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Pre-main sequence Lithium burning: the quest for a new structural parameter

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Abstract. We present the results of stellar evolutionary computations to study the sensitivity of lithium depletion in models of mass and metallicity close to solar, and its dependence on the micro – macro physical inputs in the models, like thermodynamics, mixing, overshooting and the convective model. We find that even marginal chemical inhomogeneities in stellar formation regions lead to a spread in Li–abundances for such stars.

We show that a general update in the physical inputs reverses the previously established framework of the problem: solar models including the most recent opacities and equation of state, a Full Spectrum of Turbulence (FST) convection theory and a diffusive description of mixing deplete lithium very efficiently during the pre–Main Sequence (pre–MS). The present solar abundance could be then compatible with all the initial lithium having been burnt during this phase, with no need to invoke depletion during the MS lifetime. This new *standard* pre–MS Li–depletion is however not consistent with the observed Li–abundances versus mass in young open clusters (e.g. α Per and the Pleiades). We are then led to interpret it as *the maximum possible depletion* for non rotating, non magnetic stars, and look for physical mechanisms which can *inhibit* pre–MS depletion.

We then included in our code an approximated modeling of the influence of a magnetic field B on the convective envelope. We show that even relatively low values of B are sufficient to largely inhibit Li–depletion during pre–MS. A dynamo generated magnetic field of intensity related to stellar rotation would then lead to different Li–abundances at the end of the pre-MS phase, according to different rotational histories of stars, in qualitative agreement with the observed spread in Li–abundances in young open clusters stars.

We discuss the possibility that the right balance between magnetic field and metallicity (and overshooting, if any) can be the relevant parameter in the evaluation of the amount of ^7Li which should eventually survive after the pre-MS phase. Models of masses $1.25 \leq M/M_\odot \leq 0.7$ are compared with the open cluster $^7Li - T_{\rm eff}$ observations.

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1. Introduction

During the pre-MS phase, stellar temperatures rise to values at which light elements burning begins to occur. Lithium has been the subject of extensive work during the recent past (Bodenheimer 1965; D'Antona & Mazzitelli 1984; Vandenberg & Poll 1989; Proffitt & Michaud 1989; Deliyannis et al. 1990; Deliyannis & Pinsonneault 1990; Ryan et al. 1992; Swenson et al. 1994; D'Antona & Mazzitelli 1994) both due to its cosmological interest, and because it is regarded as a good indicator of the pre-MS history of stars. ^7Li is destroyed via the reaction $^7Li(p,\alpha)^4He$ starting at $T \sim 2.5 \cdot 10^6 K$, first at the centre of the star and then, if the temperature is large enough, also at the base of the convective envelope. This extablishes a tight relationship between the inward extension of the envelope and the amount of ^7Li left at the surface. We expect larger depletion in lower mass stars which, being cooler, have deeper envelopes and, more generally, in the presence of physical processes –like overshooting– which mix the surface matter with deeper and hotter layers.

Historically theoretical research on Li–depletion is connected with the following, still unsolved, problems:

i) the large observed solar Li–depletion, as compared to other solar–type stars.

ii) the spread in Li–abundance observed at the end of the pre–MS in young open clusters, at least for masses $M < 1.1 M_\odot$.

Point (i) deserves particular attention, since no theoretical model until now was able to reproduce the large drop in the solar ^7Li abundance, from the initial value of log $N(^7Li) \sim 3.3$ found in the solar system (Michaud & Charbonneau 1991) to the current value of log $N(^7Li)_\odot = 1.16 \pm 0.1$ (Anders & Grevesse 1989). Other depletion mechanisms have been then suggested, acting during the MS lifetime of the Sun. Examples are: rotationally induced mixing associated with the transport of angular momentum through the radiative – convective interface (Endal & Sofia 1976; Pinsonneault et al. 1990), complicated by the interaction between meridional circulation and turbulence (Zahn 1992; Chaboyer & Zahn 1992); gravitational settling (Michaud & Charbonneau 1991); both the above mechanisms (Chaboyer et al. 1995a,b); mixing by gravity waves (García Lopez & Spruit 1991; Schatzman 1993). A recent attempt to explain Li–observations for the Hyades through pre–MS depletion alone is by Swenson et al. (1994), who included in their models the Rogers & Iglesias (1992a) opacities, larger than former ones around the Li–burning temperatures. More pre–MS depletions was found than with previous models; the huge solar Li–depletion could not, however, be achieved (Faulkner 1991; Swenson & Faulkner 1992).

D'Antona & Mazzitelli (1994, hereinafter DM94) have shown that a key role for the inward penetration of the surface convective envelope is played by the turbulent convection model. Contrarily to the mixing lenght theory (MLT) based models, which predict relatively low Li–depletion, models employing the recent Canuto & Mazzitelli (1991, 1992) full spectrum of turbulence (FST) convection model displayed a quite large Li–depletion (by a factor $\sim$ 10). This *was not* consistent with the observations of open clusters (Martin 1997); in fact, the comparisons made in DM94 clearly showed that only FST models computed with the Kurucz (1993) low–T opacities, or MLT models with Alexander & Ferguson (1994) low–T opacities could be made consistent with the α Per data. Examining these results, Strom (1994) suggested that the Li–depletions in DM94 should be considered as the *upper boundaries* to pre–MS depletion.

More recently, several improvements in the input physics became available, and it is now worth to update the computations. The bottom line of the present work is that the new pre-MS "standard" solar models show such a huge Li–depletion that the solar ^7Li abundance can be achieved by pre–MS depletion only, without invoking any long–term MS mechanism. This result is at variance with our whole previous understanding of the observational patterns. In particular, even considering the result correct for the Sun itself, it *is not* possible that *all* stars of solar mass have the same large depletion in pre–MS, otherwise one can not explain lithium in young open clusters.

We then examine how Li–depletion depends on some physical and chemical inputs. In the end we introduce a new parameter and study –still in a first approximation– the influence of a magnetic field B on the thermal structures of the largely convective pre–MS stars (Spruit 1987). The results show that Li–depletion markedly decreases when increasing B; it can be orders of magnitude lower even with fields which, when emerging at the surface, are already quite low ($\leq$ 50G). As a strict correlation between the intensity of a dynamo–generated magnetic field and rotation is expected to exist, these findings qualitatively explain the correlation rotation – ^7Li which is found among open cluster stars and, in a first order approximation, also the quantitative, observed Li–abundances. This is seen when we finally show some comparisons of our results with observations of lithium in the clusters α Per, Pleiades and Praesepe.

2. Observational overview

Recently, more accurate measurements of ^7Li in F, G and K dwarfs in young open clusters became available. Among others, Soderblom et al. (1990, 1993a,b) Balachandran et al. (1988, 1996), Boesgaard (1987) and Boesgaard & Budge (1988), García Lopez et al. (1994), in a series of papers compared Li depletion in pre-MS low mass stars in α Per, Hyades, Praesepe and Pleiades. These clusters have nearly solar metallicity (Hyades and Praesepe have somewhat larger Z, and the Pleiades perhaps slightly lower –Boesgaard & Friel 1990) and ages ranging from $\sim$ 50Myr up to $\sim$ 600Myr (Henry et al. 1977, Boesgard & Budge 1988, Cayrel de Strobel 1990, Meynet et al. 1993). The results of these observations can be summarized as follows:

- stars with $M \geq 1.4M_{\odot}$ do not experience any pre-MS Li–depletion. They reach the MS with log $N(^7Li) \sim 3.3$, which is generally regarded as the initial Li–content for pop I compositions. Stars in the range $1.25M_{\odot} \leq M \leq 1.4M_{\odot}$ reach the MS with little or no Li–depletion.

- stars with $0.9M_{\odot} \leq M \leq 1.25M_{\odot}$ show evidence of Li–depletion during pre-MS. It is possible to fix a reasonably tight MS $T_{\rm eff}$ vs. log $N(^7Li)$ relation, with a small spread around the mean values.

- the picture completely changes for $M \leq 0.9M_{\odot}$, where the observed spread increases up to one order of magnitude or more. Only the Hyades preserve a tighter correlation for the MS $T_{\rm eff}$ – ^7Li abundance.

- the situation is even more dramatic for masses $M \leq 0.80 \div 0.75M_{\odot}$, where the spread can grow up to two orders of magnitude. Of course, one can not exclude that at least a fraction of this spread is of "observational" origin (namely it depends on observational scatter and/or on the interpretation of the observed equivalent widths in terms of abundances). Also note that, for $M \lesssim 0.8 \div 0.75M_{\odot}$, *all the theoretical models* foresee a complete Li–depletion in pre–MS, at variance with observations.

It is relevant to stress that the observed correlations log $N(^7Li)$ vs. $T_{\rm eff}$ for both αPer ($\sim$ 50Myr) and Pleiades ($\sim$ 100Myr) are very similar to one another. Since these two clusters have different ages, we can hypothesize that ^7Li depletion for these stars is largely determined by their pre-MS history, otherwise an age effect should be present too.

Also, given a value of $T_{\rm eff}$ (or, equivalently, of MS mass), an inspection of the run of log $N(^7Li)$ versus the rotational velocity ($v \cdot \sin i$, being i the unknown inclination of the rotation axis) shows that in most cases stars with lower rotational velocities have larger Li–depletion (Soderblom et al. 1993a). Indeed, Butler et al. (1987) first noticed that Li–rich stars within the Pleiades appeared to be rapid rotators, with rotational rates up to 100 times the solar one.

Insight on the problem could finally benefit also from results for locked binaries, whose low mass components generally present larger Li–abundances than single stars of same spectral type (and probably mass): see, e.g. Ryan & Deliyannis (1995), Barrado y Navascués & Stauffer (1996).

3. Input physics

We computed solar evolutionary tracks starting from early pre–MS, prior to D–burning, since our aim was to have physically realistic and thermally relaxed models when starting investigation of Li–depletion during pre–MS phases. The initial Li–abundance has been set to log $N(^7Li)$ = 3.3; we must however recall that the fractional amount of Li–depletion does not depend on the initial value since the $^7Li(p,\alpha)^4He$ reactions have no sensitive feedback on the structure of the star. The initial Li–abundance can be thus scaled up or down when making comparisons with given sets of observations (e.g. the open cluster data sets).

3.1. Microphysics update

The tracks have been computed by making use of the recently updated ATON 2.0 code; a complete description of it and of the input physics may be found in Mazzitelli et al. (1995) and in Ventura et al. (1998). We summarize here the most relevant features:

1 for the EOS we adopt Mihalas et al (MHD, 1988) in the range $\log T < 3.7$; $\log \rho < -2$; in the range $3.7 \leq \log T \leq 8.7$ the OPAL thermodynamics tables (Rogers et al. 1996) are instead used. In DM94 models only of the Mihalas et al. EOS was used;

2 we use Alexander & Ferguson (1994) opacities for $T \leq$ 6000K, and OPAL updated opacities (Rogers & Iglesias 1992a,b, Iglesias et al. 1992, Rogers & Iglesias 1993) at larger T: DM94 models were computed either with a preliminary release of Alexander opacities (1993, private communication), or with Kurucz (1993) opacities at low–T, and with the 1992 OPAL tables in the interior, which, around the Li-burning temperatures, displayed lower values of opacity than the following release, as discussed in Iglesias et al. 1992.

3.2. The convection model

The convective temperature gradient in the present models has been always evaluated via an FST model, with the updated turbulent fluxes by Canuto et al. (CGM 1996). In DM94 the FST computations had been performed with the previous Canuto & Mazzitelli (1991) fluxes. Only one test with the MLT has been performed for comparison. A detailed description of the use of the FST model (value of the Kolmogorov constant, convective scale length, a tiny amount of overshooting from the surface convective layer used as a *fine tuning* parameter β, as opposed to the *completely free tuning* parameter α in the MLT etc.) can be found in D'Antona et al. (1997, DCM), where also the main references to the successfull tests performed by various authors in various evolutionary phases can be found; in the following, unless otherwise specified, we will always imply that all the computations have been performed in an FST framework.

3.3. Treatment of overshooting

Convective overshooting should be in principle present in stellar structures, since it is an experimentally well known characteristics of any turbulent fluid. More difficult is to compute, starting from first principles, the amount of overshooting in stellar structures, and yet the information would be relevant when studying Li–depletion in pre–MS, since D'Antona and Mazzitelli (1984) have shown that it can play a crucial role by mixing the bottom of the shrinking convective envelope with deeper and hotter layers.

Overshooting is a non–local outcome of turbulence. Up today, all the attempts at getting simple recipes for stellar overshooting treating non–locality as a perturbation have failed (Canuto 1992). The few attempts at computing overshooting coupled to stellar structure in spite of the enormous numerical difficulties involved (Xiong 1985, Grossman 1996), have provided large "equivalent" overshooting thicknesses from a convective core ($> 1 \sim 1.5H_p$), not consistent with the much lower values ($\leq 0.25H_p$, Maeder & Meynet 1987, 1989; Stothers and Chin 1993) found when comparing observations of MS of young open clusters to results of parametric computations. Aa a matter of fact, the only semiempirical consideration which can help us in the present framework comes from Basu & Antia (1997). They have shown on helioseismological grounds that the overshooting from below the solar convective envelope cannot exceed $\sim 0.05H_p$. We will somewhat arbitrarily extend this latter conclusion to pre–MS stars of different masses, and perform test computations with instantaneous mixing below the formally convective envelope of 0.1 H_p at most.

3.4. Diffusive mixing

Since the nuclear ^7Li lifetimes at the bottom of the convective envelope can be of the same order of magnitude of the turbulent mixing times, the approximation of instantaneous mixing can be a very crude one, since even in the convective envelope ^7Li can show a non–flat profile, with a minimum at the convective bottom. Instantaneous mixing is then likely to provide an overestimate of the actual amount of ^7Li burnt in pre–MS. ATON 2.0 code also allows computations with diffusive mixing according to the diffusion equation (Cloutman & Eoll 1976) describing the local temporal variation of the i^{th} element, but including (burdensome) full coupling between nuclear evolution and mixing (Sackmann et al. 1974) for all the chemical species considered:

$$(\frac{dX_i}{dt}) = (\frac{\partial X_i}{\partial t})_{nucl} + \frac{\partial}{\partial m_r}[(4\pi r^2 \rho)^2 D \frac{\partial X_i}{\partial m_r}]$$

The diffusion coefficient D should be computed according to: $D = 16\pi^2 r^4 \rho^2 \tau$, where τ, the turbulent diffusion timescale, is a function of the one-point density-radial velocity correlation $< \rho_i' u' >= -\tau \partial \rho_i / \partial r$. Unfortunately, knowledge of the density–velocity momentum requires still unavailable solutions of the Navier-Stokes eqs. for a compressible stellar fluid in a huge variety of cases. We will then approximate D with $D = \frac{1}{3}ul_d$ where u is the average turbulent velocity and l_d the FST convective scale length.

Note that within the MLT the physical reliability of the above choice for D can be disputable, since the velocity is the one for the largest (unique) eddy, whereas turbulent mixing is experimentally known to occur at the smallest (dissipative) scales; moreover, the parametrization $l_d = \alpha H_p$ grows meaningless when approaching the convective boundaries, where the turbulent scale length can be orders of magnitude lower. In an FST environment both the above problems find solution, since the velocity is the weighted average over all the scales, and l_d is just the geometrical distance from the boundary.

In the following, we will always use the instantaneous mixing approximation since we are only interested in internal comparisons; one of these comparisons will be however performed also with a diffusive mixing pre–MS evolution. For more details on the diffusive scheme and on the numerical problems met with the inversion of the huge matrix required, see Ventura et al. (1998).

3.5. Influence of a magnetic field on convection

We finally describe how we dealt with the problem of including the effect of a magnetic field on convection. Stars in the pre–MS phase rotate relatively fast compared to the present Sun ($1 \lesssim P(days) \lesssim 10$, e.g. Bouvier et al. 1993), thus producing a magnetic field due to dynamo-effect. The rotational rate diminishes with age due to total angular momentum losses (e.g. Pinsonneault et al. 1989, Ghosh 1995). It is thus likely that the Sun itself experienced higher magnetic fields than the current one (surface $B_{\odot} \sim 1 \div 2$G).

In the case of MLT, Gough & Tayler (1966) and Moss (1968) included the effect of a small magnetic field B finding that the new criterion to get convective instability becomes:

$$\nabla_r \geq \nabla_{ad} + \delta, \qquad (1)$$

with $\delta = \frac{B^2}{B^2+\gamma P}$ where γ is the ratio of the specific heaths and P the local value of pressure. Including this latter term in the cubic equation for the flux, one then gets the convective (superadiabatic) temperature gradient.

In the FST case, the equation for the flux is not an algebraic one and an analytic solution as in the MLT case cannot be derived. However, Eq. (1) is a modified Schwarzschild cryterion for convective instability independent of the convective model. As for the superadiabatic gradient, we tested the MLT case for values of δ in the range $0.0 \div 0.5$ and found that, as long as $\delta < 0.05$, the value of the gradient came out equal to the unperturbed one plus δ itself, the maximum discrepancy from this rule of thumb being of a very few percent of δ. Since the rule was found to hold for any flux (low or large), we assumed it to be valid independently of the convective model. We then limited our FST computations to values of $\delta \leq 0.05$, evaluating the FST temperature gradients as the gradients in the absence of magnetic field increased by δ. This confined us to values of B at the surface lower than $\sim$ 70G for all the masses considered here. Should it turn out from a more sophysticated analysis that the above rule of thumb is not completely correct, the main framework of the results will not be substantially modified.

The next problem was how to scale the magnetic field from the surface deep inside the star, down to the centre or to the bottom of the convective envelope. Since we are in the line of including in the ATON code rotation according to Endal and Sofia (1976) approximation (Sanctos Mendes et al. 1997), we postpone the problem of evaluating the dynamo–generated field from first principles, and simply assume that the same ratio between magnetic and gas energy density found at the surface was preserved throughout inside the star. This corresponds to assuming that B^2 scales like P and, thus, $\delta \simeq$ const.

We are aware that this is the most disputable of our choices. Note however the following three arguments.

–*Semiempirical argument*: in the present sun, the surface magnetic field is about 1 G, while the magnetic field at the bottom of the convective envelope is thought to be of the order of some in 10^4 G (Spruit 1990), also on the ground of helioseismological results. If we consider the solar pressure stratification we find $\delta \sim 10^{-5}$, almost constant through the envelope.

–*Theoretical argument*: a fossil magnetic fields at the centre of solar–type stars at the end of the Hayashi phase can be as large as 10^7 G (Dudurov & Gorbenko 1991) while it is of the order of a few ($\sim$ 10) G at the surface. Also in this case we have $\delta \sim 10^{-3}$, constant throughout the star. The ratio E_m/E_g between magnetic and gravitational energy is then nearly constant, and the same we expect from the virial theorem for the ratio magnetic to gas energy in contracting pre-MS stars with no large sources of nuclear energy.

–*Epistemic argument*: in any case, we restricted our computations to relatively weak magnetic fields; for pre–MS stars, an extreme field larger than 10^3 G has been observed in TAP 35 (Basri et al. 1992). We can then say that, even if $\delta \neq$ const. inside the star, we expect in real stars larger values of δ close to the surface than the ones here considered, and perhaps lower values in deep layers, at least partially compensating. Let us then explicitly state that we are, in the present paper, interested to study the qualitative and semi–quantitative effect of the magnetic field due to rotation on Li–depletion; the values of the surface magnetic fields we will quote here ($\mathscr{B}$) are then not to be taken as the exact values of B at the surface of pre-MS stars, but are related to these latter in a way we will know only when detailed rotating models with dynamo will be available.

4. The "standard" model and the Lithium–mass relation

The main results are shown in Table 1 and in the Figs. 1 – 3. We will consider as "standard" track the solar model obtained by assuming chemical composition $Y = 0.28$, $Z = 0.02$. The helium abundance is obtained by requiring the fit of the present solar luminosity at the solar age of 4.6×10^9yr. The metallicity adopted is at the top of the range allowed for the solar model. A metallicity of $Z = 0.017 \div 0.018$ is probably more adequate (Grevesse 1984, Grevesse & Noels 1993) but, since we already

Table 1. Input parameters for the computed sequences

Model	$M/M_{\odot}$	Z	Y	Convection	EOS	λ_{ov}/H_p	$\mathscr{B}$	$\log N(Li)$
STD	1.00	0.020	0.28	FST(CGM)	OPAL	0.00	0	-0.62
M095	0.95	0.020	0.28	FST(CGM)	OPAL	0.00	0	-2.30
M105	1.05	0.020	0.28	FST(CGM)	OPAL	0.00	0	0.62
MIHEOS	1.00	0.020	0.28	FST(CGM)	MIHALAS	0.00	0	-0.03
MLT	1.00	0.020	0.28	MLT	OPAL	0.00	0	1.72
DIFFMIX	1.00	0.020	0.28	FST(CGM)	OPAL	0.0	0	-0.15
varY	1.00	0.020	0.27	FST(CGM)	OPAL	0.00	0	-0.93
varZ	1.00	0.017	0.28	FST(CGM)	OPAL	0.00	0	1.06
OV01B00	1.00	0.020	0.28	FST(CGM)	OPAL	0.1	0	-7.19
OV01B30	1.00	0.020	0.28	FST(CGM)	OPAL	0.1	30	1.93
OV005B15	1.00	0.018	0.28	FST(CGM)	OPAL	0.05	15	0.71
OV005B20	1.00	0.018	0.28	FST(CGM)	OPAL	0.05	20	1.55

know that, the larger Z the larger Li–depletion (D'Antona & Mazzitelli 1984), we chose the upper limit for $Z_{\odot}$ as it amplifies the effect of the different parameters on pre-MS Li–burning.

The standard track shows a much larger Li–depletion than in DM94 (present depletion about three orders of magnitude larger). Part of the difference is due to the different value of Z (0.019) adopted in DM94 since, as we already know and are going to better elucidate, around the solar metallicity, Li–depletion for a star of solar mass is a strong function of Z. Another fraction of the difference is due to the update in the opacities, which are now somewhat larger than in the first OPAL release just at the temperatures of ^7Li burning (Iglesias et al. 1992), leading to slightly deeper convective envelopes. Also the thermodynamics conspired (see later) in increasing Li–depletion. Finally, the update of the FST convective fluxes from those by Canuto & Mazzitelli (1991) to the CGM ones (which are in the average larger, thus leading to lower superadiabaticities and deeper convective envelopes) again worked in the direction of increasing pre–MS Li–depletion (D'Antona & Mazzitelli 1997).

The present situation is then that, with the most updated physical inputs, we have a reverse problem with solar ^7Li with respect to a few years ago. In fact, the predicted pre–MS depletion is presently *too large* to explain observations. Not only there is no need to introduce slow mixing mechanisms acting during the MS to further deplete the still large abundance of ^7Li left after pre–MS; we now have the opposite problem of understanding if some plausible physical mechanism acting in pre–MS can counteract Li–burning.

We checked the variation in Li–depletion for a small variation in the total mass of the star. The ^7Li final abundance is a growing function of the mass as expected, since more massive stars have shallower convective envelopes in pre–MS. In Fig. 1 we show the huge difference in the final Li–abundance (three orders of magnitude) between the models of 0.95 (M095 track) and 1.05 $M_{\odot}$(M105 track). This result unambiguously shows that enormous care has to be taken when reducing observations from the ^7Li–$(B - V)_0$plane to a ^7Li–$T_{\rm eff}$ one through $(B-V)-T_{\rm eff}$ relations or, even more, to a ^7Li–mass relation.

Namely, a small observational uncertainty in the MS value of $(B - V)_0$, or small errors in the theoretical $(B-V)-T_{\rm eff}$ and MS $T_{\rm eff}$–mass relations would turn out in associating to a given star, of observed ^7Li abundance, a value of $T_{\rm eff}$ (or mass, almost linear with $T_{\rm eff}$ in the MS region of interest) slightly different from the real one. The very steep relation ^7Li–mass would then amplify the difference between the theoretically predicted Li–depletion for that "observational" mass and the actual ^7Li abundance. It is worth noting that exact knowledge of the chemistry of the observed sample of stars is required, since both $(B-V)-T_{\rm eff}$ and $T_{\rm eff}$–mass relations are a function of Z.

5. Thermodynamics and convection theory

Before entering the discussion of the possible explanations for both the presently observed solar ^7Li abundance and abundances observed in young open clusters, let us warn the reader about uncertainties still weighing on the main micro/macro–physical inputs. This should help understanding the degree of reliability of the present generation of theoretical models, and avoiding trivial mistakes when rising conclusions from comparisons between observational and theoretical data.

First we will discuss the effect of the thermodynamic treatment on Li–depletion in pre–MS, mainly through the value of the adiabatic gradient which, in the end, determines the thickness of the convective envelope. In Fig. 1 we show the standard track compared to a track (MIHEOS) computed assuming, as the only difference, the Mihalas et al. (1988) equation of state in place of the OPAL one. Remember that in DM94 the Mihalas et al. EOS was adopted.

The MIHEOS track shows lower Li–depletion than the STD one by a factor 4. In order to understand the reason for this apparently large difference between results arising from two apparently equally updated thermodynamic treatments, we computed several tracks by increasing from 5000 K (as in the standard track) to larger and larger values of T the point at which we switch from the Mihalas et al. to the OPAL EOS. The final Li–abundances were the same as for the STD track as long as the Mihalas et al. EOS was substituted only up to relatively

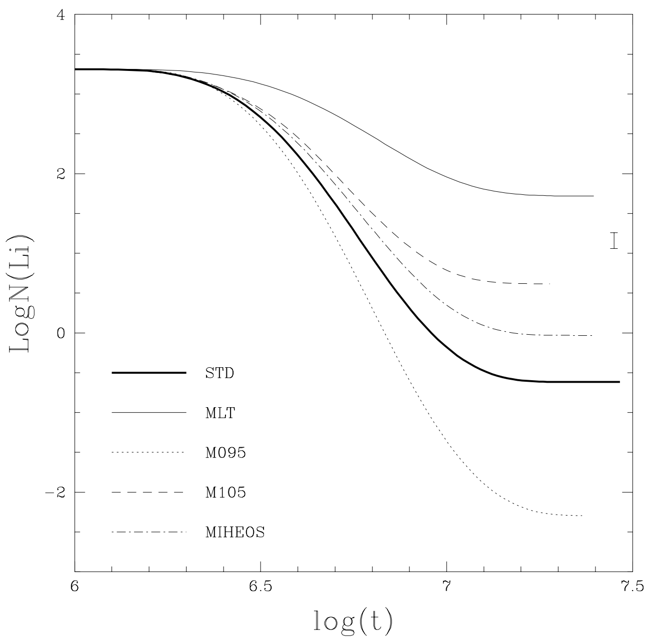

Fig. 1. Comparison between the standard model lithium depletion as a function of log age and models differing in mass (0.95 and $1.05M_{\odot}$), or in the EOS, or in the convection treatment. The depletion with the Mihalas et al. thermodynamics is smaller by a factor ~ 4, due to the different behaviour of the adiabatic gradient in the partial ionization regions. The MLT model leads to lower pre-MS Li-depletion than the FST model, due to the lower convective fluxes, large superadiabaticity and narrower convective regions.

low T's (that is: below H and He–ionization, $2 \times 10^4 \div 10^5$K). When, on the contrary, it was adopted also to describe the H and He–ionization region, the resulting Li–depletion suddenly decreased and never changed any longer, also increasing the transition temperature to 5×10^6 K, well past Li–burning.

The difference is then in the treatment of the partial ionization regime, namely in the value of the adiabatic gradient in those regions which largely influence the convective envelope thickness. It is presently hard to say which of the two EOS' is more physically sound: we chose the OPAL one both for consistency with the opacities and because extensive tables are provided for several H–abundances at a given Z. However, a warning immediately arises: since pre–MS Li–depletion is largely affected by the value of the adiabatic gradient in partial ionization regime, no interpolation between pure–H and pure–He compositions can be adopted in these computations, since pure element compositions do not include the reciprocal influence of ionization, which is instead dominant for the effect under scrutiny (Saumon et al. 1995). An indirect proof of the importance of having a correct treatment of the adiabatic gradient will result at the end of Sect. 8, where we discuss the computations including a variable magnetic field.

Next test deals with the influence of the convection model on Li–depletion. In Fig. 1 we show the difference between the standard track and an MLT one (MLT track) computed with the value of the free parameter fitting the present sun, that is: α = 1.55. Pre-MS Li–depletion is orders of magnitude lower, as expected since the MLT fluxes are too low, and they require in the average larger values of superadiabaticity than any FST treatment. The convective envelope is then shallower and Li–burning stops at an earlier phase.

6. Chemistry, magnetic field, diffusion and overshooting

As anticipated, Z=0.02 is likely to be an upper limit for the solar metallicity. In Fig. 2 we present our results obtained by varying the chemical composition of a solar mass star. A relatively large change in ^4He abundance causes small variations in the ^7Li final abundance, while a 15% decrease in the value of Z makes the ^7Li abundance to vary *by almost two orders of magnitude*. The higher Z track results in a larger depletion, as in that case we know that opacity is larger and the convective envelope gets deeper. The assumption $Z_{\odot}$ = 0.017 might give a value for the final ^7Li abundance which is in excellent agreement with that presently observed. However, we are not claiming that this solves the problem of the sun, both since Z=0.017 is only a lower limit for the solar metallicity, and because of the still unknown effect possibly due to other physical inputs (see later).

In this framework, it is interesting to speculate that even small chemical inhomogeneities in a cloud giving birth to an open cluster might be responsible of a fraction of the observed ^7Li abundances spread detected in young clusters.

We then discuss the results obtained for the solar model when including the effect of the magnetic field as discussed in Sect. 4.4. As already mentioned, the magnetic field forces larger convective temperature gradients, thus leading to a minor penetration of the convective envelope and to less ^7Li depletion. We therefore expect higher ^7Li abundances for higher values of $\mathscr{B}$, which is actually what we observe from Fig. 3. We see that a value of the solar magnetic field of $\mathscr{B}_{\odot}$ = 15 G might lead to the observed Li abundance in the Sun with no need of further hypotheses.

This result, although only semi–quantitative as above noted, is to be taken seriously. At present, the debate about the mechanisms generating magnetic fields in stellar structures (including fossil magnetic fields) is still open, and even in the presence of rotating stellar models it would not be so easy to give sound quantitative estimates of the internal profiles of B starting from first principles. Nevertheless, hints about the solar internal constitution and measurements of surface magnetic fields (and rotation periods) of pre–MS stars do not exclude at all –not to say suggest– the presence of internal magnetic fields of magnitude even larger than those adopted in the present computations. As an example, the track $\mathscr{B}$=20 G would require, at the base of the convective envelope and at the end of the pre–MS Li–burning phase, $\mathscr{B} \sim 3 \times 10^6$G.

We also tested the diffusive algorithm for coupled Li–burning and mixing. Although the nuclear lifetimes of lithium at the bottom of convection turned out *relatively* long with respect to mixing times, a profile of ^7Li was indeed detected inside the convective region, and this led to a not negligible cumulative

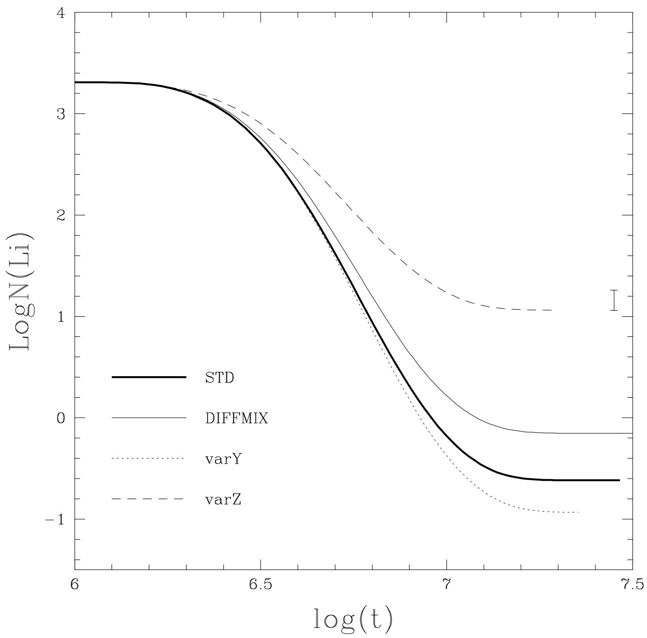

Fig. 2. Effects of different chemical abundance on solar pre-MS Li depletion. A reduction of Z within values still acceptable leads to a decrease of two orders of magnitude in depletion, and to the observed abundance. Also the results obtained with a diffusive algorithm coupling nuclear burning and turbulent mixing are shown. Li–depletion is decreased by a factor 3; this is to be kept in mind, since diffusion is a more physically sound approximation than instantaneous mixing.

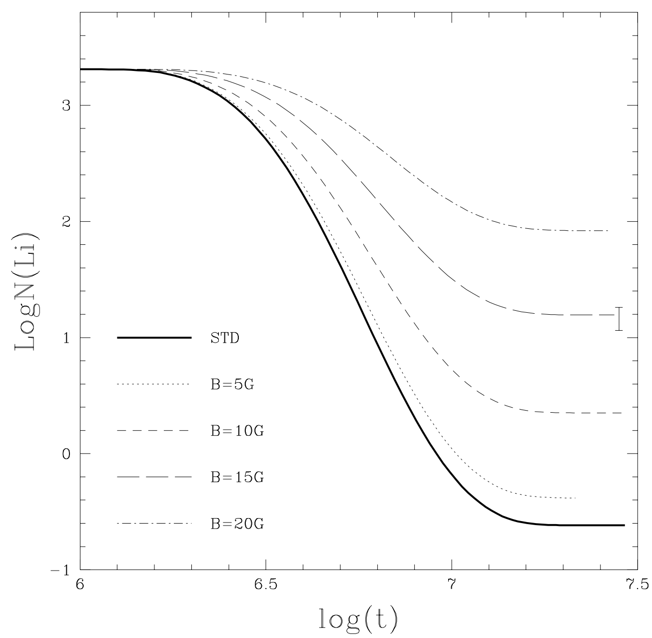

Fig. 3. Effects of different magnetic fields on solar pre-MS Li depletion. The larger is $\mathscr{B}$, the lower is Li depletion. Note that the value of δ (extra–gradient) for all the tracks shown never reached up $\delta = 0.01$.

effect at the end of pre–MS burning: Li–depletion turned out to be 3 times less than with instantaneous mixing.

Although this result cannot yet be assumed as definitive, since it depends on the approximations adopted to model the diffusive coefficient, it is nevertheless instructive. A "sensible" model for diffusion, which is already likely to be more physically sound than instantaneous mixing, does affect pre–MS Li–depletion and has to be included in all the future computations if absolute, quantitative results are to be looked for. We recall the reader's attention on the fact that, like in the case of Li–production in the convective envelopes of asymptotic giant stars (Sackmann et al. 1974), nuclear depletion and mixing are to be treated *together*. Separately applying nuclear evolution and then diffusive mixing would lead nowhere.

Overshooting too may influence the amount of lithium which is burnt: this is because it carries ^7Li inside deeper regions, where it is destroyed: models computed with overshooting will necessarily have smaller residual abundance of Li. D'Antona & Mazzitelli (1984) found that an overshooting distance $\lambda_{ov} = 0.7H_p$ was necessary to fit the Hyades $\log N(^7Li) - T_{\rm eff}$ curve; yet this extra-mixing was not enough to reproduce the solar observed value. Vandenberg & Poll (1989), adopting more recent (and larger) opacities (LAOL: Huebner et al. 1977), showed that a lower extra-mixing ($\lambda_{ov} = 0.25H_p$) was required to fit the same cluster.

These attempts to increase Li–depletion were justified by the large values of residual Li–abundances found in low mass stars with solar metallicity, with the opacities of the epoch and by adopting the MLT to describe turbulent convection. As we have seen, the problem is now reversed. And yet overshooting can be present, and we better study also the effect of this feature on pre–MS Li depletion.

The effect of an overshooting $\lambda_{ov} = 0.1H_p$ from the base of the convective envelope in our models can be seen in Table 1 in the model OV01B00. Li–depletion is increased by more than six orders orders of magnitude; this effect, however, can be more than completely reset by a magnetic field of $\mathscr{B}$ = 30G only (model OV01B30). It seems then reasonable that a balance between metallicity, magnetic field and overshooting can play a key–role in determining the real extent of pre–MS ^7Li depletion inside the stars.

A possible reasonable metallicity for the solar model might be $Z = 0.018$ (Grevesse & Noels 1993). Together with an overshooting of $\lambda_{ov} = 0.05H_p$, model OV005B15 shows that the current solar situation may be easily reproduced if we hypothesize that a magnetic field $\mathscr{B} \sim$ 15G was present in the Sun during the pre-MS phase, and working with diffusive mixing. This is our present reasonable guess for the pre–MS evolution of the Sun. With $\mathscr{B} \sim$ 20G (model OV005B20), room is left for some MS depletion associated with slow mixing mechanisms.

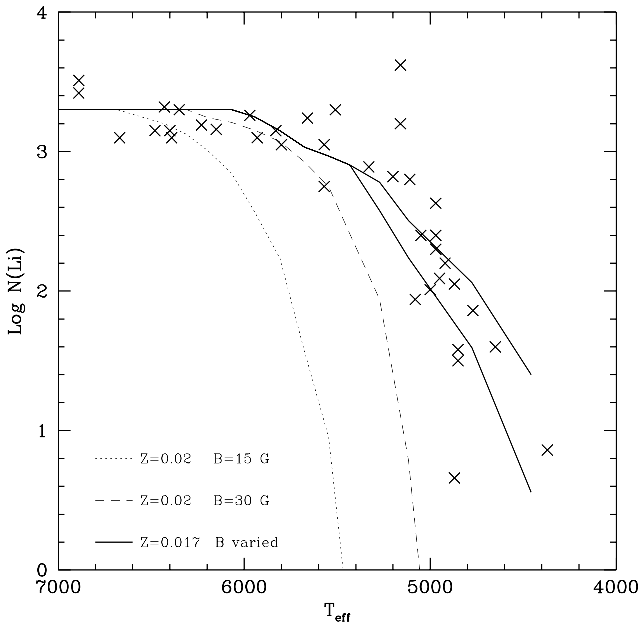

Fig. 4. Comparison of theoretical depletion seuqences with the α Per data by Balachandran et al. (1988, revised in 1996). The two solid lines are relative to magnetic fields increasing when decreasing the mass; the upper one corresponds to 5 G less than the lower one.

Table 2. Input parameters for the models with varied $\mathscr{B}$

$M/M_\odot$	Z	$\mathscr{B}$	$\log N(Li)$
0.70	0.017	50	0.54
0.70	0.017	55	1.40
0.75	0.017	45	1.48
0.75	0.017	50	2.07
0.80	0.017	40	2.22
0.80	0.017	45	2.51
0.85	0.017	35	2.59
0.85	0.017	40	2.79
0.90	0.017	35	2.91
1.00	0.017	30	3.04
1.00	0.020	5	-0.38
1.00	0.020	10	0.35
1.00	0.020	15	1.19
1.00	0.020	20	1.92

7. Possible effect of mass accretion on the final Lithium abundance

All the above discussion ignores possible pre–MS mass accretion from the disk. Accretion occurring *before* the major Li–burning stage is not relevant in this context, but accretion *during* or *following* the burning phase may be relevant. Let us compare the accretion timescales $M/\dot{M}$ with the evolutionary (thermal) pre–MS timescales $t_{KH} \sim 2\times10^7 M^2/RL$ (M, L and radius R in solar units). For the Sun, the main Li–depletion phase occurs at $L_{Li} \sim 0.6 L_\odot$, while the radius is already close to the present one. Then $t_{KH} \sim 2\times10^7/L_{Li}$, and accretion rates as large as $\sim 3\times10^{-8} M_\odot$/yr can affect the stellar and the surface lithium evolution; rates comparable to those observed in some classical TTauri's (e.g. Basri & Bertout 1989). Unfortunately, performing numerical computations with rotating models accreting from a disk is still far ahead of us; here we can only treat accretion as a first order perturbation –from the point of view of the surface chemistry– to hydrostatic, constant mass models. We have two cases:

- accretion only *during* the Li–burning phase: the mass of the star will be *larger* at the end of burning, so it will show *less* lithium than that due for its final mass (remember how much Li–depletion increases when decreasing total mass). This possibility is interesting, but can not help us, as we are looking for mechanisms leading to less Li–depletion in pre–MS.

- accretion also *after* the Li–burning phase. This case has been already discussed by D'Antona (1993). Starting from a $0.95M_\odot$star and accreting $0.05M_\odot$with interstellar Li–abundance, dilution will occur in the convective envelope which, at the end of Li–burning, is still $\sim 0.2M_\odot$. The final surface Li–abundance will be then about 1/4 of the interstellar one, consistent with those detected in some solar mass stars in open clusters.

Late accretion could be then, in principle, a way to increase the surface Li–abundance at the end of pre–MS. There is however an observational hint that this mechanism is not so efficient, at least in the majority of stars. The rotation rate attained by stars when they reach the MS depends on the variation of momentum of inertia during the pre–MS and on the exchange of momentum with the surroundings. It is commonly accepted (Königl 1991, Cameron & Campbell 1993) that the magnetic linkage between the star and the disk prevents the star's spin up which would be due to the decrease of the momentum of inertia in the approach to the main sequence. Stars preserving a disk (and accreting) for longer times will be then *slower* rotators on the MS (e.g. Bouvier 1994). Actually, observations indicate that *faster* rotators (having presumably lost their disks in earlier phases) display more lithium. The interplay among rotation, accretion and Li–depletion is far from being understood!

8. The case of open clusters

On the basis of the above discussion, our tentative explanation for the low solar Li–abundance is that it was achieved as a result of pre–MS depletion in a star left, in its first evolutionary phases, with a small rotation rate, possibly due to the formation of the planetary system. Only a small dynamo generated magnetic field could then counteract the "standard", large depletion suggested by our models for non rotating or slowly rotating stars, which should destroy lithium more efficiently than faster rotating stars. This is also consistent with the large spread of abundances found by King et al. (1997) among the Sun and the solar twins 16 Cyg A and B: the two components of this system differ in Li–abundance by a factor ≥ 4.5, bracketing the solar abundance and testifying that the solar surface Li–evolution is not an isolated anomaly. Although King et al. (1997) line of reasoning is very

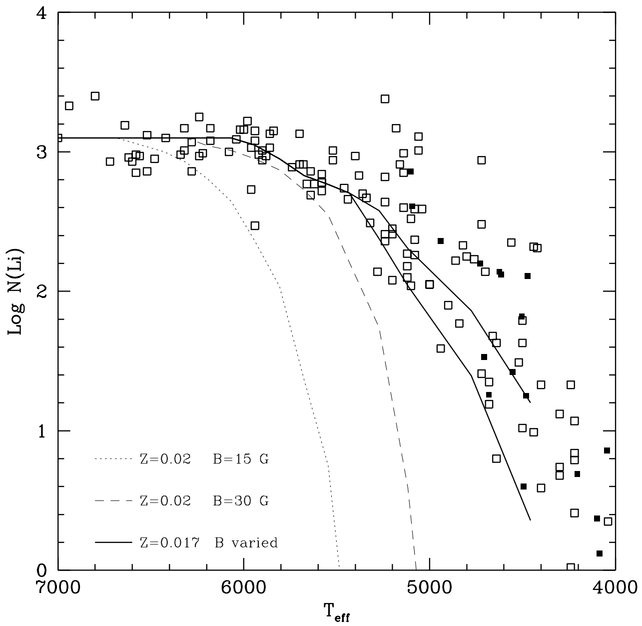

Fig. 5. Comparison of theoretical depletion seuqences with the Pleiades data by Soderblom et al. (1993a) (open squares) and by García Lopez et al. (1994) (full squares).

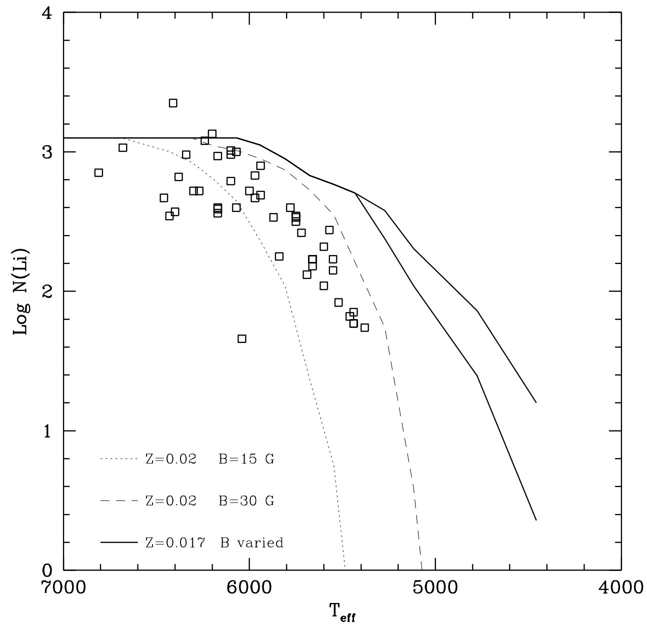

Fig. 6. Comparison of theoretical depletion sequences with the Praesepe data by Soderblom et al. (1993b).

different from ours, we come to the same conclusion that the formation of a planetary system, with the associated loss of angular momentum from the star, could go together with larger Li–depletion.

We however know that some $1M_\odot$ star in open clusters should maintain a large fraction of their ^7Li, if we wish to reproduce the observed correlation ^7Li–$T_{\rm eff}$ for the cluster stars. It is then important to understand which parameters influence this correlation, to get a consistent –though preliminary– framework of Li–evolution.

We show in Fig. 4 the α Per data by Balachandran et al. 1988 (as revised by Balachandran et al. 1996) compared with some "depletion curves". We show the $\mathscr{B}$=15 and $\mathscr{B}$=30G depletion lines for Z = 0.02, which *do not agree* with the observations. In order to reproduce the average envelope of the ^7Li–$T_{\rm eff}$ relation we need to reduce the metallicity to Z = 0.017 (a reasonable choice) and to introduce a "variable" magnetic field, almost linearly increasing for decreasing mass (see Table 2). The fit of the observed data is thus "ad hoc", and indicates, as a zero order approximation, that the average $\mathscr{B}$ (or rotation rate?) must increase with decreasing mass. Note that, also for the largest values of $\mathscr{B}$, we always got in our models $\delta < 0.02$. This latter result indirectly tells us also that an over (under) estimate of the *true* value of the adiabatic gradient by $\sim$ 0.01 would lead to orders of magnitude of under (over) estimate in the Li–depletion. This adds quantitative information to our previous discussion about the influence of thermodynamics through the adiabatic gradient.

The same holds for the Pleiades data by Soderblom et al. (1993a) and García Lopez et al. (1994) shown in Fig. 5: here we see more clearly that the low mass stars with larger abundances can be reasonably fitted by assuming that these stars had larger magnetic fields during their pre–MS evolution, probably due to higher rotation rates.

As for the Praesepe (Soderblom et al. 1993b), we see in Fig. 6 that the data can be explained by larger metallicity and smaller rotation rates, corresponding to the two curves of $\mathscr{B}$ = 15G and 30G. The metallicity of Praesepe is in fact close to the Hyades one, and larger than solar (Boesgaard & Budge 1988). Also notice that the low values of Li–abundances at $T_{\rm eff} \simeq 6500$ are already affected by the depletion due to the presence of the "lithium dip" first found in the Hyades (Boesgaard & Budge 1988).

In conclusion, playing a little with magnetic fields, and recalling that part of the observed spread can be due both to observational problems and to the large sensitivity of Li–depletion on mass and chemical composition, the procedure here adopted seems to be able to provide sensible fits to the observations, spread included, even if we cannot claim "perfect" or "definitive" fits, in view of the several uncertainties still weighing on theoretical models.

9. Conclusions

We presented our new pre–MS solar models and discussed their sensitivity to some physical parameters like mass, magnetic field and metallicity, and to the input micro/macro physics.

A 15% decrease in the metallicity $Z_\odot$ adopted for the Sun, from $Z_\odot$ = 0.02, would bring the solar Li–abundance to the observed value. More generally, we may conclude that small inhomogeneities in the star formation regions might at least partially explain the large ^7Li abundance spread which is observed in low mass stars belonging to young open clusters.

We know that during the pre-MS phase stellar rotation produces non negligible magnetic fields via dynamo-effect. We therefore worked out a semi – quantitative description of how the picture presented changes due to the presence of a magnetic field $\mathscr{B}$, being aware of the fact that it contributes to inhibit convection, thus leading to higher residual Li–abundances. We show that a value of $\mathscr{B} \sim 10 \div 15$G would provide in pre–MS all the Li–solar depletion (but no more), if we adopt the FST model to estimate the convective fluxes, a metallicity $Z_\odot = 0.02$ and a diffusive treatment of turbulent mixing coupled to nuclear evolution. This latter description of mixing turns out to be mandatory if correct quantitative results are looked for. The usual MLT treatment of stellar convection is unable to reproduce the solar depletion, unless some extent of overshooting from the bottom of the convective envelope is invoked (of course, MS mechanisms of Li–depletion may act to bring the Sun to the present abundances.

A small amount of overshooting ($\lambda_{ov} = 0.05 \div 0.1H_p$) would lead to very low values of $\log N(^7Li)$, but this effect can be completely reset by a moderate magnetic field ($\mathscr{B} \sim 25 \div 30$G). The right balance between a magnetic field acting in the direction of increasing Li–abundance in these stars, and a possible overshooting which favours Li–burning, could then also play a key–role in determining which is the amount of lithium surviving destruction after the pre–MS phase.

Accordingly, the Li–spread observed in open clusters stars can be mainly attributed to differences in their rotational rates, though observational uncertainties and small chemical inhomogeneties might contribute too. Playing with magnetic fields, we can construct models which nicely fit the observed ^7Li–$T_{\rm eff}$ relation.

Before drawing definitive conclusions about the small value of the solar Li–abundance we must wait for a physically sound theory of the rotational history of the Sun during the pre-MS phase. Room is still left (even if not strictly required) for some amount of Li–depletion due to slow processes acting during the MS lifetime.

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