order to have an independent check of this problem, in this paper we present the results of a series of rotating stellar models computed with the ATON code, with particular emphasis on the structural effects (always meant, throughout this text, as only hydrostatic effects) of rotation on the lithium abundances of low-mass, pre-main sequence stars. Some preliminary results already have been presented (Mendes et al. 1997).

2. Model features

The general features of the ATON stellar structure code are described in Mazzitelli (1989), Mazzitelli et al. (1995) and references therein. The pre-main sequence models start in an arbitrary fully extended convective configuration with a central temperature of $\log T_{\rm c} = 5.7$ (and thus prior to the onset of deuterium burning), to which $t = 0$ is attributed (see D'Antona & Mazzitelli 1997 for a discussion of attributing theoretical "ages" to pre-main sequence models).

2.1. Rotation

Rotation was implemented according to the approach taken by Endal & Sofia (1976), which uses the Kippenhahn & Thomas (1970) method but with an improved potential function due to the inclusion of a third term related to the distortion of the figure of the star. As it is well known, this approach incorporates only the hydrostatic effects of rotation and is far from a full treatment of rotational effects, which should include internal angular momentum redistribution and surface angular momentum loss. Three rotation laws have been implemented, namely rigid body rotation, local conservation of angular momentum throughout the whole star, and local conservation of angular momentum in radiative regions and rigid body rotation in convective ones. Following Endal & Sofia (1976) and Pinsonneault et al. (1989), these rotation laws were chosen to represent a set of physically plausible rotation laws. Although recent data from both helioseismology (Thompson et al. 1996) and numerical models (e.g. Brummel et al. 1995) give a quite different picture for the present sun, it should be kept in mind that in the sun mechanisms of redistribution of angular momentum have been active for almost 5 billion years, altering its initial distribution.

It should be noted that, in general, local conservation of angular momentum in pre-main sequence stars implies radial differential rotation (as the star contracts along the Hayashi track), which (except for rotation constant on cylinders) is clearly a non-conservative rotation law. Though the Kippenhahn & Thomas method was originally developed for conservative rotating forces, even for non-conservative ones the baroclinity caused by rotation will be small (Endal & Sofia 1978), and following these last authors we also assumed that the angular velocity is constant along a level surface. A more rigorous treatment of a non-conservative rotation law of the form $\omega = \omega(r)$ can be found in Meynet & Maeder (1997).

2.2. Input physics

The opacities adopted in the current version of the ATON code are taken from Iglesias & Rogers (1993), supplemented by those at low and intermediate temperatures from Alexander & Ferguson (1994) or Kurucz (1993). The initial angular momentum for all models was estimated according to the relations given by Kawaler (1987) for stars of spectral type later than F2 (see Table 1). The chemical composition was set with Y=0.28 and Z=0.0175. As for the convection model, the calcu-

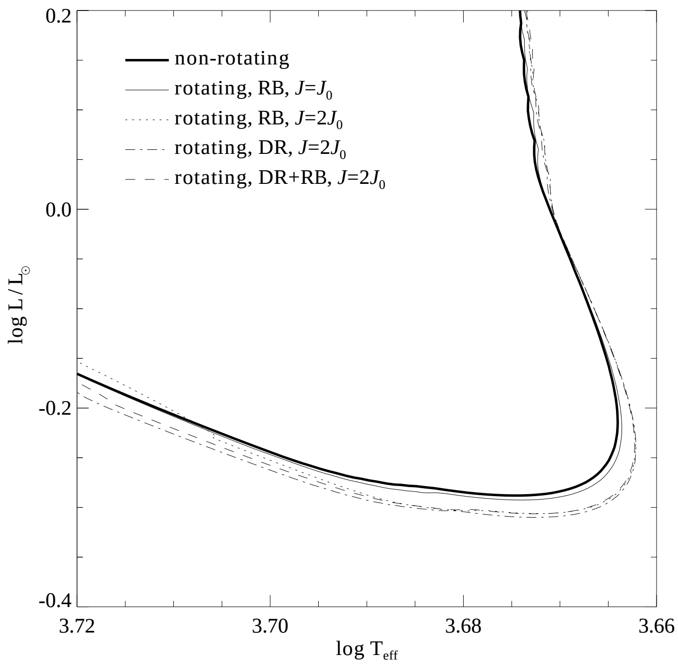

Fig. 1. Detail of the evolutionary tracks for rotating models of 1 $M_\odot$ under different initial angular momentum and different rotation laws, for the MLT convection model. *RB* stands for rigid body rotation; *DR*, local conservation of angular momentum throughout the whole star; and *DR+SB*, local conservation of angular momentum in radiative regions and rigid body rotation in convective ones.

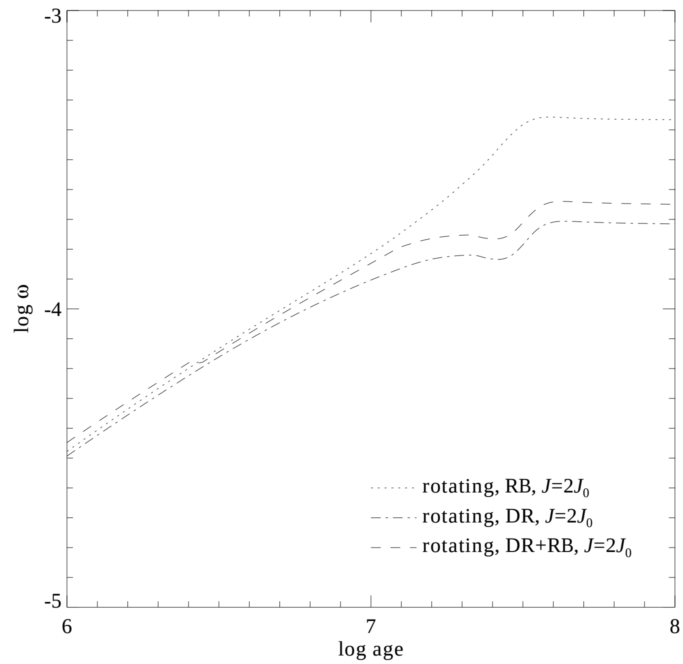

Fig. 2. Surface angular velocity, as a function of age, for the rotating models of 1 $M_\odot$. The convection model is the CM.

Table 1. Initial angular momentum adopted for the models

Mass ($M_\odot$)	J_0 (g cm^2 s^{-1})
1.2	1.874×10^{50}
1.1	1.720×10^{50}
1.0	1.566×10^{50}
0.9	1.412×10^{50}
0.8	1.257×10^{50}
0.6	9.470×10^{49}

lations were done under both mixing length formalism (MLT), with α (ratio of the mixing length λ to the pressure scale height) set to 1.5, and the Full Spectrum of Turbulence (FST) model employing the fluxes by Canuto & Mazzitelli (1991, 1992, hereinafter referred to as CM). A full description of the characteristics of this model can be found in D'Antona et al. (1997). Here we simply remember that the convective scale is taken to be the distance from the boundary of the convective region, increased by a small "overshooting" length β, which allows to precisely fit the solar model. Here the β is set to $0.175H_p$. Remember that this "overshooting" parameter regards only the mixing scale, and is not a parameter of chemical mixing. In any case, no real overshooting is allowed at the base of the convective layer, which would alter lithium depletion (e.g. Ventura et al. 1998).

3. Main results

3.1. Structural effects of rotation

We have calculated rotating stellar models of 0.6, 0.8, 0.9, 1.0, 1.1 and 1.2 solar masses. The results confirm what other researches have already found (e.g. Sackmann 1970; Pinsonneault et al. 1989; Martín & Claret 1996): the evolutionary tracks of rotating stars shift towards lower effective temperatures and luminosities, simulating the evolutionary path of a non-rotating star of lower mass (the so-called *mass-lowering effect*; see Sackmann 1970). However, we have also found that these differences are very small, being considerable only for high initial angular momentum, as can be seen from Fig. 1, where we also show the individual effects of rotation for each of the adopted rotation laws. Fig. 2 shows the time evolution of the surface angular velocity for the 1.0 $M_\odot$ models.

3.2. Rotation-induced lithium depletion

For the purpose of comparison with other works, we discuss here only the results for the rigid body rotation case, but we anticipate that, in accordance with previous work (e.g. Tassoul 1978 and references therein), our results are qualitatively the same for all rotation laws used, as the structural effects of rotation do not depend on the chosen rotation law when the initial angular momentum J_0 is kept fixed. Our main results can be summarized as follows:

a. while the star is fully convective, rotation causes an initial decrease in the lithium depletion rate.
b. soon after a radiative core is developed, this situation is inverted and rotation *increases* the lithium depletion.

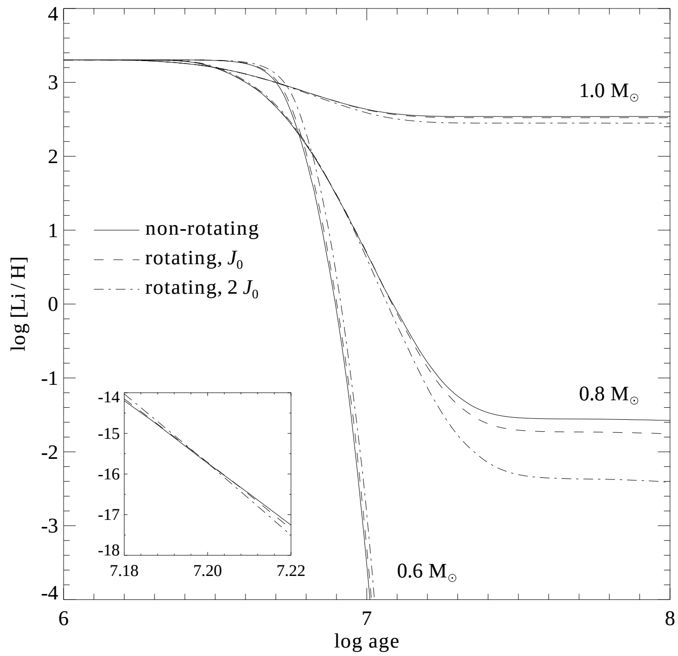

Fig. 3. Lithium depletion as function of age for $1.0, 0.8$ and $0.6\ M_\odot$ for two different initial angular momentum. The metallicity is Z = 0.0175 and the convection model is the MLT. The detail at the lower left corner shows the transition from lower to greater lithium depletion for the 0.6 $M_\odot$ model.

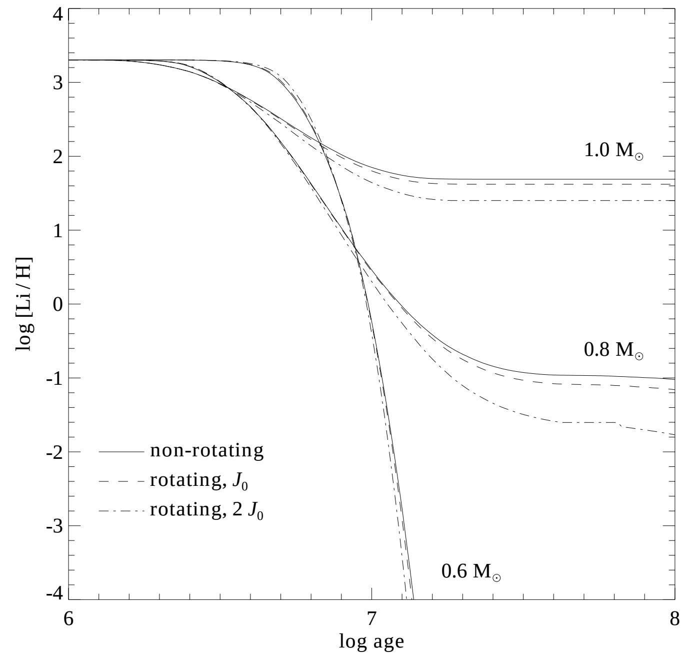

Fig. 4. Same as Fig. 3, but for the CM (1992) turbulent convection model. Note that, for this convection model, the transition from decreased lithium depletion to increased lithium depletion occurs at an earliest stage than for the MLT, as can be seen for the 0.6 $M_\odot$ model.

c. the higher the initial angular momentum, the higher the lithium depletion after the development of the radiative core.
d. the qualitative effects of the rotation-induced lithium depletion are equal for both mixing length theory and the Canuto & Mazzitelli turbulent convection model.

Figs. 3 and 4 exemplify these results, and show the variation of the lithium concentration (in the scale $N[\mathrm{Li}] = 12 + \log \frac{N[\mathrm{Li}]}{N[\mathrm{H}]}$) as a function of age, for masses of 1.0, 0.8 and 0.6 solar masses with two different initial angular momentum values (corresponding to J_0 and $2J_0$) and for both MLT and CM convection models. Items (a), (b) and (c) are fully compatible with the previous results obtained by Pinsonneault et al. (1990). This can be easily understood by recalling that rotating stars mimic lower-mass, non-rotating ones. So, as long as the rotating star is fully convective, its central temperature is smaller than that of the non-rotating case; this effect becomes more pronounced as we go toward smaller masses, as they have smaller moments of inertia. On the other hand, this situation changes when the radiative core develops, for then the temperature at the base of the convective envelope results higher in the rotating stars than for the non-rotating ones, and so contributes to greater lithium depletion specially for low-mass stars in their pre-main sequence stages (Bodenheimer 1965; D'Antona & Mazzitelli 1984). This can be seen in Fig. 5, where we plot the run of the temperatures as a function of age for both rotating and non-rotating 0.8 $M_\odot$ and 0.6 $M_\odot$ solar models. Item (d) is a trivial result, and it simply tells us that the *structural* effects of rotation are not affected by the chosen convection model.

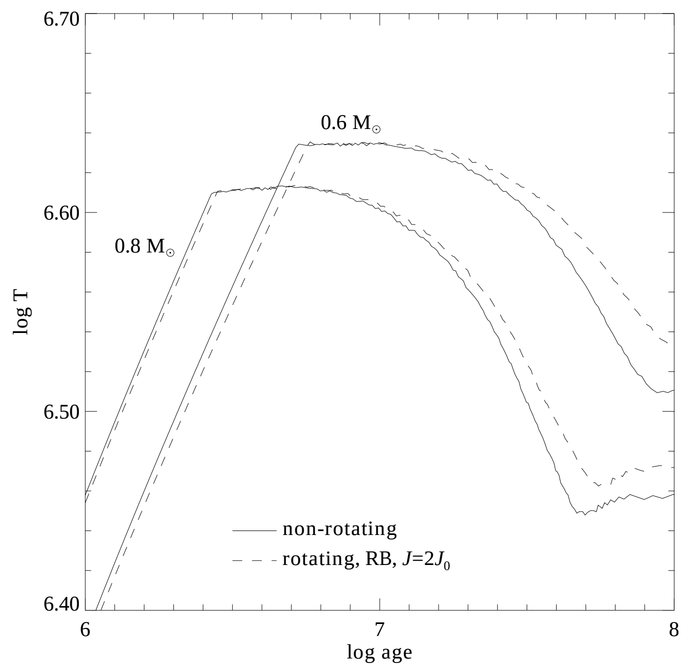

Fig. 5. Temperatures at the base of the convection zone for rotating and non-rotating stellar models of 0.6 $M_\odot$ and 0.8 $M_\odot$. For the linear part (fully convective phase) this refers to the central temperature. Results shown for the MLT model.

It is also worth to compare the run of lithium concentration against the effective temperature with those of D'Antona & Mazzitelli (1994). Fig. 6 exemplifies our results, and shows that using the more recent opacities of Iglesias & Rogers (1993)

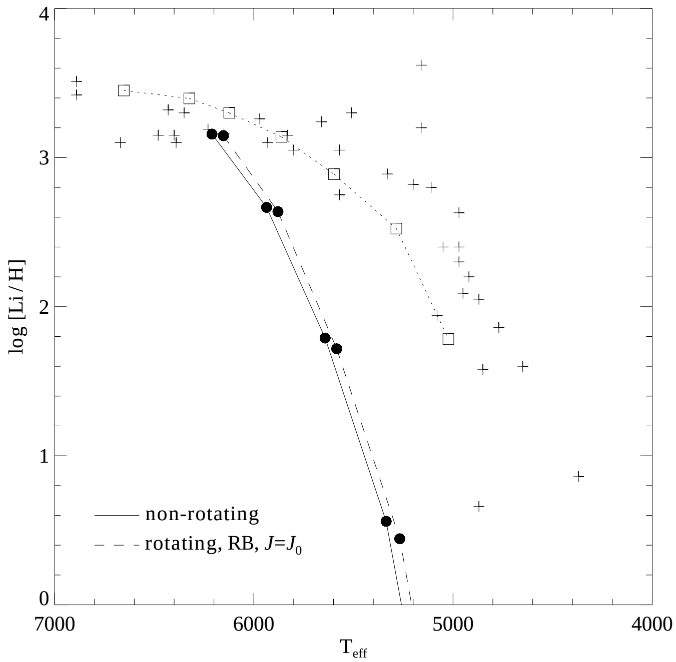

Fig. 6. Lithium abundance as a function of the effective temperature at the age of 5×10^7 years; the squares and filled circles mark masses ranging from 1.2 to 0.8 solar masses with steps of 0.1. The dotted line is the respective one from the "ku cm" model of D'Antona & Mazzitelli (1994, their Fig. 19). The crosses are the α Persei data from Balachandran (1996). For ease of comparison with the former authors, the initial lithium concentration was normalized at $\log N[Li] = 3.5$, though it is probably lower (~ 3.3).

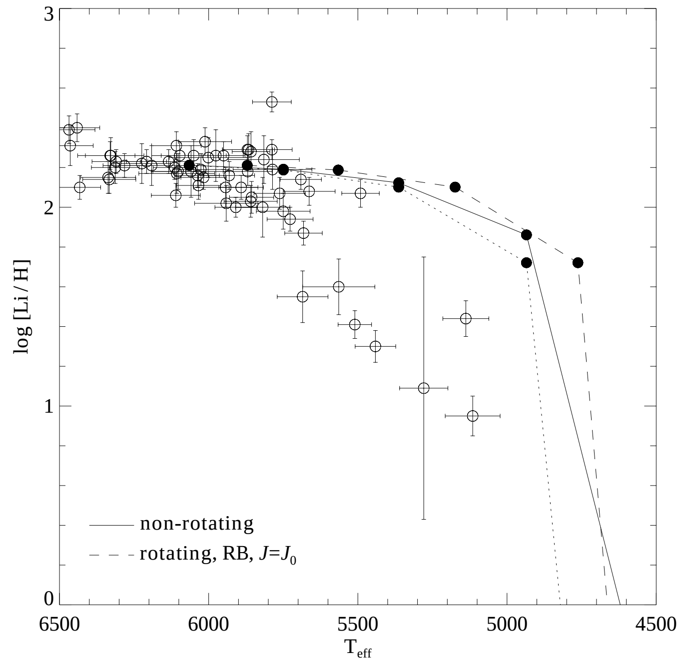

Fig. 7. Lithium depletion as function of effective temperatures for non-rotating and rotating models, at Z=0.001. The open circles refer to the lithium abundances of halo subdwarfs from Bonifacio & Molaro (1997), while the filled ones have the same meaning as in Fig. 6. The dotted line corresponds to the rotating models but at the same effective temperatures of the non-rotating models.

has a stronger effect on lithium depletion than rotation itself. It also shows that the non–rotating models have a larger $T_{\rm eff}$ than the rotating models of the same mass, so that, for a given $T_{\rm eff}$, the rotating sequence actually shows a *lower* depletion than the non–rotating sequence. Notice however that:

1. the effect is very small, especially compared to what is required to explain the observed spread;
2. when the age increases, the total angular momentum will not be conserved, and the main sequence location of the initially fast rotating models will become even closer to the non–rotating main sequence. (This caveat is even more important when discussing the very old population II stars, whose rotation rate today is certainly much reduced with respect to the rate on arrival to the main sequence, 10 billion years ago).

3.3. Low metallicity stars

As we have seen, the lithium depletion of both rotating and non–rotating models of solar metallicity, employing the most updated opacities, equation of state and convective fluxes, is incompatible with the lithium observations of young open clusters, while the D'Antona & Mazzitelli (1994) results were at least partially compatible with them (see Fig. 6). Previous generation models gave much too low lithium depletion to explain the open clusters patterns, so that the necessary additional depletion was generally attributed to secondary mixing mechanisms acting on a timescale much longer than pre–main sequence burning. In the presence of a larger than necessary pre–main sequence lithium burning, a possible escape from this problem would have been that rotating models structurally deplete less lithium (Martín & Claret 1996), but this is not confirmed by our computations.

We must then answer the following immediate question: does this problem occur also for the population II stars, that is, is the "Spite plateau" of low metallicity subdwarfs *preserved* in computations adopting the same updates in the physics? To answer this problem, we have computed models of non rotating and rotating stars of 0.7, 0.65, 0.60, 0.55 and $0.50 M_\odot$, with metallicity Z=0.002. The results are presented in Fig. 7, where our model stars, at an arbitrary large age of 10^{10} years, are superimposed on the observational data of Bonifacio & Molaro (1997). Here we plot the rotating models both at their own $T_{\rm eff}$ (dashed line) and at the $T_{\rm eff}$ of the non–rotating models (dotted line) considering that, after 10 billion years, rotation will have been drastically slowed down due to mechanisms of angular momentum loss. We see that the plateau is maintained in both rotating and non rotating models. This is reasonable, as the Livermore new computations have acted mainly to increase the population I values of opacities, and the global effect of improvements is less critical when the metallicity is drastically reduced. This result is particularly welcome, as the "Spite plateau" is certainly one of the most firm constraints for our knowledge of population II lithium abundance. The debate rests,

Table 2. Lithium depletion values for the low-metallicity (Z=0.001) rotating and non-rotating stellar models. The labels NR and R at each stellar mass stand for non-rotating and rotating models, respectively.

Mass ($M_\odot$)	Age= 2×10^7 yr		$Age=1\times10^{10}$ yr	
	$\frac{N(Li)}{N_0(Li)}$	log [Li/H]	$\frac{N(Li)}{N_0(Li)}$	log [Li/H]
0.70 (NR)	0.963	2.212	0.963	2.212
0.70 (R)	0.961	2.211	0.961	2.211
0.65 (NR)	0.921	2.192	0.919	2.191
0.65 (R)	0.917	2.190	0.911	2.187
0.60 (NR)	0.816	2.140	0.786	2.123
0.60 (R)	0.801	2.132	0.748	2.102
0.55 (NR)	0.555	1.972	0.431	1.862
0.55 (R)	0.511	1.937	0.313	1.724
0.50 (NR)	0.120	1.308	0.003	−0.336
0.50 (R)	0.009	1.172	6.3×10^{-7}	−3.970

in this field, on the reality of the dispersion or even trends in abundance among the plateau stars, appreciated by some researchers (e.g. Deliyannis et al. 1993; Thornburn 1994; Ryan et al. 1996) but disputed by others (Molaro et al. 1995; Spite et al. 1996; Bonifacio & Molaro 1997). Apart from the cosmological implications it raises, the possible existence of a dispersion on the plateau (if any) would indicate the action of some stellar and/or Galactic processing. Candidates for the stellar processing have been considered in the literature, such as rotational mixing (Pinsonneault et al. 1992), microscopic diffusion (Chaboyer & Demarque 1994) or stellar winds (Vauclair & Charbonnel 1995). Though we have not yet included the effects of rotational mixing in our models, Fig. 7 shows that additional mixing mechanisms are needed to explain the pattern of lithium abundances below $T_{\rm eff}\sim5800$K, which can not be attributed to standard mixing.

As for the structural effects of rotation, our models show that they become significant only for stars with $T_{\rm eff}<5400$K, that is, away from the plateau. Also burning during the main sequence lifetime is important for these stars (although not as significant as the pre–main sequence burning) as it can be seen from the data in Table 2.

4. Discussion and final remarks

It is important to stress that our results are qualitatively similar to those from Pinsonneault et al. (1990), but were obtained with updated opacities; so, the differences between these results and those by Martin & Claret (1996) cannot be attributed to the adopted opacities, as suggested by the latter authors. Besides, preliminary tests using Martin & Claret's less accurate gravitational potential did not change our overall results.

We have seen that the *structural* effects of rotation on the lithium depletion of low-mass, pre-main sequence stars can not reduce the difference between theoretical and observed lithium depletion patterns: in fact these effects *increase* lithium depletion, while a reduction would be needed, to be consistent with the smaller depletion in faster rotating stars in young open clusters. This situation can become even worse if we take into account the cumulative effects due to the rotation-induced mixing caused by the internal redistribution of angular momentum, which is highly dependent of the hydrodynamical instabilities triggered by rotation (see e.g. Zahn 1993). In fact, the results of Pinsonneault et al. (1990, 1992) suggest that this rotational mixing increases even more the lithium depletion of such stars. In order to check for this effect, current work is in progress to introduce angular momentum loss and redistribution in the ATON code.

On the other side, as pointed out by Strom (1994), the *older* pre-main sequence stars (those ones with ages close to the Hyades, and whose surface velocities are decreasing due to surface angular momentum loss) exhibit a correlation between rotation and lithium depletion opposed to that seen in pre-main sequence stars, that is, the faster rotators show a greater degree of lithium depletion. This clearly shows that other physical mechanisms must play a role on the lithium depletion pattern of low-mass stars, both pre-main sequence and more evolved ones. For example, Spruit (1987) argued that the larger dynamo-induced magnetic fields in rapid rotators could inhibit turbulent mixing. A preliminary analysis of this possibility is successfully explored by Ventura et al. 1998.

For the low metallicity subdwarfs, we can say that the structural effects of rotation are negligible for those ones which lie on the Spite plateau. However, as the effective temperatures at which significative depletion begins are lower, for the theoretical models, than those observed in such stars, once again we are lead to the conclusion that other physical mechanisms must be taken into account if we want a better match with the observations.

Acknowledgements. The authors wish to thank Drs. L. P. R. Vaz and E. L. Martín for their helpful comments and suggestions, and are also indebted to the referee for pointing out many improvements to the manuscript. Luiz T. S. Mendes thanks the hospitality of the Osservatorio Astronomico di Roma, where part of this work was carried out. Partial financial support from the Conselho Nacional de Pesquisa e Desenvolvimento (CNPq), Brazil, and from the Consiglio Nazionale delle Ricerche (CNR), Italy are acknowledged.

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