ABUNDANCE SIGNATURES OF INTERNAL STELLAR STRUCTURE IN F STARS

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ABSTRACT. We have determined Li abundances from high resolution, high signal-to-noise spectra near 6700 Å of the F dwarfs in several galactic clusters and in the field. The Li–temperature profiles show large Li depletions in the mid–F stars indicating that matter has been circulated (or diffused) downward in the stars. This brings new observational evidence about the details of stellar envelope structure. Li depletions occur in stars with T = 6400 – 6900 K, with depletions of over an order of magnitude for those with T = 6500 – 6800 K. The relationship to rotation, galactic Li, and the halo star Li content is discussed.

1. INTRODUCTION

The surface contents of both Li and Be provide sensitive probes to the internal structure of stars. For example, the Sun destroys Li by (p,α) type reactions at $\sim$2.5 x 10^6 K and has lost 99 percent of its Li, while it burns Be at $\sim$3.5 x 10^6 K and has lost none of its original Be apparently. The temperature at the base of the solar convection zone in solar models is only 1.9 x 10^6 K (D'Antona and Mazzitelli 1984), not enough for Li (or Be) destruction. For a hotter star, 1.25 $M_\odot$, the stellar model is only 6 x 10^5 K at the bottom of the surface convection zone. Thus, according to the models, convection alone does not circulate Li and Be to regions of the star where they can be destroyed. However, some main sequence stars of $\geq$ 1 $M_\odot$ do show depletion of Li or of both Li and Be, so other mixing mechanisms are required.

2. OBSERVATIONS

Spectra for a number of F main-sequence stars in open clusters and in the field have been obtained near the 6700 Å region at the 3.6 m Canada–France–Hawaii telescope on Mauna Kea and at the 5 m Hale telescope at Palomar. Those from the CFHT are Reticon spectra from the f/8.2 coudé camera and cover 135 Å with a spectral resolution of 0.11 Å and typical S/N values of 350 – 600. Those from Palomar are TI CCD spectra from the 72–inch coudé camera and cover 110 Å with 0.21 Å resolution and 300 – 500 in S/N. Because of the high signal–to–noise ratios, highly accurate Li abundances can be determined and, for stars with no detectable Li line, very low upper limits can be ascertained which correspond to very large (2

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– 3 orders of magnitude) Li depletions.

The spectra have been flat–fielded, wavelength–adjusted, and continuum–flattened according to the usual procedures. (See Boesgaard and Tripicco 1986b and Boesgaard, Budge, and Burck 1988) for details.) Equivalent widths or upper limits have been measured for Li I λ6707 and for several Fe I lines. A weak Fe I line (2 – 4 mÅ) blends with the Li I line on the short wavelength side; to account properly for that in the calculations, the abundance of Fe/H must be found.

3. ABUNDANCE RESULTS

Stellar temperatures have been determined through use of several photometric indices and calibrations. Models of Kurucz (1979) have been used with a model atmosphere abundance routine to predict the Li I (and Li I + Fe I) equivalent widths for various abundances.

Figure 1 shows the Li–temperature profile for the F field stars (data from Boesgaard and Tripicco 1986b), the Hyades F dwarfs (primarily from Boesgaard and Tripicco 1986a), the Coma F dwarfs (from Boesgaard 1987a), and for the UMa Group F stars (from Boesgaard, Budge, and Burck 1988). The three open clusters

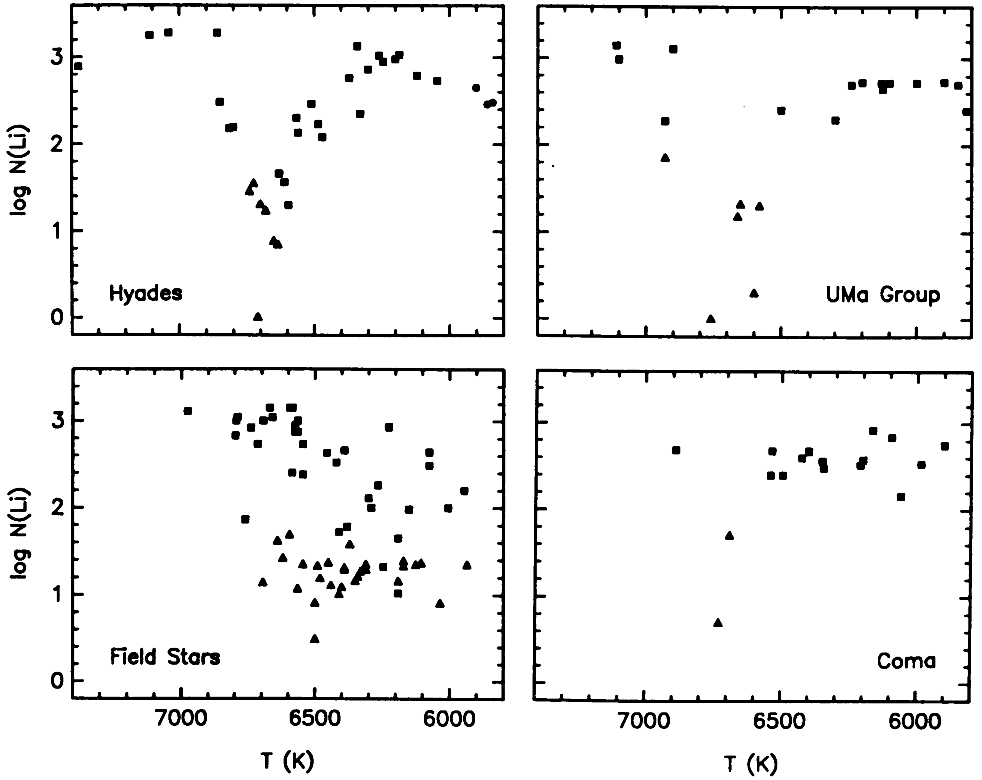

Figure 1. The Li–temperature profile for F field dwarfs, the Hyades F dwarfs, the Coma F dwarfs and the UMa F dwarfs. Triangles represent upper limits.

(ages 7 x 10^8, 5 x 10^8, and 3 x 10^8 yr, respectively) all show a pronounced drop in Li content in the middle F star range, near temperatures 6400 – 6900 K, or in stars about 20 percent more massive than the sun. The field stars are not all affected by this phenomenon: about half of the stars in this temperature regime show the normal Pop I abundance, Li/H = 10^{-9} or log N(Li) = 3.0, and about half show large Li depletions.

An interpretation of the Hyades F star Li depletions in terms of diffusion has been put forward by Michaud (1986). His calculations show that chemical separation takes place below the convection zone because the upward radiative acceleration on Li is less than the downward acceleration of gravity for the middle–F stars. For the cooler F stars the diffusion time scale is too long to see the effect in the 7 x 10^8 yr lifetime of the Hyades cluster. His calculations do not match the observations in two ways: they predict that Li will be supported in the early F stars resulting in overabundances of Li and they predict only an order of magnitude or so for Li depletions while more than two orders of magnitude are found. Both of these effects can be reconciled with the observations if the stars are losing mass at rates of about 10^{-14} – 10^{-15} $M_\odot$ yr^{-1}.

It is possible that complex circulation patterns are present in the stellar envelopes relating to rotation, differential rotation and magnetic fields. Figure 2 shows the drop in the measured $v \sin i$ values (from Kraft 1965) with temperature over the Li "chasm" in the Hyades. As one goes toward cooler temperatures in the F dwarfs the stellar rotation declines and the outer convection zone deepens. The interplay between these two phenomena may result in the sudden drop in the surface Li content followed by the slower rise. In the Li chasm it appears that the rapid rotators are more severely depleted in Li.

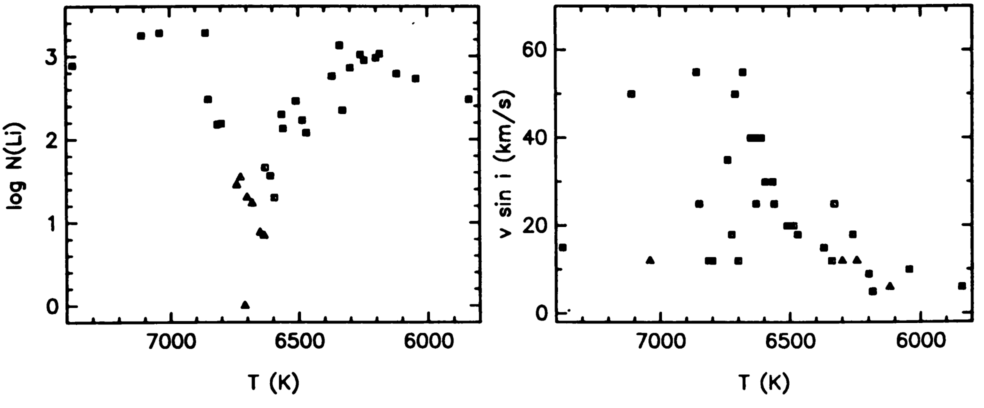

Figure 2. The Li–temperature and v sin i–temperature profiles for the Hyades F dwarfs.

4. DISCUSSION AND CONCLUSIONS

All the galactic clusters appear to have the same amount of Li as shown by the F dwarfs that are hotter than the mid–F star Li gap, log N(Li) ~ 3.0. This is the same amount as seen in the chondrites (Nichiporuk and Moore 1974), the F field stars (Boesgaard and Tripicco 1986b), F and G visual binaries (Boesgaard and Tripicco 1987) and T Tauri stars (Mundt *et al.* 1983). These objects span the age range from $\sim 10^6$ to 5×10^9 yr. From this we can infer that there has been no measurable enrichment of Li in the galactic disk since the formation of the solar system.

The four galactic clusters in which Li in the F dwarfs has been recently studied – UMa at 3×10^8 yr (Boesgaard, Budge, and Burck 1988), Coma at 5×10^9 yr (Boesgaard 1987a), Hyades at 7×10^8 yr (Boesgaard and Tripicco 1986a and Boesgaard 1987b) and NGC 752 at 2×10^9 yr (Hobbs and Pilachowski 1986) – all show evidence of the deep Li depletions in the mid–F stars first shown by Boesgaard and Tripicco (1986a) in the Hyades. In addition, visual binaries with ages of 8×10^8 – 3×10^9 yr also show this effect. The "Li chasm" occurs at B – V = 0.40 – 0.47, or T ≈ 6400 – 6900 K. The chasm has a width of only 300 K at the log N(Li) = 2.0 level.

In the Hyades the bottom of the Li gap is at T ~ 6650 K where the depletions of Li are at least 3 orders of magnitude. As the the temperature decreases, the value of log N(Li) increases and $v \sin i$ decreases. For the stars in the Hyades Li chasm there appaers to be an inverse relation between log N(Li) and $v \sin i$ such that the more rapidly rotating stars are more depleted in Li.

On the cool side of the Li dip the three clusters that have ages near 5×10^8 show a flat distribution of Li *vs.* temperature with a log N(Li) value of ~2.7, slightly below the initial value found in the F stars on the hot side of the Li chasm. These stars have apparently undergone some Li depletion, the amount of which may be age related but is not very mass dependent. This flatness from T ~ 5800 – 6300 K is reminiscent of the flatness in the Li–temperature plot for the halo dwarfs. (See Figure 3.) The similarities in the flatness and in the spread of log N(Li) values at a given temperature indicate that it is possible that the halo stars have undergone Li depletion (diffusion?) during their long lifetimes from an initial level higher than that presently observed.

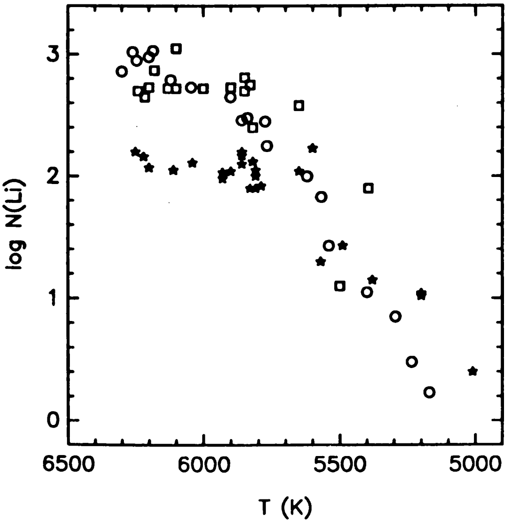

Figure 3. The Li–temperature profile for the late F and G dwarfs of the Hyades (open circles), the UMa group (open squares) and the halo dwarfs(filled stars).

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The data for the halo stars in Figure 3 are only for those with velocities (relative to the local standard of rest) $\geq \pm$ 100 km s^{-1} and with [Fe/H] ≤ -1.4; the temperature and Li values are from Spite, Maillard, and Spite (1984), Spite and Spite (1986), and Hobbs and Duncan (1987). The Hyades values are from Boesgaard (1987b) and those for UMa from Boesgaard *et al.* (1988).

The complex Li–temperature profile found for F and G dwarfs in galactic clusters indicates that the internal stellar structure and processes are more complicated than had been recognized. Calculations of the internal circulation of matter (certainly of Li atoms) caused by stellar rotation, especially differential rotation, are needed as are more sophisticated calculations of the effects of diffusion in both young stars and in halo stars.

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DISCUSSION

SNEDEN Could you please expand on your points suggesting
a) a constancy in Li over the age of the galactic disk, and
b) the apparent depletion of Li in halo stars.

BOESGAARD The "initial" Li abundance, which all the stars in a cluster are born with, must be determined from the F dwarfs on the hot side of the Li dip in the mid-F dwarfs. These values -log N(Li)=3.0- are the same from cluster to cluster and the same as the T Tau stars and the solar system values. On the cool side of the Li dip, T=5800-6400 K, there seems to be only very weak dependance of Li on temperature ; the stars in the three clusters, Hyades, Coma, and UMa (with ages ~ $5x10^8$ yrs.) show depleted Li -log N(Li)=2.7. The older cluster, NGC 752 (with age ~ $2x10^9$ yrs.) shows -log N(Li)=2.4 in this temperature regime. The halo stars at log N(Li)=2.1 and age ~ $12x10^9$ yrs. may be showing a similar depletion with age in this temperature region.

F. SPITE First my congratulations for the beautiful work of Ann Boesgaard.
About the comparison of the flat part of clusters and of pop.II dwarfs : if it is expected to find a plateau with small scatter for a cluster, in which all stars have the same age and metallicity, it is more difficult to understand for pop.II dwarfs which may have the same age but widely different metallicities. And up to now, the theories of lithium depletion predict depletion rates dependent on metallicities.

BOESGAARD However, there does seem to be a real spread in the Li abundances at a given temperature in the halo stars. This indicates that some depletion may have occured. All the halo stars plotted have [Fe/H]<-1.4.

DUNCAN Comment on F. Spite's question.
I suggest waiting until this afternoon, when I will discuss if star to star variations are real, and the effect of [Fe/H] differences on Li destruction rate.

NISSEN There has also ben observation of Li in F stars in the old, open cluster M67 (Pilachowski et al., and Spite et al.). Do these results fit your Li - age relation for the plateau around $T_{eff} \approx$ 6000-6400 K ?

BOESGAARD The hottest main-sequence stars (late F dwarfs) left in M67 barely reach the plateau region. However, these authors have observed six stars in this temperature range with log N(Li) values all near 2.5.