LITHIUM IN YOUNG CLUSTERS AND PRE-MAIN SEQUENCE STARS

EDUARDO L. MARTÍN[1,2]
[1] *University of California at Berkeley*
[2] *Instituto de Astrofísica de Canarias*

ABSTRACT.
This review covers observational and theoretical results published from 1994 to 1997 on the topic of lithium in low-mass pre-main sequence (PMS) stars and young open clusters (age<1 Gyr). The observational patterns of PMS and main sequence (MS) lithium depletion as a function of age, mass and rotational evolution are discussed, as well as the present level of agreement between models and observations. Phenomenological evolutionary models have not yet properly taken into account all the constraints imposed by lithium and rotation data. For solar-mass stars, strong PMS rotational decoupling between the convective and radiative regions, and slow recoupling, seems promising for explaining the timescale of MS lithium depletion. Lithium and planets are probably connected in being both fossil records of different initial conditions in otherwise nearly identical stars. The utility of lithium as an age diagnostic depends primarily on the stellar mass. Useful empirical rules can be defined for dating low-mass stars with lithium. However, the parameter space in which lithium can be used as a clock is limited.

1. Introduction

"Standard" models of stellar evolution are those that include convection as the only chemical mixing mechanism in stellar interiors (perhaps rather than standard we should call them "zeroth-order"). The treatment of convection is usually one-dimensional, using a free parameter (α) for linking the mixing length to the pressure gradient. The model predictions of the rate of depletion of light elements (D, Li, Be) are quite sensitive to the value of α chosen (D'Antona & Mazzitelli 1994, Forestini 1994, Martín & Claret 1996). Standard models are quite successful in reproducing most of the Solar data, including the latest heliosismology results (e.g. D'Antona 1997). However, the solar abundance of lithium remains a puzzle because this element is depleted in the Sun's photosphere by about a factor of about 200 with respect to the meteoritic abundance, whereas standard models predict much less depletion.

We do not yet have astroseismology data for probing the evolution of solar-like stars, but we do have lithium abundances. The lithium observations are feasible with ground-based spectroscopy because the strongest line in cool stars is the resonance LiI doublet at 670.8 nm, which is conveniently located at the peak efficiency of CCD detectors. Thus, it is not surprising that lithium is one of the elements that has been most frequently observed in the last few years. There are more stars with lithium abundance measurements than with abundances of other more familiar elements like carbon and oxygen. A catalog of lithium abundances, in the same vein as the Cayrel de Strobel et al. (1992) compilation of stellar iron abundances, would be worthwhile.

Open clusters have the advantage of providing a snapshot of the stellar evolution at a fixed age. Standard models predict that most of the solar lithium depletion should have taken place in the pre-main sequence (PMS) phase, when the convective envelope was deep enough to reach the lithium burning inner layers. After about 50 million years (Myrs) the Sun stabilized in the zero-age main-sequence (ZAMS) where the convective region was shallower than the lithium burning zone. Therefore, no further lithium depletion after about 50 Myrs can be expected in standard models. As will be discussed later, this is clearly in contradiction with the observations of lithium in open clusters. There must be processes of lithium depletion active during the main-sequence (MS). Several mechanisms have been proposed based on different physical sources: mass-loss, rotational-braking, rotational turbulence, overshooting, internal gravity waves, microscopic diffusion. They may alternatively dominate at different masses and on different timescales. The pattern of MS lithium depletion is so complex that there seems to be room for more than one physical process. It is also important that the lithium observations can discard some mechanisms, and put constraints on parameters such as the amount of MS mass loss and convective overshooting.

In this paper, I will focus on results that have been obtained in the last 3 years. Good reviews on lithium observations and theory prior to 1994 can be found in the proceedings of the 8th Cambridge Cool Stars Workshop (Balachandran, Pallavicini, Pinsonneault, Strom). The organization of the rest of this review is the following: Section 2. A discussion of observations of lithium in the youngest stars; Section 3. A summary of the observations of lithium in young open clusters; Section 4. My personal assessment of our present understanding of PMS lithium depletion, with emphasis on the rotation connection; Section 5. A comparison of models of MS lithium depletion with observations and comments on what the observations seem to be telling us (beware of speculation); Section 6. Some rule-of-thumb guidelines for using lithiumas an age indicator ("render unto Caesar what belongs to Caesar ...").

2. Lithium in the youngest stars

Not so long ago, one could safely talk about "T Tauri stars" (TTS) and everybody would understand them to be the "youngest stars", i.e. the first visible manifestation of newly born stars. However, this is no longer the case. Some colleagues have chosen to define "Weak T Tauri stars" (WTTS) as any kind of PMS stars, thereby stretching the term TTS to older ages where stars lose most of the attributes of extreme youth, including their pristine surface lithium abundances. Such a broad definition of TTSs has been contested, and the subject is presently a matter of debate (see several contributions to the proceedings of the 10th Cambridge Cool Stars Workshop). It appears that lithiumcould play a key role in the spectroscopic definition of the WTTS and Post-TTS classes (Herbig 1978, Martín 1997).

Two recent papers have derived lithium abundances in PMS stars of the Orion star-forming region. Cunha et al. (1995) derived a mean lithium abundance of log N(Li)=3.2±0.1

(in the customary scale of log N(H)=12), including NLTE effects. On the other hand, Duncan & Rebull (1996) claimed an average of log N(Li)=3.8 in another sample, but they did not take into account NLTE effects, which are known to lower the lithium abundances when the lines are saturated (Carlsson et al. 1994, Pavlenko et al. 1995, Pavlenko & Magazzù 1996). Moreover, the Duncan & Rebull spectra have lower quality than the Cunha et al. data. Magazzù et al. (1992) and Martín et al. (1994) had concluded that log N(Li)=3.2 is the initial lithium abundance of young stars, and the recent results in Orion are consistent with it. Hereafter, I will refer to log N(Li)=3.2 as the "cosmic" value, which is very close to the solar system meteoritic abundance of 3.3. The upper envelope of lithium abundances in young open clusters is also very similar to 3.2, indicating that the interstellar lithium abundance in the local Galactic disk has remained unchanged during the last 5 Gyrs. This constraint should be taken quite seriously by models of the chemical evolution of the Galaxy.

3. Lithium in young open clusters

In Table 1, I have compiled information on all the young (age<1 Gyr) open clusters for which lithium data is known to me as of October 1997. They are ranked by increasing order of age. The best procedure for dating open clusters is a matter of recent controversy (Basri 1997), and the values listed in the table should be considered as indicative only. The same applies to the distances.

Several age groups can be made from Table 1: I. 30–50 Myrs (IC clusters, Blanco 1 and αPer), II. 100 Myrs (Pleiades), III. 200–250 Myrs (NGC 1039 and NGC 6475), IV. 600–800 Myrs (NGC6633, Hyades, Praesepe). The age differences from one group to the next are large enough that they do not overlap. Investigation of lithium abundances inside each age group can reveal the dependance of lithium depletion with factors other than age. The comparison of different age groups will mainly reflect evolutionary effects.

Table 1 also gives the iron abundances with respect to the Sun derived spectroscopically, or when those are not available, the metallicities inferred from photometric indices. The metal content is an important parameter in lithium depletion (VandenBerg & Poll 1989, Swenson et al. 1990). The number of cluster members with lithium abundance measurements, and the references where the data can be found are given in the last two columns of the Table. The volume of data, over 550 stars, is impressive. The bulk of it has been published in the last 4 years, indicating that this is a rapidly developing field.

4. Pre-main sequence lithium depletion

The physics of PMS lithium depletion in contracting, fully convective stars is relatively simple and can be treated almost analytically (Bildsten et al. 1997). However, stars heavier than 0.5 $M_\odot$ develop a radiative core during their PMS lithium depletion, and the physics become more complex. When the radiative region extends beyond the radius where lithium thermonuclear burning is efficient, standard models predict that lithium depletion at the stellar surface should stop. Some non-standard effects like mass-loss (Swenson & Faulkner 1992) or overshooting (VandenBerg & Poll 1989) would induce more lithium depletion than the standard model, but others could go in the opposite

Tab. 1 - Young Open Clusters with lithium data

Name	Age	D	[M/H]*	ref.	No.	ref.
IC 2391	35	150			10	1
IC 2602	35	150			28	2
IC 4665	35	150			14	3
αPer	50	165	-0.054±0.046	4	77	5,6,7,8,9
Blanco 1	50	240	+0.23±0.02	10	15	11
Pleiades	100	125	-0.034±0.024	4	166	5,6,12,13,14
NGC 1039 (M34)	200	450	-0.03**	15	49	16
NGC 6475	220	250	+0.110±0.034	17	34	18
NGC 6633	600	310	-0.11	19	21	19
Hyades	700	45	+0.127±0.022	4	90	20,21
Praesepe	800	170	+0.07	17	63	22

References: 1. Stauffer et al. 1989, 2. Randich et al. 1997a, 3. Martín & Montes 1997, 4. Boesgaard & Friel 1990, 5. Boesgaard et al. 1988, 6. García López et al. 1994, 7. Balachandran et al. 1996, 8. Zapatero-Osorio et al. 1996, 9. Randich et al. 1997b, 10. Edvardsson et al. 1995, 11. Panagi et al 1994, 12. Soderblom et al. 1993a, 13. Jones et al. 1996, 14. Oppenheimer et al. 1997, 15. Canterna et al. 1979, 16. Jones et al. 1997, 17. James & Jeffries 1997, 18. Lynga 1987, 19. Jeffries 1997, 20. Thorburn et al. 1993 (and references therein), 21. Soderblom et al. 1995, 22. Soderblom et al. 1993b.

Notes: * Values with error bars are spectroscopic [Fe/H] abundances, the rest are photometric metallicity estimates. ** Photometry indicates same metallicity as the Pleiades.

direction of inhibiting PMS lithium depletion (Martín & Claret 1996). Particularly useful in constraining PMS models are data relevant to the beginning of the lithium depletion. Martín et al. (1994) tried to estimate the luminosity at which WTTSs start showing significant lithium depletion (log N(Li)$\leq$2.8). However, they did not have many low-lithium stars in their sample, and most of those came from X-ray observations. It is not proven that those lithium poor stars are related to the molecular clouds, and hence their distance and H-R diagram positions might be in error. The luminosity and mass at which PMS lithium depletion starts is still undetermined. The Hipparcos output catalog might be helpful, but there are probably not enough low-mass PMS stars included in it. Future space missions for measuring trigonometric parallaxes in faint stars would be very valuable.

Since standard models are tuned to fit the Sun, it is important to compare their predictions of PMS lithium depletion for 1 $M_\odot$ with the cluster data of age groups I and II (30–100 Myrs). The observations show that stars with $T_{\rm eff}$ $\geq$5500 K have experienced little PMS lithium depletion (<0.5 dex). Only two clusters in these age groups have metallicities available (αPer and Pleiades), and both are close to solar. Standard models with solar composition predict that in the ZAMS the Sun had $T_{\rm eff}$ $\sim$5600 K. The predicted PMS solar lithium depletion depends on the opacities and convection parameterization. Some standard models clearly predict more PMS lithium depletion than 0.5 dex for 1 $M_\odot$, for instance those of VandenBerg & Poll (1989) and Table 1 of D'Antona & Mazzitelli (1994). Such models are in trouble given the constraints imposed by the cluster data. For masses lower than the Sun, the standard models tend to predict too much PMS lithium depletion with respect to cluster observations (García López et al. 1994, Randich et al. 1997a). An increase in the electron screening potential of the Li-proton reaction (Straniero 1997) would increase the rate of lithium depletion and make things worse than they already are. The tendancy to increase the opacities over the last few years, also contributes to predicting larger PMS lithium depletion. One possibility to find an agreement between observations and theory has been proposed by Martín & Claret (1996). They show that models with solid-body (SB) rotation predict less PMS lithium depletion than standard models without rotation. Earlier rotating models by Bisnovatyi-Kogan et al. (1979) also suggested that rotation decreases the temperature of the stellar interior, but Mendes et al. (1997) appear to find different results. SB rotation is a simple approximation that may be unrealistic. Angular momentum transfer calculations in stellar interiors put the shoe on the other foot, predicting higher lithium depletion for faster rotation (Chaboyer et al. 1995a,b) which is inconsistent with observations. It is clear that standard models (including the solar model) need substantial improvements for explaining quantitatively the lithium abundances in young open clusters. A great challenge for future models seems to lie in identifying a way to reduce the rate of PMS depletion. This needs perhaps a revision of the treatment of convective mixing.

The dispersion of lithium abundances among cluster members with similar T_{eff} is more food for thought. It is very intriguing that there is a range of T_{eff} where lithium abundances tend to be higher for higher surface rotation. In the Pleiades, this happens for 5500–4500 K, as first noted by Butler et al. (1987). All other works have confirmed the Li-rotation relationship, except for Russell (1996) who looked at the LiI 610.4 nm subordinate line in a few Pleiades stars and claimed that the abundances obtained from this line were systematically higher and showed less scatter than those from the resonance line. Close inspection of the analysis done by Russell (1996) shows that his gaussian deblending technique overestimated the strength of the subordinate line, which is blended with stronger lines in his spectra. I have estimated from Russell's own figures that he overestimated the LiI 610.4 nm equivalent widths by factors 2 to 3. When this flaw is taken into account, the lithium abundances obtained from both LiI lines agree within 0.2 dex.

For T_{eff} <4500 K the Li-rotation connection breaks down, as first suggested by Martín (1993) and García López et al. (1994), and later confirmed with more stars by Jones et al. (1996). In these cooler stars the spread in lithium abundance is smaller than in the early and mid-K Pleiads, but it is still much larger than the formal error bars. What other factor can cause a lithium spread that is not linked to surface rotation in these stars? Standard models only have one alternative; an age spread. Could the late-K (4500–4000 K) Pleiads with higher lithium be younger than those with lower lithium? The answer is probably no, for two reasons. First, these stars have masses lower than 0.7 $M_\odot$ and are expected to be still contracting. Younger PMS stars are brighter, but I have not found any correlation between V magnitude and lithium in these stars. Second, the stars in the same T_{eff} range in αPer show lithium abundances that are intermediate between the high- and low-lithium Pleiades stars (Randich et al. 1997b). Therefore, it is unlikely that an age spread is responsible for the lithium dispersion in the late-K

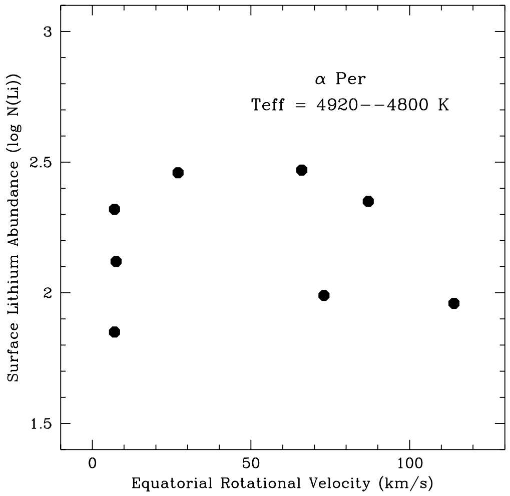

Fig. 1. A plot of lithium abundances versus equatorial rotation velocities for early-K αPer members with photometric measured periods.

Pleiads. The only agent that seems to be able to play an important role is rotation, despite the fact that we do not see a direct Li-rotation connection.

Let's return to the early-K stars, which show the largest lithium spread in αPer and the Pleiades. Is there a correlation between lithium and rotation for them? The cleanest way to find an answer is to plot equatorial rotation velocities against lithium abundances for stars with similar $T_{\rm eff}$. Fortunately, there has been ongoing progress in the measurements of photometric rotation periods through spot modulation. I have used a compilation of rotation data provided by J. Stauffer. The number of stars with both a photometric period and a lithium abundance is sufficient to show that there is not a direct correlation between these two quantities. In Fig. 1, 8 αPer members (AP43, 56, 70, 72, 91, 93, 98 and 117) in the narrow $T_{\rm eff}$ range 4920 K – 4800 K are shown. Their $T_{\rm eff}$ and lithium abundances have been revised by Randich et al. (1997b). The Li-rotation connection appears to be driven by the fact that some slow rotators, but not all, have quite low lithium abundances. Since the dispersion in lithium abundances is also present in the younger IC clusters (Martín & Montes 1997, Randich et al. 1997a), the source of the Li-rotation connection must be in the early PMS evolution. Standard models predict that lithium depletion for these stars is quite efficient at ages 10–20 Myrs. Unfortunately, there has not been any lithium study in clusters of such ages.

Theoretical understanding of the PMS evolution of rotation has received considerable impetus in the last few years (cf. Bouvier 1997). However, the models remain only partially phenomenological because they do not take into account the impact of the rotational evolution on stellar structure and the burning of light-elements. It is not clear, for instance, whether strong PMS convective envelope/radiative core decoupling is necessary for explaining the rotation data or not. It seems that models with solid body rotation (Martín & Claret 1996) make different predictions about lithium depletion than models with inner angular momentum transfer (Chaboyer et al. 1995a,b). Future evolutionary models should take into account both the lithium and rotation data for constraining their adjustable parameters. The fact that stars in αPer with the same T_{eff} and the same moderate rotational period ($\sim$6 days), can have lithium abundances different by $\sim$0.6 dex (example: AP72 and AP98), suggests that they have had different early-PMS rotational history. The cause for the lithium difference might be due to different initial conditions. Some slow rotators may have been coupled to their disks for a long time ($\geq$10 Myrs), while others may have decoupled earlier but they were born with smaller angular momentum. It will be interesting to explore the effect of disk-locked angular momentum evolution on PMS lithium depletion. Future work should not only be dedicated to the fascinating theoretical aspects of the PMS lithium problem. Observations of more young cluster members to measure lithium abundances and rotation periods will increase the statistical significance of the empirical constraints on the models. Monitoring for variability of both LiI strengths and photometric periods in PMS stars on timescales of years is also very worthy, as they provide crucial information on the roles of magnetic activity cycles and surface differential rotation.

5. Main sequence lithium depletion

Two recent papers have addressed the need for studies of clusters covering the age gap between the Pleiades and the Hyades. James & Jeffries (1997) and Jones et al. (1997) have studied lithium and rotation in NGC 6475 and NGC 1039, respectively. They did not know about each other, and hence they did not compare the lithium abundances in these two clusters. In Figure 2, this comparison is made. It is relevant to note that NGC 6475 has slightly older age (Meynet et al. 1993) and higher metallicity than NGC 1039 (caution: the metal abundance for the latter cluster is not spectroscopic). Both parameters favour lithium depletion in standard models, but the observations do not show any difference between these two clusters. The lithium depletion pattern at an age of $\sim$200 Myrs does not seem to be very sensitive to small age (10%) or metallicity (0.1 dex) differences. The main sculptor of this lithium pattern is the stellar mass, and the substructure is engraved by a subtle agent that may well be related to the angular momentum history. An empirical connection between lithium and rotation, similar to that of younger clusters, seems to hold in NGC 1039 as well (Jones et al. 1997).

Does MS lithium depletion decrease or increase the dispersion in lithium abundances observed in αPer and the Pleiades? For stars in the T_{eff} domain 6200–5400 K, Jones et al. (1996) claim that the dispersion stays about the same between the Pleiades and NGC 1039, and increases for the Hyades. They carefully cleaned the samples by discounting tidally-locked binaries, upper limits and suspect members (this has not been done in Fig. 2). For cooler stars, it is less clear what does MS depletion to the lithium spread, because the Hyades only has upper limits for T_{eff} $\leq$5000 K. The comparison between the Pleiades and NGC 1039 indicates that the spread may decrease for stars with 5400–4700 K and remain the same, or increase slightly, for stars with 4700–4000 K.

Few non-standard models have attempted to explain the spread in lithium abundances among the members of young open clusters. The boldest attempt is that of

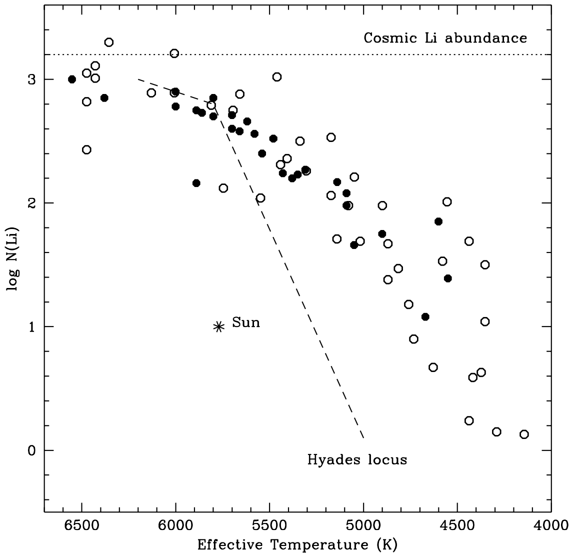

Fig. 2. A plot of lithium abundances versus effective temperatures for stars in NGC 1039 (open symbols) and NGC 6475 (filled symbols). The Sun's present lithium abundance and the locus of lithium abundances in the Hyades cluster are also shown for comparison.

Chaboyer et al. (1995b). Their models produce lithium dispersions that increase with age at all masses because of the effects of the rotational-induced mixing that they use. This is clearly inconsistent with the observed evolution from 100 Myrs to 200 Myrs for open cluster stars with T_{eff} 5500–4000 K. The Chaboyer et al. models include microscopic diffusion and several rotationally-driven instabilities. Models including other non-standard physics, like internal wave diffusion (Montalbán & Schatzman 1996) offer a promising way of chemical mixing in radiative regions, but it remains to be worked out how they behave in the presence of rotation instabilities. The only mechanism of MS lithium depletion that does not need mixing in the radiative regions is mass-loss, but Swenson & Faulkner (1992) have already shown that it cannot explain the Hyades data. MS lithium depletion is somehow connected to the rotational evolution, as evidenced by the Hyades K-type tidally-locked binaries, which have higher lithium abundances than their single or wider binary cluster counterparts which have been spun down (cf. Barrado y Navascués & Stauffer 1996). Nevertheless, some MS depletion acts even in the Hyades tydally-locked binaries because they have lower lithium abundance than the α Per and Pleiades single stars with similar T_{eff} and rotation periods.

The lack of success of standard and non-standard models in providing a satisfactory fit of the lithium patterns in young open clusters suggests that this field is fertile for new ideas. The observations of lithium have proved to be a continuous source of amusement for researchers. A recent surprise has come from the discovery of a giant extrasolar planet orbiting the star 16 Cyg B (Cochran et al. 1997). Both components of the visual binary 16 Cyg have spectra that are nearly indistinguishable from the Sun, except in the strength of the LiI line. According to King et al. (1997), 16 Cyg A has log N(Li)=1.27$\pm$0.05, 16 Cyg B has log N(Li)$\leq$0.6, and the Sun has log N(Li)=1.05$\pm$0.06. Both Cochran et al. and King et al. argued about a link between the presence of giant planets and lithium depletion in solar-type stars. The latter authors even suggested that there might be a correlation between increasing planetary mass and lithium depletion. It appears too premature to try to draw any empirical relationship because we still know few extrasolar planets, and some stars may have larger planets with periods longer than the detection thresholds of the radial velocity surveys. Moreover, it is unclear what the connection between planetary masses and disk masses is, because massive disks may lead to planetary migration. In such a process, planets lose mass and migrate inward (Lin et al. 1996, Trilling et al. 1997). Nevertheless, if there is a correlation between the mass of the largest planet around a star, and its surface lithium depletion, it would be a very nice confirmation that the spread in lithium abundances in otherwise nearly identical stars is due to different initial conditions at the stellar birth. The latest extrasolar planet found around a solar-type star, namely ρCrB (Noyes et al. 1997), has a minimum mass larger than Jupiter's (1.1 M_J/sini) and a lithium abundance (log N(Li)=1.1, Fernández Figueroa et al. 1993) slightly higher than the Sun. Hence, it does not fit well with the correlation suggested by King et al. (1997), although it may be argued that ρCrB has retained more lithium due to its low metallicity ([Fe/H]=-0.19, Noyes et al. 1997).

As illustrated in Fig. 2, MS lithium depletion in solar-type stars is a slow process. The Sun has a lithium abundance lower by more than an order of magnitude than Hyades stars of the same mass. These Hyades stars have low surface rotation velocities, with little scatter. The spread in surface rotation velocities for solar-mass stars observed in αPer, and to a lesser extent in the Pleiades, disappears for older ages (NGC 1039 and Hyades, Jones et al. 1997). This is well understood with the classical mechanism of magnetic wind braking. Therefore, for solar-mass stars the timescale of surface spin down is much faster than that of surface lithium depletion. For lower mass stars the timescale of spin down increases, and that of lithium depletion decreases. The coincidence of a large spread in surface rotation velocity and lithium abundances in young open clusters for masses around 0.8 $M_\odot$ indicates that these are the stars where the timescales of surface spin down and lithium depletion are similar. For lower mass stars the timescale of spin down becomes slower than that of lithium depletion, and hence the Li-rotation relationship is expected to break down, as observed. Qualitatively, the mass-dependent timescales for both lithium and rotation MS evolution can be understood as a result of the mass-dependent depth of the convective envelope. In the Sun, the convective zone (CZ) represents less than 3% of the total mass. The mass fraction in the CZ increases steeply as a function of mass, until it reaches nearly 100% below 0.3 $M_\odot$. The larger the mass of the CZ, the longer the timescale for braking it down and the shorter the timescale for mixing Li. However, the lithium burning region lies just within the radiative zone (RZ) for MS stars with masses larger than about 0.5 $M_\odot$. Somehow, the upper radiative layers where lithiumcan survive, feel the turnmoil of the lower convective layers. The more massive the CZ, the stronger the turbulence at its base could be, and the faster the mixing of lithium in the RZ below it.

Since solar-mass stars quickly converge in surface rotation, apparently losing the memory of different initial angular momentum conditions, what agent can cause the observed different rates in surface lithium depletion at later stages of the MS evolution? The high efficiency of magnetic spin down, noticeable even in the short age span between αPer and the Pleiades, strongly indicates that it is only the CZ that's being braked. Of course, we only have data on the surface rotation, but the presence of a rapidly rotating RZ may have observable consequences that need to be investigated in detail. A strong decoupling between the CZ and the RZ appears to be a reasonable way of explaining the fast spin down of solar-mass stars, although models have not been able to discard SB rotation evolution on the basis of the existing rotation data (Krishnamurthi et al. 1997). As way of explaining the slow development of a spread in lithium abundances in solar-mass stars during MS evolution, the hypothesis of strong CZ/RZ rotational decoupling (and subsequent slow recoupling) is much more promising than SB or efficient recoupling. The recoupling timescale would have to be of the order of the age of the Sun, in order to allow for star to star differences to develop in the rate of MS lithium depletion. Decoupling would be weaker for lower mass stars, and SB rotation is probably a good approximation for very low-mass stars and brown dwarfs. A full description of how varying degrees of CZ/RZ differential rotation exactly affect the timescale of lithium depletion needs numerical computations that are beyond the scope of this paper.

6. Lithium as a stellar age indicator

Lithium is a classical age indicator, although it has frequently been criticized mainly because of the spread in lithium abundances among the members of young open clusters. Nevertheless, it remains a useful age diagnostic if careful considerations of the mass-, metallicity- and rotational evolution- dependent depletion timescales are allowed for. The main advantage of lithium over other age indicators (H-R diagram, chromospheric activity, etc) is that it can provide age estimates that rely only on spectroscopic measurements (T_{eff} or spectral type, and LiI equivalent width), which are independent of distance. Thus, it can be used for studying the evolutionary status of stellar populations of unknown distance, as for instance the widespread X-ray emitting stars found by the Rosat All-Sky Survey (Martín 1997).

There are some simple observational rules that show the ability and limitations of lithium for dating stars: I. Any star later than G9 with log N(Li)>1 is younger than 700 Myrs, II. Any star later than K5 with log N(Li)>2 is younger than 200 Myrs, III. Any star later than K7 with log N(Li)>2 is younger than 100 Myrs, IV. Any star later than M0 with log N(Li)>1 is younger than 35 Myrs. Lithium as a chronometer has varying sensitivity for different stellar masses. For G-type stars, it is useful only for ages longer than about 1 Gyr because of the unefficient PMS depletion, and the long MS depletion timescale. For K-type stars, it can be used up to ages of about 700 Myrs, but it is not very accurate due to the influence of rotation. For M-type stars, lithium is depleted so fast that it cannot be used for ages larger than about 200 Myrs because it becomes undetectable.

In young open clusters lithium depletion opens a "Li-chasm or canyon" (it would be desirable to use different words for this phenomenon and for the "Li-dip or gap" in F-type stars) which is expected to start in the early-M stars and widen up with age (e.g. Fig. 16 in D'Antona & Mazzitelli 1994). The physics of lithium depletion in the cool side of the chasm are simpler because the objects are fully convective (Bildsten et al. 1997). Observations of lithium depletion in the very late-M members of open clusters offer a promising clock, which may prove to be a reliable calibration of the age scale of young open clusters. On the hotter side of the chasm, our understanding of PMS lithium depletion will also improve with better knowledge of cluster ages. The first lithium observations around the substellar boundary in the Pleiades cluster indicate that its age is older than previously thought (cf. Basri 1997). It will be exciting to see the results of more lithium observations in the cool side of the chasm in the Pleiades and in other young clusters where the hot side has been studied (Table 1). Such work is under way. Finally, I should stress the importance of studying the lithium abundances of a population of stars with ages in the range 5 to 20 Myrs, whether as members of a cluster or as visual binaries or as dispersed post T Tauri stars. At these ages, both sides of the chasm are expected to be fully convective, and would yield a very good test of standard evolutionary models.

Acknowledgements

I thank John Stauffer for sharing with me his compilation of rotation data and for comments that improved the manuscript. I also thank Gibor Basri, Franca D'Antona and Sofia Randich for helpful comments. This research has made use of the Simbad database, operated at CDS, Strasbourg, France.

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