

INTERNAL ROTATION, MIXING AND LITHIUM ABUNDANCES

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Abstract. Lithium is an excellent tracer of mixing in stars as it is destroyed (by nuclear reactions) at a temperature around $\sim 2.5 \times 10^6$ K. The lithium destruction zone is typically located in the radiative region of a star. If the radiative regions are stable, the observed surface value of lithium should remain constant with time. However, comparison of the meteoritic and photospheric Li abundances in the Sun indicate that the surface abundance of Li in the Sun has been depleted by more than two orders of magnitude. This is not predicted by solar models and is a long standing problem. Observations of Li in open clusters indicate that Li depletion is occurring on the main sequence. Furthermore, there is now compelling observational evidence that a spread of lithium abundances is present in nearly identical stars. This suggests that some transport process is occurring in stellar radiative regions. Helioseismic inversions support this conclusion, for they suggest that standard solar models need to be modified below the base of the convection zone. There are a number of possible theoretical explanations for this transport process. The relation between Li abundances, rotation rates and the presence of a tidally locked companion along with the observed internal rotation in the Sun indicate that the mixing is most likely induced by rotation. The current status of non-standard (particularly rotational) stellar models which attempt to account for the lithium observations are reviewed.

1. Introduction

Li^1 is a sensitive tracer of mixing in stellar radiative regions as it is easily destroyed at temperatures above $\sim 2.5 \times 10^6$ K. For solar type stars, the Li destruction region is located below the surface convection zone in standard models. As a consequence, standard stellar models predict that Li should not be depleted at the surface of solar type stars. This is a rather robust prediction of stellar evolution theory, which has been known for 40 years (Schwarzschild *et al.*, 1957). However, comparisons between the solar photospheric Li abundance and the Li abundance in meteorites show that the Sun has depleted a substantial amount of Li at its surface (Greenstein & Richardson, 1951). The solar Li depletion problem has posed a challenge to stellar evolution theory for 40 years, and the solution to this puzzle is still open to debate.

The Sun is unique in that helioseismic observations allow us to probe the interior structure and rotation of the Sun. These observations can put constraints on possible solutions to the solar Li depletion problem, but by themselves solar observations cannot uniquely determine the cause of solar Li depletion. Observations of stellar Li abundances allow one to study the Li depletion problem as a function of age, metallicity and stellar mass. As such, they provide a powerful test for mechanisms which attempt to explain the solar Li depletion. The discovery of a large dip in Li abundances around 6600 K in the Hyades (Boesgaard & Tripicco, 1986) was not predicted by theorists, and remains a major challenge to theoretical stellar evolution models. There is increasing evidence that a dispersion in Li abundances exists among stars with similar ages, metallicities and masses (Soderblom *et al.* 1993; Boesgaard *et al.* 1998). Such a dispersion suggests that another stellar property is important in determining the amount of Li which is depleted in stars. There is mounting observational evidence that rotation plays a key role in determining the amount of Li depletion in a star (Barrado y Navascués & Stauffer 1997; Jones *et al.* 1997). In this review, I will discuss the relationship between mixing, rotation and Li abundances in stars.

2. Solar Observations

The present photospheric abundance of Li in the Sun has been depleted by a factor of 140 ± 40 as compared to the meteoritic value of $\log N(\text{Li}) = 3.31 \pm 0.04$ (Anders & Grevesse, 1989)². Solar models which do not allow for transport or mixing in the radiative regions of the Sun predict very little Li depletion (a factor of 2 – 3). This has been a remarkably robust prediction of standard stellar structure theory which has remained unchanged for 40 years (Schwarzschild *et al.* 1957; Chaboyer *et al.* 1995a), despite the fact that the opacities and nuclear reaction rates used in stellar structure codes have changed considerably over this time period. Current solar models imply that the region where Li is destroyed in the Sun is $\sim 0.05 R_{\odot}$ below the base of the

¹In this review I will use Li to represent ^7Li , the isotope which is produced by big bang nucleosynthesis. ^7Li accounts for $\sim 93\%$ of the total Li abundance in meteorites. Observers typically measure the total Li abundance, while theoretical models determine depletion factors for ^7Li and ^6Li . The ^6Li isotope is destroyed at much lower temperatures and ^7Li . When making the comparison between the observations and theory, it is usually assumed that the ^6Li contribution to the stellar Li content is negligible. However, see the discussion on halo stars (§4) where observations of ^6Li may be used to elucidate the mixing mechanism operating in these stars.

²Using the standard notation where $\log N(\text{Li}) \equiv 12 + \log[N(\text{Li})/N(\text{H})]$.

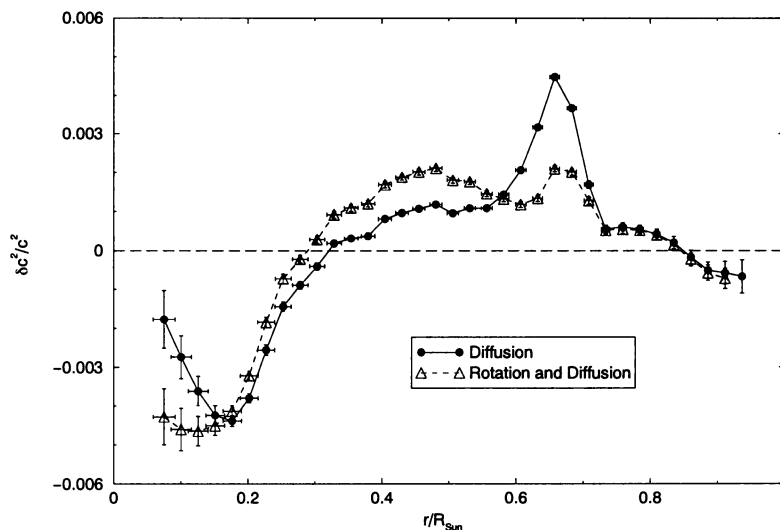


Figure 1. The difference in the square of the sound speed (c^2) between two solar models and the actual Sun, as determined from helioseismology.

solar convection zone. The Li depletion in the Sun suggests that some material from the region where Li is destroyed has been transported to the convection zone, leading to the observed Li depletion at the surface.

The cause of this transport process is still a matter of debate. Observations of Be can constrain the nature of this transport process, as Be is burned at a higher temperature (3.5×10^6 K) than Li, and so probes the deeper interior of the Sun. Observations of the photospheric and meteoritic Be abundances suggest that Be has been depleted at the solar surface by a factor of 1.8 ± 0.5 (Anders & Grevesse, 1989). Thus, at the 3σ level it appears that the Sun has indeed depleted Be at its surface. This is supported by the work of King *et al.* (1997), who found a minimum surface solar Be depletion level of 12%.

Helioseismic observations can be used to probe the interior structure and rotation of the Sun and provide a strong test for stellar evolution theory. The observed frequencies of the solar p -modes depend primarily on the sound speed c in the solar interior and so it is relatively straightforward to invert the helioseismic observations to probe the variation of sound speed with depth in the Sun. In order to linearize the problem, this inversion is typically done with respect to a theoretical solar model. The data which are now available from the GONG project (Harvey *et al.*, 1996) and SOHO satellite (Rhodes *et al.*, 1997) allow for a very precise determination of the sound speed in the Sun, down to $r \simeq 0.1 R_\odot$. A typical example of a solar sound speed inversion is shown in Figure 1, which shows that current solar models are able to match the observed value of c^2 to within 0.5% throughout the solar interior. This is a remarkably achievement for stellar evolution theory, made possible by many advances in the last 5 years in the opacities and equation of state used within stellar evolution codes. Another important advance has been the realization that diffusion (whereby the elements heavier than hydrogen sink to the center of the star) must be included in solar models in order to match the helioseismic observations (Christensen-Dalsgaard *et al.*, 1993;

Guenther *et al.*, 1996).

Although the match between the helioseismic observations and theoretical models is impressive, the observations are extremely accurate, and the remaining differences between the models and the Sun can be used to continue to improve the physics used in stellar models. Figure 1 indicates that there is a large error in the diffusion model near the base of the solar convection zone ($r \sim 0.7 R_{\odot}$). Detailed studies of this region have suggested that this error is due to the sharp change in the mean molecular weight which occurs at the base of the solar convection zone in models which include diffusion (Gough *et al.*, 1996). The most likely explanation is that some form of slow turbulent mixing is operating below the base of the solar convection zone (Basu, 1997). The model labeled 'rotation and diffusion' in Figure 1 includes slow turbulent mixing generated by rotation (Chaboyer *et al.*, 1995a), and provides a much better match to the observed Sun near the base of the convection zone than the model which only includes diffusion. Helioseismic observations provide strong evidence that slow turbulent mixing occurs below the base of the convection zone in the Sun.

Helioseismology can also probe the interior rotation rate of the Sun. The global modes of oscillation in the Sun can be described by the spherical harmonics, of radial order n , degree ℓ , and horizontal order m (cf. Thompson *et al.* 1996). If the Sun were spherically symmetric, then the observed oscillations would depend only on n and ℓ . Rotation breaks the spherical symmetry of the Sun, leading to a splitting of the common n, ℓ modes into different m values. The degree of this splitting can be used to infer the solar rotation rate as a function of depth within the Sun. Current data allows for a reliable rotation rate inversions down to $r \sim 0.4 R_{\odot}$. Rotation rate inversions done by a number of authors, using different data sets have all reached essentially the same conclusion. In the radiative interior there is quasi-rigid rotation, while a latitude-dependent rotation exists in the entire convection zone (Thompson *et al.*, 1996; Corbard *et al.*, 1997; Kosovichev *et al.*, 1997). The transition between these two regimes occurs in a thin layer below the base of the convection zone and is referred to as the solar tachocline. Recent work suggests that the tachocline is very narrow, with a width estimated to be $r = (0.020 \pm 0.005) R_{\odot}$ (Basu, 1997) or $r = (0.05 \pm 0.03) R_{\odot}$ (Corbard *et al.*, 1998).

3. Young Cluster Observations

Observations of Li in young cluster stars can be used to empirically determine the amount of stellar Li depletion as a function of age, mass and chemical composition. These observations provide very strong constraints for stellar models. A striking result from early observations of Li abundances in cluster stars was the existence of a dip in Li abundances in the F stars (around $T_{\text{eff}} \simeq 6600$ K) in the Hyades cluster (Boesgaard & Tripicco, 1986). Stars around this temperature range have Li abundances which are at least 1.0 dex lower than stars which are hotter or cooler than the dip (see Figure 2). This dip was not predicted by theoretical models. Stars on the hot side of the Li dip do not have convective envelopes, and stars on the cool side of the Li dip have small convective envelopes. The Li dip occurs in stars with very small convective envelopes. The Hyades is a somewhat metal-rich cluster ($[Fe/H] = +0.1$, (Boesgaard & Friel, 1990)) which is approximately 600 Myr old (Perryman *et al.*, 1998). Observations of Li abundances in other clusters (the Pleiades in particular) have shown that the Li dip does not exist for stars on the zero age main sequence (ZAMS) (Soderblom *et al.*, 1993).

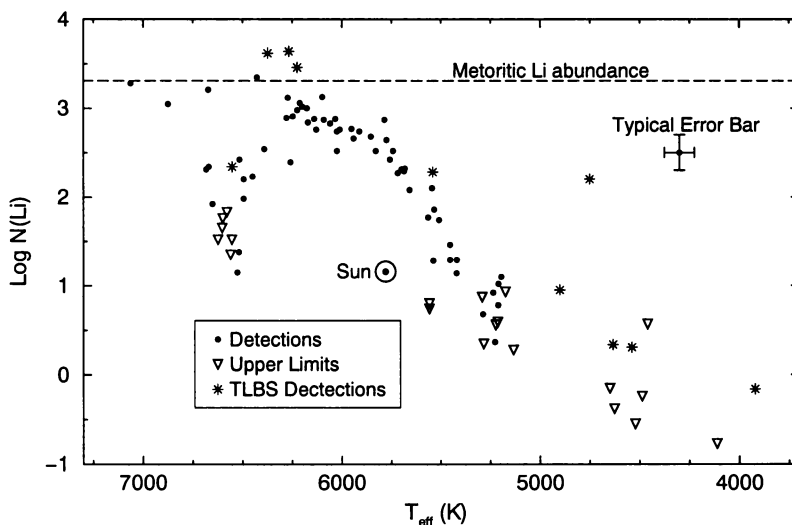


Figure 2. Observations of Li in the Hyades (Balachandran 1995; Barrado y Navascués & Stauffer 1997). The photospheric solar Li abundance is indicated by the solar symbol \odot , and the meteoritic Li abundance is given by the dashed line.

In addition to the Li dip, there are a number of interesting features in Figure 2. In particular, it appears that the tidally locked binary stars (TLBS) have (on average) a higher Li abundance than single stars or binaries which are not tidally locked (Barrado y Navascués & Stauffer, 1997). This is in good agreement with the theoretical work of Zahn (1994), who postulated that Li depletion is due to rotational mixing and this rotational mixing does not operate in TLBS. The excess Li abundance observed in TLBS is strong evidence that rotation plays a key role in Li depletion.

The Hyades stars around the solar temperature ($T_{\text{eff}} = 5780$ K) have significantly higher Li abundances than the Sun (Figure 2). This is despite the fact that the Hyades is slightly more metal-rich than the Sun and so theoretical models would predict that the Hyades stars should deplete more Li than the Sun on the pre-main sequence. This suggests that Li depletion in these cooler stars ($T_{\text{eff}} \lesssim 6000$ K) occurs on the main sequence, a conclusion which is reinforced by the observed Li abundances in the Pleiades (Chaboyer *et al.*, 1995b).

Another interesting feature of Figure 2 is that the highest Li abundances observed are similar to the meteoritic Li abundances, suggesting that there has been no significant Li enhancement over the last 4 Gyr. It is important to note that the only stars which have Li abundances similar to the meteoritic abundances are either TLBS, or are on the hot side of the dip (and hence, do not have a surface convection zone). The question then arises, do all single stars with surface convection zones deplete Li? The stars which have the least amount of Li depletion are those on the cool side of the Li dip, around $T_{\text{eff}} = 6200$ K. In a seminal paper, Boesgaard (1991) demonstrated that, even for the stars around $T_{\text{eff}} = 6200$ K, there was a clear correlation between their Li abundance and age. Older stars have lower Li abundances, implying that all stars with surface convection zones deplete Li on the main sequence. The work of Boesgaard (1991) utilized observations from a number of different observers, and

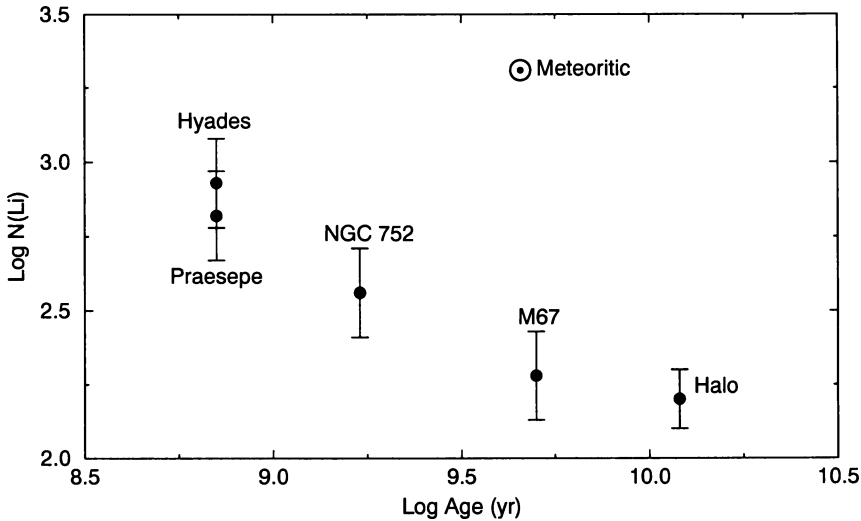


Figure 3. The mean abundance of Li for stars in the temperature range $6300 \leq T_{\text{eff}} \leq 6100$ K in four different clusters, as a function of the cluster age (data from Balachandran 1995). The mean abundances for stars in the same temperature range in the halo is taken from the data of Ryan *et al.* (1996). The meteoritic Li abundance is also indicated.

included stars with a rather large range in effective temperatures. In order to see if this had any effect on her conclusions, I have repeated the analysis of Boesgaard (1991) using the uniform data set compiled by Balachandran (1995) and only included stars with $6300 \leq T_{\text{eff}} \leq 6100$ K. The results are shown in Figure 3. Even with this restricted data set it is clear that older stars have lower Li abundances, implying that Li depletion has occurred on the main sequence for stars around $T_{\text{eff}} = 6200$ K. It is interesting to note that halo stars in the same temperature range appear to match the trend found in open cluster stars (see §4).

The existence of a dispersion in Li abundances at a given effective temperature within a cluster has been the subject of a number of observational papers. If such a dispersion exists, it proves that something besides age, mass and chemical composition must control Li depletion in stars. Thorburn *et al.* (1993) studied in detail the existence of a dispersion among Hyades stars. They found that a such a dispersion does exist for stars with $T_{\text{eff}} = 6100$ K, with $\sigma_{N(\text{Li})} \sim 0.15$ dex. The existence of a dispersion among the cooler stars was more difficult to prove, though the data did suggest that a small dispersion of $\sigma_{N(\text{Li})} \sim 0.09$ dex existed among the G stars ($T_{\text{eff}} \sim 5500$ K). In contrast, there is clear evidence for a Li dispersion in this temperature range among the Pleiades (a solar metallicity cluster whose stars are on the ZAMS) stars, while there is little evidence for a dispersion among the hotter Pleiades stars (Soderblom *et al.*, 1993). There was also clear evidence for a correlation between rotation rates and Li abundances in the Pleiades, with the fastest rotators having the highest Li abundances. A recent paper by Jones *et al.* (1997) studies in detail the dispersion in Li abundances (at a given effective temperature) among the Pleiades (age 70 Myr), M34 (age 250 Myr) and the Hyades (age 600 Myr). They found that the dispersion among the lower mass stars ($M \sim 0.65$ to $0.95 M_{\odot}$) is greatest on the

ZAMS, and decreases with age. The fastest rotating stars have the highest Li abundances. In addition, they found that Li was depleted on the main sequence, leading Jones *et al.* to conclude “*high rotation preserves lithium during pre-main sequence evolution and that a high angular momentum loss rate accelerates lithium depletion after the star is on the main sequence*”. This is a key observational fact, which implies that rotation must lead to mixing and Li depletion in low mass main sequence stars.

However, the basic assumption used in the above analysis, that a dispersion in Li equivalent widths corresponds to a dispersion in Li abundances has been brought into question by Stuijk *et al.* (1997). These authors suggest that magnetic activity (which leads to the formation of spots and flares on cool stars) may affect the Li line strength. Thus, the observation that fast rotators have high Li equivalent widths could be due to the fact that fast rotators are more active stars than slow rotators. The work of Stuijk *et al.* (1997) is based upon theoretical models (which have known problems), and is a schematic feasibility analysis, rather than a definitive statement that magnetic activity affects Li line strengths. Nevertheless, it raises a key point which clearly requires more attention in the future.

4. Halo Star Observations

Observations of Li in very old stars has the potential to determine the primordial Li abundance. Li is one of only 3 elements (the others being H and He) which are believed to have been produced in significant amounts by big bang nucleosynthesis. Thus, the determination of the primordial Li abundance is a key constraint on theoretical models of big bang nucleosynthesis. In their pioneering work, Spite & Spite (1982) measured Li abundances in 13 metal-poor (halo) stars, and found that all of the stars had nearly identical Li abundances. As there was no relation between Li abundances and metallicity, this suggested that the observed Li abundance was the primordial Li abundance. Since then, there have been numerous studies of Li abundances in halo stars. These studies confirmed that halo stars with $T_{\text{eff}} \gtrsim 5600$ K have nearly identical Li abundances, independent of their metallicity or temperature (Spite *et al.*, 1984; Rebolo *et al.*, 1988; Hobbs & Duncan, 1987; Hobbs & Thorburn, 1991).

However, this assumption was brought into question by the discovery of a number of hot halo stars which have abundances significantly lower than the plateau (Hobbs *et al.*, 1991; Spite *et al.*, 1993; Thorburn & Beers, 1993; Thorburn, 1992). About ~ 5% of the halo stars in the plateau effective temperature range have low Li abundances. These stars demonstrate that at least some hot halo stars do deplete Li, leaving open the possibility that plateau stars may have also depleted Li. The current status of Li abundances measurements in halo stars is shown in Figure 4.

The existence of a dispersion among the Li plateau stars would strongly suggest that even these stars have depleted Li. The question of whether or not a dispersion exists among the plateau stars is an open one. Deliyannis *et al.* (1993) performed a dispersion analysis in the Li equivalent width–colour data and concluded that an intrinsic Li/H dispersion of 10% existed among the plateau stars. Furthermore, a uniform analysis of ~ 80 plateau halo stars found a correlation between Li abundances, effective temperatures and metallicity (Thorburn, 1994). Hotter, and/or more metal-rich stars were found to have higher Li abundances. This work was confirmed by Ryan *et al.* (1996). Using a sub-set of the above observations, and adopting a different effective temperature scale Molaro *et al.* (1995) and Bonifacio & Molaro (1997) found no evidence for a dispersion, or correlation with $[\text{Fe}/\text{H}]$.

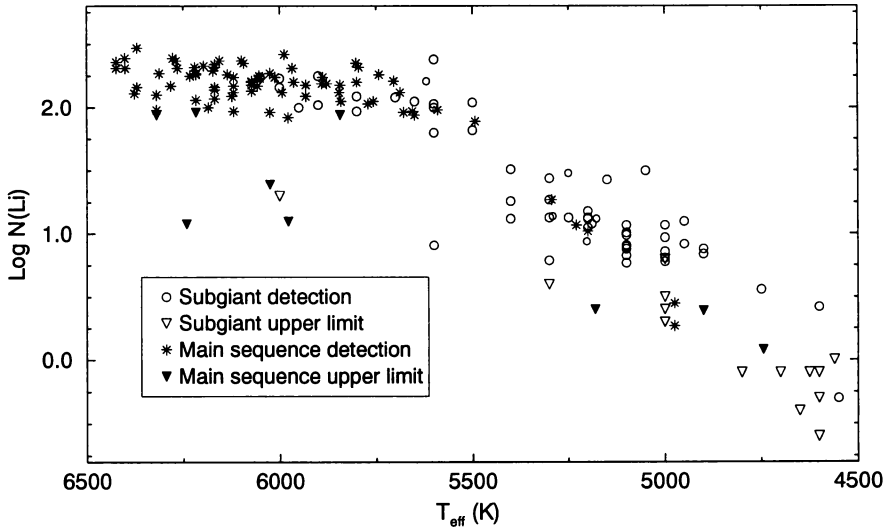


Figure 4. Li abundances in low metallicity ($[\text{Fe}/\text{H}] < -1.0$) field stars (halo stars). Data from Pilawchowski *et al.* (1993), Thorburn (1994), and Deliyannis *et al.* (1994).

In order to directly probe for the existence of a Li dispersion among hot halo stars, Boesgaard *et al.* (1998) have determined Li abundances of 7 stars in the globular cluster M92 ($[\text{Fe}/\text{H}] = -2.1$). Stars in a given globular cluster all have the same metallicity, age and reddening. In addition, it is possible to observe a number of stars with virtually the same colour, implying that the stars all have the same effective temperature. Boesgaard *et al.* (1998) observed 4 stars with virtually identical effective temperatures, of which 1 star has a significantly higher Li abundance than the others. In all other aspects (including a detailed element by element analysis), the star with the high Li abundance is virtually identical to the other 3 stars. This observation strongly suggests that a dispersion in Li abundances exists among hot halo stars and that this dispersion is due to stellar depletion from a higher primordial Li abundance.

Observations of ${}^6\text{Li}$ can also be used to determine if the plateau stars have depleted Li. ${}^6\text{Li}$ is destroyed at much lower temperatures than ${}^7\text{Li}$, so that if enough mixing has occurred to deplete ${}^7\text{Li}$, virtually all of the ${}^6\text{Li}$ should be destroyed. An observation of ${}^6\text{Li}$ in a hot halo star would suggest that there has not been any significant depletion of ${}^7\text{Li}$ in these stars, and that the observed ${}^7\text{Li}$ abundance is very close to the primordial abundance³. The best evidence for a ${}^6\text{Li}$ detection in a hot halo star has been presented by Smith *et al.* (1993) and Hobbs & Thorburn (1997). Both of these groups claim a detection of ${}^6\text{Li}$ in the subgiant HD 84937 ($[\text{Fe}/\text{H}] = -2.4$, $T_{\text{eff}} = 6100\text{ K}$). The careful analysis of Hobbs & Thorburn (1997) led them to conclude that ${}^6\text{Li}/{}^7\text{Li} = 0.08 \pm 0.04$ in HD 84937. Thus, the detection is significant at

³Standard big bang nucleosynthesis predicts that all of the Li production will be in the form of ${}^7\text{Li}$. ${}^6\text{Li}$ can be produced by cosmic ray spallation in the interstellar medium. Deliyannis & Malaney (1995) have suggested that ${}^6\text{Li}$ may be produced by stellar flares at the surface of the star, implying that an observation of ${}^6\text{Li}$ in the photosphere of a star does not constrain the depletion of ${}^7\text{Li}$ in the stellar interior.

the 2σ level. It is premature to conclude that ${}^6\text{Li}$ has definitively been detected in a hot halo star.

Halo stars cooler than the plateau show progressively lower lithium abundances, similar to that seen in open clusters. This is true both for main sequence stars, and subgiant stars (see Figure 4). In both cases, the deepening convective envelopes have brought Li depleted material to the surface of the star. It is interesting to note that stellar evolution models which incorporate the latest available input physics are unable to correctly reproduce the onset of Li depletion observed in main sequence or subgiant halo stars (Chaboyer, 1995). This implies that the models are in need of revision, and casts doubt on the ability of the models to correctly predict the amount of ${}^6\text{Li}$ depletion which occurs.

5. Theoretical Models

The preceding sections have made it clear that Li depletion has occurred in stars with a variety of masses and ages, for which standard stellar evolution models predict no Li depletion. A number of mechanisms have been proposed which deplete Li, in order to explain some or all of the Li observations. These Li depletion mechanisms include: overshoot, mass loss, mixing induced by gravity waves, diffusion, and mixing induced by rotation.

Overshoot at the base of the convection zone has been proposed by a number of authors (most recently by Ahrens *et al.* 1992) to explain the depletion of Li in the Sun. Solar models which include an overshoot of ~ 0.24 pressure scale heights at the base of the convection zone are able to reproduce the observed solar Li depletion. However, this Li depletion occurs on the pre-main sequence, implying very low Li abundances in young, cool ($T_{\text{eff}} \sim 5800\text{ K}$) stars. This is not seen in any of the open cluster observations (including the Hyades, Figure 2 and the Pleiades). Open cluster observations rule out fast overshoot at the base of surface convection zones as a viable explanation of the observed solar Li depletion (Chaboyer *et al.*, 1995b).

Large amounts of mass loss ($\sim 0.05 M_{\odot}$) sufficient to expose Li depleted material at the surface of a star has been suggested as a cause of the F star Li dip (Schramm *et al.*, 1990). However, a detailed stellar evolution study by Swenson & Faulkner (1992) found that mass loss alone could not explain all open cluster Li observations. Furthermore, a detailed study of Be abundances among Li dip stars has detected moderate Be deficiencies among stars with severe (but detected) Li abundances (Stephens *et al.*, 1997). The mass loss hypothesis requires that all of the Li be depleted before any Be depletion occurs, in contradiction with these observations.

Press (1981) suggested that internal gravity waves generated at the base of the convective envelope of a star may produce weak mixing in the radiative interior. This suggestion was studied in detail by García López & Spruit (1991), who found that mixing induced by internal gravity waves could explain the Li dip observed in F stars if the intensity of the gravity waves was increased by a factor of 15 above mixing length estimates. The degree of Be depletion predicted by these observations appears to be incompatible with the observations of Stephens *et al.* (1997).

The diffusion of Li out of the surface convection zone was suggested by Michaud (1986) to be the cause of the Li gap. The models required a small mass loss rate ($10^{-15} M_{\odot} \text{ yr}^{-1}$) to explain the lack of Li depletion on the hot side of the dip. Helioseismology indicates that He diffusion occurs in the Sun (§2), indicating that Li diffusion should also be operating in stars. As the diffusion time scales for Li and Be

are similar, Be and Li should be depleted by the same amount if diffusion is the cause of the Li dip. Observations indicate that the degree of Be depletion is much smaller than Li depletion in dip stars (Stephens *et al.*, 1997), ruling out diffusion as the sole cause of the Li dip. Diffusion is also unable to explain the Li depletion observed in the cooler stars ($T_{\text{eff}} \lesssim 6000$ K) like the Sun (Chaboyer *et al.*, 1995b).

It has been known for over 70 years that thermal imbalances in rotating stars give rise to large scale flows (von Zeipel, 1924; Eddington, 1925; Sweet, 1950). Thus, it is not surprising that a number of authors have suggested that the Li observations can be best explained by mixing induced by rotation (e.g. Charbonneau & Michaud 1988; Vauclair 1988; Pinsonneault *et al.* 1990,1992; Charbonnel *et al.* 1992,1994; Zahn 1992; Chaboyer & Demarque 1994; Chaboyer *et al.* 1995a,1995b; Deliyannis & Pinsonneault 1997). The exact physics underlying rotation induced mixing is still not well understood, leading to a variety of approaches in dealing with the mixing. The Yale rotational models (Pinsonneault *et al.* 1990,1992; Chaboyer & Demarque 1994; Chaboyer *et al.* 1995a,1995b; Deliyannis & Pinsonneault 1997) are perhaps the most ambitious, as they self-consistently include the structural effects of rotation along with the coupled transport of angular momentum and material due to a variety of rotation induced mixing mechanisms. These models, along with those of Charbonnel *et al.* 1994 are able to reproduce a number of features of the observed Li abundances, including the cool side of the Li dip and the main sequence depletion of Li in the Sun and similar temperature cluster stars. Generically, these models also predict a correlation between rotation velocities and Li abundances (observed in young clusters) and that tidally locked binary stars should not deplete Li (Zahn, 1994) as observed in the Hyades (Barrado y Navascués & Stauffer, 1997). The rotation models do a good job of matching the Be observations (Stephens *et al.*, 1997) in the Li dip stars (Deliyannis & Pinsonneault, 1997). These models also predict that a dispersion of Li abundances (due to a dispersion in initial rotation velocities) should exist for stars with equal ages, masses and metallicities, as observed in open clusters.

The small (or non-existent) dispersion among the plateau stars in the halo puts strong constraints on the rotation induced mixing models (Chaboyer & Demarque, 1994), but does not rule them out. Rotation induced mixing models predict some main sequence Li depletion for all stars with surface convection zones, in good agreement with the observations. By extension, these models also predict significant Li depletion among metal-poor halo stars implying that the primordial abundance is higher than the plateau value (Pinsonneault *et al.*, 1992; Chaboyer & Demarque, 1994). The exact amount of Li depletion depends on the details of the models. The Yale models predict a factor of ~ 10 depletion, implying a primordial Li abundance of $\log N(\text{Li}) = 3.1$, a value which is incompatible with standard big bang nucleosynthesis and current estimates for the primordial abundances of helium and deuterium. However, these models do not match all of the observations, and there are considerable uncertainties associated with these models. Thus, the exact amount of Li depletion which has occurred in the plateau stars is still an open problem.

One of the key problems with the Yale rotational models is that angular momentum transport was inefficient, leading to fast rotating cores. This is clearly in contradiction with helioseismic observations of the solar internal rotation (§2). An easy way to correct this problem has recently been identified by Kumar & Quataert (1997) and Zahn *et al.* (1997). These authors found that low-frequency gravity waves could be excited by convection in the Sun. These gravity waves can transport angular momentum very efficiently. The estimates for the time scale of mixing by these two groups are very similar to each other, and suggest that rigid body rotation would

be enforced in the solar radiative region on time scales of 10^7 to 10^8 years. Another difficulty with the Yale models which included the combined effects of rotation and diffusion was that the inclusion of diffusion lead to a differential Li depletion across the effective temperature of the halo Li plateau (Chaboyer & Demarque, 1994). The derived Li abundances did not agree with observations of the most metal-poor stars. This difficulty in reproducing the plateau Li abundances when diffusion is included can be overcome by the addition of a modest stellar wind ($\sim 10^{-12.5} M_{\odot} \text{ yr}^{-1}$) in the models (Vauclair & Charbonnel, 1995).

6. Summary

There is a wealth of data on Li abundances and rotation velocities in stars with a variety of ages, masses and metallicities. This data clearly indicates that Li depletion occurs on the main sequence for all stars with a surface convection zone. This is in direct contradiction with standard stellar evolution theory. A number of possible mechanisms which lead to extra Li depletion have been put forth. The dispersion in Li abundances at a given age, metallicity and temperature, the correlation between Li abundances and rotation velocities in Pleiades, the fact that tidally locked binary stars in the Hyades have an excess Li abundance as compared to single stars, and the detection of moderate Be deficiencies among Li dip stars with detectable Li abundances, all imply that that rotation induced mixing is leading to Li depletion on the main sequence. Helioseismic observations of the Sun support this hypothesis, for they show that slow form of slow mixing is operating below the base of the solar convection zone (Basu, 1997). Current stellar models which incorporate rotation induced mixing explain many, by not all of the observations. Models which are able to account for all of the data are likely to include diffusion, rotation induced mixing, angular momentum transport by gravity waves and/or magnetic fields and modest stellar winds.

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