DECAY OF LIGHT ELEMENTS IN STELLAR ENVELOPES

Ann Merchant Boesgaard
Institute for Astronomy, University of Hawaii

I should like to confine this discussion of the decay of the light elements to Li, Be, and B since the observations of D and He^3 in stars are not relevant to the decay in stellar envelopes. The light elements are trace constituents best observed in the resonance lines. Only Li I and Be II have resonance lines which can be studied from ground-based observations. Therefore we know the most about abundances in stars where these ions can be observed and how those abundances are affected by stellar evolution. I will first discuss the cosmic or initial abundances of Li, Be, and B to establish the "zero-point" from which the decay occurs. Then observations and interpretations relevant to the decay and to stellar evolution will be considered.

1. COSMIC OR INITIAL ABUNDANCES

Zappala (1972) determined the value for "initial" Li from a combination of observations of the Li content in T Tauri stars, young clusters (Hyades, Pleiades, NGC 2264), meteorites. His result, in the ratio of the number of atoms, is Li/H = 10^{-9} within a range of ± a factor of 2.

In a careful study of the solar Be abundance Chmielewski, Müller, and Brault (1975) find Be/H = 1.4×10^{-11} from high-resolution, center-and-limb observations and a non-LTE analysis. I have recently redetermined the Be abundance in 33 F and G dwarfs (Boesgaard 1976a). The observed Be II (λ3131) equivalent widths were compared with line strengths predicted from Carbon and Gingerich (1969) model atmospheres; values of effective temperature and gravity appropriate for each star were found from the Strömgren narrow-band photometric indices, Hα, c_1, b-y, as mentioned by Cayrel in his talk this morning. Figure 1 shows the Be/H values as a function of temperature. For 27 stars (including the sun) the average value Be/H is 1.3×10^{-11}; the range of values is ± a factor of 2. (I will discuss the 6 stars which appear depleted in Be in the next section about the decay of light elements.) The values

Edith A. Müller (ed.), Highlights of Astronomy, Vol. 4, Part II, 209-216. *All Rights Reserved.*

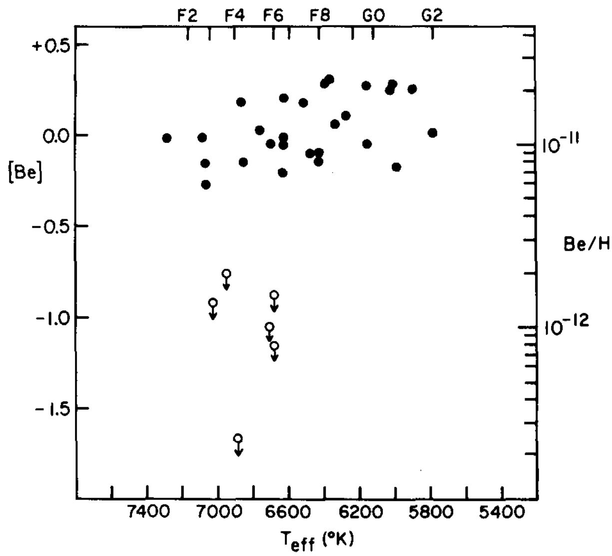

Figure 1. Be in F and G dwarfs.

of Be/H found in meteorites, the sun, and six Hyades dwarfs agree with the field-star average.

The resonance lines of B I are near 2500 Å and of B II at 1362 Å. New <u>Copernicus</u> observations at 0.05 Å resolution of B II have been made in Vega and Sirius by Praderie, Boesgaard, Milliard, and Pitois (1977). Figure 2 shows a sample of these spectra; the B II line is blended with V III in Vega while only the V III feature is present in Sirius. The analysis, including non-LTE effects, results in a ratio of B/H of 1.5×10^{-10}. Kohl, Parkinson, and Withbroe (1976) have made center-and-limb rocket observations of the B I resonance lines in the solar photosphere at a resolution of 0.03 Å. From spectrum synthesis they derive $B/H = 4 \times 10^{-10}$. The results for the sun and Vega are in approximate agreement, but B is depleted in Sirius.

In round numbers, the cosmic or initial abundances are: $Li/H = 10^{-9}$, $Be/H = 10^{-11}$, $B/H = 10^{-10}$.

2. LIGHT ELEMENT DECAY AND STELLAR EVOLUTION

The light elements are fragile and are destroyed by proton fusion at temperatures of $2\text{-}4 \times 10^{6}$ °K. The most fragile is Li, which forms 2 helium nuclei after fusion with a proton. Thus the light elements exist only in a thin outer region of the star where the temperature is $< 3 \times 10^{6}$ °K. For example, at the end of the main-sequence lifetime of a 1 solar-mass star, Li will remain only in the outer 2.5% (by mass) of the star, Be in the outer 4.8% and B in the outer 18%.

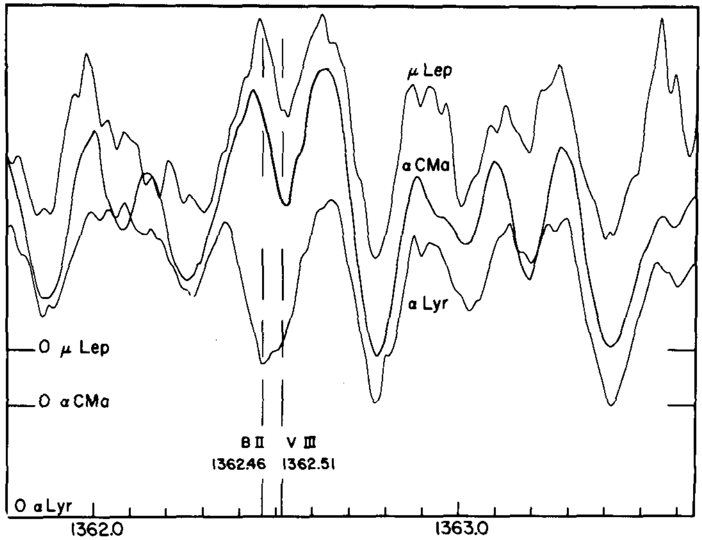

Figure 2. Copernicus observations for the B II resonance line.

To understand the destruction of light elements, it is necessary to know where the base of the convection zone is relative to the layer where the temperature is hot enough for destruction. If the temperature at the bottom of the convection zone is greater than the critical temperature for proton fusion, then Li, Be, and B will be depleted on the stellar surface.

During pre-main sequence evolution, low mass stars are fully-convective and according to calculations by Bodenheimer (1965) virtually all the Li will be destroyed in pre-main-sequence and main-sequence evolution in K and M dwarfs. Observations of the Li content in young stars by various workers (Zappala, 1972; Danziger, 1967; Catchpole, 1971) show that post-T Tauri/pre-main-sequence stars have 2-50 times less Li than the T Tauri stars.

For main-sequence stars Herbig (1965) has shown that the Li content is a function of both stellar mass and age: there is a range in Li at a given main-sequence spectral type and there is a decrease in the maximum Li content for stars of later spectral types. The correlation with age is in the sense that younger main-sequence stars have more Li. However, stellar and solar models indicate that the convective zones in F and G dwarfs are not deep enough to burn Li. Several ideas have been proposed to explain the observed Li depletion. The effect of a deeper convective zone can be achieved by convective overshoot, by rotational braking leading to turbulence below the convective zone, by diffusion of Li. Straus, Blake, and Schramm (1976) have recently rediscussed convective overshoot; they find that the amount of overshoot possible is greater for larger mass stars, i.e. F dwarfs could have more overshoot than G dwarfs. This is necessary to explain (1)

https://doi.org/10.1017/S1539299600003300 Published online by Cambridge University Press

why some F stars show no Li and (2) why there is a gradual, rather than rapid, decrease of Li with stellar mass. At an IAU colloquium on stellar ages, S. Vauclair (1972) showed that diffusion of Li below the convective zone could cause a slow depletion of Li in agreement with the observations.

Now there is an additional complication in the F and G dwarfs: Figure 1 shows a group of Be-deficient stars which are markedly separate from the group of stars with normal Be content. The six Be-deficient stars are all Li-deficient and all hotter than 6600 °K, but have no other similarities in age, metallicity, duplicity, position in the galaxy, etc. (see Boesgaard 1976a). The challenge is to find a mechanism(s) which can result in one-third of the hotter stars being deficient in both Be and Li, two-thirds of the hotter stars having Be but some with and some without Li, while all the cooler stars show Be. Clearly observations of both Li and Be in main-sequence stars are indicators of some aspects of internal stellar structure.

There is a second major mechanism of decay of Li, Be, and B which occurs in post-main-sequence evolution. The idea of dilution of the surface content of Li was first suggested by Iben (1965) to explain the Li content in the two $3M_\odot$ components of Capella. The stars leave the main-sequence with a thin outer shell which contains Li and virtually no outer convection zone; as they evolve to the red giant region of the HR diagram, the convective envelope deepens and spreads the Li throughout the convection zone. This results in a decrease of the surface Li even though the Li is not destroyed since the temperature at the bottom of the convective envelope is not high enough for nuclear burning of Li (or Be or B).

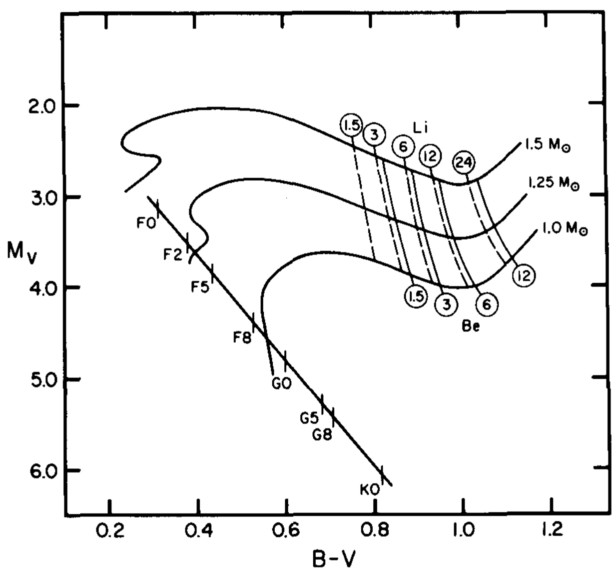

Figure 3. Curves of equal Li (--) and Be (—) dilution.

https://doi.org/10.1017/S1539299600003300 Published online by Cambridge University Press

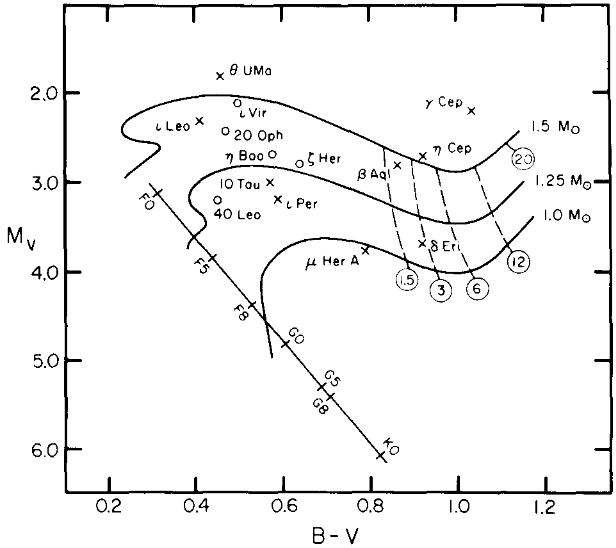

Figure 4. Subgiants observed for Be.

Figure 3 shows an HR diagram with curves of equal dilution of Li and of Be for stars in the 1-1.5 $M_\odot$ range (Boesgaard 1976b). Herbig and Wolff (1966) examined the Li content in a number of F and G subgiants, but unfortunately only one of their stars in the Li dilution region showed enough Li to give more than an upper limit on the Li abundance. In addition, the large range of Li values in main-sequence stars makes the interpretation of the Li content in evolved stars complicated. Boesgaard and Chesley (1976) have looked at the Be content in subgiants. Their results are shown in Figure 4. In the post-main sequence/pre-Be-dilution region there are stars with the main-sequence Be abundance (X in Figure 4) and some stars which are Be-deficient (O in Figure 4), the descendents of the main-sequence Be-deficient stars. Those stars in the Be-dilution region show less Be and less by the predicted amounts. This work appears to confirm that dilution of light elements does take place during post-main-sequence evolution and indicates some of the details of stellar structure and convective mixing.

Figure 5 shows an HR diagram for the Hyades where observations of Be in both dwarfs and giants have been made by Boesgaard, Heacox, and Conti (1977) and of Li in the dwarfs by Zappala (1972) and in the giants by Bonsack (1959). (The stars in which Be was observed are indicated by open circles; the points A, B, and C correspond to positions where the calculations of Li and Be dilution were made.) Relative to the dwarfs, Be is deficient in the giants by at least a factor of 30 and Li is deficient by about 180 times. Dilution alone can explain a deficiency of 25x for Be and only 60x for Li. An additional effect is needed to account for the larger observed deficiencies. The most probable explanation is mass loss. Both Li and Be are confined to a thin

https://doi.org/10.1017/S1539299600003300 Published online by Cambridge University Press

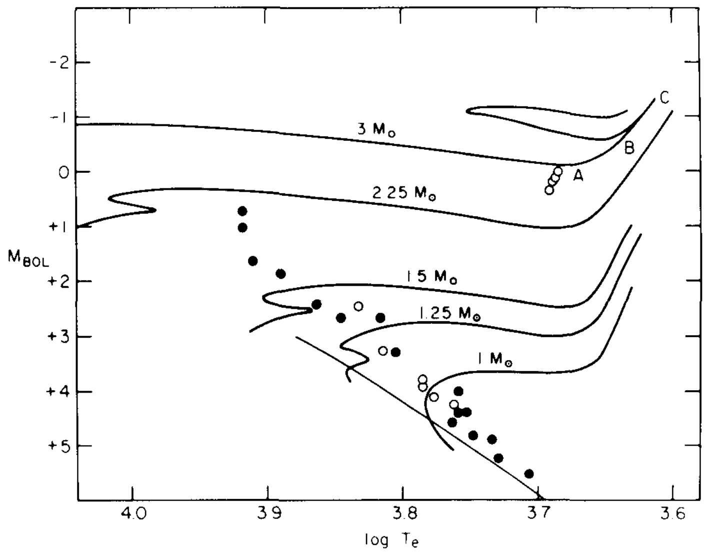

Figure 5. HR diagram for the Hyades.

outer shell. If 1% of the outer mass is lost it will increase the effect of the Li dilution by a factor of 2 (or 120x) and of the Be dilution by 20 percent. If the mass is lost on the main-sequence, the rate required is about 10^{-12} $M_\odot$/yr and if it is lost during post-main sequence evolution, it would be at the rate of about 10^{-9} - 10^{-10} $M_\odot$/yr. Such slow mass loss rates are not inconsistent with observations which show no evidence of circumstellar material.

Weak support for this slow mass loss is found in the observations of the Li content of field giant stars. Figure 6 shows the Li abundance as a function of surface temperature or spectral type for F, G, K, and M giants. (The arrowheads indicate upper limits.) There is a huge range in the Li content from cosmic Li/H of 10^{-9} to 10^{-13}. The stars represent a large range of masses and the Li contents reflect pre-main-sequence and main-sequence depletion, post-main-sequence dilution (with typical amounts being factors of 30-60) and mass loss effects. We see F giants with the cosmic Li abundance and F giants with little Li due to main-sequence depletion. We see M giants with the cosmic Li diluted by 60x and M giants showing cosmic Li down by a factor of 10^4 due to depletion by nuclear burning, dilution, and mass loss.

Decay of the light elements is caused by 1) nuclear destruction--including convective depletion, diffusion, convective overshoot, turbulence from rotational braking, meridional circulation and 2) dilution and 3) mass loss effects. The observations can be well understood in terms of these effects and give strong support for theoretical ideas on stellar structure and evolution.

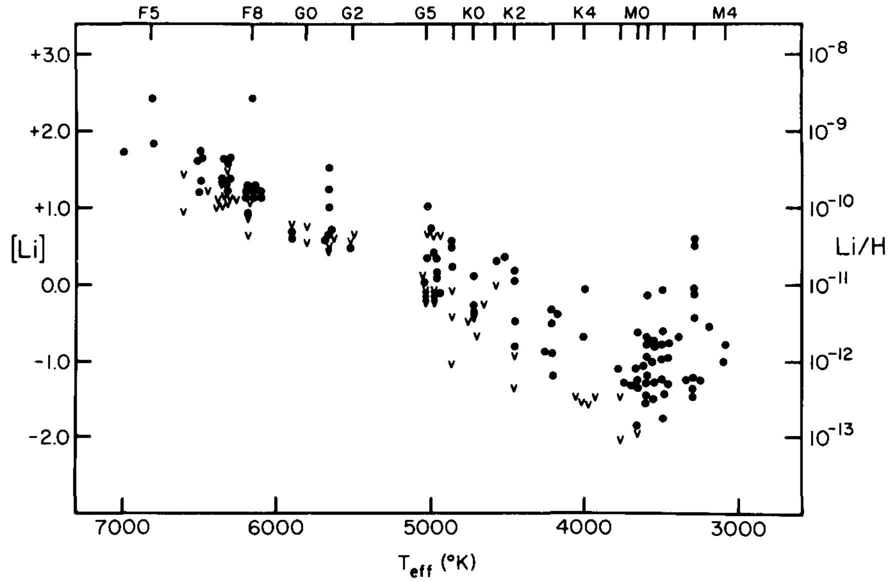

Figure 6. Li in giant stars.

REFERENCES

Bodenheimer, P.: 1965, Astrophys. J. 142, 451.

Boesgaard, A.M.: 1976a, Astrophys. J. 210, in press.

Boesgaard, A.M.: 1976b, Publ. Astron. Soc. Pacific 88, 353.

Boesgaard, A.M. and Chesley, S.E.: 1976, Astrophys. J. 210, in press.

Boesgaard, A.M., Heacox, W.D., and Conti, P.S.: 1977, Astrophys. J. in press.

Bonsack, W.K.: 1959, Astrophys. J. 130, 843.

Carbon, D. F. and Gingerich, O.C.: 1969, in Proceedings of the Third Harvard-Smithsonian Conference on Stellar Atmospheres, ed. O. Gingerich (Cambridge: MIT Press), p. 377.

Catchpole, R.M.: 1971, Monthly Notices Roy. Astron. Soc. 154, 15P.

Chmielewski, Y., Muller, E.A., and Brault, J.W.: 1975, Astron. Astrophys. 42, 37.

Danziger, I.J.: 1967, Astrophys. J. 150, 733.

Herbig, G.H.: 1965, Astrophys. J. 141, 588.

Herbig, G.H. and Wolff, R. J.: 1966, Annales d' Astrophys. 29, 593.

Iben, I., Jr.: 1965, Astrophys. J. 142, 1447.

Kohl, J.L., Parkinson, W.H., and Withbroe, G.L.: 1976, Astrophys. J. Letters, in press.

Praderie, F., Boesgaard, A.M., Milliard, B., and Pitois, M.L.: 1977, Astrophys. J., in press.

Straus, J.M., Blake, J. B. and Schramm, D. N.: 1976, Astrophys. J. 204, 481

Vauclair, S.: 1972, L'Age des Etoiles, I.A.U. Colloquium No. 17, G. Cayrel de Strobel and A.M. Deplace, eds. (Paris: Meudon Obs.), p. 38-1.

Zappala, R. R.: 1972, Astrophys. J. 172, 57.

Figures 1, 3, and 6 are reproduced through the courtesy of the Publications of the Astronomical Society of the Pacific.

Figures 4 and 5 are reprinted with permission of The Astrophysical Journal, published by the University of Chicago Press for the American Astronomical Society. Figure 4 is from a paper by A.M. Boesgaard and S.E. Chesley appearing in the Dec. 1, 1976 issue, and Figure 5 is from a paper by A.M. Boesgaard, W.D. Heacox, and P.S. Conti appearing in the May 15, 1977 issue.