LITHIUM AND BERYLLIUM IN STELLAR ATMOSPHERES

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ABSTRACT: Abundances of Li and Be in field stars and clusters in Population I are reviewed. New results are presented on Li in a blue straggler in M67. Observations are presented of new Be–deficient F dwarfs of Population I and of some old disk and Population II dwarfs which apparently have the solar Be content.

INTRODUCTION

The stellar abundances of Li and Be are of interest in such diverse areas as cosmology, the origin of the elements, stellar structure and evolution, the chemical evolution of the Galaxy. Lithium was identified in sunspots in 1907 (Hale and Adams), in carbon stars in 1940 (McKellar), in T Tauri stars in 1947 (Sanford). Beryllium was thought to be present in the sun in 1895 (Rowland and Tatnall).

The standard Big Bang produces Li and some Be can be made in non-standard Big Bang models. Spallation reactions on C, N, O atoms in the interstellar medium by Galactic Cosmic Rays produce isotopes of Li, Be, and B. In stellar interiors nuclear reactions with protons destroy Li in regions where the temperature is higher than about 2.5 x 10^6 K and Be where T is above about 3.5 x 10^6 K.

LITHIUM IN POPULATION I STARS

Field Stars

In order to find the "initial" Li in Population I field stars Boesgaard and Tripicco (1986a) obtained high–resolution, high signal–to–noise (S/N) Reticon spectra with the Canada–France–Hawaii telescope of F dwarfs. Abundances of Li/H were found from the spectra of 75 stars with spectral resolution of 0.1 Å and S/N of 200 – 600. The mean for the 18 F0 – F2 V stars (T_{eff} between 6500 – 7000 K) is $<Li/H> = 1.02 (\pm 0.34) \times 10^{-9}$ or log N(Li) = 3.01 ±0.13 where log N(H) = 12.00. These stars are all younger than 2 x 10^9 yr. Figure 1 shows the Li values for the 75 field stars.

The original value of Li/H that Pop I stars are born with can also be found in the F dwarfs of young clusters. For the Pleiades at 7 x 10^7 yr and α Per at 5 x 10^7 yr Boesgaard, Budge, and Ramsay (1988) found a mean of 2.98 ±0.13 for log N(Li) for 21 stars from Palomar CCD coudé spectra at 0.2 Å resolution and 100–300 S/N ratios. A similar result was found for 12 Pleiades F dwarfs by Pilachowski, Booth, and Hobbs (1987) from KPNO coudé feed CCD spectra at

0.5 Å resolution and 50 – 140 in S/N; their mean for the 12 F stars is log N(Li) = 3.03 ±0.16. These results confirm the value of the "initial" Li in the field F dwarfs so the Pop I value can be taken as:

$$\log N(\mathrm{Li}) = 3.0 \pm 0.1, \text{ where } \log N(\mathrm{H}) = 12.0.$$

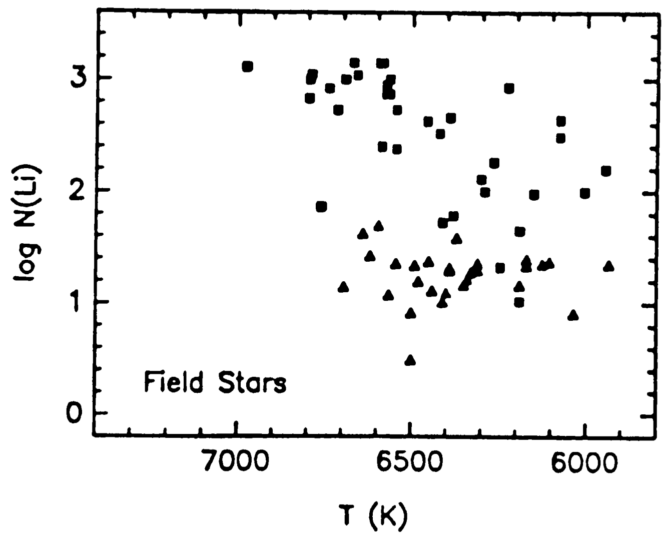

Figure 1. The Li–temperature plot for F field stars from Boesgaard and Tripicco (1986a). The triangles represent upper limits for Li. The stars in the upper left with temperatures greater than 6500 K are thought to have undepleted Li abundances.

Clusters

High quality data and analysis techniques have been used by Cayrel *et al.* (1984) to find Li abundances in the Hyades G stars. Their data delineate the very striking, steep fall–off of Li content with decreasing stellar mass (increasing convection zone depth) for G dwarfs. High S/N (350 – 600) and spectral resolution (0.1 Å) observations by Boesgaard and Tripicco (1986b) revealed severe Li deficiencies in the Hyades F dwarfs in the narrow temperature range of 6400 – 6800 K (masses near 1.2 – 1.3 $M_{\odot}$). This discovery indicates that the internal stellar structure and mixing processes that lead to Li depletion are complicated. Figure 2 shows the Li–temperature profile for the Hyades F and G dwarfs with data from Cayrel *et al.* (1984), Boesgaard and Tripicco (1986b) and Boesgaard and Budge (1988). Similar Li depletions in F dwarfs in clusters have been found in NGC 752 (Hobbs and Pilachowski 1986, Pilachowski and Hobbs 1988), Coma (Boesgaard 1987a), UMa Group (Boesgaard, Budge, and Burck 1988), and Praesepe (Boesgaard and Budge 1988). These clusters range in age from 3 x 10^8 yr (UMa) to 1.7 x 10^9 yr (NGC 752).

As discussed above Li is apparently not depleted in the F stars of the Pleiades and α Per (Boesgaard, Budge, and Ramsay 1988, Pilachowski, Booth and Hobbs 1987). These younger clusters still show their original Li content. There is a hint in both data sets of possible incipient depletion near 6500 K, but at a level of only 0.1 dex. The Li depletions in the older clusters, therefore, must have occurred during main sequence evolution, not during the pre–main sequence phase. Additional data and references can be found in the recent articles by Boesgaard (1988) and Hobbs and Pilachowski (1988).

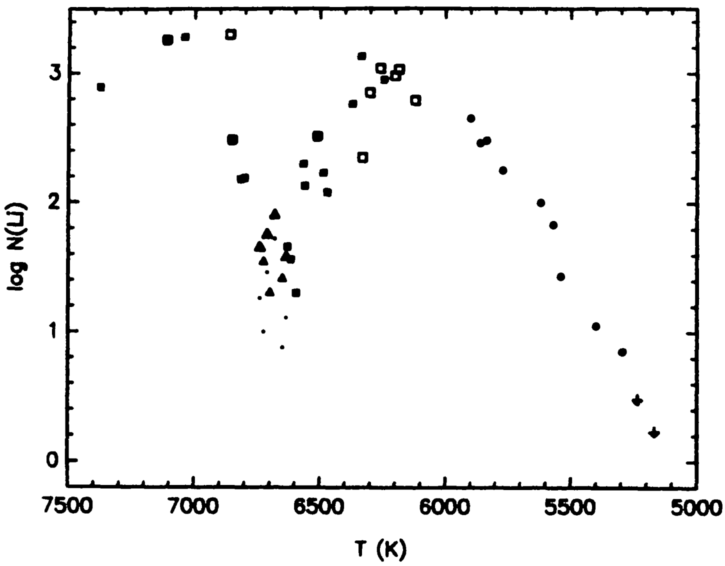

Figure 2. The Li–temperature profile for the Hyades F and G dwarfs from Boesgaard and Budge (1988); the filled circles are the G star data from Cayrel *et al.* (1984). Filled squares and triangles are from Boesgaard and Tripicco (1986b), open symbols are from Boesgaard and Budge, while open symbols with the dots are the weighted averages from those two papers. Triangles represent upper limits on the Li abundance, but the small dots represent alternative upper limits from a Li–Fe blend synthesis.

The Li depletions in the Hyades F stars have been interpreted by Michaud (1986) as being caused by microscopic diffusion of Li atoms below the convection zone. A chemical separation takes place because the downward acceleration of gravity is greater than the upward radiative acceleration on the ionized Li atoms. The time scale for this diffusion is long so that the effect could be seen in stars the age of the Hyades, but not at the age of the Pleiades. To obtain a better match with the observed Li values, he suggests that mass loss at the rate of about 10^{-14} – 10^{-15} $M_{\odot}$ yr^{-1} has been taking place.

The role of rotation in the Li depletion in the F stars in clusters may be important. Boesgaard (1987b) has examined the Hyades $v \sin i$ values from Kraft (1965) as a function of temperature and Li abundance. Moving toward lower mass, cooler temperature F dwarfs, stellar rotation declines and the outer convection zone increases in depth. In the middle of the Li dip where the depletions are large, the rotation is fairly high, 30 – 50 km s^{-1}. On the cool side of the dip, as the rotation declines dramatically, Li is less and less depleted. Recently, Charbonneau and Michaud (1988) demonstrate that models with meridional circulation can match the Li depletions on the cool side of the

Li dip. Material from the deeper stellar regions where Li has been destroyed by nuclear reactions will be brought to the surface by this circulation and dilute the surface Li mixture. Vauclair (1988) has proposed that Li can be circulated to deeper layers and destroyed by turbulence below the convection zone that is induced by rotation.

M 67

Lithium abundances have been determined for dwarfs and giants in the old open cluster, M 67, by several authors, including Balachandran (1990) in these proceedings. It is interesting to search for Li in the blue stragglers in M 67 in order to test the hypothesis that blue stragglers are the result of a binary star that has coalesced into a higher mass single star which would still be near the main sequence. A variation on this is that sufficient mass transfer and mixing would take place so that the additional nuclear fuel available would prolong the main sequence life of the stars. It is expected that such stars would be so thoroughly mixed that all Li would be destroyed. Thus the presence of Li in blue stragglers would argue against the idea that they result from coalesced or strongly interacting binaries.

Palomar 60–inch echelle spectra taken by K. G. Budge indicated the possible presence of Li in the spectrum of f–131 = S–1082. In March 1989 E. D. Friel and I took high–resolution spectra of this and two other blue stragglers in M 67 with the CFHT coudé spectrograph and Reticon detector in the Li I region. Figure 3 shows the H–R diagram of M 67 from Sanders (1989) with the location of f–131 indicated; it is a genuine member and clearly a blue straggler.

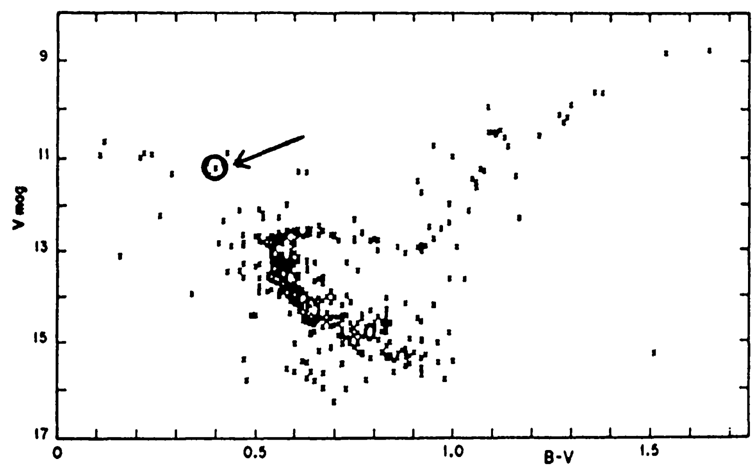

Figure 3. H–R diagram of M 67 from Sanders (1989). The position of f–131 is shown by the arrow and the circle.

Figure 4 shows the sum of three CFHT exposures of f–131 with a S/N of about 110. There is no evidence for Li I; the arrow points to the expected position of the Li I feature. A nearby, weak line has an equivalent width of 9 mÅ providing a conservative upper limit for a Li line. At a temperature of 6700 K this corresponds to L/H $\lesssim 10^{-10}$, not a very meaningful upper limit. This star could have destroyed its Li through mixing via the binary hypothesis, or via the mechanism that depletes the Li in the Hyades Li gap. Neither f–153 nor f–156 in M 67 showed evidence of a Li I feature either; those stars are hotter and the spectra are less well–exposed, however.

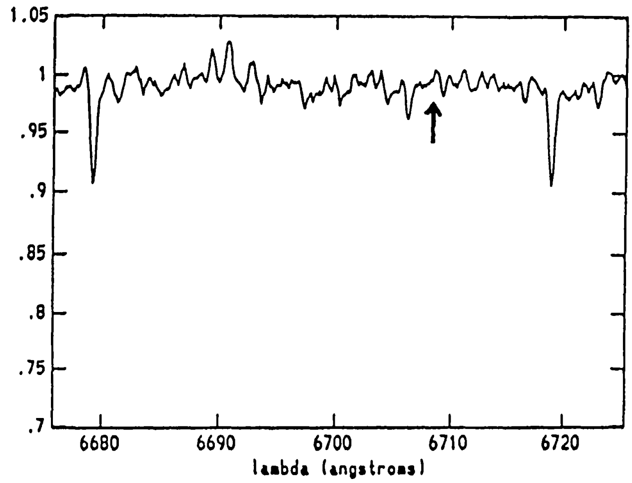

Figure 4. Part of the Li region spectrum of the blue straggler, f–131, in M 67. The arrow points to where the Li line would be.

BERYLLIUM IN POPULATION I STARS

Field Stars

Observations of Be can tell us about the internal stellar structure and processes that affect the light elements. The combination of observations of both Li and Be provide additional constraints because Li is destroyed at 2.5 x 10^6 K while Be is destroyed at 3.5 x 10^6 K. However, Be abundances are best determined from the resonance doublet of Be II at 3130 and 3131 Å where the spectrum is crowded, the atmospheric extinction is high, and modern detectors have fairly low quantum efficiency.

Observations of Be in field stars were discussed by Boesgaard (1976). Although most of the stars showed the same Be content as the sun, Be/H = 1.4 x 10^{-11}, several of the hotter F dwarfs were markedly deficient in Be. The only characteristics that the Be–deficient stars had in common were their surface temperatures (6600 – 7000 K) and their severe Li deficiencies. New observations have been made of Be in F field stars by Boesgaard and King in July 1989 at the CFHT with the coudé spectrograph and CCD detectors. Examples of the preliminary reduction of these spectra are shown in Figure 5.

A special search was made to try to find additional Be–deficient F dwarfs in order to understand the cause of the deficiency. An enlarged sample of main sequence stars with light element deficiencies should help to define better which parameters affect the mixing processes in the envelope. The observing program, therefore, included many Li–deficient stars. Stars which are depleted in Li will not necessarily deplete Be, e.g. the sun, since the surface material must circulate to deeper layers to destroy Be than to destroy Li. It is expected though, that any star that is depleted in Be will have lost its Li. The stars observed in July can be readily divided into groups that clearly show Be II lines and those that do not; as can be seen in Figure 5 the differences are obvious.

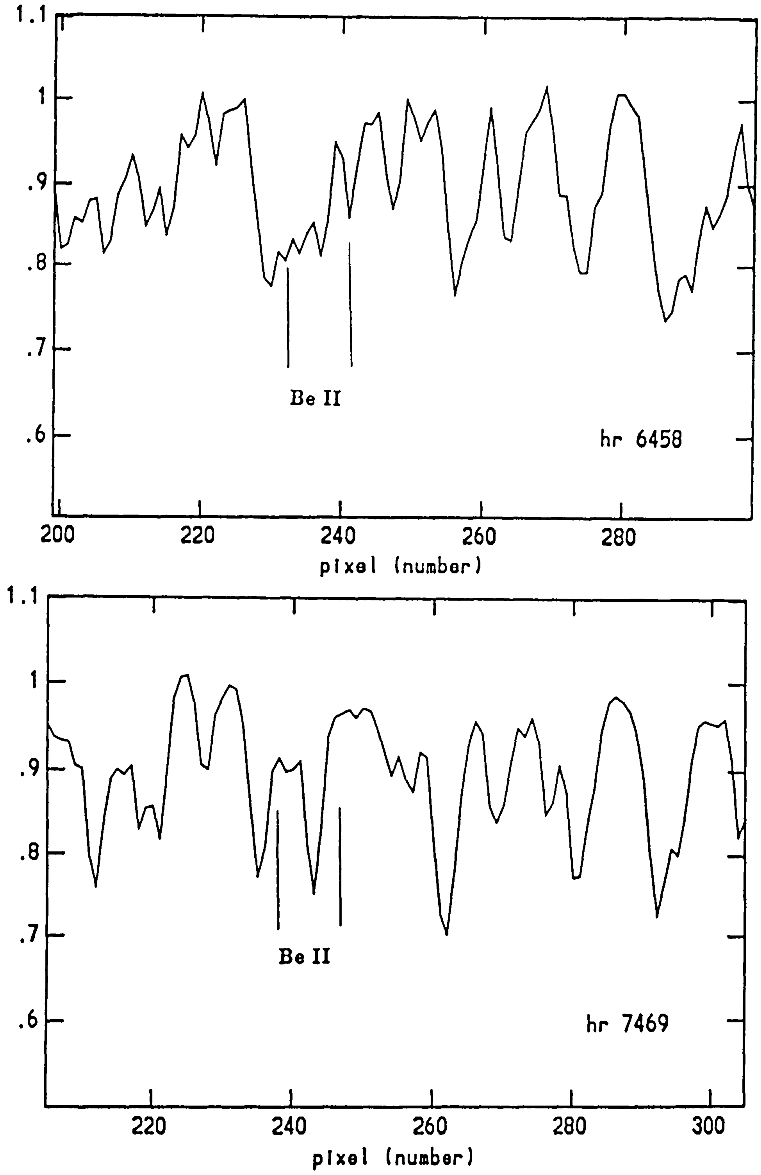

Figure 5. Examples of recent CFHT spectra of field stars. HR 6458 is an old disk, Li–depleted (log N(Li) < 0.9) G0 V star that *has* Be. HR 7469 is a Population I, Li–depleted (log N(Li) < 1.0) F4 V star that is Be deficient.

The H–R diagram of the stars we observed for Be is shown in Figure 6. The Be–deficient stars cluster in one area – near the position of the Li dip in the Hyades, B – V = 0.40 – 0.47.

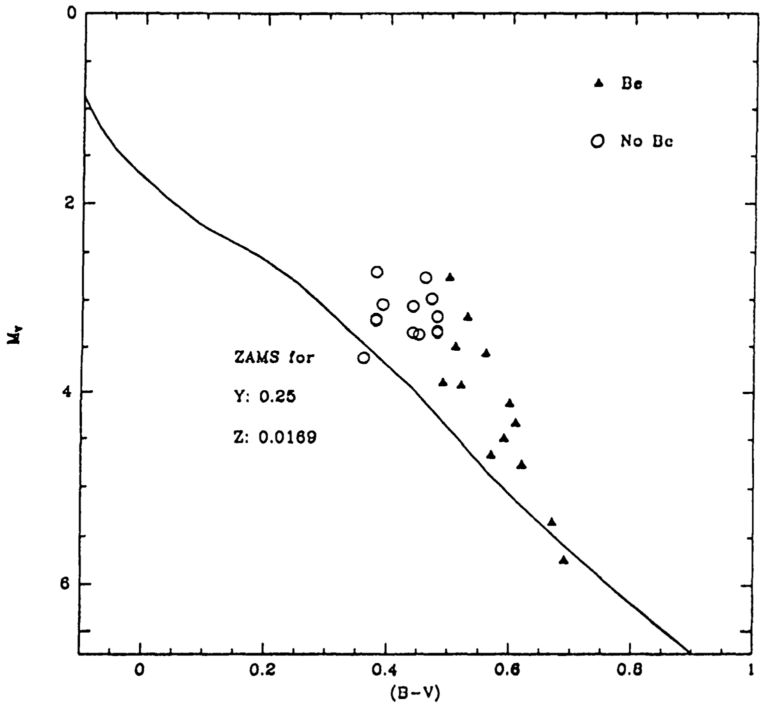

Figure 6. H–R diagram of stars observed for Be by Boesgaard and King at CFHT. The open symbols are stars which are clearly Be–deficient and the filled triangles are stars with strong Be II lines. The Be–deficient stars cluster near the area where the severe Li deficiencies are found in the Hyades.

Some old disk and halo stars were also observed for Be. Surprisingly, all the old disk stars appear to have strong Be II features, even those with metallicities as low as [Fe/H] = –0.6. One example is HR 9088. As reported by Budge, Boesgaard, and Varsik (1988), the halo star, HD 76932, with [Fe/H] = –1.1 has very prominent Be II lines. The F5 IV–V star, α CMi = HR 2943, is known to be Be–deficient. Its spectrum is compared with that of HD 76932 in Figure 7. The difference spectrum in the lower panel shows the clear signature of Be. The spectrum synthesis shows Be/H to be about 7 x 10^{-12}, only a factor of two less than solar. Ryan *et al.* (1990) reported at this conference on new halo star Be observations, adding to earlier observations by Rebolo *et al.* (1988).

It is important to understand the evolution of Be in the galactic disk. Beryllium is produced by spallation reactions on C, N, and O nuclei by galactic cosmic rays of energies >100 MeV. Tracing the amount of Be enrichment traces the history of the early production of energetic cosmic rays (and thus supernovae) as well as the early production of CNO atoms.

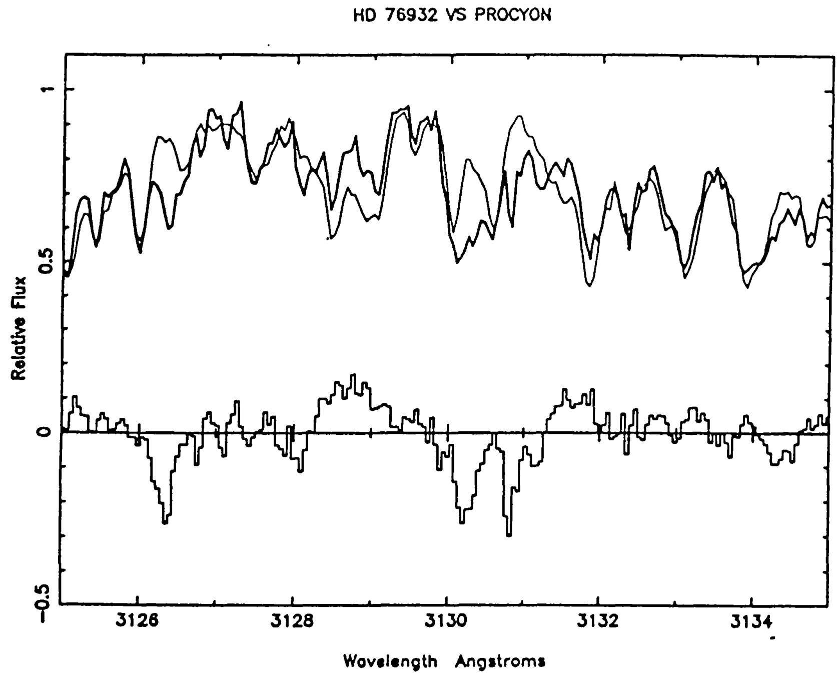

Figure 7. Be II region spectra of α CMi (light line) and HD 76932 (heavy line) from observations of Budge, Boesgaard and Varsik. The lower panel is the difference spectrum showing clear the presence of the Be lines near 3130 Å.

Clusters

Of the open clusters that show the pronounced Li-depletions in the mid–F dwarfs, the Hyades are the closest, even so its F dwarfs are just barely bright enough to be observed at sufficient resolution with modern detectors to study the crowded spectral region near the Be II lines. In order to map the extent of the mixing that the Li abundances give evidence for, Boesgaard and Budge (1989) observed Be in several Hyades F dwarfs through the Li dip. At spectral dispersions of 0.3 – 0.5 Å px^{-1} and S/N ratios of about 100, they obtained CCD spectra of 8 stars spanning the Li dip with temperatures of 6470 – 7040 K. They derived abundances of Be/H of about 10^{-11}, or [Be/H] = 0.0 to –0.2. There is virtually no change in the Be content across the temperature region where there are large deficiencies in Li in the Hyades. This can be seen in Figure 8 where both Li and Be abundances in the Hyades are plotted. The Be results thus provide a powerful constraint on the models of the mixing processes. The age of the Hyades provides another constraint, since there are field stars which *are* depleted in both Li and Be in this temperature region.

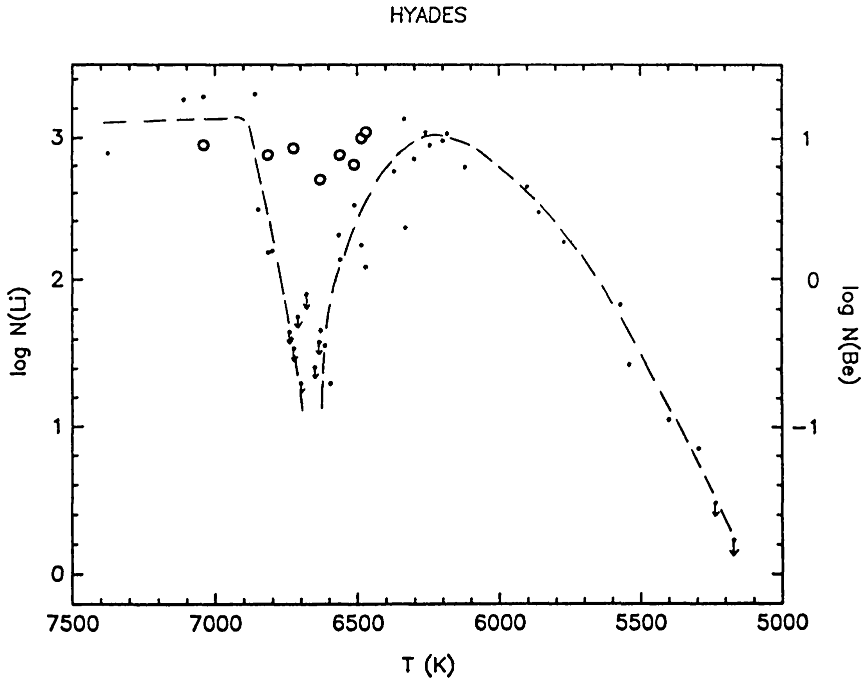

Figure 8. Log Li abundances (small dots) and log Be abundances (open circles) on the scale where log H = 12.00 plotted against temperature for the Hyades from Boesgaard and Budge (1989). The arrows on the Li points represent upper limits. Li references are given in Figure 2. The Li–temperature profile is sketched in with the dashed line. There appears to be no change in the Be abundances in spite of the large Li deficiencies.

SUMMARY

Several points were covered concerning Li and Be in Population I solar–type stars:

The initial value for Li in Pop I stars was shown to be Li/H = 10^{-9} or log N(Li) = 3.0 ($\pm$0.1) on the scale of log N(H) = 12.0.

There is a temperature regime in F stars in clusters where there are large Li deficiencies. This is seen in the Hyades, Coma, UMa, Praesepe, NGC 753, M 67, all clusters with ages > 5 x 10^8 yr.

No Li dip in the F stars in the young clusters, Pleiades and α Per, which are 5 – 7 x 10^7 yr old. Therefore the phenomena leading to the depletion of Li occurs during main sequence, not pre–main sequence, evolution. One possible contributing parameter is stellar rotation.

Li is apparently not in the blue straggler observed in M 67. The upper limit on the abundance Li/H is $<10^{-10}$. The Li could be diminished by either the coalescense of a binary star or by the mechanism that acts in the Hyades F dwarfs of that temperature range.

All the Be-depleted field stars are Li depleted, although the converse is not true – as expected. The field stars that are Be–deficient are in the temperature region where the Hyades, and other clusters, stars are Li–deficient.

Be is not depleted in Hyades F dwarfs where Li is severely deficient. So matter is not circulated to temperatures as high as 3.5 x 10^6 K, apparently.

Be is present and strong in some old disk stars. This indicates that Be was produced early in the history of the galactic disk.

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