

## Lithium and Rotation in Pop I stars

Sushma V. Mallik

*Indian Institute of Astrophysics, Bangalore 560034, India*

**Abstract.** Lithium abundances have been determined for 130 stars sampled on the basis that they have just about completed depletion of Li on the main sequence and have not yet begun their ascent on the red giant branch. The main goal is to study the effects of rotation on Li depletion. Analysis of the data reveals that fast rotating stars have suffered little depletion whereas slowly rotating stars have both low and high Li abundances. No one-to-one correlation appears to exist between Li abundance and the present *v sin i*. The large observed spread in Li abundance is perhaps a consequence of an initial range in rotational velocities in stars spinning down to low values on the main sequence. An attempt is made to study the Li evolution as a function of age, mass and rotation against the backdrop of the evolutionary tracks on the HR diagram.

### 1. Introduction

Lithium is a fragile element burning at only a few million degrees through the reaction  ${}^7\text{Li}(p, \alpha){}^4\text{He}$  and therefore an excellent probe of physical processes occurring inside stars. In a typical main sequence star, Li survives in the outer 40% of the stellar radius and is depleted inside of it. Standard stellar models do not predict depletion of Li in the MS stars (except the coolest dwarfs of  $T_{\text{eff}} < 4000\text{K}$ ) because the convection zone only lies within the outer 10% of the stellar radius in the much shallower and cooler region than the Li preservation boundary. However, there is enough observational evidence now to suggest that Li depletion is a rule, rather than the exception in F and G dwarfs (Duncan 1981; Balachandran 1990; Randich et al. 1995, 1999; Lebre et al. 1999). In fact, a vast majority of them are severely depleted in lithium, in contrast to the predictions of the standard stellar model calculations which include only convective mixing. In such a model of say an F star, the Li abundance goes down a little from  $\log N(\text{Li})$  around 3.3 to 2.7. This is understood to be a consequence of the destruction of Li in the pre-MS phase when the base of the convection zone is deep and hot enough to destroy Li (D'Antona & Mazzitelli 1994).

It is clear that the stellar models which ignore possible effects due to rotation, diffusion, mass loss, magnetic fields etc. fail to reproduce the observed Li abundance patterns in F and G dwarfs and that some additional physics is occurring inside these stars as emphasized by Deliyannis, Pinsonneault & Charbonnel (2000). Several non-standard processes have been investigated in the past in order to explain such large spreads in Li abundance and large depletions in many of them. The present study was undertaken to explore, in particular, the effects of rotation on the depletion of Li in F and G stars. A fresh look at this problem was triggered off by two recent observational developments. The

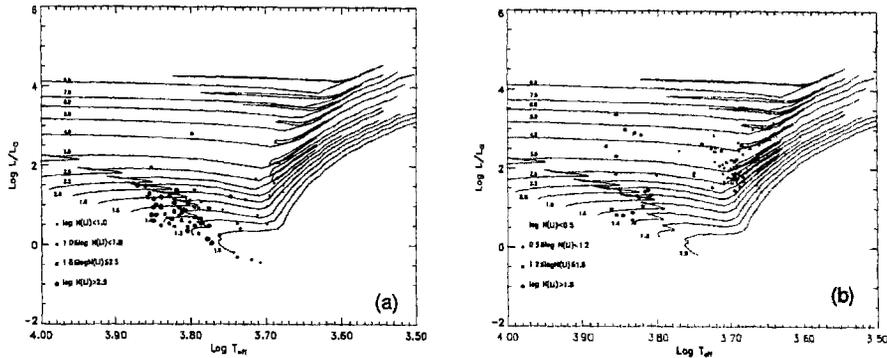


Figure 1. Stars chosen on the basis of their spectral classification on the HR diagram a) dwarfs and subgiants b) giants. Evolutionary tracks of Girardi et al. (2000) are shown for masses ranging from 1.0 to 7.0  $M_{\odot}$

first is the catalogue of rotational velocities measured with high precision in a large number of F, G and K stars by de Medeiros & Mayor (1999). The other is the Hipparcos Catalogue, a single source which gives parallaxes with accuracy of  $\sim 1$  milliarcsec for distances  $\leq 100$ pc. Thus one can actually trace the evolution of Li abundance of a star on the HR diagram against the backdrop of the evolutionary tracks as a function of mass, age and rotation.

## 2. Observations

Based on their spectral classification, a sample of 235 F, G and K dwarfs, subgiants and giants was selected from the Bright Star Catalogue, the [Fe/H] Catalogue (Cayrel de Strobel et al. 1997) and de Medeiros & Mayor Catalogue spanning a large range in [Fe/H] and  $v \sin i$ . CCD spectra of these stars were obtained in the Li region at a spectral resolution of  $\sim 0.35 \text{ \AA}$  using the coude echelle spectrograph at the 102cm telescope at the Vainu Bappu Observatory in Kavalur. With the measured Li EQWs as the input and an appropriate choice of models based on the stellar parameters from the grid of model atmospheres due to Gustafsson et al. (1975) generated by Luck (1992), Li abundances were determined using MOOG (Snedden 1973, upgraded 2001). The plot of dwarfs and subgiants shown in Fig. 1a on the HR diagram superposed against evolutionary tracks of Girardi et al. (2000) reveals that some of them have already begun their ascent up the red giant branch (RGB). Similarly, when giants are plotted on the HR diagram (Fig. 1b), it is seen that several of them are still on the subgiant branch and some are lying close to the main sequence. Stars lying on the RGB were discarded and a sample of 135 stars was selected based on their location on the HR diagram which is consistent from the point of Li evolution in the sense that they are completing MS depletion or have just about completed it and some of them are undergoing subgiant dilution but none have evolved far enough to have suffered depletion on the RGB.

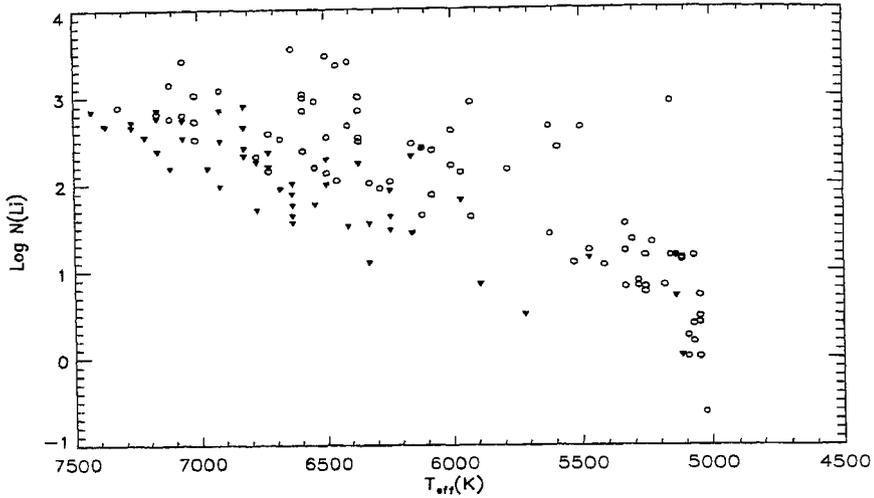


Figure 2. Li abundance vs. effective temperature. Inverted triangles denote stars with upper limits to lithium abundance

### 3. Interpretation

Li abundances of these stars plotted against effective temperature (Fig.2) suggest a fairly sudden drop at around 5300-5400K which marks the onset of dilution on the subgiant branch due to the deepening of the convective envelope. One notices this process is rather fast in terms of time and the range of  $T_{\text{eff}}$ . The inverted triangles denote stars with upper limits to Li abundance. There is a large spread in Li for  $T_{\text{eff}} = 6400-6800\text{K}$  which corresponds to the Li dip first discovered by Boesgaard & Tripicco (1986). A more striking feature is the large spread in Li abundance seen in stars to the right of this and to the left of the drop at 5300K which suggests main sequence depletion is indeed occurring in stars. The plot of their rotational velocities against  $T_{\text{eff}}$  (Fig.3) shows a rotational discontinuity at  $\sim 6400\text{K}$  to the right of which stars have spun down to low values, lower than  $20 \text{ km s}^{-1}$  and stars to the left display a large range in  $v \sin i$ . So the stars between 6400 and 5400K (late F and early G stars) that display a large spread 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  $v \sin i$ .

In Fig.4 these stars are plotted on the HR diagram superposed on evolutionary tracks of masses ranging from  $1.0$  to  $7.0 M_{\odot}$ . The increasing size of the circles denotes higher  $v \sin i$ . Lithium evolution is better understood with more bins in Li abundance. Here, however, only 2 Li abundance bins are shown; the open circles denote stars with  $\log N(\text{Li}) \geq 2.0$  and filled circles are stars with  $\log N(\text{Li}) < 2.0$ . It is obvious from this figure that stars of lower masses ( $\leq 1.3 M_{\odot}$ ) have already spun down to lower values. On the other hand, the more massive stars do so only towards the end of the subgiant branch. What is worth

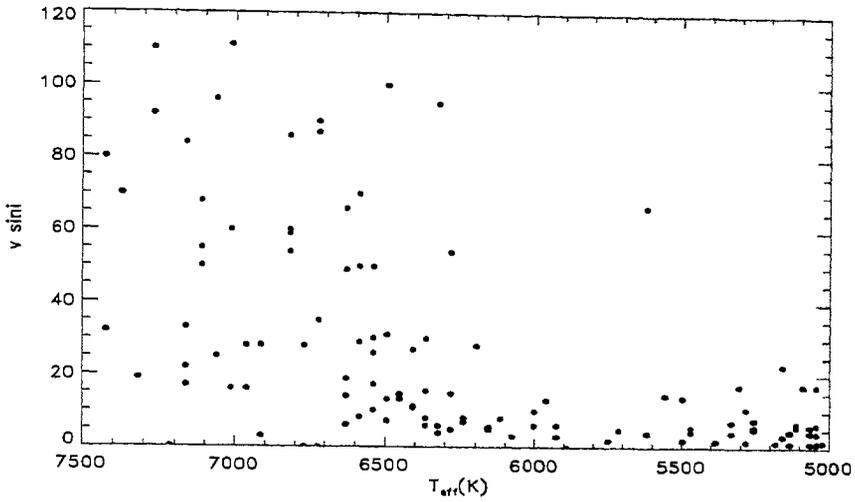


Figure 3.  $v \sin i$  vs. effective temperature

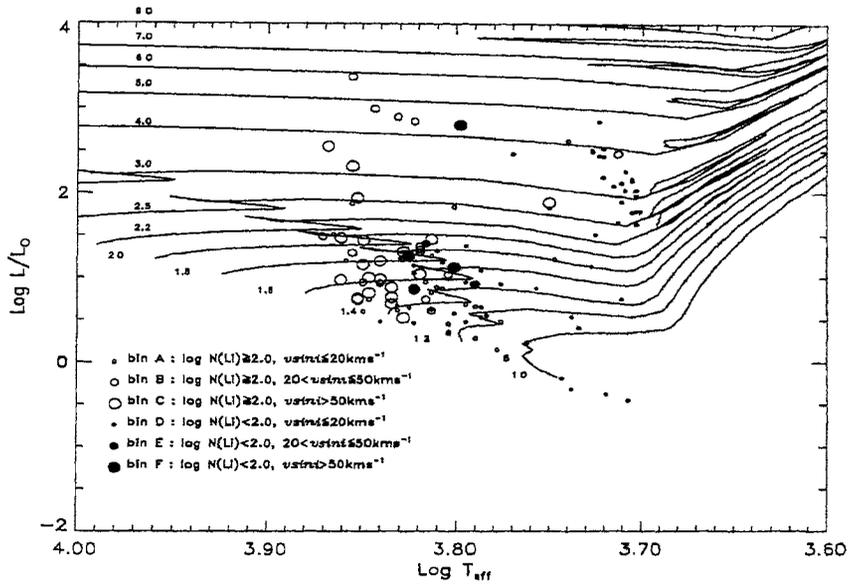


Figure 4. HR diagram of the observed stars. Symbols of increasing size denote increasing  $v \sin i$ . Unfilled circles denote  $\log N(\text{Li}) \geq 2.0$  while the filled ones are with  $\log N(\text{Li}) < 2.0$ . Also shown are theoretical evolutionary tracks of Girardi et al. (2000) for stars of initial masses ranging from 1.0 to 7.0  $M_{\odot}$

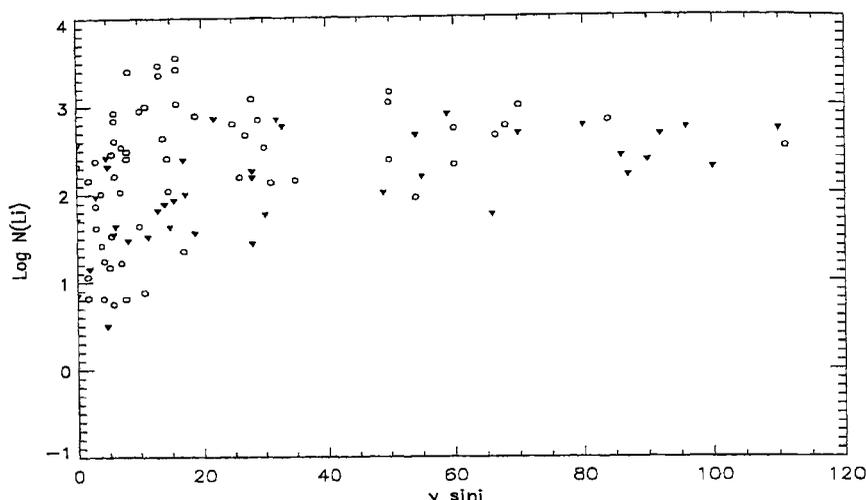


Figure 5. Li abundance vs.  $v \sin i$  for stars of  $T_{\text{eff}} \geq 5300\text{K}$ . Inverted triangles are stars with upper limits to lithium abundance

noting here is that there is a large spread in  $\log N(\text{Li})$  for stars of low  $v \sin i$  for all masses whereas for stars of high  $v \sin i$  and larger masses,  $\log N(\text{Li})$  tends to have only higher values. This is true even if the stars in the Li dip are not considered. This is more clearly demonstrated in Fig.5 where  $\log N(\text{Li})$  is plotted against  $v \sin i$ . Here stars of  $T_{\text{eff}} \leq 5300\text{K}$  which have already started undergoing subgiant dilution have been excluded. This trend seems to be dictated by the idea that stars which are still fast rotators have suffered little loss of angular momentum and hence have hardly undergone any mixing and hence have 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 therefore have undergone more effective mixing and hence larger Li depletion. There does not seem to be a one-to-one correlation between Li abundance and the present projected rotational velocity. The above correlation may perhaps be driven by the initial rotational velocity the star is endowed with. It is tempting to think of a scenario where a group of stars with, say, the same initial  $\log N(\text{Li})$  and a range in  $v \sin i$  as they arrive on the main sequence exhibit a large scatter in Li abundance after they have all spun down.

Such an interpretation of the present data by no means proves that mixing induced by differential rotation is the only viable mechanism that explains large scatter in Li abundances in stars otherwise similar. An attempt has been made to explore whether such a mechanism is supported by observations and it does not appear to be at odds with them. However, the pattern as we see it in Fig.6 has to be interpreted with caution. The inverted triangles are stars with upper limits to Li abundance. The lower envelope running from high Li and high  $v \sin i$  to low Li and low  $v \sin i$  appears to skirt these upper limits. This perhaps arises because the minimum detectable EQW of the Li line increases for an obvious

reason with increasing  $v \sin i$ . On the other hand, the upper boundary is almost independent of  $v \sin i$ . It would be worth increasing the sample still more to make sure whether the lower envelope has a real physical basis or is an artifact of the limited nature of the sample. Either way, it lends a strong statement on the link between Li abundance and rotation.

## References

- Balachandran, S. 1990, ApJ 354, 310  
Boesgaard, A.M., Tripicco, M.J. 1986, ApJ 302, L49  
Cayrel de Strobel, G., Soubiran, C., Friel, E.D., Ralite, N., Francois, P. 1997, A&ApS 124, 299  
De Medeiros, J.R., Mayor, M. 1999, A&ApS 139, 443  
D'Antona, F., Mazzitelli, I. 1994, ApJS 90, 467  
Deliyannis, C.P., Pinsonneault, M.H., Charbonnel, C. 2000, IAU Symp.198 on The Light Elements and their Evolution, eds. L. da Silva, M. Spite, J.R. de Medeiros (published by ASP), p.61  
Duncan, D.K. 1981, ApJ 248, 651  
ESA 1997, The Hipparcos & Tycho Catalogues, ESA SP-1200  
Girardi, L., Bressan, A., Bertelli, G., Chiosi, C. 2000, A&ApS 141, 371  
Gustafsson, B., Bell, R.A., Eriksson, K., Nordlund, A. 1975, A&Ap 42, 407  
Lebre, A., de Laverny, P., de Medeiros, J.R., Charbonnel, C., da Silva, L. 1999, A&Ap 345, 936  
Luck, R.E. 1992, private communication  
Randich, S., Pallavicini, R., Pasquini, L., Gratton, R. 1995, Mem. Soc. Astron. Italia 66, 387  
Randich, S., Gratton, R., Pallavicini, R., Pasquini, L., Caretta, E. 1999, A&Ap 348, 487  
Snedden, C.A. 1973, Ph.D. Thesis, The University of Texas, Austin