LITHIUM DEPLETION IN PRE–MAIN-SEQUENCE SOLAR-LIKE STARS

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ABSTRACT

We examine the internal structure of solar-like stars in detail between 0.8 and 1.4 $M_\odot$ and during pre–main-sequence phase. Recent opacity computations of OPAL along with a new hydrodynamical mixing process have been considered. We also introduce up-to-date nuclear reaction rates and explore the impact of accretion, mixing length parameter, nonsolar distributions among metals, and realistic rotation history. Models predict lithium depletion that we compare to the $^7$Li content observations of the Sun and four young clusters of different metallicities and age. We show that we can distinguish two phases in lithium depletion: (1) a rapid nuclear destruction in the T Tauri phase before 20 Myr, whatever the mass in our range and largely dependent on the extension and temperature of the convective zone, and (2) a second phase where the destruction is slow and moderate and which is largely dependent on the (magneto)hydrodynamic instability located at the base of the convective zone. Regarding composition we show the interest that takes on helium and above all the mixture of heavy elements: carbon, oxygen, silicon, and iron. We outline the importance of the O/Fe ratio. We note a reasonable agreement on lithium depletion for the two best-known cases, the Sun and the Hyades, for solar-like stars. Other clusters suggest that processes which may partly inhibit the predicted pre–main-sequence depletion cannot be excluded, in particular for stars below ~0.9 $M_\odot$. We finally propose different research areas such as initial stellar models and more realistic atmospheres which could contribute to understanding better this early phase of evolution and which will be the object of subsequent works.

Subject headings: convection — stars: abundances — stars: interiors — stars: pre–main-sequence — stars: rotation

1. INTRODUCTION

Dynamical effects have been mainly ignored in classical stellar evolution during several decades even if they have been explored theoretically (Zahn 1974, 1992). Nowadays, helioseismology provides observational constraints on such effects and therefore allows us to begin to introduce them in the description of main sequence (MS) stars (Frolich et al. 1997; Gabriel et al. 1997; Kosovichev et al. 1997). It permits observations of the solar convective layer complex motions. Moreover, acoustic mode determination allows the extraction of the rotation and sound speed profiles down to the energy generation core (Kosovichev et al. 1997; Dziembowski 1998; Turck-Chieze et al. 1997). Meridional circulation begins to be accessible to the solar seismic observations, and some (magneto)hydrodynamical instability has been put in evidence at the base of the convective zone. In order to see the consequences of such a process, we have focussed our attention on two elements, $^7$Li and $^9$Be, which are destroyed in stars from the center to regions located slightly below the natural transition between transport of energy by radiation and by convection. Lithium surface abundance history is directly related to physical processes in this region, which is at the same time important for understanding dynamos in stars and also probably the role of the internal magnetic field in general. Brun, Turck-Chieze, & Zahn (1999, hereafter BTZ99) have invoked the hydrodynamical instability proposed by Spiegel & Zahn (1992) to explain both recent helioseismic results and the solar lithium depletion. They introduced a turbulent term in the equation of diffusion. This term is directly related to local rotation and differential rotation. Evolution of such a mixing term with recorded surface rotation history of Sun-like stars in open clusters finally explains the present observed solar photospheric element abundances. It also produces the right order of magnitude of lithium destruction as a function of time for open clusters older than a gigayear (NGC 752, M67).

In this paper we focus on the different ingredients of the MS and above all pre–main-sequence (pre-MS) structural evolution of solar-like stars through the excellent indicator which is the $^7$Li surface abundance. From that viewpoint stellar evolution models have received a lot of attention for a long time. Almost 40 yr ago pre-MS evolution was already proposed to explain the low solar $^7$Li abundances relative to the solar system value as well as field stars and Hyades depletion pattern with temperature (Bodenheimer 1965). Bodenheimer described the main features of lithium burning in pre-MS. Accurate $^7$Li observational data for open clusters have similarly been obtained for a while (Zappala 1972). They have outlined the complex history of this element and suggested depletion with age on MS. In the past 20 yr many theoretical and observational works have addressed the topic. These investigations suggested that the understanding of lithium abundance might be related to many different nonstandard processes extending from microscopic diffusion (Michaud 1986) to large-scale mixing through rotation (Baglin, Morel, & Schatzmann 1985), angular momentum evolution (Pinsonneault et al. 1989), or internal waves (Schatzmann 1993). During pre-MS lithium depletion strongly depends on typical temperatures within convection zones and therefore input physics (Proffit & Michaud 1989). Currently there is no safe explanation of lithium history among solar-like stars. It is very likely that various phenomena are indeed responsible for pre-MS and MS $^7$Li evolution as well as G-type star depletion pattern and lithium dip. This controversial subject therefore
remains a broad and active area of research (D’Antona & Mazzitelli 1994, 1997; Ventura et al. 1998; Palla 1999; D’Antona, Ventura, & Mazzitelli 2000).

This work intends to show results involving recent opacity and nuclear reaction rate determination. We consider possible variations of composition and nonsolar repartition among metals as in the next decade many improvements in the knowledge of the detailed photospheric composition of the young stars are anticipated. We envision variations of mixing length parameter with age and a new hydrodynamical instability along with a realistic rotation evolution. We outline the impact of such improvements on the topic of early phases of evolution, which is meant to be better constrained by future seismic informations. In § 2 we describe the bases of the stellar models we use and examine the solar case in details. The role of the different elements through their composition and the opacity coefficients are discussed in detail in § 3. Section 4 is dedicated to convection and accretion and § 5 to rotation. Finally, we give some perspectives in § 6.

2. PRE–MAIN-SEQUENCE EVOLUTION OF SOLAR-LIKE STARS

2.1. Physics and Global Evolution

In this study we consider models in the mass range from 0.8 to 1.4 $M_\odot$ and different compositions corresponding to the Sun, the Pleiades, and the Hyades. Our starting point is a fully adiabatic polytrope with a central temperature of $\sim 3 \times 10^5$ K and a radius of 20 $R_\odot$ for a 1 $M_\odot$ star. Thus, the computation begins prior to deuterium burning, which corresponds to the observed birth line (Stahler 1988). We observe that models are still fully convective polytropes when the star reaches the birth line with a radius of about 6 $R_\odot$, so we expect no consequences of this early-phase computation except the idea to take as a hypothesis an initial polytropic structure.

Models have been computed using the CESAM code (Morel 1997) and all the updated physics useful for the refined solar models (see Brun, Turck-Chièze, & Morel 1998). For the reaction rates of the $p$-$p$ chain and CNO cycle, we consider the compilation of Adelberger et al. (1998), and for the $^7$Li($p$, $x$)$^4$He the work of Engstler et al. (1992). We use OPAL equation of state (Rogers, Swenson, & Iglesias 1996) and opacities (Iglesias & Rogers 1996) above 5800 K. For lower temperatures the OPAL equation of state is replaced by the MHD equation of state (Mihalas, Dappen, & Hummer 1988), and the opacities are from Alexander & Ferguson (1994). Interpolation of opacities is performed using the v9 birational spline package of Houdek (Houdek & Rogl 1996). The atmosphere is connected to the envelope at optical depth 10 where the diffusion approximation for radiative transfer becomes valid (Morel et al. 1994). The (atmospheric) opacity is Rosseland mean opacity extracted from Alexander & Ferguson (1994) or Kurucz (1992) sets. We therefore do not use gray approximation. Surface boundary conditions are $\rho = 3.55 \times 10^{-9}$ g cm$^{-3}$ when $\tau = 10^{-4}$. Standard mixing length theory (MLT) is applied, and the convection zone is completely chemically homogeneous.

During the pre-MS, stars are in quasi-hydrostatic equilibrium and slowly contract toward zero-age main sequence (ZAMS) within a timescale comparable to their Kelvin-Helmholtz timescale. Defining ZAMS as the age where the thermonuclear hydrogen fusion provides 99% of stellar energy, the pre-MS lifetime varies from 30 Myr for a star of 1.4 $M_\odot$ Pleiades composition up to 100 Myr for a 0.8 $M_\odot$ star of the Hyades composition. The Sun lies in between, with a pre-MS of $\sim 50$ Myr. The transition from fully convective to radiative core structure depends on mass and composition. Higher mass stars contract faster, increase internal temperatures faster, and so decrease radiative thermal gradients faster. Moreover, lower metallicity accelerates contraction and decreases opacities which also favor radiative stratification. Therefore, lower metallicities and higher masses give rapid rise to a radiative core. A massive (1.4 $M_\odot$) Pleiades composition star develops a radiative core after 0.85 Myr and a 0.8 $M_\odot$ Hyades composition star after 3.5 Myr. In the solar case, the radiative core exceeds 1% of total mass at 1.8 Myr and then quickly accelerates in mass and radius to reach dimensions very close to its actual dimensions at 25 Myr.

As a result of the swift convective movements, surface matter is repeatedly exposed to physical conditions that prevail in the deep interior. Figure 1 illustrates this point in showing the time-dependent evolution of the thermodynamical quantities (temperature and density) and lithium abundance at the base of the convection zone (hereafter BCZ) in regard to the photospheric lithium for the case of a young Sun. At the beginning of the considered evolution BCZ (which coincides with the stellar center) is too cool to allow lithium burning. As the star evolves on pre-MS, deep regions of convection zone temporally exceed the $^7$Li burning point in typical stellar conditions ($\sim 2.5 \times 10^6$ K). $^7$Li therefore offers a direct insight over stellar internal structure and evolution as it is extremely sensitive to the appearance of the radiative core. We note that early $^7$Li depletion occurs in the very beginning of pre-MS. Effectively, for 1 $M_\odot$, the BCZ temperature increases rapidly from less than $10^6$ to approximately $4 \times 10^6$ K at 2 Myr; the density increases also (but not quite simultaneously) up to 2 g cm$^{-3}$ between 7 and 8 Myr. Then they slowly sink...
toward values which are very near the conditions of the BCZ of the present Sun. This evolution results in $^7\text{Li}$ burning from 2 to 20 Myr. The way depletion occurs presents several difficulties. First, depletion takes place just at the BCZ as convection rapidly recedes in mass fraction passing from the whole star mass at 1 Myr to less than 20% 20 Myr later. Moreover, depletion typical time evolves rapidly and decays to very low values compared to timescale evolution of the stellar structure down to $\sim 10^5$ yr at BCZ. These peculiarities impose a small time step and very thin meshes.

Computations suggest that a third difficulty must arise. Early radiation zone stratification hardly differs from convection stratification. In other words, the newly stabilized medium is (and stays for at least 10 Myr) close to convective instability. We can illustrate this using polytropes: the adiabatic polytrope ($P \propto \rho^{1+1/n}$ with $n = 3/2$) is "harder" than its radiative counterpart ($P \propto \rho^{1+1/n}$ with $n = 3$). The radiation zone which represents half of the stellar mass at 10 Myr should be more concentrated in the core. Figure 2 shows the contrary. The fact that radiation energy transport replaces convective motions does not mean that radiative stratification immediately establishes. At 10 or 20 Myr the stratification in the radiation zone is still very close to adiabatic stratification. This has consequences on rotation evolution as we shall see in § 5. We believe this property to be related to the Kelvin-Helmoltz time value. The stellar interior needs at least this time to redistribute thermal energy and evolve from convective to radiative structure. This suggests that little modifications in stellar structure or new phenomena taken into account could easily change BCZ position at times from 10 to 20 Myr. We may, for instance, suppose that even a low-energy density magnetic field would stabilize or destabilize the region. This point leaves a priori room for many nonstandard mechanisms that will have to be investigated and that will probably lead to substantial variations in pre-MS surface $^7\text{Li}$ depletion (Ventura et al. 1998).

**Fig. 2.**—Solid lines present the mass distribution of polytrope vs. radius for a 1 $M_\odot$ star. Upper solid line corresponds to a polytrope of index $n = 3$ (representative of radiative stratification); lower solid line corresponds to a polytrope of index $n = 3/2$ (adiabatic stratification). Dashed lines present model stratifications at 10 Myr (lower line) and 30 Myr (upper line) for solar composition and mass. Crosses on these lines are BCZ. It is noteworthy that at 10 Myr stratification is still almost adiabatic, albeit more than 50% of stellar mass is in the radiation zone.

**2.2. Adjustment of Evolution Parameters for $^7\text{Li}$ Burning**

The $^7\text{Li}$ reaction rate is extremely sensitive to temperature. For typical pre-MS conditions, at the maximum temperature of BCZ (3.5–4 × 10^6 K) this rate varies from $T^{18}$ to $T^{19}$. The depletion is therefore very sensitive to conditions near the base of the convection zone (Fig. 3). Consequently, the photospheric $^7\text{Li}$ depletion strongly depends not only on the mass of the convection zone but also on the precision of the mass shell division at BCZ. This point is essential to perform valid integrations. We have adjusted the mesh in order to limit the variation of the reaction rate at BCZ between two layers to 15%; this corresponds typically to meshes of 0.005 $M_\odot$ or 0.003 $R_\odot$. Moreover, the typical $^7\text{Li}$ pre-MS burning requires also a very accurate resolution relative to time integration. Figure 3 shows the evolution of the characteristic time along the evolution. At 3–4 Myr we find a characteristic destruction time at BCZ of only $8 \times 10^4$ to $1.3 \times 10^5$ yr (depending on composition). Thus, we have adjusted the typical step size to be a factor of 10 lower than the characteristic depletion time. In Figure 3 we have shown three conditions corresponding to the maximum of the temperature at BCZ (3 Myr), to the arrival on ZAMS, and to the present age of the Sun. For each condition, the depletion time varies by approximately 1 order of magnitude from BCZ to the right end of the plot, but this extension corresponds to only 10% variation of the mass of the convection zone.

**Fig. 3.**—Temperature dependence of the $^7\text{Li}$ depletion characteristic time around BCZ for a diffusive solar model ($X = 0.70821$, $Y = 0.2722$). The solid line corresponds to the solar age, dashed line to the ZAMS position, and dot-dashed line to a 3 Myr star. Triangle, cross, and diamond represent the positions of the BCZs.

**2.3. Solar Lithium Burning during Pre–Main-Sequence**

Pre-MS $^7\text{Li}$ depletion within stars of roughly solar mass and composition has been estimated in various previous investigations (Bodenheimer 1965; D’Antona & Mazzitelli 1984; Proft & Michaud 1989; Ventura et al. 1998). These last three studies suggest that lithium depletion will increase as input physics is updated. D’Antona & Mazzitelli (1984) find that a solar mass star depletes $\sim 13\%$ of its initial lithium. The authors choose $Y = 0.23$, $Z = 0.02$, and $\alpha_{\text{MLT}} = 2$. Proft & Michaud (1989) find that a solar mass
star depletes from \( \sim 32\% \) to \( \sim 69\% \) of its initial lithium. These values correspond to the same \( x_{\text{MLT}} \) = 1.5 but make different assumptions on the composition. The first one refers to \( Y = 0.28, Z = 0.0169 \) as the second one refers to \( Y = 0.28, Z = 0.024 \). Proffit & Michaud (1989) suggest that the difference from the D’Antona & Mazzitelli (1984) depletion rates is probably due to opacity improvements. They moreover remark that the gap would get even wider if they were to use D’Antona & Mazzitelli (1984) parameters (\( Y \) and \( x_{\text{MLT}} \)). The gap between 1984 and 1989 results increases toward low masses and gets even wider if one considers very recent work from Ventura et al. (1998). A model from these authors having solar mass and composition (\( Y = 0.28 \) and \( Z = 0.02 \)) and using MLT \( x_{\text{MLT}} \) = 1.55 brings initial lithium fraction 3.3 dex down to 1.72 dex (a decrease of a factor of \( \sim 40 \)). Although a bit larger, such depletion is the same order of magnitude as what our computations suggest. The present work therefore confirms the tendency of depletion to increase with updated physics. We find that lithium lessens by roughly a factor of 10 in solar mass and composition star (we take \( Y = 0.2722, Z = 0.01959, x_{\text{MLT}} = 1.766 \)). Opacities must partly be responsible for this evolution, but new estimations of nuclear reaction rates should also be responsible for this increase. The Engstler et al. (1992) \( ^7\text{Li}(p, x)^9\text{Be} \) astrophysical factor is indeed increased by 30% in comparison with older values (see BTZ99). Finally, the correct attention to the adapted time step to lithium depletion rate is a third possible source of dispersion (as shown below). Table 1 compares our computations to previous ones.

Figure 4 presents the results for the evolution of the Sun in pre-MS. Following the work of BTZ99, we have computed models of the Sun, in introducing (or not introducing) microscopic diffusion. Depending on this choice, the initial composition \( Y = 0.2722, Z = 0.01959 \) (or \( Y = 0.2624, Z = 0.01763 \)) is adjusted to get the correct luminosity and radius at the present age, calibrated with an accuracy better than \( 4 \times 10^{-4} \). Figure 4 shows that the microscopic diffusion has no effect on the pre-MS. It is too slow a process as it results in a change of photospheric helium and metal abundances of only 10% along the whole life of the Sun (Turbott et al. 1998). We have to note here a crucial point in \(^7\text{Li} \) pre-MS depletion. Sun-like stars change much faster on pre-MS than on MS because evolutionary timescale is primarily related to contraction (hence to Kelvin-Helmoltz time \( \tau_{\text{KH}} \)), which is much smaller than nuclear reaction time \( \tau_n \). Yet one should not expect any calculation on lithium during early pre-MS to provide correct results without some cautions. Despite the fact that \( \tau_{\text{KH}} \ll \tau_n \) forces us to adopt in the code small temporal steps, these are much larger than the \(^7\text{Li} \) burning time at BCZ (\( \tau_{\text{BCZ}} \)) at these ages. The following comparison illustrates this. In diffusive models \(^7\text{Li} \) depletion is increased by a factor of 3.5 between a star where time evolution is always less than 1/10 of \( \tau_{\text{Li}} \) and a model where the time step is given by the evolution of the structure. For nondiffusive models this ratio goes up to 5.3. Once time step is well below \( \tau_{\text{Li}} \), no change in \(^7\text{Li} \) depletion is seen at a given composition for various time steps and with or without diffusion. In all of the following computations we take the time step to be \( \tau_{\text{Li}}/10 \) as long as lithium is rapidly depleted (prior to \( \sim 30 \text{ Myr} \)). Furthermore, the burning rate is mass averaged over the convection zone. We have checked that the results are robust to the choice of time step. If we decrease the time step down to \( \tau_{\text{Li}}/30 \), \(^7\text{Li} \) depletion increases by only 3.5%. With the time step adjusted for a good treatment of \(^7\text{Li} \) burning, the difference of about 0.5 dex after 20 Myr (a factor of 3 in destruction) between diffusive and nondiffusive models is only due to the change of initial composition. This shows the great dependence of the lithium burning on the composition (see next section). Such precise computation of the lithium burning in the pre-MS was not included in the previous work of BTZ99.

Of course, the notion of calibration between diffusive and nondiffusive models is not justified in the study of young clusters, but the great sensitivity of this calibration shows already the difficulty of predicting lithium burning in the pre-MS stage.

\(^7\text{Li} \) is generally not the only probe of the stellar internal structure, but \(^6\text{Li} \) is depleted at lower temperature and is of

**Table 1**

| Mass \((M_\odot)\) | DM84 | PM89a | PM89b | V98 | PT01 |
|-----------------|------|-------|-------|-----|------|
| 0.91...........| 0.664 | 0.467 | 0.118 | ... | 0.002 |
| 1.1........... | 0.871 | 0.679 | 0.317 | 0.026 | 0.071 |
| 1.1........... | 0.949 | 0.823 | 0.535 | ... | 0.244 |

*Note.—Our results (PT01) are compared to previous ones of D’Antona & Mazzitelli 1984 (DM84), Proffit & Michaud 1989 (PM89), and Ventura et al. 1998 (V98). PM89a and PM89b correspond to \( Z = 0.0169 \) and 0.024, respectively. For 1.1 and 1 \( M_\odot \), no depletion is predicted on MS. For a 0.9 \( M_\odot \) star D’Antona & Mazzitelli do not predict depletion on MS, but we and Proffit & Michaud 1989 predict it. For these low-mass stars lithium fraction therefore refers to a fixed age of 70 Myr. Results of Ventura et al. 1998 are provided here only for solar mass stars as they do not give results for other masses in the MLT framework.*
no help here. We have observed that \(^{9}\)Be burning gives similarly poor indications. In fact, computed stellar models of 0.8–1.4 \(M_\odot\) show a \(^{9}\)Be depletion of less than 0.04 dex whatever the cluster membership (from Pleiades to Hyades).

3. THE ROLE OF THE DETAILED COMPOSITION

3.1. Open Cluster Evolution

Open clusters allow a direct test of \(^{7}\)Li evolution with time and/or composition. In this paper we focus our attention on two young and two middle-aged clusters: Pleiades and Blanco I (\(\zeta\) Sculptoris) for the former Hyades and Coma for the latter. The objective is to distinguish metallicity from age effects. Blanco I and the Hyades apparently are metal-rich clusters with, respectively, \([\text{Fe/H}] = 0.14 \pm 0.01\) (Jeffries & James 1999); however, Blanco I is much younger than the Hyades and with an age around 50–90 Myr, comparable to the Pleiades, which is estimated to be 70 Myr old (Patiño 1978). On the other hand, the Pleiades and Coma have metallicities very slightly below solar with \([\text{Fe/H}] = -0.034 \pm 0.024\) (Boesgaard & Friel 1990) and \([\text{Fe/H}] = -0.052 \pm 0.026\) (Friel & Boesgaard 1992), respectively, but Coma has an age of 500 Myr comparable in age to the old Hyades of \(~\sim 600\) Myr (Perryman et al. 1998). It should be mentioned that composition data are undoubtedly more reliable in the case of the Hyades or Pleiades than in the case of Blanco I, which is more distant \((\sim 250 \pm 30\) pc) than all other clusters and has been less studied.

Unlike the Sun, microscopic diffusion has a negligible effect in the evolution of these young or middle-aged clusters. We compute a decrease of 1.3% and 0.8% for helium and metals in the Hyades solar mass star case. As such variations always remain largely smaller than error bars over metallicity or helium content, it is immaterial to study an initial composition effect resulting from diffusion. This is particularly true for lithium. Let us however remark that microscopic diffusion time appears roughly 10 times shorter for F-type stars. We compute a decrease of, respectively, 10% and 6% for helium and metals in 1.4 \(M_\odot\) \((T_\text{eff} \sim 6600\) K) at Hyades age. However, at an age of 50 Myr decreases of helium and metals are only 0.6% and 0.4% so that it is not plausible that microscopic diffusion changes early lithium history even in the case of slightly more massive stars than the Sun.

In this study we do not consider different initial \(^{7}\)Li abundances. In all four clusters stars more massive than 1.4 \(M_\odot\) \((T_\text{eff} > 6900\) K) exhibit the same \(^{7}\)Li content of 3.2–3.3 dex for the Pleiades, Hyades (Soderblom et al. 1993), and Coma (Boesgaard 1987). The Blanco I depletion pattern is furthermore identical to that of the Pleiades (Jeffries 1999). The early F star abundances remain unchanged and are compatible with both very young T Tauri stars (Magazzu, Rebolo, & Pavlenko 1992) and the interstellar medium (ISM) present \(^{7}\)Li value (Knauth et al. 2000). Indeed, it seems that there was no significant evolution in the Galactic gas \(^{7}\)Li/H ratio over the last 1.7 Gyr (Hobbs & Pilachowski 1988) so that the initial \(^{7}\)Li does not vary from the Hyades formation time until today. For all the clusters we take the same standard value of 3.27 dex for initial \(^{7}\)Li abundances.

In the following we will investigate the effects of the composition on the lithium burning in separating the effects of deuterium, helium, and metals.

3.2. Sensitivity of the Lithium Burning to the Deuterium Composition

Deuterium, the most fragile element, is depleted around \(5 \times 10^{5}\) K in stellar interiors. The Galactic evolution leads to a continuous decrease because of astration. Recent measurements show an abundance of \((D/H)_{\text{ISM}} = 1.46 \pm 0.09 \times 10^{-5}\) (Piskunov et al. 1997) or \((D/H)_{\text{ISM}} = 1.60 \pm 0.09 \times 10^{-5}\) in the direction of Capella (Linsky et al. 1995), whereas the presolar value is estimated as \((D/H)_{\text{pre}} = 0.026\) (Boesgaard & Friel 1992) or \((D/H)_{\text{pre}} = 0.024\) (Friel & Boesgaard 1992), respectively, but Coma has an age of 500 Myr comparable in age to the old Hyades of \(~\sim 600\) Myr (Perryman et al. 1998). It should be mentioned that composition data are undoubtedly more reliable in the case of the Hyades or Pleiades than in the case of Blanco I, which is more distant \((\sim 250 \pm 30\) pc) than all other clusters and has been less studied.

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the metal/helium relation coming from globular clusters and Galactic bulge measurements do not lead to similar helium fractions (Deliyannis, Demarque, & Kawaler 1990). Changes here are not so important, so we retain here solar system abundances as a reference point.

We have estimated the impact of helium variation on lithium depletion around solar composition, for Pleiades age, together with reasonable variations of the mixing length parameter \( \alpha \), and metal fraction. The effect of the mixing length parameter is small: an increase of 5% leads to a decrease of \( ^7\text{Li} \) content by 20%. On the contrary, the impact of the composition is high: an increase of \( \Delta Y = 0.025 \) leads to a decrease of lithium burning by 64\%, the corresponding \( \Delta Z = 0.025/3 \) leads to an increase of lithium burning by a factor of 300, and the correlated variation of helium and metallicity leads to an increase of lithium burning by a factor of 60. We address the metallicity dependence more precisely in the next section. The anti-correlation between lithium depletion and helium is reported in previous calculations. D’Antona & Mazzitelli (1984) analyze helium mass fractions 0.23 and 0.28. There the rate of lithium fraction remaining from their initial fraction to this helium mass variation \( [(^7\text{Li}/^7\text{Li}_0)/\Delta Y] \) is roughly 3.3 and 1.3 for 0.9 and 1 \( M_\odot \) stars, respectively. Considering a helium variation (~ 0.05) from 0.2624 to 0.32, we correspondingly find rates 2.7 and 4.7 for 0.9 and 1 \( M_\odot \) stars. This is the same order of magnitude as the D’Antona & Mazzitelli (1984) one although our dependence seems a bit larger. The sensitiveness on helium fraction can easily be understood since opacities in stellar interiors reduce with helium content: less electrons are available for the same amount of matter. If we assume that helium content is a free parameter, we can speculate as to what level it should be increased to agree with the observations in the Pleiades case. Lithium abundances being scattered for any given effective temperature, one has first to derive a mean value. Figure 5 (dashed line) shows a third-degree polynomial least-squares fit of observed abundances. We obtain helium fractions of 0.36 for a 0.85 \( M_\odot \) star, 0.32 for 1 \( M_\odot \), and 0.3 for 1.4 \( M_\odot \). These very high values seem difficult to justify.

Recent work by Deharveng et al. (2000) on helium abundances in \( \text{H II} \) Galactic regions shows \( \text{He}/\text{H} \) to be below 0.105 where it can safely be determined from \( \text{He}^+/\text{H}^+ \) ratios. This corresponds to a helium mass fraction below 0.3. Another work indicates that the helium mean mass fraction should be 0.28 \pm 0.02 in the Galactic bulge (Minniti 1995), which is probably an upper limit to Galactic abundances as most chemically evolved star populations are expected to be near the center of our Galaxy. A second difficulty is that the helium mass fraction would have to vary with mass by about 20\%. This certainly is not what we observe in the Pleiades. Nevertheless, it is clear from this analysis that a proper determination of helium is crucial for understanding the young cluster lithium evolution.

3.4. Sensitivity of Lithium Burning to the Metallicity

We have computed several models to describe the 1 \( M_\odot \) Hyades and Pleiades stars. These models rely on physics described in § 2.1. Table 2 summarizes these results. We have calculated three types of models: the first one (A) uses metallicity deduced from the observation of iron given in § 3.1 and the \( \alpha \) parameter calibrated on solar models (1.766). The second model (B) adopts the same composition, but three different values of \( \alpha \) were used to account for recent two-dimensional hydrodynamical evaluations (see § 4.1). The third model (C) is an extremal model in the sense that it adopts the lowest metallicity and highest helium content within error bars in an attempt to cancel discrepancies between calculations and observations. In the Hyades case we have added a supplementary model (D) introducing the value of 0.283 in helium mass fraction claimed by Pinsonneault et al. (1998). Other Hyades models have been computed, and we discuss them in more detail in § 3.5.

On the MS effective stellar temperatures evolve slowly. The temperature of an open cluster solar mass star will therefore be reliable independently of age uncertainties. Moreover, these temperatures do not vary much within composition uncertainties or \( \alpha \) parameter different evaluation along early pre-MS (see Table 2). For instance, the 1 \( M_\odot \) Hyades model exhibits a variation of less than 10 K around 5450 K between 550 and 700 Myr (idem for the model including \( \alpha \) parameter effects on early pre-MS variation but around 5500 K).

We note in Figures 5 and 6 that \( ^7\text{Li} \) depletion is too strong on pre-MS for solar-type stars with Pleiades or Hyades composition. This agrees with recent results from Morel et al. (2000) of the B component of the \( \iota \) Pegasi binary system. With an estimated age of 56 Myr for the system and \( [\text{Li}] = 2.69 \) dex for the B component, this 0.819 star is clearly underdepleted. This problem is pointed out in other recent studies. Ventura et al. (1998), using the full spectrum of turbulence of the Canuto, Goldman, & Mazzitelli (1996) prescription for modeling the convection, found also a too strong depletion for solar composition stars and similarly a very strong dependence on metallicity and mass.

It is well known that open cluster stars exhibit an anti-correlation between effective temperature and lithium abundances. Moreover, the dispersion in lithium abundances grows when temperature declines. This dispersion is too large to be due to abundance uncertainties (Soderblom et al. 1993). This is also too large to be due to color errors as the vector of temperature errors is nearly parallel to the mean lithium-\( T_{\text{eff}} \) trend in cool open cluster stars. Moreover, this dispersion is already observed in \( ^7\text{Li} \) equivalent abundance.
width as a function of color (Soderblom et al. 1993; Thorburn et al. 1993). At a given effective temperature there are undoubtedly real star-to-star differences.

Observations for each star give an effective temperature and a lithium abundance, but these quantities are not directly measured as they are deduced from photometric measurements such as \((B-V)\) and equivalent width of a particular spectral absorption line. Measurements are always slightly scattered, and moreover there are unavoidable errors when doing conversions. For the Pleiades open cluster, Soderblom et al. (1993) find uncertainty for an effective temperature of \(~130\) K and uncertainty for \(\text{Li} \sim 0.057 \text{ dlex}\). For the Blanco I cluster Jeffries & James (1999) give an effective temperature uncertainty of \(~250\) K and an abundance uncertainty of 0.11 dex. Figures 5 and 6 clearly show that such uncertainties are not large enough to recover agreement to computations. As we mainly analyze 1 \(M_\odot\) evolution, we concentrate on corresponding error bars. It is generally found in the literature that these stars verify \(0.6 < (B-V) < 0.75\). In fact, lithium abundances are such steep functions of effective temperature that if we use this criterion, we gather in the same sample stars with very different \(^7\text{Li}\) fractions. Let us consider the Hyades case. In the Thorburn et al. (1993) data, the mean value of lithium content for stars exhibiting \(0.6 < (B-V) < 0.75\) is \(N(^7\text{Li}) = 2.0 \pm 0.6\) dlex, but if we limit to \(5400 < T_\text{eff} < 5500\) K, which is what we get in computation, we get \(N(^7\text{Li}) = 1.3 \pm 0.1\) in the same data set. The small sample presently discussed greatly reduces differences between observations and numerical predictions. Yet differences are not definitively cancelled out, and it is obvious from Figures 5 and 6 that such possible misleading associations between stellar mass and \((B-V)\) will not succeed in explaining the very large observation/theory gap concerning lower mass stars.

Table 2 shows that expected dispersions among metallicity or uncertainties on helium fraction can be responsible for dispersion of lithium abundances. In the Pleiades case, the metallicity variation from \(-0.034\) dlex \((Z = 1.632 \times 10^{-2})\) to \(-0.058\) dlex \((Z = 1.535 \times 10^{-2})\) minimal value corresponds to 6% in metal mass fraction and produces 0.35 dlex variation in photospheric lithium, which is quite the order of observed dispersion for solar mass stars within this cluster. In the Hyades case, helium uncertainties at a level of \(~7\)% correspondingly produce 0.6 dlex \(^7\text{Li}\) disper-

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**Table 2**

| Model          | \(Z\) (mass fraction) | \(Y\) (mass fraction) | \(\alpha\) | \(^7\text{Li Content}\) (dex) | [O/Fe] | Tachocline | \(T_\text{eff}\) (K) |
|----------------|------------------------|------------------------|-------------|-------------------------------|--------|-------------|---------------------|
| **Solar Models** |                        |                        |             |                               |        |             |                     |
| Reference       | 1.959 \times 10^{-2}   | 0.2722                 | 1.766       | 2.0                           | 0      | No          | 5776                |
| Tachocline 1    | 1.903 \times 10^{-2}   | 0.2695                 | 1.748       | 0.35                          | 0      | Yes, \(\gamma_\text{disk} = 0.5\) | 5777                |
| Tachocline 2    | 1.903 \times 10^{-2}   | 0.2695                 | 1.748       | 1.1                           | 0      | Yes, \(\gamma_\text{disk} = 10\) | 5777                |
| **Pleiades Models** |                    |                        |             |                               |        |             |                     |
| A              | 1.632 \times 10^{-2}   | 0.2624                 | 1.766       | 2.6                           | 0      | No          | 5717                |
| B              | 1.632 \times 10^{-2}   | 0.2624                 | 1.935, 1.850, 1.766 | 2.4 | 0      | No          | 5715                |
| C              | 1.535 \times 10^{-2}   | 0.2679                 | 1.766       | 2.75                          | 0      | No          | 5801                |
| **Hyades Models** |                    |                        |             |                               |        |             |                     |
| A              | 2.367 \times 10^{-2}   | 0.2633                 | 1.766       | 0.9                           | 0      | No          | 5450                |
| B              | 2.367 \times 10^{-2}   | 0.2633                 | 1.935, 1.850, 1.766 | 0.5 | 0      | No          | 5466                |
| C              | 2.180 \times 10^{-2}   | 0.28                   | 1.766       | 1.75                          | 0      | No          | 5646                |
| D              | 2.28 \times 10^{-2}    | 0.283                  | 1.766       | 1.55                          | 0      | No          | 5632                |
| E              | 1.57 \times 10^{-2}    | 0.26                   | 1.766       | 2.64                          | -0.2   | No          | 5802                |
| F              | 1.94 \times 10^{-2}    | 0.26                   | 1.766       | 1.98                          | -0.2   | No          | 5638                |
| G              | 1.57 \times 10^{-2}    | 0.26                   | 1.766       | 2.3                           | -0.2   | Yes, \(\gamma_\text{disk} = 10\) | 5805                |
| H              | 1.57 \times 10^{-2}    | 0.26                   | 1.766       | 1.75                          | -0.2   | Yes, \(\gamma_\text{disk} = 0.5\) | 5804                |

**Note.**-- All models include microscopic diffusion. Several \(\alpha\) parameter values have been considered: 1.766 is the value assumed if at solar age it is deduced from solar calibration; 1.748 results from slightly different calibration when tachocline mixing is taken into account; 1.935 and 1.850 are values induced from hydrodynamical simulations (Ludwig et al. 1999). For Pleiades composition we take \(\alpha = 1.935\) before 15 Myr and \(\alpha = 1.85\) from 15 to 22 Myr. For Hyades composition we take \(\alpha = 1.935\) before 20 Myr and \(\alpha = 1.85\) from 20 to 28 Myr. Lithium dlex fraction is presented at appropriate age. The last column provides effective temperature to outline composition impact on it.

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**Fig. 6.**--*Crosses:* \(^7\text{Li}\) abundances for members of the Hyades (Thorburn et al. 1993 data). *Triangles:* Blanco I (Jeffries 1999 data). Lines show model computation for different masses at \(~625\) Myr. Solid line is a prediction of the standard (corresponding to model Hyades A) model of Hyades composition. Dashed line is a prediction of the case E model (see section on opacities). Small diamonds on both lines represent a 1 \(M_\odot\) star.
sion between model types A and D. Composition variations are therefore able to explain $^7\text{Li}$ dispersion through a pre-MS initial depletion effect, but mass accretion could contribute to it also (§ 4). If such variations explain lithium dispersions in the young Pleiades or Coma, they also have to deal with middle-aged cluster observations. In the Hyades, dispersion in the $T_{\text{eff}}^{-1}$-$^7\text{Li}$ relation has considerably decreased.

3.5. Opacity Role on $^7\text{Li}$ Burning

Because of the strong dependence of lithium pre-MS depletion on metallicity, opacity effects in stellar interiors have been studied (Turck-Chièze et al. 1993; Turck-Chièze 1998; Turcotte & Christensen-Dalsgaard 1998). The increase of solar-like star metal opacities is responsible for the transition between radiative and convective energy transport. In the present Sun, the main contributors to the opacity at BCZ are oxygen and iron. They correspond, respectively, to 36% and 20% of the total opacity (Table 3). The situation is somewhat similar regarding pre-MS, but the principal metal contributors to opacity are not the same because the medium is denser and hotter. The roles of oxygen and iron are of the same order of 20%, then neon, silicium, and magnesium each represent approximately 10% of total opacity.

Up to now we have deduced metallicity from $[\text{Fe/H}]$, in keeping the solar distribution inside the metals. There have been hints that solar abundances may deviate from mean ISM abundances and that the solar system would not be representative of general trends (Gies & Lambert 1992). Regarding open clusters, a similar situation could appear even if direct determinations have to be considered cautiously as a result of chromospheric activity (see Cayrel, Cayrel de Strobel, & Campbell 1985 for the Hyades). Let us consider the Hyades. It is the closest and probably the best representative of general trends (Gies & Lambert 1992). Let us just signal one caveat regarding silicium: Cayrel et al. (1985) find $[\text{Si}/\text{Fe}] = (-0.36 \pm 0.02)/[\text{Fe}/\text{H}] - 0.044 \pm 0.010)$. This relation once again suggests that our Sun could be overabundant in oxygen when compared to other stars. Moreover, Garcia Lopez et al. (1993) claim that oxygen to hydrogen metallicity is close to $[\text{O}/\text{H}] = -0.07 \pm 0.05$ dex in solar-like Hyades stars. This result is qualitatively consistent with the previous relation. If we apply this law, the Hyades appear now metal-poor in oxygen compared to the Sun; this is in agreement with helium determinations from Perryman et al. (1998). Neon is not detectable in the solar-like star photosphere, but its ratio to oxygen measured in H II regions is remarkably constant for different $[\text{O}/\text{H}]$ (Meyer 1989). Indeed, neon, silicium, and magnesium are expected to vary like oxygen because of their common origin in Type II supernovae. Consequently, we decide to take the same variation for silicium and magnesium as for oxygen. Let us just signal one caveat regarding silicium: Cayrel et al. (1985) find $[\text{Si}/\text{H}] = 0.16 \pm 0.05$. Carbon cannot be ignored at least on MS, but its origins are still a matter of debate (Gustafsson et al. 1999). We let it vary like oxygen.

We have generated opacity tables for this nonsolar metal distribution using the devoted Lawrence Livermore National Laboratory Web site. By doing so we have chosen to model two cases. In the first one (case E), every metal varies like oxygen except iron peak elements; in the second case, we let every metal vary like iron except the oxygen, to test the dependence of lithium depletion on oxygen (case F). In case E, which is the most realistic, lithium abundance is 2.6 dex (instead of 0.9 dex) for a 1 $M_\odot$ star. The shift of oxygen abundance from 0.127 to $-0.07$ dex increases lithium fraction by a large amount of 1.1 dex. Then the shifting of every metal but iron peak ones to the level of oxygen increases again lithium fraction by 0.6 dex. This dramatic increase in lithium fraction is shown in Figures 6 and 7. Lithium in solar-like Hyades stars becomes quite compatible with observations. There are two reasons for this: first, the decrease in metal fraction reduces BCZ temperatures; and secondly, it increases effective temperature for any given mass. Solar mass stars are shifted from $\sim 5450$ to $\sim 5800$ K. The large effect of metal might at first seem worrying. However, one has to keep in mind two points. Firstly, metals determine roughly 80% of opacities at BCZ during pre-MS. Secondly, lithium depletion is a very steep function of temperature (see Fig. 3). Furthermore, we remark that such a large impact of metallicity on depletion is reported in other recent studies (Chaboyer, Demarque, & Pinsonneault 1995). Ventura et al. (1998) use an OPAL opacity table, although a slightly older version. They claim that a decrease of 15% in the value of $Z$ (around $Z = 0.02$) makes the $^7\text{Li}$ abundance vary by almost 2 orders of magni-

| Element | MS (%) | Pre-MS (%) |
|---------|--------|------------|
| H ...... | 20     | 13         |
| He ...... | 11    | 6          |
| C ...... | 8      | 2          |
| N ...... | 5      | 1          |
| O ...... | 36     | 19         |
| Ne ...... | 9     | 13         |
| Mg ...... | 3    | 11         |
| Al ...... | <1    | 1          |
| Si ...... | 3      | 12         |
| S ...... | 4      | 5          |
| Ar ...... | 1.5   | <1         |
| Ca ...... | 2     | <1         |
| Fe ...... | 16    | 22         |
| Ni ...... | 1     | 2          |
| Na, P, Cl, K, Ti, Cr, and Mn ...... | <1 | <1         |
tude. The present effect of oxygen (0.2 dex represents ~60%), which is half of metal fraction, is quite compatible with this last result.

We note that even lower mass stars appear in good agreement with observations. Figure 7 outlines the importance of metals in lithium depletion. It also shows that oxygen plays a more determinant role than iron for pre-MS evolution.

If opacities are crucial at the base of the convection zone, they are also of first importance in the atmosphere, as they determine depth where material becomes convective and this affects significantly the convection zone extension. The deeper convection starts in atmosphere the more efficient it is and the deeper it goes in the envelope. For low effective temperatures encountered on the Hayashi track many contributors to opacity have to be considered. The lowest temperature we reach in computation is 3200 K, and below 5000 K molecules are not negligible anymore. It is therefore likely that improvements of present models may be made when using new atmosphere models (Hauschildt, Allard, & Baron 1999). Here we have mainly used Alexander & Ferguson (1994) opacity tables and checked that there was no important discrepancy induced when using low-temperature Kurucz opacity tables (Kurucz 1992). For the case A composition star, the final (and maximal) difference between otherwise similar models is less than 0.1 dex, which is very small if we recall that the global depletion factor is more than 2 dex in this case.

In typical pre-MS conditions H\textsuperscript{−} remains the main opacity source. The metals provide a larger part of free electrons when temperature lowers. Alexander & Ferguson (1994) opacity tables have been computed for solar composition and are not adapted for case E. We can evaluate average ionization states of all components in atmospheric thermodynamic conditions. For the coldest (~3164 K) and most diffuse (1.5 \times 10^{-10} \text{ g cm}^{-2}) conditions, iron peak elements and oxygen are, respectively, responsible for ~10% and 0.25% of electron density. When opacity evaluation changes from Alexander to OPAL table, temperature is log \( T = 3.75 \) and density is typically a few times 10\textsuperscript{-7} g cm\textsuperscript{-3}. We estimate iron peak elements to be responsible for ~30% of electron density and the contribution of oxygen to be negligible.

In case E metal fraction is reasonably scaled by oxygen, which is the main mass contributor for heavy elements. Case E is therefore slightly warmer than the case A model, and its BCZ is at a lower temperature. At ~6 Myr the case A BCZ is located at 0.3 \( M_\odot \) where \( T = 3.99 \times 10^9 \text{ K} \); the case E BCZ is located at 0.4 \( M_\odot \) where \( T = 3.72 \times 10^9 \text{ K} \). On the other hand, by scaling every metal on oxygen, we underestimate iron peak element fraction (and effects) in the atmosphere where they could provide up to 30% of free electrons. If the right iron peak element fraction was considered in the atmosphere, electron density would be enhanced. Convection would start closer to the surface and would therefore be less efficient. Thus, we can expect that our values of BCZ temperature are in case E a bit too high. Figure 8 shows however that the changes among metal fractions are mainly felt at BCZ. Differences in temperature as a function of mass never exceed 5%, and changed opacities mainly affect BCZ but not the global structure.

4. MACROSCOPIC EFFECTS: CONVECTION AND ACCRETION

4.1. Efficiency of Convection

The usual MLT parameter value relies on solar calibration. There is no reason to believe that it is universal. Recent work based on hydrodynamical simulations (Ludwig, Freytag, & Steffen 1999) has investigated possible calibrations of mixing length for solar-type stars. This work shows a dependence of \( \alpha \) on effective temperature and surface gravity. For temperatures between 7100 and 4300 K and surface gravities 2.54 < log \( g \) < 4.74, \( \alpha \) varies from 1.3 to more than 1.7. Using this work, we find negligible evolution of \( \alpha \) on the Hayashi track for a 1 \( M_\odot \) object where surface gravity varies significantly but effective temperature remains almost constant. On the contrary, once the radiative core becomes important and the star leaves the Hayashi track, the increase of the effective temperature
could justify a change of the $\alpha$ value. For a solar composition model this occurs at about 12 Myr, i.e., slightly before the end of the $^7$Li burning phase. In order to follow the effective temperature impact on $\alpha$, we have computed models of 1 $M_\odot$ stars for Pleiades, solar, and Hyades composition. Effective temperature being sensitive to composition, age changes of $\alpha$ parameters vary with both of them. Temperature differences on the Hayashi track are approximately 70 K if one changes from solar to Hyades composition. In the region of interest in temperature and gravity, differences in $\alpha$ are not significant over such a narrow temperature range, and the same $\alpha$ can be used. After leaving the Hayashi track temperature differences increase up to 200 K, but the star evolves toward solar MS conditions in a zone where there is a “plateau” in $\alpha$ (Ludwig et al. 1999). Here again one can adopt a unique value so that for the present study the change in $\alpha$ corresponds to temperature and not composition. On this point the Ludwig et al. (1999) results agree with those of Fernandes et al. (1998), who found that $\alpha$ is almost constant in the Sun and four low-mass star systems having metallicities between solar and $-0.31$ dex and helium content from 0.25 to 0.28. For these reasons we use the same values in the mixing length parameter whatever the composition. Pleiades and solar composition being close, we only made a distinction between this group and the Hyades. Between these two groups composition determines the time spent on the Hayashi track. We have considered three different $\alpha$ values: on the Hayashi track, when the radiative stratification begins to influence surface temperature, and on the MS where the value results from usual solar calibration. Following advice from Ludwig et al. (1999), we have adopted $\alpha$ values they proposed after reestimate by 0.1 and use their values as scaling factors. If the star has solar or Pleiades composition, $\alpha = 1.955$ before 15 Myr, $\alpha = 1.85$ between 15 and 22 Myr, and $\alpha = 1.766$ after 22 Myr, which is our solar calibration MS value. If the star has Hyades composition, we use the same values but at different times and change the limits to 20 and 28 Myr. Higher metallicity results in slower contraction and evolution. In the Hyades case only the initial value of $\alpha$ is important because after 20 Myr $^7$Li burning is over.

Results of the hydrodynamical calibration must be considered cautiously. Firstly, low-temperature molecular opacities are not included in the Ludwig et al. (1999) calculations, and we are presently exploring low effective temperature regions. Secondly, a recent result about $\iota$ Pegasi binary system calibration predicts opposite evolution of $\alpha$ with effective temperature (Morel et al. 2000). Thirdly, two-dimensional calculations have to be confirmed by three-dimensional hydrodynamical calculations.

In these calculations, $^7$Li depletion is increased (Table 2, case B) as the convection zone extends deeper to higher temperatures with more efficient convection. We note nevertheless that such modification leads to less lithium destruction than using a full spectrum of turbulence as Ventura et al. (1998).

4.2. Mass Accretion

Observations of T Tauri star accretion luminosities lead to mass accretion rates spanning from a few times $10^{-8}$ up to a few times $10^{-6}$ $M_\odot$ yr$^{-1}$ (Hartigan, Edwards, & Ghandour 1995; Gullbring et al. 1998). This wide range probably originates from real star-to-star differences although such low accretion rates are very difficult to evaluate (Hartmann 1998) and suffer from large uncertainties. Accretion can affect $^7$Li stellar photosphere abundances in mainly three different ways. First, it has a structural impact as it modifies the stellar mass; consequently, the gravitational potential and the stratification change. Secondly, providing ISM abundance material to the surface of the star has a direct chemical impact. Thirdly, accretion should also change stellar boundary conditions, which is probably the most difficult part of the accretion phenomenon to modelize.

Our hydrostatic calculation takes accretion into account in a crude fashion. The accreted mass modifies only the external layers of the star and does not directly affect global surface boundary conditions (pressure, temperature, luminosity). Mass is simply added on the outermost layer of the star. We limit our study to accretion rates below $10^{-7}$ $M_\odot$ yr$^{-1}$, and following Hartmann (1998), we consider a global accreted mass of a few times $10^{-2}$ $M_\odot$. As recent hints suggest that accretion could last longer than usually believed and perhaps deal with larger accreted masses (Muzerolle et al. 2000), so we will then also investigate the effects of 0.1 $M_\odot$ accreted.

4.3. A Low Global Accretion Mass

We first evaluate $^7$Li photosphere variations through accretion by simply considering different nonaccreting stellar masses. For a 2% accretion mass, if the structural effect is dominant, the final minimal $^7$Li photosphere fraction is the one of the 0.98 $M_\odot$ nonaccreting star. This minimal fraction is 1.92, compared to 2.13 for 1 $M_\odot$ for a solar composition. Then the maximal fraction can also be evaluated, if we consider that the chemical mixing is dominant. This value is obtained in considering a 1 $M_\odot$ star but artificially increases the $^7$Li photosphere fraction by diluting in the external convection zone the $^7$Li mass contained in 0.02 $M_\odot$ of ISM material. The $^7$Li maximal fraction is 2.61 for a 1 $M_\odot$ star.

A real accreting star has a lower mass all the way through accretion phases and depletes both its initial lithium and the lithium it receives from accretion. Thus, in the following we consider accretion impact on $^7$Li burning for a solar composition star and 2% $M_\odot$ total accreted mass at varying temporal rates. Starting with a 0.98 $M_\odot$ stellar object, we consider a “fast accretion” rate model of $10^{-9}$ $M_\odot$ yr$^{-1}$ during 2 Myr, which gives a lithium content of 2.12 dex, and then a “slow accretion” rate model of $10^{-8}$ and $10^{-9}$ $M_\odot$ yr$^{-1}$ during 1 and 10 Myr, respectively, which gives a lithium content of 2.08 dex. This kind of simulation does not affect depletion by more than 0.05 dex. The general trend of accretion is to lower the $^7$Li fraction so we can conclude that structural effects are predominant over chemical effects. The effect is sufficient neither to recover the agreement with observational $^7$Li fraction nor to explain the spread in young clusters.

Accretion will have different consequences on lithium burning if it could last long enough, i.e., after the major $^7$Li pre-MS depletion phase. Near-IR excess of very low accretion rates of $10^{-9}$ $M_\odot$ yr$^{-1}$ is currently not detected (Hartigan et al. 1995). The simple evaluation we make just above illustrates that a variation of only very few percent of stellar mass could have a nonnegligible chemical impact because after 10 Myr the external convection zone is 10% or lower than the stellar mass. Then, an accretion rate as low as $10^{-9}$ $M_\odot$ yr$^{-1}$ could significantly change the ZAMS lithium surface fraction.
4.4. Larger Accretion Rates Applied to the Pleiades Composition

A total of 90% or more of stellar final mass is accreted during short (less than 1 Myr) class 0 and class I stages that extend up to a few times $10^5$ yr before the classical T Tauri phase (Andre, Ward-Thomson, & Barsony 1999 and references therein). We consider here both different final masses from 0.9 to 1.1 $M_\odot$ and different globally accreted masses, i.e., $2 \times 10^{-2}$ or $10^{-1} M_\odot$. The stars now have Pleiades composition. As we have seen in the solar case, the structural effect of accretion is maximum when accretion is slow; therefore, we restrict our computation to the "slow" accretion process: $10^{-8}$ or $5 \times 10^{-8} M_\odot$ yr$^{-1}$ during the first megayear and then $10^{-9}$ or $5 \times 10^{-9} M_\odot$ yr$^{-1}$ from 1 to 11 Myr. In these conditions, accretion still increases $^7$Li depletion and confirms solar trend. In Table 4 we give lithium abundance relative to hydrogen as a function of mass and with or without accretion in the case of the Pleiades. The lower the mass the higher the accretion impact. Accretion could therefore explain initial lithium dispersion that also seems to increase toward low effective temperatures.

For a comparison, we estimate observational lithium abundance dispersion in the data set of Soderblom et al. (1993); we divide into 200 K bins. For each bin we then compute mean abundance value and dispersion. Between 4200 and 6000 K, we find that dispersion varies from 0.65 to $\sim 0.1$ dex exhibiting the well-known general trend to decrease when temperature increases. Around $T_{\text{eff}} = 5720$ K (1 $M_\odot$) it is $\sim 0.12$, while around $T_{\text{eff}} = 5350$ K (0.9 $M_\odot$) it is $\sim 0.32$. As can be seen in Table 4, these results are qualitatively and quantitatively comparable to predicted dispersion resulting from accretion of 10% of $M_\odot$. We conclude that accretion could explain early MS dispersion. Results suggest also that the more a star accretes the more it depletes $^7$Li because once again in these cases structural effects dominate chemical effects. $^7$Li is not refreshed at a sufficient level to compensate for the additive burning due to the lower mass.

We now evaluate the minimal accretion rate necessary to counteract mass effect for stellar masses of 0.9 and 1 $M_\odot$ (Table 5). Every $10^6$ yr the photosphere $^7$Li fraction diminishes by a given amount, and knowing the convection zone mass and ISM $^7$Li fraction, we compute a "nominal" mass accretion rate necessary to exactly compensate losses. One could however argue that 1 $M_\odot$ Pleiades have not kept initial $^7$Li fractions. They indeed depleted from the ISM value $\sim 3.2$ down to $\sim 2.8$. Taking this into account, we compute a new accretion rate in the following way: if a fraction $\alpha$ of "nominal" accretion is provided every megayear, only $1 - \alpha$ of the quantity of depleted $^7$Li with no accretion will finally be depleted. We find that new accretion rates should be lowered from "nominal" ones by 0.32 dex, and we provide results in Table 5. Results do not really change within the considered mass range. When compared to observations of present star-forming regions (Calvet & Gullbring 1998; Muzerolle et al. 2000), these accretion rates seem slightly too high. The required accretion rates exceed strongest reported accretion observations by approximately 0.5 dex, which brings us close to the observational upper limits.

It is clear that conclusion on the accretion rates requires improved detection of mass accretion estimates to rates as low as $10^{-9} M_\odot$ yr$^{-1}$ for a large number of very young clusters, especially for low-mass stars and corresponding photospheric lithium content. Therefore, preceding results are mainly illustrative rather than conclusive. Moreover, the accretion process has to be approached hydrodynamically and may be in considering periodic phenomena, to take into account the modified boundary conditions.

5. MACROSCOPIC EFFECTS: THE INFLUENCE OF THE ROTATION

Regarding solar-like stars, open cluster $^7$Li abundances suggest a general depletion over MS which is in contradiction with standard evolution code results. We will examine in this section the role of the internal rotation firstly on the pre-MS structure and secondly on the possible tachocline mixing process inside the radiation zone.

5.1. Rotation Structural Effects

Within the last decade many theoretical works have been led in the field of angular momentum transport in stellar interiors. Such works encounter difficulties to explain rotation velocity evolution. For instance, models invoking hydrodynamic angular momentum transport (Pinsonneault et al. 1989) predict strong differential rotation in the solar interior, which is contradicted with helioseismology results. Models with angular momentum transport induced by internal magnetic fields (Keppens, MacGregor, & Charbonneau 1995) can fit observations with a core...
envelope coupling time of the order of 10 Myr. They, however, encounter problems in reproducing the slowest rotators in open clusters and early MS rotational evolution.

Core rotation could still significantly differ from surface rotation. Rotation rate is presently observed to be constant in most of the solar radiation zone and varies with latitude in the solar convection zone. However, it could have been a varying quantity in the initial stellar radiative and/or convective interior. We investigate here purely structural effects of varying internal rotation and examine the consequences on effective temperature, luminosity, and lithium content. The models we consider have Hyades composition where the stars below 1 $M_\odot$ all have experienced an initial rotational history increase until ZAMS followed by a strong decrease (see § 5.2). On the other hand, they are still at the beginning of ZAMS, so there are probably no long-term MS effects on lithium. This cluster therefore seems to us quite appropriate to study early rotational effects. We compute three models in the case of a very short-lived circumstellar disk of 0.5 Myr. The first model (SBR) assumes solid body rotation throughout the star, the second model (DR) assumes complete decoupling between radiative and convective zones, and the last model (FR) assumes solid body rotation in convection zone and every stellar mass shell keeps its initial angular momentum in the radiative stratification part. If the first model corresponds to zero coupling time between convection and radiation zones, this coupling time is infinite in the latter ones.

A well-known structural effect of rotation is the decrease of the effective temperature and to a less extent of stellar luminosity (Sills, Pinsonneault, & Terndrup 2000). For the SBR stellar model we compute equatorial velocity of 74 km s$^{-1}$ on ZAMS ($\sim$57 Myr). This gives rise to a temperature decrease of only 23 K in comparison with the nonrotating model. Under analog conditions, the polynomial formula of Sills et al. (2000) gives a discrepancy of 15 K. The same model. Under analog conditions, the polynomial formula of de Solla (1996) gives a discrepancy of 15 K. The same before 20 Myr, and at this age $^7$Li pre-MS depletion is over. There are two reasons for this. Firstly, radiation zone stratification is still hardly underadiabatic until 30 Myr as we already explained in § 2.1. Secondly, stellar wind loss represents only 12% of initial momentum at 20 Myr (vs. $\sim$99% at solar age). Contraction of the whole star therefore stays homologous, and coupling time between zones has no impact. Unless initial conditions are different from solid rotation for the initial fully convective body, there are no requirements to bother about angular momentum loss or exchanges during early pre-MS $^7$Li burning phases.

In the preceding lines we have been concerned by structural effects as far as they result from a correction to local gravity. We do not note any significant impact of these effects on the present problem. Now there are other means by which rotation might affect stellar structure. Convective movements are sensitive to rotation through Coriolis force. This effect is known for long in earthly atmospheric global circulation notably in the intertropical region. Siess & Livio (1997) suggest that convective cells could be twisted by rotation, allowing therefore a smaller $\alpha_{MLT}$ to the convective zone. As long as precise hydrodynamical computations are led on that phenomenon, it is, however, difficult to say much more about this solution.

5.2. The Turbulence at the Base of the Convection Zone

We consider now that the rotation induces a hydrodynamical instability in the tachocline layer at the top of the radiation zone (Spiegel & Zahn 1992). Such an instability has been studied by BTZ99 to interpret the helioseismic results (Kosovichev et al. 1997) and could partly be at the origin of lithium destruction during the MS. The introduction of a time-dependent turbulent term in the diffusive equation permits a better agreement on solar photospheric light elements between observations and models. BTZ99 remark that in the present Sun, tachocline mixing is thin enough not to deplete $^9$Be. However, tachocline mixing depends on rotation and differential rotation, which is poorly known in pre-MS stars.

We reexamine this process introducing a more realistic rotation history in pre-MS. A 1 $M_\odot$ model of Hyades composition and including tachocline mixing will not deplete more than 0.03 dex in $^9$Be from formation until ZAMS and none afterward. Beryllium depletion does not occur, although rapid rotation and high BCZ temperatures do. This is the reason why we do not discuss $^9$Be in this study.

The Skumanich law (Skumanich 1972) has been used to infer rotational time evolution in MS (as in BTZ99), but such a law cannot be extend to young pre-MS stars which initially rotate slowly and then experience strong acceler-

| Model       | Lithium at 7 Myr | Lithium at 20 Myr | Lithium at 0.7 Gyr |
|-------------|------------------|-------------------|-------------------|
| No rotation | 2.06             | 0.96              | 0.91              |
| SBR         | 0.11             | 0.07              | 0.07              |
| DR          | 0.11             | 0.08              | 0.07              |
| FR          | −0.01            | −0.07             | −0.05             |
Figure 9 presents corresponding equatorial velocity evolutions over early MS rotation rates. Following BFA97, we adjust efficiency of the wind to brake the star, which has consequences over early MS rotation rates. Following BFA97, we adjust the rotational evolution laws so that the frequency is $430 \text{ nHz}$ at solar age. To reach the $430 \text{ nHz}$ level and at least as deep as $0.4$ in present solid rotation models, we adjust the rotational evolution toward ZAMS. We reevaluate here tachocline mixing in using a more realistic rotation law that should apply over both pre-MS and MS. Thus, we adopt the approach of Bouvier, Forestini, & Allain (1997, hereafter BFA97) to calculate different sets of rotation evolution for $1 \odot$ stars under the three following assumptions: (1) stars rotate as solid bodies; (2) stars are locked to a defined angular velocity as long as they interact with the initial surrounding disk; and (3) magnetic wind braking acts all along pre-MS and MS and, depending on rotation speed, produces varying angular momentum loss rate

$$\frac{dJ}{dt}_w = -K\Omega^2 \left( \frac{R}{R_\odot} \right)^{1/2} \left( \frac{M}{M_\odot} \right)^{-1/2}$$ if $\Omega < \omega_{\text{sat}}$, \hspace{1cm} (1)

$$\frac{dJ}{dt}_w = -K\Omega \omega_{\text{sat}}^2 \left( \frac{R}{R_\odot} \right)^{1/2} \left( \frac{M}{M_\odot} \right)^{-1/2}$$ if $\Omega > \omega_{\text{sat}}$. \hspace{1cm} (2)

Figure 9 presents corresponding equatorial velocity evolution for solar mass and composition.

$K$ and $\omega_{\text{sat}}$ are adjusted to fit observations of surface rotation rates. Surface magnetic field in solar-type stars seems to increase with $\Omega$ up to $\sim 10\Omega_\odot$ and then saturates (Saar 1996). Saturation value determines a transition in the efficiency of the wind to brake the star, which has consequences over early MS rotation rates. Following BFA97, we adjust $\omega_{\text{sat}} = 14\Omega_\odot$. $K$ determines the rotation rate at solar age. Recent helioseismic measurements (Corbard et al. 1997) give internal solar rotation rates. A latitudinal dependence of rotation frequency is observed in the convection zone, from $460 \text{ nHz}$ at the equator down to $370 \text{ nHz}$ at $60^\circ$ latitude. Radiative zone then experiences rigid rotation at the $430 \text{ nHz}$ level and at least as deep as $0.4 R_\odot$. In present solid rotation models, we adjust the rotational evolution laws so that the frequency is $430 \text{ nHz}$ at solar age. To reach this rotation rate at actual solar age, we adjust $K$ to $3.25 \times 10^{47} \text{ g cm}^2 \text{ s}^{-1}$ in the expression of the braking law. This value is a little larger than the one used by BFA97 ($2.7 \times 10^{47} \text{ g cm}^2 \text{ s}^{-1}$) as we tend toward a slower rotation velocity than surface equatorial: $2.7 \times 10^{-6} \text{ rad s}^{-1}$ instead of $2.9 \times 10^{-6} \text{ rad s}^{-1}$.

We then consider three different $\tau_{\text{disk}}$ durations for star/disk coupling time: 0.5, 3, and 10 Myr. The value of 0.5 Myr corresponds to a star that ceases disk locking evolution on its birth line or a few 0.1 Myr after depending on mass and composition. A value of 3 Myr is the median disk lifetime as estimated by BFA97. Finally, 10 Myr corresponds to a persistent disk. At this age only $10\% - 30\%$ of young stars still show the IR and millimeter radio emission expected if an optically thick disk is present (Strom 1995). The star is kept on a velocity of $9.1 \times 10^{-6} \text{ rad s}^{-1}$ until it uncouples from the disk. Then, owing to gravitational contraction, it accelerates up to $2.70 \times 10^{-5}$ and $1.75 \times 10^{-4} \text{ rad s}^{-1}$ after $\sim 30$ Myr for $\tau_{\text{disk}}$ equal to 10 and 0.5 Myr, respectively. Such rotation rates correspond to equatorial velocities that span from 20 to 120 $\text{ km s}^{-1}$. Afterward the stars decelerate rapidly toward the same low velocity whatever the disk lifetime. At the Hyades age the stellar equatorial velocity is in the narrow range from 4 to $6 \text{ km s}^{-1}$.

Metallicity has direct impact on rotation evolution. We evaluate rotation history for three sets of metallicities: Pleiades, Sun, and Hyades. From the former to the latter composition contraction time toward ZAMS increases. Peak velocities are reached later and are slightly lowered, mainly as a result of higher moment of inertia and radius. A $1 \odot$ Pleiades star reaches maximal velocity at 29 Myr, whereas its Hyades counterpart reaches it at 33 Myr. Moreover, with the radius being a bit larger, the wind braking affects more surface rotation. For a typical disk lifetime of 3 Myr we estimate peak velocity to be 120 and 113 $\text{ km s}^{-1}$ for Pleiades and Hyades compositions. These values are reached around 29 and 33 Myr, respectively.

Purely structural effects of rotation have been included the same way as in the preceding section. Rotational centrifugal acceleration effects are added to gravity. This modifies the equation of hydrostatic equilibrium and radiative gradient. At radius $r$ and angular velocity $\omega$, the present stellar code integrates the "mean" effect of rotation by subtracting $2\omega^2/3$ to gravitation. Then rotation velocities are also taken into account in a macroscopic rotationally induced diffusion coefficient $D_T$ (eq. [14] in BTZ99) and tachocline thickness $d$ (eq. [11] in BTZ99) that determines tachocline mixing efficiency. These coefficients are assumed to follow the scaling laws (suggested by BTZ99)

$$D_T \propto \Omega^{0.75 \pm 0.25},$$ \hspace{1cm} (3)

$$d \propto \Omega^{(1.3 \pm 0.1)/4}. \hspace{1cm} (4)$$

5.2.1. The Solar Case

Rotation induces a strongly increased depletion of photospheric $^7\text{Li}$. Structural modifications do not play any significant role on pre-MS as well as on MS unless the stellar disk lifetime is very short. For a 3 Myr disk lifetime we note no differences exceeding 0.1 dex in $^7\text{Li}$ between a model that includes rotation structural changes and a model that does not. Stellar structures and evolutions are similar. On the contrary, rotationally induced mixing dramatically changes $^7\text{Li}$ history. The 3 Myr disk lifetime star experiences an enhanced destruction of $^7\text{Li}$ during radiative core development phase when compared to the nonrotation model. $^7\text{Li}$ abundance is lowered from $\sim 2.1$ dex without rotation down to $\sim 1.8$ dex. This increases $^7\text{Li}$ depletion during pre-MS in comparison with previous calculations using only the Skumanich law (BTZ99). However, the final result is not much altered. $^7\text{Li}$ depletion depends on disk lifetime.
TABLE 7

| \(\tau_{\text{disk}}\) (Myr) | Lithium at ZAMS | Lithium at 0.7 Gyr | Lithium at 4.6 Gyr |
|-----------------------------|-----------------|-------------------|-------------------|
| 0.5                        | 1.34            | 0.84              | 0.35              |
| 3                          | 1.80            | 1.43              | 0.95              |
| 10                         | 1.90            | 1.56              | 1.10              |
| 20                         | 1.92            | 1.61              | 1.16              |

\(\tau_{\text{disk}}\): Variation is important between \(\tau_{\text{disk}} = 0.5\) and 3 Myr but more moderate for longer disk lifetimes (Table 7; Figs. 10 and 11).

Typical scatter between long- and short-lived disk is 0.5 dex and tends to grow slightly on MS. This does not agree with open cluster observations that show no dispersion in \(^7\text{Li}\) abundances from Pleiades to Hyades as can be seen on previous plots. On the other hand, spread reappears in much older clusters such as M67 (Jones, Fischer, & Soderblom 1999). With a photospheric lithium of 1.1 dex, the Sun is expected to have experienced a long-lived disk star (Fig. 10), if this approach is correct. However, one has to be extremely cautious when drawing such a conclusion. Pre-MS depletion phase is overestimated as young open cluster observations suggest.

5.2.2. The Hyades Case

The tachocline thickness and macroscopic diffusion coefficient depend on the rotation history and the metallicity. However, if scaling laws of equations (3) and (4) are correct, we compute that differences in metallicity of 0.1 dex do not induce large enough modifications in rotation speed to significantly change tachocline diffusion coefficient or thickness in pre-MS. The general behavior noticed for the Sun is also observed for this cluster. However, the computation shows that higher velocity rotating stars do exhibit larger \(^7\text{Li}\) depletion, which does not agree with present observations, indicating that rapid rotators have higher \(^7\text{Li}\) rates than their slower counterparts (Soderblom et al. 1993; García López, Rebolo, & Martin 1994). This point suggests that tachocline mixing, as it is now introduced in calculations, and probably any mechanism that would mix radiatively stabilized layers on pre-MS, could be partly inhibited. It is noteworthy that low-mass star rotation is presumably evolving slower. A 0.8 \(M_\odot\) star should reach peak velocity at 50 Myr. Moreover, such a star will retain its angular momentum longer so that tachocline mixing retains longer efficiency. This brings the star the wrong way for it is the lighter stars that present the largest discrepancy in \(^7\text{Li}\) content between current models and observations.

6. SUMMARY AND PERSPECTIVES

This study confirms that lithium offers an extremely interesting insight over solar-like stellar structure and evolution as a result of its low depletion temperature. There is presently a discrepancy between computations of classical stellar models and observations. Classical models predict no lithium depletion on MS, whereas it seems to be observed in open cluster lifetimes. It is reasonable to think that lithium evolution on MS is connected to some slow mixing rotationally induced process(es) that occurs at the top of the radiative zone. In the specific case of our Sun such a process is supported by differences between theoretical and measured sound speed in this part of the star (BTZ99) and by the agreement between photospheric observations and predictions for helium, metals, and lithium. During pre-MS, the lithium problem is reversed and classical up-to-date theoretical models generally predict too strong depletion. We confirm that this depletion strongly depends on metallicity in the calculation. It is not evident that it is currently observed in young open clusters. In this regard Coma and Blanco I rather suggest an age dependence. Moreover, early dispersion in lithium abundances has to be explained.

In this paper we have studied the impact of different microscopic or macroscopic processes on pre-MS lithium depletion. First, we note the important role of the choice of...
Such material infall could supply lithium and other metals to protoplanetary systems which are not detectable today. On the other hand, it is also possible for young stars not to accrete during the first megayear following star formation. Accretion is likely to explain dispersion in lithium abundances such as carbon, oxygen, silicium, and iron on young T Tauri stars and on the previously studied open clusters stars. Similarly, helium fraction needs to be accurately determined (Pinsonneault 1997). Accretion is likely to explain dispersion in lithium abundances such as carbon, oxygen, silicium, and iron on young T Tauri stars and on the previously studied open clusters stars. To solve this problem, we encourage measurements of photospheric abundances such as carbon, oxygen, silicium, and iron on young T Tauri stars and on the precociously studied open clusters stars. Such additional data can be deduced from binary systems, high-mass stars, and importantly in solar-like stars thanks to the future asteroseismology developments.

Macroscopic processes are at play through accretion, rotation, and convection modeling. Such processes are now crucial to understand accurately stellar evolution (Pinsonneault 1997). Accretion is likely to explain dispersion in $^7$Li fraction measurements, but it fails to bring mean abundances to an acceptable level. In the Pleiades case, required accretion rates at a given time are at the upper limit of observations for young T Tauri. To improve significantly the situation, they should last so long that total accreted mass would indeed be $\sim 20\%-30\%$ of solar mass during the first megayear following star formation. On the other hand, it is also possible for young stars not to accrete from classical gas and dust disks but from planetesimals of protoplanetary systems which are not detectable today. Such material infall could supply lithium and other metals in low-mass convective envelopes of post-T Tauri stars.

Rotationally induced mixing gives satisfactory results regarding photospheric solar lithium abundance. These results are moreover consistent with Hyades open cluster observation when oxygen and iron fractions are correctly, i.e., separately, considered. The rotation mixing process we consider is, however, unable to explain initial spread in $^7$Li surface abundances. Treating more properly the fruitful MS tachocline mixing (BTZ99) in pre-MS leads to results not supported by observations (King et al. 2000 and references therein). We find a rotation-$^7$Li depletion correlation on ZAMS. However, it is important to keep in mind two points. Firstly, we recall that the present rotationally induced mixing is not related to angular momentum transport in the stars. It therefore offers a possible but certainly partial vision of lithium MS evolution. ZAMS rotational velocity should affect $^7$Li depletion because of subsequent angular momentum redistribution (Pinsonneault et al. 1999 and references therein). Secondly, the rotationally induced mixing process we invoke has a necessary transitory regime that we did not take into account. For these two reasons $^7$Li depletion predictions of the tachocline mixing are more reliable between the Hyades and older clusters than absolute predictions from star formation. Hyades solar-like stars are already slow rotators and might have lost most of their angular momenta. From Hyades to older clusters, lithium should evolve long-term (stationary) mixing effects, and indeed the tachocline mixing gives rise to the observed characteristic time ($\sim 1$ Gyr) for $^7$Li depletion on MS.

Finally, it is possible that the convection parameter $a_{\text{MLT}}$ is sensitive to rotation, and hydrodynamical simulations suggest that it should be changed along the Hayashi track. The effect we mention is not very large, contrary to some previous studies, but more work is needed to be sure. We have emphasized the absence of a well-established radiative stratification in central parts during phases preceding 20 Myr, which is a tricky point. The first phase of lithium burning occurs at the frontier between cooler convective medium and hotter radiative (but almost convective) medium that lies beneath. This means that very slight additional perturbation (through overshooting or instability, for instance) could give rise to a much stronger lithium depletion. This also means that a very slight stabilization phenomenon, related to magnetic field as is suggested by Ventura et al. (1998), could save a large fraction of lithium.

All these remarks on macroscopic phenomena encourage complementary studies implying a hydrodynamics approach. This is also true to check if the star is initially fully convective and rotates as a solid body. The answers to those questions can only be extracted from earlier phases that include protostellar collapse and take into account hydrodynamical processes such as accretion in a consistent and more rigorous manner.

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