LITHIUM AND BERYLLIUM IN MAIN SEQUENCE STARS

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ABSTRACT. Li and Be abundances in Main Sequence stars later than F0 are reviewed. Observations of Li in open cluster stars and metal-poor dwarf halo stars has promoted the development of a great variety of models invoking transport processes in the outermost layers of these stars. Although measurements in their present state do not allow to establish definitive conclusions on which process is the most important for each range of masses, they do manifest that metallicity and stellar rotation play an important role in controlling the processes which trigger disappearance of these elements from stellar atmospheres.

1. Introduction

Abundances of Lithium (whose isotope ^{7}Li will be referred to as Li) and Beryllium (^{9}Be) in stellar atmospheres, provide very valuable information on stellar structure and evolution, as well as other fields of Astrophysics such as nucleosynthesis in the Big Bang (see e.g. Wagoner et al. 1967; Malaney and Fowler 1988, 1989) or the chemical evolution of the Galaxy (Audouze and Silk, 1989 and references therein). Li and Be nuclei are destroyed in the interiors of stars at relatively low temperatures (about 2.5 10^6 and 3.5 10^6 K, respectively). In low Main Sequence (MS) stars, these temperatures are reached slightly below the base of the superficial convective zone or inside the convective zone. Therefore, the processes which transport matter between the outermost layers and regions of the stellar interior (convection, gravitational settling, turbulent diffusion, meridional circulation, etc.) may cause an alteration in the contents of Li and Be with which a star has formed.

The great variety of Li and Be abundances observed in MS stars proves the existence of such transport processes. Although this may hinder our understanding of the origin of these elements and render the determination of their galactic evolution difficult, there is no doubt that, at the same time, it offers a unique possibility to obtain information about the hydrodynamics of stellar envelopes. This review will examine the present status of observations of Li and Be in Main Sequence stars with spectral types later than F0. Li measurements in hotter stars are discussed by Cayrel (this volume). Boesgaard (1976) reviewed the earliest measurements of Li, Be and B; and recent reviews on these elements can also be found in Charbonneau and Michaud (1990), Boesgaard (1990) and Rebolo (1990).

2. Lithium in Pre-Main Sequence stars

G. Michaud and A. Tutukov (eds.), Evolution of Stars: The Photospheric Abundance Connection, 85–97.

2.1. T TAURI STARS

Despite the fact that the Li I 6708 Å doublet was discovered in T Tauri stars by Sandford back in the Forties, the quantitative study on the abundance of Li was not conducted until Bonsack and Greenstein (1960). These authors showed that Li was overabundant in T Tauri stars by a factor 100 with respect to the abundance measured by Greenstein and Richardson (1951) in the Sun. Zappala (1972) measured the abundance of Li/H=10^{-9} (log N(Li)=3, in the scale log N(H)=12) in a sample of stars belonging to the young stellar cluster NGC 2264, and also in T Tauri stars of the sample observed by Bonsack and Greestein. All these stars have masses larger than twice that of the Sun. Therefore, on the basis of calculations by Bodenheimer (1965) and more recent studies by D'Antona and Mazzitelli (1984) and Proffit and Michaud (1989) there is no reason to expect that they have destroyed an appreciable fraction of their initial Li.

From an observational point of view, Li destruction in T Tauri stars has been investigated recently by Strom et al. (1989), Magazzù and Rebolo (1989, 1991) and Magazzù, Martin and Rebolo (1991). Strom et al. (1989) published preliminary results on an extensive survey of Li in Taurus-Auriga and in the Lynds 1641 complex. Magazzù and Rebolo (1989) also reported on preliminary abundances of Li for a sample of T Tauri stars in the Taurus-Auriga, Ophiucus, Chamaleon and Lupus associations. In both works, most of the stars are younger than 10^7 yr. and have masses between 0.4 and 2 $M_\odot$.

Uncertainties in deriving Li abundances in these objects are quite considerable: i) effective temperatures, derived from spectral types, are doubtful because, as is well known, these objects sometimes present changes in spectral type; ii) the adoption of a luminosity class IV or V (also uncertain in these objects) may introduce additional errors in the effective temperatures; iii) classical T Tauri stars (Herbig, 1962) may present strong veiling and accretion discs (see e.g. Hartigan et al. 1989; Bertout 1989) which may affect both the estimate of the stellar parameters and equivalent width measurements; d) NLTE effects may be considerable given that these stars show an intense radiation field in the ultraviolet which can seriously affect the formation of the doublet. Nevertheless, and despite these difficulties, our Li abundance analysis (Magazzù and Rebolo, 1991) of weak T Tauri stars has produced similar results as those from the sample of classical T Tauri stars. They may be summarized as:

i) In the most massive stars the abundances lie in the range 3.2 to 3.6.

ii) Less massive objects show a trend to lower Li abundances.

iii) In several cases, stars with 0.6 $M_\odot$ present Li depletions of more than one order of magnitude.

iv) There is considerable scatter at a given mass. Age differences, chromospheric activity, rotational history and the presence of accretion discs may be the cause. Observations of Li in multiple PMS systems may help to elucidate this issue. Magazzù, Martin and Rebolo (1991) have analyzed the abundance of Li in the UX Tau triple system (age $\sim$2 10^6 yr) formed by weak T Tauri stars with masses 1.2, 0.4 and lower than 0.2 $M_\odot$. We have found an abundance of 3.2 for the most massive, destruction of Li for almost one order of magnitude in the 0.4 $M_\odot$ and a high Li abundance of Li in the less massive object which is difficult to measure accurately in the absence of reliable atmospheric models for such cool objects (spectral type close to M6). The measurement of Li in this type of system is a powerful tool to establish restrictions to models of very low mass stars.

2.2. VERY YOUNG OPEN CLUSTERS

Stauffer et al. (1989) measured Li abundances in several stars of this cluster, at effective temperatures in the range 3600-6100 K. Given that the cluster's age is only 3 10^7 yr., the derived abundances establish limits to Li destruction in the PMS. While the hottest stars observed present abundances close to log N(Li)=3, the coolest, with masses slightly lower than 0.6 $M_\odot$, present upper limits in the range log N(Li)=1-2, showing that they must have suffered considerable Li destruction during the PMS. This result is in good agreemnet with observations of T Tauri stars of the same mass, and with predictions on Li destruction in the PMS for these masses (see Table I in Strom et al. 1989, with results by Pinsonneault et al. 1990).

3. Li in Stars with Solar Metallicity

Metallicity is one of the parameters which most affects Li depletion in stars, for instance through its effect on the depth of the convective zone. It is therefore wise to distinguish between stars with solar metallicitiy and metal deficient stars when revising Li abundances in either group.

Open clusters are a keystone in the study of the transport processes which trigger disappearance of Li from the atmosphere of stars. These systems give us homogeneous samples of stars with the same chemical composition and, in principle, the same age. We can also determine more accurately their masses and we even have information which may allow to conceive a theory on the rotational history of these stars (see Kawaler, 1988).

The first observations of Li in open cluster stars (Hyades, Pleiades, Praesepe) date from the mid Sixties (Wallerstein, Herbig and Conti 1965; Danziger and Conti, 1966). These works confirmed the dependence of Li abundance on mass and stellar age which Herbig (1965) and Herbig and Wolf (1966) had suggested for field stars.

3.1. F STARS

3.1.1. The Li gap in open clusters. Figure 1 compiles Li abundance measurements for F stars and

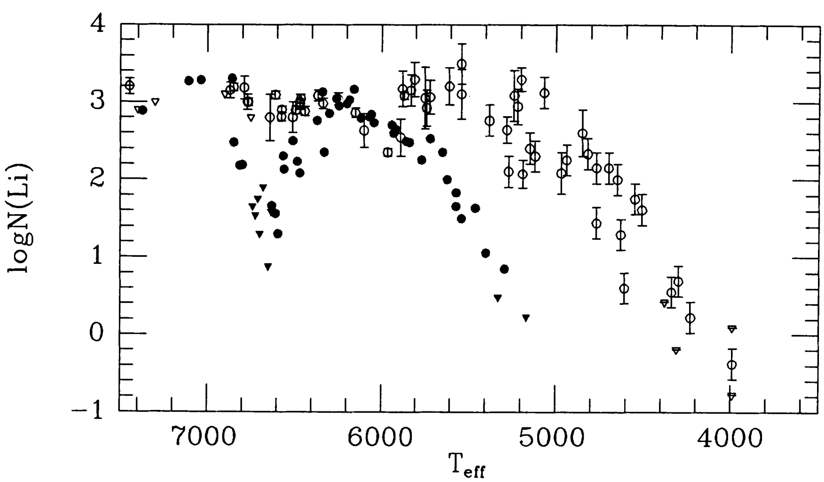

Figure 1: Li measurements in Pleiades (open circles) and Hyades (filled circles) stars. Data taken from Boesgaard and Tripicco (1986a), Boesgaard and Budge (1988), Boesgaard, Budge and Ramsay (1989), Pilachowski, Booth and Hobbs (1987), Cayrel et al. (1984) and Rebolo and Beckman (1988). Typical error bars for the measurements in the Hyades are 0.1-0.15 dex. Triangles indicate upper limits.

later stars in the Pleiades (age 6-7 10^7 yr; [Fe/H]=-0.034±0.024, Boesgaard and Friel, 1990) and in the Hyades (age 0.76 Gyr.; [Fe/H]=0.124± mean value from Cayrel et al. 1985 and Boesgaard and Friel 1990). Comparison of these two clusters synthesizes the behaviour of Li abundance in stars of these spectral types:

i) For stars with $T_{eff} \geq 6300$ K the abundance of Li in the Pleiades is virtually constant close to a value of log N(Li)=3.3 (with a dispersion of only ± 0.15 dex). In the Hyades, however, note the strong absence of Li in mid F stars with temperatures between 6400 and 6800 K, a phenomenon

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which is frequently referred to as "Li gap" or "Li dip". It was discovered by Boesgaard and Tripicco (1986a).

ii)For stars with $T_{eff} \leq 6300$ K, there is a trend to lower abundances as we reach cooler stars and greater dispersion in the Pleiades than in the Hyades. We shall discuss here F stars.

The Li gap was confirmed in other clusters and stellar moving groups by Hobbs and Pilachowski (1986a) in NGC 752 (1.7 Gyr.); Boesgaard (1987) in Coma Berenices (0.5 Gyr.); Boesgaard, Budge and Burck (1988) in the Ursa Major Group (0.3 Gyr.) and Boesgaard and Budge (1988) in the Hyades and Praesepe (0.7 Gyr.). All these observations confirm that Li disappears from the atmosphere of stars in the mentioned T_{eff} range, decreasing its abundance by nearly 2 orders of magnitude in some cases. In the Pleiades (Pilachowski, Booth and Hobbs 1987) and α Per (Boesgaard, Budge and Ramsay, 1989), F stars show a constant Li abundance. Only around 6600 K could a slight dip occur down to values of log N(Li)=2.85. This set of observations show that the gap is originated during the MS lifetime of the stars. Li depletion by a factor 50 must take place in less than 0.4 Gyr. (the age of Ursa Major). The Li depletion rate in those stars at the center of the gap is difficult to infer, mostly because observational difficulties (mainly high rotational velocity and the doublet's small equivalent width) have impeded the detection of Li at the base of the gap. Measurements by Balachandran (1990a) in the open cluster NGC 6475 (age 0.2 Gyr.) show that the gap is not as deep as the one present in the Hyades or Ursa Major, providing valuable information towards modelling the process responsible for this.

Five hypotheses have been suggested up-to-date to explain the Li gap: microscopic diffusion (Michaud, 1986); turbulent diffusion (Vauclair, 1988); meridional circulation (Charbonneau and Michaud, 1988); mass loss (Schramm et al., 1990); mixing induced by internal gravity waves (García López and Spruit, 1991). With present uncertainties in the definition and depth of the gap, it is difficult to establish limits to the validity of the different hypotheses. Below are summarized some of the difficulties which must be surmounted if the proposed explanations are to be valid:

i) Microscopic diffusion presents serious inconvenients to explain underabundances greater than a factor 30 in stars at the center of the gap. Alghough Boesgaard and Tripicco (1986a) had initially imposed limits to the abundance of Li in some stars at the center of the gap, which implied underabundances greater than 100, in a subsequent revision, Boesgaard and Budge (1988) established less restrictive limits to the abundance of Li in these stars, the strongest being log N(Li)= 1.6. Therefore, microscopic diffusion could be the cause of the gap. Michaud (1988) suggested on the basis of preliminary calculations of radiative accelerations, that oxygen could suffer diffusion in the stars of the gap. García López et al. (1990a) have observed 25 F stars in the Hyades and Ursa Major Group to determine the oxygen abundance. For stars in the temperature range 6000-7000 K, their results show great uniformity for the abundance of O within the measurement error which is estimated at ± 0.17 dex. Thus, we should discard the possibility that Li depleted stars could also be O depleted. If more detailed calculations were to confirm that O should suffer diffusion in these stars, the model would be seriously contradictory. Another possible inconvenience which arises from the microscopic diffusion model is that unless we introduce a mass loss rate of 10^{-15} $M_{\odot}$ yr^{-1} (comparable to Am-Fm stars) this model predicts the existence of strong Li overabundances in stars with $T_{eff} \geq 7000$ K, and these are not observable. Another constraint to the model arises from the observation of Li in subgiant stars with masses close to those of stars in the Li gap. It is possible that if Li has disappeared due to diffusion, it could have survived in the layers between the base of the convective zone and that of Li burning, in which case when one of these stars evolves towards the subgiant branch and develops deeper convective zones it would temporarily enrich its atmosphere with Li. The detection of this phenomenon would give considerable support to the diffusion hypothesis. Balachandran's (1990b) observations of M67 subgiants allow to infer that when these stars occupied the main sequence they suffered a strong Li depletion characteristic of stars in the gap, but they do not provide any evidence on the reappearance of Li. Her results point towards nuclear destruction of Li in the stars mentioned.

ii) Meridional circulation (Charbonneau and Michaud, 1988) may reduce considerably any Li overabundance produced by radiative acceleration at the hot end of the Li gap, while at temperatures lower than 6900 K, Li could be transported to regions where it would be destroyed. This destruction is very sensitive to the rotational velocities adopted in the calculations; for example, differences by a factor 1.5 in these velocities can cause the model to fail to reproduce the Li-T_{eff} profile. A certain amount of scatter (also to be expected) in rotational velocities leads to large differences in the model as regards Li destruction in stars with similar mass. This is not observed in the Hyades. In addition to this possible difficulty, there is another, which arises from stars in the Hyades and UMa which do not present the expected Li deficiencies despite the fact that they are rapid rotators with $T_{eff} \geq$ 6900 K. Similar cases are also found in Balachandran's (1990c) sample of field F stars.

iii) The model of turbulent mixing induced by rotation, attributes the strong Li depletion in gap stars to the increase in rotational velocity, when we move from stars G to F. The Be abundance in these stars is virtually constant (Boesgaard and Budge, 1989). Calculations of the Li/Be ratio in this model are called for to compare its reliability with observations.

iv) Schramm et al. (1990) derived the mass loss rate which would be compatible with the Li dip in the Hyades, assuming pulsation driven mass loss (Wilson, Bowell and Struck-Marcell, 1987). They obtain a rate of $0.7 \leq \dot{M}/10^{-10} \leq 1$ and suggest that in older clusters, like NGC 752, this rate would possibly lead to the disappearance of Be in these stars. It may also be expected that the Li dip in these clusters would be displaced to lower temperatures. In fact, the measurements in NGC 752 can be compatible with a slight shift in the same direction but uncertainties in T_{eff} hinder the attainment of conclusions in this respect. Mass loss may be very interesting to explain the recent observations conducted by Balachandran, Anthony-Twarog and Twarog (1990) who report a large dispersion (a factor 40) in the abundances of Li in F stars in the intermediate age open cluster IC 4651 (2.5 Gyr). The observed stars are located at the hot side of the Li dip in the Hyades, where there is no mechanism to predict Li depletion. As they note, it is possible that some of the stars are not members of the cluster. However if the stars are true members we may have to resort to an explanation in terms of different mass loss rates in them.

v) García López and Spruit (1991) show how internal gravity waves can give rise to a gap in the Li abundance, in quantitative agreement with the observed location in T_{eff} and time-scale. They suggest, as a possible test to their mechanism, the search of Be in clusters as old as NGC 752, where a significant decrease of Be would be expected.

3.1.2. Metallicity and the Li gap. It is quite possible that metallicity differences may produce an observable effect in the position and width of the Li gap. Metallicity determinations by Boesgaard (1989), and Boesgaard and Friel (1990), which are very accurate for F stars in the clusters employed in the research on the Li gap, allow to raise this issue. The Coma cluster has [Fe/H]=-0.07±0.02 (Boesgaard, 1987) and an age similar to the Hyades, whose average metallicity is higher by 0.2 dex than that of Coma, a difference larger than the error bars. Figure 4 in Boesgaard (1987) shows that at least the few determinations existent for Coma in the gap's range of temperatures, coincide completely with the measurements taken for the Hyades. This suggests that metallicity differences of this order do not affect significantly the location of the gap. A greater number of Li measurements in Coma would be very valuable.

3.1.3. The Late F Stars in Clusters. In this section I will discuss Li abundances in stars with effective temperatures between 6000 y 6300 K. Figure 1 shows how, in this range of temperatures, Li abundances in Pleiades stars are lower or, at best, similar to those in the Hyades. The initial abundance of these clusters, adopted as the average of the abundance present in stars at the hot end of the gap, is in the range 3.1-3.3, approximately 0.5 dex higher than most of the late F stars in these clusters. This situation is even more obvious in α Per (Balachandran et al., 1988), where the average value of the Li abundance in stars with this range of temperatures is 2.31. In Coma (Boesgaard, 1987), the average value is 2.6 (see also Soderblom et al. 1990). In all the observed clusters, late F stars have undergone considerable Li depletion and as shown by the comparison

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of α Per and the Pleiades, with the Hyades and Coma, this depletion is not higher in the oldest clusters; thus it is not a process of slow depletion, as diffusion, but more like a process of rapid destruction which takes place before 0.1 Gyr and which, according to what we infer from the high abundances present in stars of this mass in much older clusters (NGC 752, M67, NGC 188: Hobbs and Pilachowsky, 1988), later loses efficiency quite remarkably. Braking in late F stars may take place in only a few tens of Myr (Stauffer et al., 1989; and references therein), whereas in K stars it may adopt a characteristic time of 100 Myr. Both α Per and late F stars in the Pleiades have braked considerably; so it would be reasonable to believe that mixing induced by braking have caused the strong Li destruction observed. In the scheme reported by Pinsonneault et al. (1989) those stars with greater Li destruction must have formed with greater angular momentum. Assuming this explanation to be correct, late F stars in α Per and the Pleiades must have formed with greater angular momentum than those of equal temperature in the Hyades. An interesting test to these ideas would be the determination of rotational periods via rotational modulation of these stars.

3.1.4. F Field Stars. Measurements of Li in field F stars are very numerous. Close to 300 determinations have been reported in the works by Boesgaard and Tripicco (1986b, 1987) and Balachandran (1990c). Boesgaard and Tripicco find that cosmic abundance is preferentially located among hot and young stars. The oldest stars of their sample show the highest Li depletions observed. Balachandran (1990c) reports large dispersion (more than 2 orders of magnitude) in the Li abundance in her sample of 200 stars, which appear to require a dependence on a third parameter as well as mass and age. It is interesting to note that below 6200 K only one star out of approximately 30, present a Li abundance of log N(Li)= 3, while at higher temperatures a significant fraction of the sample ($\sim$20%) exceed this abundance value. Balachandran investigates a possible rotational effect using v sin i. The proportion of F stars with log N(Li)$\leq$2 and v sin i $\geq$20 km s^{-1} is very low, in contrast to what occurs in stars with low v sin i, which suggests that angular momentum loss affects the Li abundance in these stars. Comparison of stars with different metallicity furnishes some evidence to support a shift of the Li dip to smaller masses in the metal poor F stars.

3.2. G AND K STARS

3.2.1. Young clusters. Figure 1 shows how late G and K Pleiades stars present an outstanding dispersion, nearly 1 order of magnitude for a given T_{eff}, in their Li abundance. This is also seen in α Per (Balachandran et al., 1988) but is not present, or it occurs to a much lesser degree, in the Hyades. Duncan and Jones (1983) suggested, as a possible explanation for the Li dispersion, an age spread in the Pleiades several times larger than the nuclear age of the cluster. Observations, conducted by Butler et al. (1987), of four rapidly rotating early K dwarfs have shown that these contain more Li, by 1 order of magnitude, than slow rotators of similar spectral type which, according to the authors, could be due to the fact that stars with smaller v sin i had sufficient time to brake and destroy their Li, while the others have just reached the Main Sequence. García López et al. (1990b, this Symposium) confirm the bimodality in Li abundance between slow and rapid rotators in K stars of the Pleiades. Ca II HK and Hα observations of these stars (García López et al. 1990c) show that rapid rotators present higher activity levels. It cannot be disregarded that part of the difference in Li abundance lies in the fact that these stars are covered, to different extents, by active regions. However, monitoring of active G and K stars (see Boesgaard, 1990) and of RS CVn type stars (Pallavicini, Cutispoto and Randich, 1990), indicate an absence of rotational modulation of the Li line even when the observed stars suffered strong photometric variations during the observations. Similar monitoring of K stars in the Pleiades and α Per would be extremely interesting.

Comparison between the Pleiades and Hyades clearly shows that in Hyades G and later stars, Li destruction must have existed during their MS lifetime. The mechanism responsible for this destruction must be capable of explaining the strong dispersion in Li abundances in young clusters

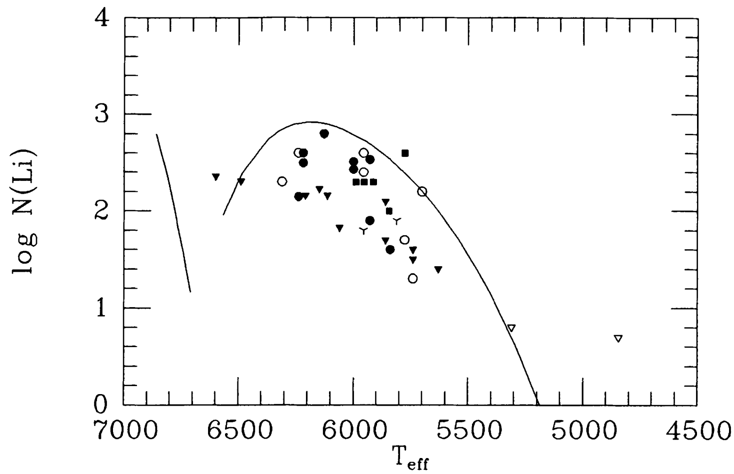

Figure 2: Li measurements versus effective temperatures for stars in NGC 752 (open circles), M 67 (filled circles) and NGC 188 (filled squares). Triangles and arrows indicate upper limits. Data taken from Hobbs and Pilachowski (1986a, 1986b), Spite et al. (1987a), García López, Rebolo and Beckman (1988) and Hobbs and Pilachowski (1988a). A solid line has been plotted indicating the depletion pattern in the Hyades. Typical error bars in Li abundances are ±0.2 dex, and ±100 K for T_{eff}.

and its possible connection with rotation, as well as the small dispersion in the Hyades. For this latter cluster, there are rotational period measurements (Radick et al., 1987), which show very little dispersion for stars of the same spectral type. A clear relation between Li abundance and rotational period was posed by Rebolo and Beckman (1988, see our Fig. 2), as a possible indication that the process which brakes these stars could also be responsible for Li destruction. Among the several mechanisms proposed to explain the Li decline in solar type stars, mixing induced by rotational braking (Pinsonneault et al., 1989) seems to satisfy the set of observational restrictions available. In this, Li destruction is greater the higher the initial angular momentum with which a star is formed, as its braking may be greater, and transport of matter to inner regions more efficient. Other mechanisms, such as mass loss (Hobbs, Iben and Pilachowski, 1989) and turbulent diffusion mixing (Baglin, Morel and Schatzman, 1985; Vauclair, 1988) could be responsible for Li disappearance in late type stars.

3.2.2. Intermediate old and old open clusters. In G stars of NGC 752 (2 Gyr) (Hobbs and Pilachowski, 1986a, 1988a), Li abundances are considerably lower than those in stars at the hot side of the Li gap, and show a high dispersion (1.5 dex). For M67, a cluster whose age is similar to the Sun's, Li measurements (Hobbs and Pilachowski, 1986b; Spite et al., 1987; García López, Rebolo and Beckman, 1988) indicate a similar situation, with a 0.7 dex scatter, higher than what is expected in view of measurement errors. Hobbs and Pilachowski (1988a) also measured Li in NGC 188 stars, finding similar abundances to those in M67 for stars of similar Teff. The age of this cluster was recently revised by Twarog and Anthony-Twarog (1989) who reduce to 6 10^9 yr. the previous estimation by VandenBerg (1985) of 10^{10} yr. With VandenBerg's determination it was quite surprising that some of the cluster's early G stars had preserved a large amount of Li. As shown by Figure 2, which comprises the measurements of the 3 clusters together with a curve representing the Li-T_{eff} relation in the Hyades, the Li abundance of these stellar systems behaves similarly. All measurements, except for one star in NGC 188, fall bellow the Hyades curve, which confirms the idea that, during their lifetime along the MS, stars of masses similar to that of the Sun suffer Li destruction. This destruction is much more effective during the first Gyr. of their lifetime, as can be inferred by comparing Figures 1 and 2. Stars with masses 1.1 $M_\odot$, or slightly higher, are capable of preserving a large amount of Li.

Another result which is derived from observations of old clusters is that the content of Li in the Galaxy's matter, in the solar vicinity (up to a distance of 0.5 kpc), has not changed significantly during the last 6 Gyr. This change is restricted to the range log N(Li)=2.6-3.2; observations in meteorites and the Li depletion pattern in the various clusters suggest that the true variation could have been lower.

The different mechanisms proposed to explain the MS depletion of Li are reviewed in Charbonneau and Michaud (1990); some are also discussed in detail in the talks by Demarque, Michaud and Vauclair (this volume). While convective overshooting (Strauss et al., 1975), microscopic diffusion (Vauclair et al., 1978) and meridional circulation have serious drawbacks to explain the phenomenology described above, turbulent mixing models (Vauclair, 1988; Pinsonneault et al., 1989; Schatzman, 1989) appear to satisfy most of the observational restrictions, even if they do not incorporate mass loss (Hobbs et al., 1989). In these models, the star's rotational history plays an important role which, unfortunately, is not easily defined observationally. Synchronized binary stars are cornerstones in the understanding of this role. Soderblom et al. (1990) describe the particular case of the Hyades star VB22 which, theoretically, should have circularized its orbit already, and which shows a much larger quantity of Li than the other stars, with equal mass, in the cluster. It is possible that this star has not suffered significant variations in its angular momentum, which is mostly orbital, and has therefore cancelled considerably the turbulence in its outermost layers, preserving a larger fraction of its initial Li. Confirmation of this speculation is subject to observations of more systems.

3.3. M STARS

Li measurements of such cool stars in the MS are scarce. In stars of the age of the Hyades, the extrapolation of the Li-T_{eff} curve suggests abundances far below log N(Li)=-2. In the Pleiades, however, detection is possible (see García López et al., 1990b). In these objects, destruction of Li during the PMS is very efficient, as discussed in Section 2. Measurements of Li in post T-Tauri M stars would be a crucial test to distinguish the quantity of Li destroyed by these stars during the PMS.

This situation of increasing destruction of Li as we move to less massive stars should change radically at the mass at which the object cannot reach the Li burning temperature (2.5 10^6 K) in its interior. It is interesting to note that stellar structure calculations on very low mass stars, conducted by different authors (D'Antona and Mazzitelli, 1984; Burrows et al., 1989), predict that this temperature cannot be attained in objects with masses lower than 0.06 $M_\odot$, which corresponds to the domain of sub-stellar systems, i.e. objects that fail to reach stable hydrogen ignition (brown dwarfs). So it is possible to use Li detection in those brown dwarf candidates as a criterion to establish their nature. The observations of UX Tau a, Magazzù, Martin and Rebolo (1990) have shown that this type of work is feasible.

4. Lithium in Low Metallicity MS Stars

4.1. THE OLD DISC POPULATION

Here, the term "old disk population" refers to those stars which were presumably formed during the epoch of formation of the galactic disc. There are different kinematic and metallicity criteria to define these stars (see e.g. Gilmore and Reid, 1983; Sandage and Fouts, 1987). We shall here consider those with a high metal deficiency (-0.3≤ [Fe/H]≤-1.3), which satisfy kinematic criteria in belonging to the thin or thick disk. Figure 3 shows a comparison between Li abundance in

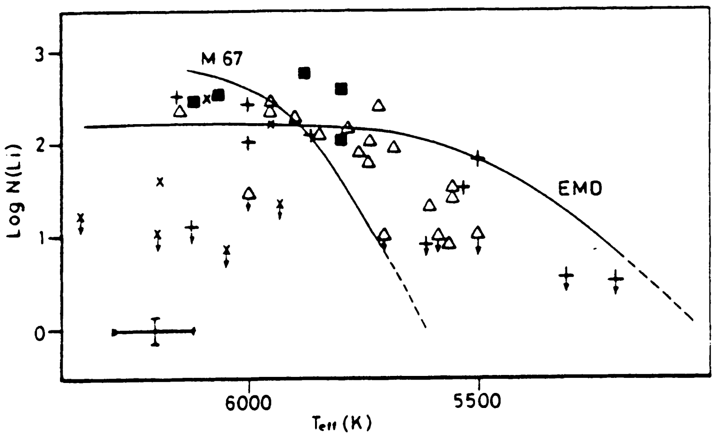

Figure 3: Li measurements for old disc stars with metallicities in the range -0.3≤[Fe/H]≤-1.3 (after Rebolo, Molaro and Beckman, 1988). The solid lines are fits to the data for M67 (previous figure) and for halo dwarf stars of extreme metal deficiency (EMD, see next figure).

these stars and the curve which would be drawn for the Li-Teff relation in old open clusters like M67 or NGC 188. As noted by Rebolo, Molaro and Beckman (1988), low metallicity stars, cooler than 5700 K, in general present higher abundances than stars in old clusters, while for hotter stars, abundances for metal poor stars are lower than those in the clusters. The nature of the mechanism which causes Li depletion seems to differ in each T_{eff} region. While in cool metal-deficient stars depletion appears to be restrained, it is more accentuated in hotter stars. A possible explanation can be raised. Hot metal-deficient stars may suffer slow diffusion of Li, which is more obvious than in metal stars due to the smaller depth of the convective zones. At cooler temperatures, convection may be sufficiently important to cancel the possible gradient of Li concentration which could be caused by gravitational settling, and at the same time the convective zone may not reach regions as deep as in higher metallicity stars possibly inhibiting Li destruction.

Irrespective of which might be the possible explanation, the observations clearly establish that, since very early epochs, the Li abundance in the disc of our Galaxy was greater than log N(Li)=2.5.

4.2. HALO STARS

Observations of Li in halo stars were pioneered by Spite and Spite (1982), who found that Li was present in stars with temperatures between 5500 and 6250 K, with a remarkably constant value around 2.05±0.15. Subsequent studies on halo stars have been conducted by Spite, Maillard, Spite (1984), Spite and Spite (1986), Hobbs and Duncan (1987) and Rebolo et al. (1988). Special attention has been devoted to extreme halo dwarfs (Spite et al., 1987b; Rebolo et al., 1987; Hobbs and Pilachowsky, 1988b). The definition of halo star is somewhat different in each of these studies, but does not affect any of the conclusions which are reported.

Figure 4 shows Li abundances versus T_{eff} for all those stars with [Fe/H]≤-1.4. Although stars with $T_{eff} \geq 5500$ K have a virtually constant Li abundance, at lower temperatures the Li abundance decreases very rapidly. Rebolo et al. pointed out the existence of a slight slope in the plateau: stars at the hotter end of the plateau appear to have higher abundances than stars at the cooler side. The least square fit to the data suggests a difference of 0.2 dex between both sides of the plateau. The mean value of the Li abundance for all these extreme metal-deficient stars is 2.08±0.09 while the mean value of the Li abundance in hot stars ($T_{eff} \geq 6000$ K), calculated giving equal weight to the measurements by different authors, is 2.16±0.04 dex. This value sets a lower bound to the Li abundance in pregalactic matter. Whether these stars have preserved there initial Li abundance is still a question of debate. Various explanations have been suggested up-to-date for the abundance

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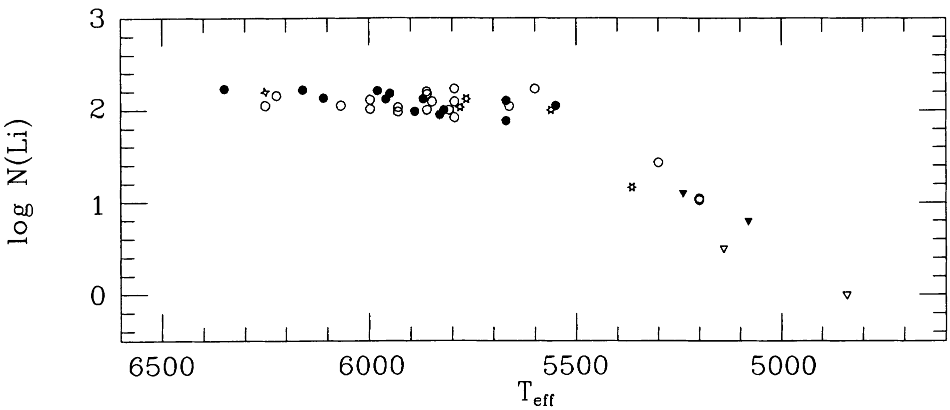

Figure 4: Li abundances versus T_{eff} for stars with [Fe/H]$\leq$-1.4. Sources of data: filled circles, Rebolo, Molaro and Beckman (1988), Rebolo et al. 1987; open circles, Spite et al. (1984); Spite and Spite (1986). For stars in common in these works, mean values are plotted as asterisks. The hottest cross identifies the star LP 608-62 in Hobbs and Duncan (1987). Typical error bars are $\pm$0.15 dex for Li and $\pm$100 K for T_{eff}.

plateau:

i) Microscopic diffusion. It was posed by Michaud et al. (1984), but the fit between prediction and observations is poor, specially for the hotter side of the plateau. More recent calculations by Proffit and Michaud (1990), including effects of He diffusion, suggest that the initial abundance in plateau stars was at least a factor 1.7 higher.

ii) Turbulence. Vauclair (1988) suggested an explanation in the frame of Zahn's (1987) theory, where rotational velocity plays a critical role. In his scheme, halo stars would preserve their intial Li if their velocities did not exceed 3 km s^{-1} during their lifetime.

iii) Standard convection. D'Antona and Mazzitelli (1984) reported that the Li-T_{eff} curve for halo stars could be explained in terms of less deep convection zones. Deliyannis, Demarque and Kawaler (1990), using standard evolution, are able to explain not only the Li plateau, but also the depletion curve of the coolest halo dwarfs. They find that no substantial burning occurs during the PMS and MS evolution of the more massive halo dwarfs.

A definitive answer to the question of whether Li has been preserved in halo dwarf stars may come from the detection of ^{6}Li in them. Because this isotope is much more fragile than ^{7}Li, its detection would be a strong case for the preservation of Li. Measurements in cool halo stars (Maurice et al., 1984) and in one of the hotter halo stars (Pilachowski, Hobbs and De Young, 1989) have established an upper limit to the isotopic ratio ^{7}Li/^{6}Li$\geq$ 10. Given that standard nucleosynthesis in the Big Bang does not predict a considerable production of ^{6}Li, it would be reasonable to search for this isotope in stars where presence of Be had been detected previously, as this would indicate that interaction of cosmic rays with the ISM could have already formed an appreciable quantity of ^{6}Li in the Medium (see Rebolo et al., 1988b).

5. Beryllium in Main Sequence Stars

5.1. SOLAR METALLICITY DWARF STARS

A systematic study of the abundance of Be in MS stars was performed by Boesgaard (1976b) who

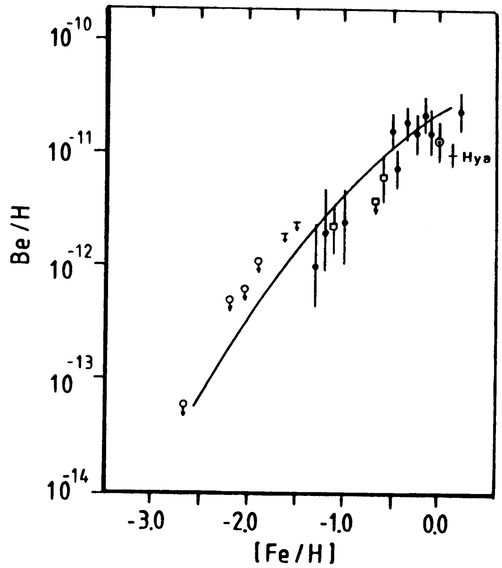

Figure 5: Beryllium abundance, versus metallicity for stars over a wide metallicity range. Dots and squares are measured values, and arrows attached to symbols indicate upper limits. Data taken from: Rebolo et al. (1988b), dots; Beckman, Abia and Rebolo (1989), open squares and Ryan et al. (1990) open circles. The solid line represents a model of galactic evolution of Be (Abia and Canal, 1988).

found that the abundance of this element was not as sensitive as Li at the effective temperatures of the stars. The average value of the observed abundances was Be/H=1.3 ($\pm$0.4)10^{-11}, very close to those measured in the Sun by Ross and Aller (1974) or Chmielewski et al. (1976). Boesgaard already noted that some F stars in her sample presented evidence of Be destruction. All the Be-depleted stars were also Li-depleted. Boesgaard and Budge (1989) measured 8 F stars in the Hyades, in the Li gap region, and found a virtually constant Be abundance around 10^{-11}, very similar to that found by Boesgaard, Heacox and Conti (1977) in another six Hyades stars: 1 10^{-11}. Other Be measurements in old disk stars were published by Dravins and Hulqvist (1977) and Boesgaard and Chesley (1976).

5.2. BE IN METAL-POOR STARS

Molaro and Beckman (1984) established an upper limit,of 25% the solar abundance, to the abundance of Be in the metal-poor star HD 76932. The first detection of Be in highly metal-poor stars was published by Rebolo et al. (1988b) who measured values between 10^{-12} and 2.5 10^{-12} in stars with metallicities in the range -1$\leq$[Fe/H]$\leq$-1.3. Upper limits of this order were established in stars with lower metallicity. These measurements are given in Figure 5, together with other measurements for stars with higher metallicities, taken by Beckman, Abia and Rebolo (1989) and the results reported by Ryan et al. (1990) which confirm and improve our previous determinations.

The observations indicate that i) the abundance of Beryllium has increased progressively during the Galaxy's lifetime, at least by 2 orders of magnitude, up to the solar value, becoming enriched very rapidly in early epochs. ii) The maximum contribution to Li abundance in halo stars, which might be due to spallation of Cosmic Rays in the ISM, is 0.1 dex (see Rebolo et al., 1988).

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