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# Lithium in Stars on the Main Sequence and Beyond

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**Abstract.** $^7$Li provides a rare constraint on the baryonic density of the Universe and because of its fragile nature, it is also an excellent diagnostic of the physical processes occurring inside stars. The study of Li in Pop.I stars is crucial to understanding its primordial abundance. Observations suggest that a vast majority of them deplete their Li severely, in contrast to the predictions of the standard stellar models. A fresh study of 130 stars we undertook supports the idea that the large spread in Li is driven by the rotational history of the star. Open clusters reveal much more because each represents a sample with the same age and metallicity. I discuss briefly what we have learnt from their studies.

*Keywords* : stars : Li abundance - stars : rotation - open clusters : Li

## 1. Introduction to the Lithium problem

$^7$Li is one of the few elements along with D, $^3$He and $^4$He that formed at the time of the Big Bang and is also one of the most easily destroyed elements, burning at only a few million degrees ($\geq 2.5 \times 10^6 K$) via the reaction $^7\mathrm{Li}(p, \alpha)^4\mathrm{He}$. As a result, it is an excellent probe into the physical processes occurring inside stars. Precisely because of the same reaction, an accurate determination of Li abundance can put a constraint on the baryon density of the Universe and thus test the predictions of the model of Standard Big Bang Nucleosynthesis. The study of Li is therefore very important in Pop.II halo dwarfs that are so metal-poor that they provide a sample with nearly the primordial value. The pioneering work by Spite & Spite (1982) on such stars augmented later by larger data samples (Rebolo et al. 1988; Lambert et al. 1991; Ryan et al. 2001; Chen et al. 2001) showed that over a fairly large temperature range, they have a nearly constant value of Li abundance at log N(Li) ~ 2.1 on the scale where log N(H) = 12.0, as displayed in Fig.1a. This so-called Spite plateau or Lithium plateau has come to be recognized as the primordial value of Li abundance. Now with the 10m class of telescopes, it is possible to observe stars in old globular

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clusters like M92 which are even more ancient than the very metal-poor halo dwarfs. Li in these stars is thought to be the original Li abundance in the gas out of which these stars formed 10-15 Gyrs ago. Even in these stars Li is observed to be close to ~2.1 (Boesgaard et al. 1998). There has been a tremendous amount of research on the small spread of about 0.25 dex around the Li plateau to ascertain whether it is just the observational error or it is the inherent spread of Li in stars suggesting depletion or production processes occurring inside them. This scatter does not shake the SBBN model but it raises the possibility of Li in stars being of not entirely primordial origin. This is eventually linked to the Li abundance in Pop.I stars which is what I am going to focus on.

log N(Li) in Pop.I stars is observed to be up to a maximum of ~3.3. It is the same value observed in the interstellar medium, in meteorites, in T Tauri stars and in stars of young clusters and this is inferred as the present Galactic Li abundance. In a typical main sequence (MS) star, only 2-3% of the stellar mass is cooler than the Li burning temperature and thus Li survives only in this region (which is about 40% of the stellar radius) and is depleted inside of it. As the star evolves to become a red giant, the deepening convective envelope mixes the Li-preservation region with the Li-free one and thus dilutes Li. According to the standard stellar model calculations, the convection zone in a MS star, however, lies only within the outer 10% of the stellar radius except for the coolest dwarfs. So it is impossible to deplete Li on the MS. But there is enough observational evidence now to suggest that actually a vast majority of F and G Pop.I stars are severely depleted in Li (Balachandran 1990, Randich et al. 1999, Lebre et al. 1999), in contrast to the predictions of the standard stellar models which include only convective mixing and ignore effects due to rotation, diffusion, mass loss, magnetic fields etc. Fig.1b displays the evolution of Li with metallicity for stars of $T_{eff}$ > 5800K believed to have preserved Li that they were endowed with at birth. The upper envelope seems to represent a progressive increase of log N(Li) from the very metal-poor stars to the solar metallicity ones. It is worth noting the remarkably large spread in Li present in the metal-rich stars. In order to be certain that the Li plateau abundance is pristine, it is important to identify production mechanisms that increase Li by a factor of 10 over the lifetime of the Galaxy and depletion mechanisms that reduce Li in Pop.I stars.

The model most cited and tested for the mixing and depletion of Li and other light elements below the convection zone is the rotationally-induced mixing model which transports angular momentum and material via turbulence (Pinsonneault et al. 1989, Charbonnel et al. 1994). The idea is that stars arrive on MS rotating rapidly. They undergo a spin-down while on the MS. The rotational models suggest that the outer layers of a star are spun down first due to winds from the surface, leaving the star in a state of differential rotation. The turbulence generated by the shear forces with the different layers rotating at different rates, triggers mixing in the deeper layers causing Li depletion. It is tempting then to think of a scenario where a group of stars with the same initial Li content and a range in *v sini* as they arrive on the MS would end up exhibiting a large spread in Li abundance after they have all spun down.

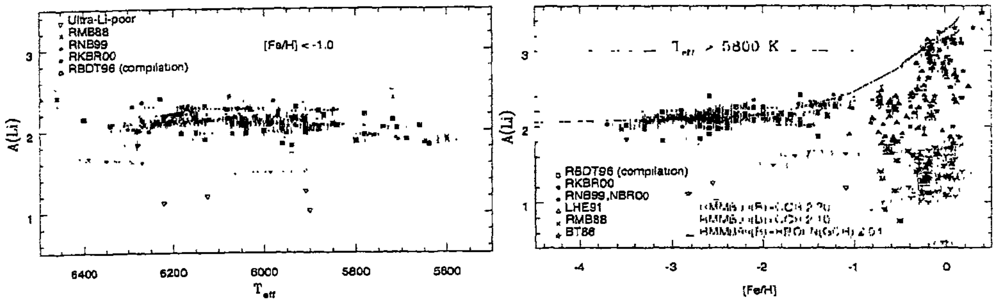

**Figure 1. a.** Variation of Li abundance with $T_{\rm eff}$ for halo dwarfs. **b.** Evolution of Li with metallicity. The data in both these figures are compiled from various sources. These figures are adapted from Ryan (2000).

## 2. Observations, Interpretation and Implications

An attempt was made to explore whether such an idea could be supported by our observations. A fresh look at this problem was triggerred off by two recent observational developments. The first is the determination of rotational velocities with high precision (Catalogue of Rotational and Radial Velocities by de Medeiros & Mayor 1999). The other is the knowledge of stellar distances and hence luminosities for a very large number of stars from the Hipparcos Catalogue which gives parallaxes with accuracy of ~1 milliarcsec for distances ≤ 100pc. One could thus trace the evolution of Li abundance of stars on the HR diagram against the backdrop of the evolutionary tracks as a function of mass, age and rotation. Based on their spectral classification, a sample of 220 F, G and K dwarfs, subgiants and giants was selected from the Bright Star Catalogue (Hoffleit & Jaschek 1982) & the [Fe/H] Catalogue of Cayrel de Strobel et al. (1997) and plotted on the HR diagram superposed against theoretical evolutionary tracks to see what stage of evolution they lie in. Based on the location on the HR diagram, a sample of 130 stars was selected such that they have more or less completed MS depletion and have not evolved far enough to have suffered depletion on the RGB. CCD spectra of these stars were obtained in the region of the Li I line at 6707.8Å at a spectral resolution of ~0.35Å (R ~ 20,000) using the coude echelle spectrograph at the 102cm telescope at the VBO at Kavalur. With the measured Li EQW as the input and an appropriate choice of models from the grid of model atmospheres due to Gustafsson et al. (1975, upgraded 1992) generated by Luck (1992), Li abundances were determined using the LTE line synthesis code MOOG (Sneden 1973, upgraded 2001). For stars rotating more rapidly than 35 km $\rm sec^{-1}$, Li abundances were determined by fitting synthetic spectra to the observed, using $v \sin i$ and log N(Li) as free parameters.

Li abundances of these stars plotted against $T_{\rm eff}$ (Fig.2a) show a gradual decrease with a fairly sudden drop at ~5300K which marks the onset of dilution on the subgiant branch due to the deepening of the convective envelope. What is worth noting is the large spread in log N(Li) seen in stars to the left of this implying that depletion is indeed occuring on the MS. The plot of their projected rotational velocity vs. $T_{\rm eff}$ (Fig. 2b) shows a sharp cut-off around 6400K to the right of which all stars have spun down to low values ($v \sin i \leq 20$ km $\rm s^{-1}$) while stars to the left

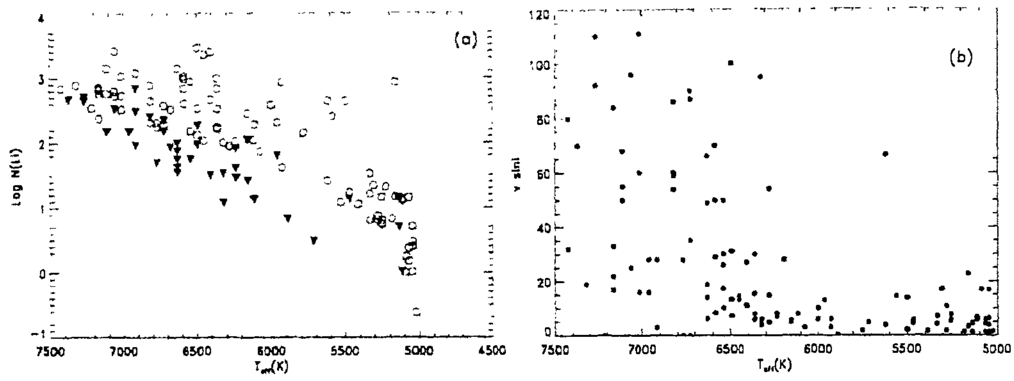

**Figure 2.** **a.** Li abundance and **b.** *v sini* vs. $T_{eff}$ for the stars observed. Inverted triangles in **a.** denote upper limits to Li abundance.

display a large range in *v* sin*i*, from 2 to higher than 100 km $s^{-1}$. So the stars in the temperature range 5300-6400K that display a large dispersion in Li have already spun down. On the other hand, early F stars perhaps because of their thinner convective envelopes retain more or less their intrinsic range in *v* sin*i*. All these stars are plotted on the HR diagram in Fig.3a. The tracks are due to Girardi et al. (2000) for a typical Pop.I composition ($Y$ = 0.273 and $Z$ = 0.019) shown for masses ranging from 0.8 to 7.0 $M_\odot$. The increasing size of circles denotes higher *v* sin*i*. These along with the log N(Li) bins are defined in the key. It is obvious from the diagram that stars of lower masses ($\leq 1.3 M_\odot$) have already spun down to low values. The more massive stars do so only towards the end of the subgiant branch evolution. The thing to note is that there is a large spread in log N(Li) for stars of low *v* sin*i* for all masses. Li-poor stars are all slow rotators and are conspicuously absent at large *v* sin*i*. Rapidly rotating stars and stars of higher masses tend to have undepleted values of Li. Fig.3b clearly demonstrates this trend. This trend seems to be dictated by the idea that stars which are still fast rotators have suffered little loss of angular momentum and have therefore hardly undergone mixing and retained their initial Li. Among the slowly rotating stars, those born as slow rotators tell the same story but those born as fast rotators have suffered much larger losses of angular momentum and have therefore undergone more effective mixing and hence greater Li depletion. There does not seem to be a one-to-one correlation between Li abundance and the present projected rotational velocity. Instead, the above correlation appears to be driven by the rotational history of the star.

However, we note in Fig.3b that the lower envelope running from high Li and high *v* sin*i* to low Li and low *v* sin*i* appears to skirt the stars with upper limits to Li abundance denoted by inverted triangles. This trend perhaps owes itself to the fact that the minimum detectable EQW of the Li line increases with increasing *v* sin*i*. The lower envelope may then just be an artifact of this inherent limitation of the Li EQW measurement for large *v* sin*i* and interpreting the above trend in terms of an initial range of rotational velocities determining the observed Li spread may not have a real physical basis. Either way though, it lends a statement on the link between Li abundance and rotation. In fact, there have been at least 3 recent important observations that

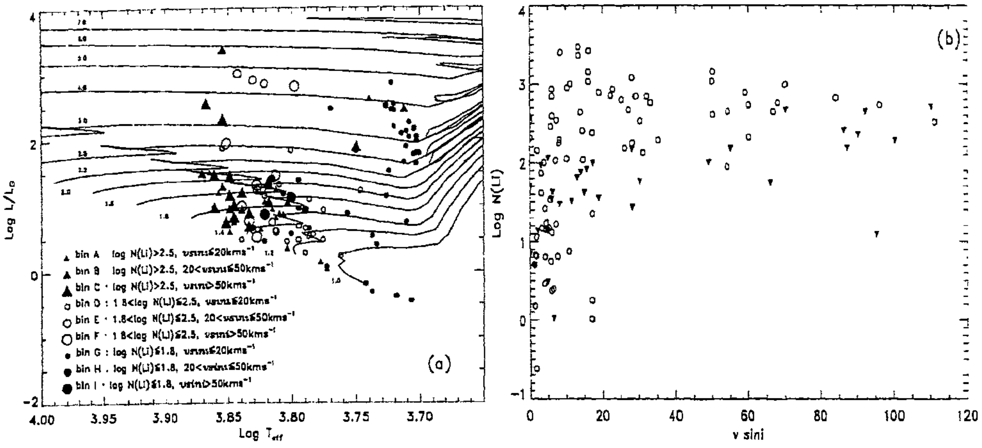

**Figure 3. a.** HR diagram of the observed stars for which absolute visual magnitudes are determined from the Hipparcos data. The bins chosen are indicated in the key. Also shown are theoretical evolutionary tracks of Girardi et al. (2000) for stars of masses ranging from 0.8 to 7.0$M_\odot$ for Pop. I composition : $Z = 0.019$, $Y = 0.273$ **b.** Li abundance vs. $v$ sin$i$. Inverted triangles denote stars with upper limits to lithium abundance.

do not support the turbulence transport model. One of the important predictions of this model is that short-period tidally- locked binaries which have different rotational histories than single stars of the same age and mass, should show significantly larger Li abundances. Balachandran (2002, private communication) has examined these in the Hyades and M67 clusters and found that the Li abundances are entirely compatible with what is observed in single stars. Secondly, this model predicts the star to have a rapidly rotating core. However, helioseismology has revealed that the present-day Sun down to $r = 0.2R_\odot$ is already rotating slowly as a rigid body. So the angular momentum transport and dissipation have been far more efficient than predicted by this model. Lastly, a slow, deep mixing predicted by this model should deplete Be too (which burns at $3.5\times10^6$K). But there is no Be depletion in the Sun.

## 3. Importance of Studies of Open Clusters

It is hard to interpret the Li abundance patterns of field stars because they span a range of age and chemical composition at any given effective temperature. Open clusters tell us so much more because each represents a sample of stars of roughly the same age and chemical composition. With high resolution spectrographs coupled to 4-10m class telescopes, an enormous amount of data on clusters of different ages and metallicities have accumulated over the last 15 years. Fig.4 sums this up for some of them. One notices here that the dwarfs of the Hyades cluster, for example, show a sharp drop in Li by over a factor of 30 in a narrow range in $T_{\rm eff}$ between 6500-6800K first identified by Boesgaard & Trippico (1986). This so called B-T dip is present in clusters older than 200 Myrs. It is also clear in the figure that each cluster displays the expected decline of Li with decreasing mass/$T_{\rm eff}$. And there is a distinct trend of older clusters having

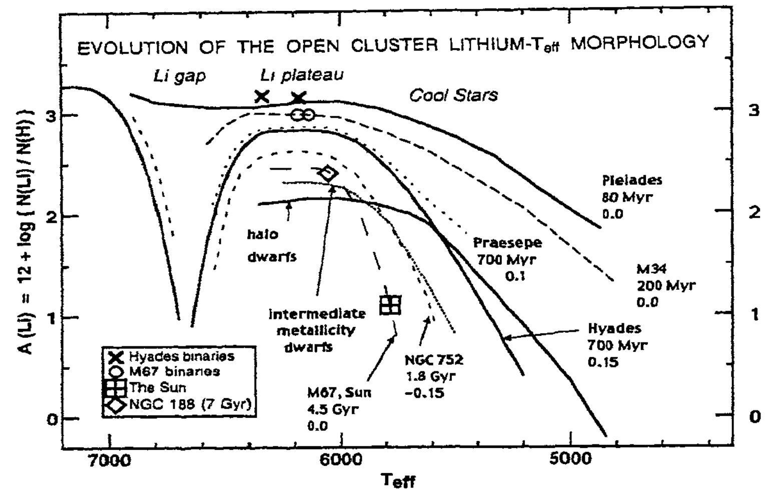

**Figure 4.** The main sequence Lithium Morphology of open clusters of different ages and composition. The figure is adapted from Deliyannis, Pinsonnealt & Charbonnel (2000).

undergone more Li depletion. For example, M 67 and NGC 752 which are 4.5 and 1.8 Gyrs old respectively almost approach Li values found in halo dwarfs. More time spent on the MS leading to larger depletion surely reflects that Li depletion is a main sequence phenomenon. Although there have been detailed systematic studies of clusters of roughly the same age and different metallicities and vice versa, the implications are still ridden with several controversies. There is a debate about whether the primordial value is at 2.1 and the Galaxy has got enriched in Li over its lifetime to 3.3 as we see in young stars. Or could the primordial value be 3.3 and has Li got depleted inside stars to 2.1 as we see in the long-lived dwarfs?

In collaboration with S. Balachandran (Univ. of Maryland) and D.L. Lambert (Univ. of Texas), I have begun a study of the $\alpha$ Persei cluster based on the data of 80 stars observed by them at R ~ 50,000 with the echelle spectrographs at the Kitt Peak and McDonald Observatories. $\alpha$ Per is a very young cluster, about 50 Myr old. It would be interesting to see how these stars fit into the picture described in Fig.4. Being very young and having arrived recently on the MS, we would expect these to retain their initial Li over much of the temperature range and according to the current understanding, certainly to lie above Pleiades. Fig.5a shows for 2 clusters, Hyades and Pleiades but it is more or less true of all clusters that there is a substantial spread in Li abundance within a given cluster at any given $T_{eff}$. It clearly implies that besides mass, age and metallicity, there are other parameters that control Li abundance; rotation among them playing a vital role. Depending upon the relative timescales of rotational braking for different stars and if the star formation within the $\alpha$ Per cluster has occurred over a finite period, its stars would have a range of rotational velocities which indeed they have as Fig.5b shows. We are curious to know how Li and rotation would be linked. The K dwarfs having barely arrived on the MS are expected to

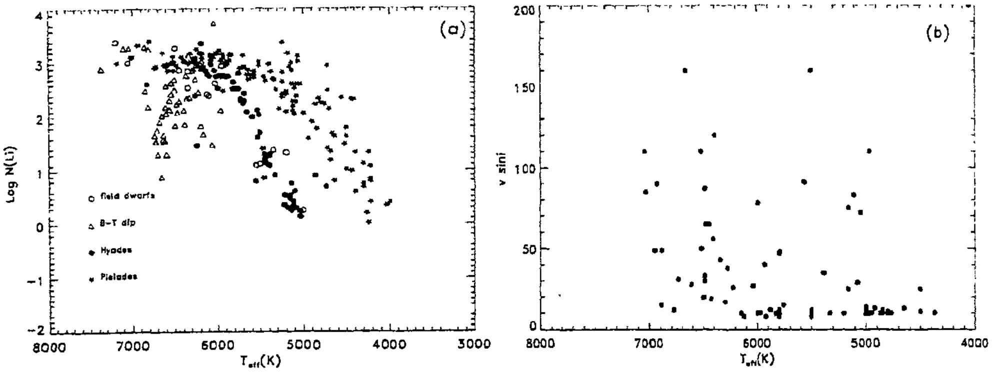

**Figure 5. a.** Li abundance vs. $T_{\text{eff}}$ for the Hyades and the Pleiades clusters. The symbols are described in the key. **b.** *v* sin*i* vs. $T_{\text{eff}}$ for the stars observed in the $\alpha$ Per cluster.

be rotating rapidly but many of them have already spun down. So would Li be unusually low in them?

It is important to emphasize that all the Li abundance determinations are based on just one spectroscopic feature, the resonance doublet of Li I at 6707.8Å. Although it is in a most easily accessible part of the spectrum, this line is often very weak, of the order of a few mÅ. For rapidly rotating stars, it becomes shallow enough to almost merge with the continuum. The synthetic fits to the spectrum then can only place upper limits to Li abundance. Also Li abundance is extremely sensitive to temperature. It is not an exaggeration to say that our understanding of the Li problem has often boiled down to finer details of stellar analysis such as temperature calibration and atmosphereic modelling. For rapidly rotating stars in the $\alpha$ Per cluster, it was not possible to determine $T_{\text{eff}}$ spectroscopically and one had to resort to photometry and colour-temperature calibrations. This was further complicated because we had to also correct for reddening claimed to be variable across the cluster. Since the $H_\beta$ flux is a reddening-free temperature indicator, we computed $H_\beta$ temperature for all the stars of $\alpha$ Per for which both $H_\beta$ and uvby photometry exist (the latter being particularly sensitive to the temperature for F and G dwarfs) and used the colour-temperature calibration to obtain reddening estimates for all these stars. We plotted these in RA and Dec as also our program stars to confirm they are uniformly spread across the cluster. Then we applied the reddening correction to the (V−I) colours we have for our stars to obtain temperatures. It is a non-trivial exercise to make sure of the accuracy of temperature for each star. This is under further scrutiny before we can pass judgement on the Li patterns we see in the $\alpha$ Per cluster.

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