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The Light Elements: Lithium, Beryllium, and Boron

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Abstract

A review of the rare light elements, Li, Be, and B, is presented. This includes a discussion of their origins, processes of destruction, and Galactic evolution. The basics of the determination of their abundances is also covered, which describes the observations, stellar parameter determinations, spectral synthesis, and associated errors. Highlights of some current observational results are presented.

1.1 Introduction

The rare light elements, lithium, beryllium, and boron, are extremely underabundant relative to their neighbors on the periodic table, light hydrogen and helium, and heavier carbon, nitrogen, and oxygen. Although Li, Be, and B are formed by nuclear fusion reactions inside stars at high temperatures, they are destroyed by other reactions at lower temperatures, i.e. closer to the stellar surface. Therefore, a method other than stellar nucleosynthesis is needed to form them. In the breath-taking paper on the origin of the elements, Burbidge, Burbidge, Fowler, & Hoyle (1957) covered the nucleosynthesis of elements by various processes, but called the process for forming ^{2}H, Li, Be, and B the x-process, where "x" was for "unknown." If these elements cannot be formed by fusing smaller nuclei together, then the alternative formation mechanism is by splitting heavier nuclei into smaller pieces. The idea of spallation was invented by Reeves, Fowler, & Hoyle (1970), and details were described by Meneguzzi, Audouze, & Reeves (1971). The basic process is that high-energy ($\sim$150 MeV) protons and neutrons bombard interstellar nuclei of C, N, and O, creating lighter isotopes. It has also been suggested that the "bullets" and the "targets" might be reversed near supernovae, where C, N, and O nuclei could be accelerated into the ambient interstellar gas including protons and neutrons (see, for example, Duncan et al. 1997, 1998; Lemoine, Vangioni-Flam, & Cassé 1998).

The easiest of the three light elements to observe is Li, and spectroscopic observations of Li have been made in a large array of stars of various ages and metallicities throughout the Hertzsprung-Russell diagram, as well as in the interstellar gas. In recent years there have been typically 100 papers a year with lithium in the title, a testament to the usefulness of the abundance of this one element. Due to the atomic and spectroscopic properties of Be and B, they have been less extensively observed. However, information on all three elements complement and supplement each other and can illuminate several issues of astrophysical interest.

In the study of light elements, the results are most often presented as plots of the light element abundance as a function of metallicity, [Fe/H], or as a function of stellar effective temperature, $T_{\rm eff}$. This provides an important context through which we can derive the astrophysical interpretation. In some circumstances, the abundance of one light element can be plotted against another to elucidate the processes at work in stellar interiors.

This review presents an overview of the origin of the light elements and their destruction in stars, the basics of light-element observations and analyses, and some recent results.

1.2 Origins and Current Observational Status

1.2.1 Lithium

The element Li can be formed by several different processes. The original source is through the nuclear reactions that occur during the first 10^3 s after the Big Bang while the temperature is $> 5 \times 10^8$ K. Two different reactions produce the isotope ^{7}Li: ^{4}He(^{3}H,γ)^{7}Li and ^{4}He(^{3}He,γ)^{7}Be, where the ^{7}Be captures an electron to become ^{7}Li.

As discussed in the first section, another major source of Li results from spallation reactions between energetic cosmic rays and abundant atoms such as C, N, and O in the interstellar gas, as first proposed by Reeves et al. (1970). These reactions could take place in the ambient interstellar gas and in the vicinity of supernovae where energetic CNO nuclei as well as energetic protons would be found. Cosmic ray interactions can also result in $\alpha + \alpha$ production, leading to Li atoms (Steigman & Walker 1992; Prantzos, Cassé, & Vangioni-Flam 1993; Ramaty, Kozlovsky, & Lingenfelter 1996).

A potentially interesting source of ^{7}Li is the ν-process in Type II supernovae (Woosley et al. 1990; Timmes, Woosley, & Weaver 1995). Neutrino irradiation gives rise to both ^{7}Li and ^{7}Be primarily in the He shell. Most is destroyed subsequently, and an evaluation of the contribution to Li by this mechanism may come from the observations of ^{11}B, which is similarly produced (Woosley & Weaver 1995), along with those of ^{7}Li. Most models produce 2–5 times more B than Li. The models do not produce ^{6}Li, ^{9}Be, or ^{10}B.

Another possibility is that the light elements could be produced in hypernovae and in superbubbles (e.g., Parizot & Drury 1999; Parizot 2000). In order not to overproduce Li, Be, and B a limit of three hypernovae for every 100 supernovae has been set by Fields et al. (2002).

It was suggested by Cameron (1955) and discussed by Cameron & Fowler (1971) that freshly synthesized Li could be found on the stellar surface of red giant stars if it had been preserved as ^{7}Be long enough to rise to the surface before capturing an electron to become ^{7}Li. The ^{7}Be would be transported by convection to temperatures cooler than the Li destruction temperature. The reaction ^{3}He(α,γ)^{7}Be would occur at temperatures hotter than 10^7 K, and the reaction ^{7}Be($e^-\nu$)^{7}Li at temperatures cooler than 3×10^6 K. This mechanism was proposed to account for the high Li content in a few S and C stars. More observational evidence of high Li in asymptotic giant branch stars has been presented by Smith & Lambert (1990) and Smith et al. (1995) and attributed to the ^{7}Be transport method with hot-bottom convective envelope burning. However, this is not thought by Romano et al. (2001) to be an important contributor to Li in disk stars. For a review of Li production in asymptotic giant branch and red giant branch stars, see Sackmann & Boothroyd (2000). Another possible site for Li production is in novae (e.g., Hernanz et al. 1996; Romano, et al. 1999).

Abundances of Li have been plotted against metallicity ([Fe/H]) for both disk stars and

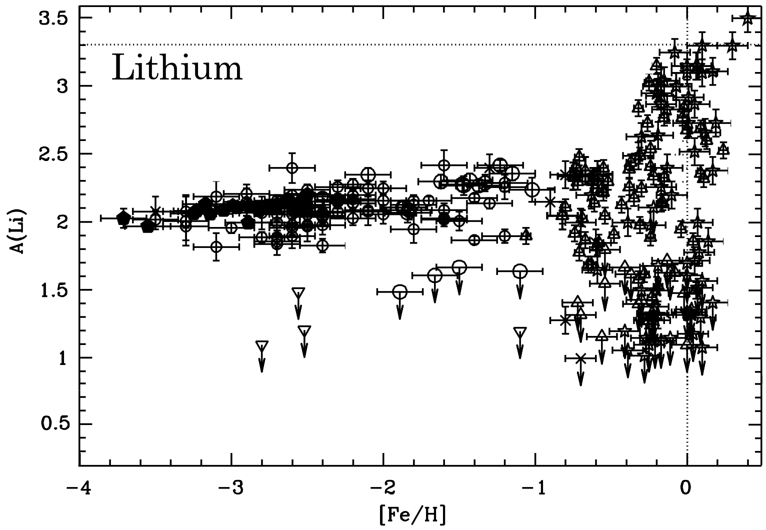

Fig. 1.1. Lithium abundances vs. [Fe/H], adapted from Ryan et al. (2001); see that paper for the original references and for the definition of the symbols. This sample includes stars hotter than 5600 K. The horizontal dotted line represents the meteoritic Li abundances, A(Li) = 3.31. The x- and y-axis scales for this and the next three figures are the same.

halo stars. Figure 1.1 shows a composite diagram adapted from Ryan et al. (2001) and includes main sequence and turn-off stars with temperatures $>$ 5600 K. (Unfortunately, it does not include the results of the 2001 work on 185 main sequence stars by Chen et al. 2001, which was published after the Ryan et al. 2001 paper.) The Li abundances are given as A(Li) = log N(Li/H) +12.00; this same notation is used for Be and B throughout. There are several features of note on this diagram. First is the apparent plateau in A(Li) at low metallicities, which is attributed to the production of Li during the Big Bang. (Controversy exists over the actual value of primordial Li deduced from this, whether there is a metallicity dependent slope, whether there is a dispersion in the plateau, whether there is depletion in the plateau stars, etc.) Secondly, there are several stars at low metallicities with low upper limits on the Li abundances. This is discussed in §1.5. Thirdly, stars near solar metallicity show an order of magnitude more Li than the plateau. And fourthly, there is a large range in A(Li). The Li-rich disk stars are preferentially younger and hotter main sequence stars (excluding Li-dip stars), while the disk stars with lower A(Li) are thought to have had their surface Li depleted via mixing of the photospheric material down to temperatures where Li is destroyed. For the coolest stars (only) this mixing can be done by the surface convection zone; other mixing mechanisms are needed for hotter stars. The rise in A(Li) that occurs between [Fe/H] = −0.4 and −0.2 is too steep to be explained by Galactic cosmic ray spallation production of Li. There is an apparent deficit of stars having high Li abundances with [Fe/H] between −1.0 and −0.4; this could be due to sampling bias or effective Li depletion from higher initial Li (also see Romano et al. 1999).

Another observational view of Li in halo stars comes from recent work on Li in globular cluster turn-off stars. Such stars are faint (V = 16 − 18 mag), and this work can only be done

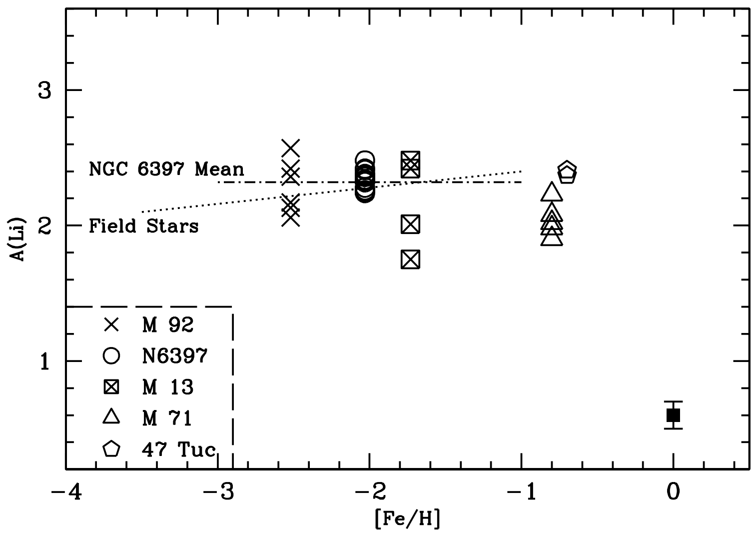

Fig. 1.2. Lithium abundances vs. [Fe/H] in globular cluster turn-off stars. The M92 results are from Boesgaard et al. (1998a), M13 and M71 are from Boesgaard et al. (2000), NGC 6397 from Bonifacio et al. (2002), and 47 Tuc from Pasquini & Molaro (1997). A typical error bar is shown in the lower right. The dot-dash line shows the mean found by Bonifacio et al. for NGC 6397, A(Li) = 2.32. The dotted line corresponds to the relation given for halo field stars by Ryan et al. (2001).

at high spectral resolution on the world's largest telescopes. Figure 1.2 shows the results for four globular clusters as a function of the Fe abundance for each cluster. These results are from Boesgaard et al. (1998a) for M92, Boesgaard et al. (2001) for M13 and M71 from Keck, from Bonifacio et al. (2002) for NGC 6397 from VLT, and Pasquini & Molaro (1997) for 47 Tuc. Bonifacio et al. (2002) conclude that their stars could all have the same Li abundance. However, for identical stars in M92 and M13 Boesgaard and colleagues find real star-to-star differences in the equivalent widths of the Li line, but not in the lines of any other elements. The red giants in globular clusters are very different from the turn-off stars in their Li content. Kraft et al. (1999) found one Li-rich red giant in the globular cluster M3, with A(Li) = 3.0; this star is thought to be ascending the red giant branch for the first time. Following this, Pilachowski et al. (2000) surveyed 261 giants in four globular clusters: M3, M13, M15, and M92. They found no other Li-rich giants, indicating that the percentage of Li-rich globular cluster giants is $<1\%$.

1.2.2 Beryllium

The dominant, and perhaps only, method for the production of ^{9}Be is by Galactic cosmic ray spallation, albeit through a modified and expanded version of the original work of Reeves et al. (1970). Ramaty, Lingenfelter, & Kozlovsky (2000; see also Ramaty & Lingenfelter 1999) describe and discuss the three modern models for spallation. There is also the possibility of production of Be in hypernovae, mentioned above for Li.

Figure 1.3 is similar to Figure 1.1, but plots A(Be) against [Fe/H] for halo and disk stars. The data are from a number of different papers but the figure presents a good overview (see

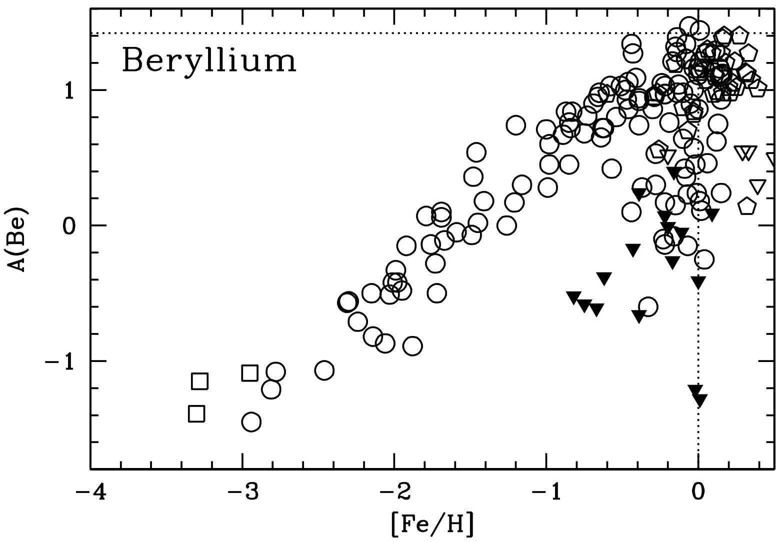

Fig. 1.3. Be abundances vs. [Fe/H]. Open circles and filled triangles (upper limits) are from Stephens et al. (1997), Boesgaard et al. (1999, 2001), and Boesgaard (2000). Open squares (low-metallicity stars) are from Primas et al. (2000a, b). The open pentagons and triangles (upper limits) are from Santos et al. (2002). The horizontal dotted line is the meteoritic Be abundance, A(Be) = 1.42.

references in the figure caption). The increase in A(Be) with [Fe/H] is obvious, and the slope of the relationship from [Fe/H] ≈ -3.0 to ~ -1.0 is close to 1. At the low-metallicity end there may be a flattening toward a plateau in A(Be). The lowest-metallicity stars are preferentially the faintest, so those observations are the most difficult and time-consuming; observations are needed of Be in more stars with [Fe/H] <-3.0. It is useful to plot A(Be) vs. [O/H] (which has a steeper slope), as done by Boesgaard et al. (1999), to elucidate Galactic evolution of Be and to investigate details of spallation of Be. King (2001) has examined the Be and B evolution via comparisons with other α-elements, Mg and Ca, finding slopes between 1.1 and 1.3.

The error bars given in the original papers indicate that there may be a real spread in A(Be) at a given [Fe/H] in the halo stars. This could result from differing degrees of efficiency in the formation of Be by spallation in different parts of the Galaxy.

For some stars with [Fe/H] >-1.0 there are Be deficiencies, including some with measured Be abundances down by 2 orders of magnitude from the meteoritic A(Be). There is a large clustering of data points with A(Be) between 1.0 and 1.4 dex near solar metallicity. It is therefore difficult to disentangle the general increase of A(Be) with [Fe/H] in the disk stars from the spread due to some minor depletion. The upper envelope of data points seems to keep increasing; however, a flattening of the slope or a gentle curvature is possible.

1.2.3 Boron

The major source of B is Galactic cosmic ray production, in the various ways discussed by Ramaty et al. (2000), Ramaty & Lingenfelter (1999), and references therein. And, as with Li, the ν-process in supernovae can potentially produce ^{11}B. (For a review of this

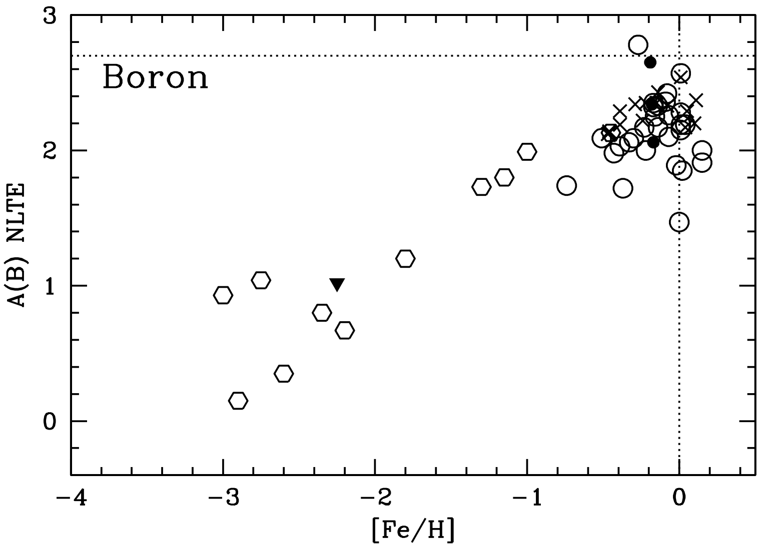

Fig. 1.4. Boron abundances from B I vs. [Fe/H]. The hexagons and the upper limit triangle are from Duncan et al. (1997, 1998), Primas et al. (1999), and García López et al. (1998); the crosses are from Boesgaard et al. (2004); the open circles are from Boesgaard et al. (1998b) and from new *HST* observations of Deliyannis et al. (in preparation); the solid circles are from Cunha et al. (2000). The horizontal dotted line is the meteoritic B abundance, A(B) = 2.70.

with emphasis on B, see Hartmann et al. 1999.) Perhaps B could be produced by hypernovae along with Li and Be.

The trend of B with Fe (from B I observations only) is shown in Figure 1.4, which is on the same scale and similar to Figures 1.1 and 1.3 for Li and Be. These observations are all from *HST* so there are fewer B data points than Be points, and far fewer than Li. The local thermodynamic equilibrium (LTE) abundances have been corrected for non-LTE (NLTE) effects from the work of Kiselman & Carlsson (1996). An increase in A(B) with [Fe/H] can be seen in the halo stars, which is similar to the trend of Be with Fe. The slope of B vs. Fe in NLTE appears not to be as steep as the slope for Be vs. Fe, although the slope from the LTE results is very similar for both B and Be. There are two stars near [Fe/H] = −3 with $A(B)_{NLTE}$ near 1.0. The values of $A(B)_{LTE}$ for those two stars are near 0.0, which makes them consistent with the other stars in the LTE version of Figure 1.4. In LTE the slope is near 1.0, while in NLTE it is near 0.7 (Duncan et al. 1997). If the slopes for Be and Be are identical (as they are in LTE), this implies a common origin for the two elements. A shallower slope for B might imply that the ν-process is an important source for B.

As in Figure 1.3 for Be, the stars with [Fe/H] $>$ 0.6 show a spread, possibly resulting from depletion of B in some of the stars. The points marked by crosses are stars that are undepleted in Be and thus expected to be undepleted in B. These stars lie along the upper envelope of the Be-Fe and the B-Fe relation (Boesgaard et al. 2004). Relative to those stars there are some half dozen stars that seem genuinely deficient in B by factors of 5 or more.

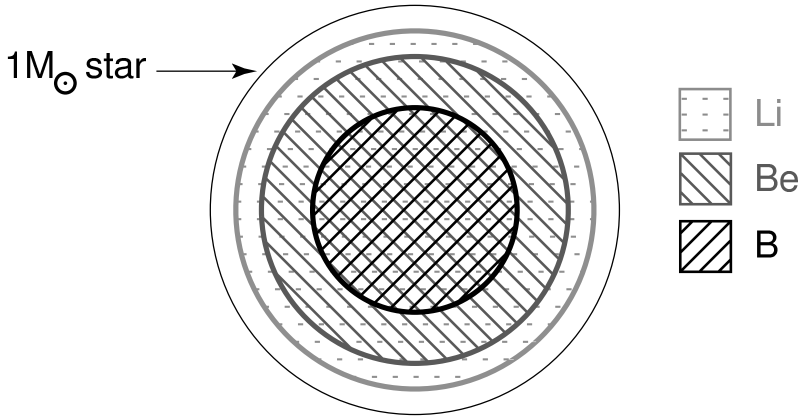

Fig. 1.5. One-solar mass model showing the region where all the Li has been destroyed, a smaller sphere where there is no Be, and a still smaller one that is devoid of B.

1.3 The Destruction of Li, Be, and B

All three light elements are susceptible to destruction in stellar interiors by nuclear reactions; some of these reactions are of the type (p,α), (p,γ), (α,n), and (α,γ). The dominant ones cause Li to be destroyed at temperatures of 2.5×10^6 K and higher, Be at 3.5×10^6 K and higher, and B at 5×10^6 K and higher. This leaves regions in the stellar interior that are deficient in Li, Be, and B. For a model one-solar mass star, only the outer shell of 2.5% by mass contains Li, only the outer 5% contains Be, while the outer $\sim$18% has B. This is illustrated in Figure 1.5 in a not-to-scale cross-section of the Sun.

The light elements can be circulated by various mixing mechanisms to the stellar interior—down to the temperatures where they are fused into other nuclear products. Among the most common proposed mechanisms are convection, microscopic diffusion, instabilities related to rotation, turbulence, gravity waves, and meridional circulation. In addition, sufficient surface mass loss can rid a star of the surface layer where the light element had been preserved. In that case the star would first lose all its Li, then all its Be, and finally all its B (if it lost $\sim$20% of its total mass).

For in-depth discussions of the destruction of light elements, see Deliyannis, Pinsonneault, & Charbonnel (2000), Pinsonneault, Charbonnel, & Deliyannis (2000), and Charbonnel, Deliyannis, & Pinsonneault (2000).

1.4 Abundance Determinations

1.4.1 Observations

Inasmuch as the abundances of the light elements are low, they are best observed in their respective resonance lines. For Li this is the resonance doublet of Li I λ6707, a ^2S–$^2P^0$ transition. The ionization potential of Li I is low at 5.39 eV, so Li is almost completely ionized in the photospheres of the stars we observe. However, the resonance line of Li II (a He-like atom) is at 199 Å, and the subordinate lines of Li II have extremely high excitation potentials. In some conditions a subordinate line of Li I λ6104 can be observed.

The most commonly observed Be features are the resonance lines of Be II, which has the same doublet structure as Li I, a $^2S - ^2P^0$ transition. These lines are in the ultraviolet just longward of the atmospheric cut-off: λ3130 and λ3131. For solar temperature stars and hotter, Be II is the dominant ionization state.

Three ionization states, B I, B II, and B III, can be used in the study of B abundances, depending on the stellar temperature. Neutral B is the dominant ion in solar-like stars, B II in A stars, and B III in hotter stars. All of the resonance lines are in the space ultraviolet, with B I λ2497, B II λ1362, and B III λ2066. The *Copernicus* satellite was used for early work on B II, some B results came from *IUE*, and *HST* is used for current observations of B I and B III.

1.4.2 Stellar Parameters and Abundance Determinations

The determination of the stellar parameters—effective temperature ($T_{\rm eff}$), surface gravity (log g), metallicity ([Fe/H]), and microturbulent velocity (ξ)—is important in deriving the correct abundances. Temperatures usually come from one or multiple color indices or Balmer-line determinations (e.g., Fuhrmann, Axer, & Gehren 1994). Values of log g can come from ionization balance or from *Hipparcos* data, along with other fundamental stellar properties. Metallicities are typically from spectroscopic studies, but may come from photometric and spectroscopic indices. Some empirical calibrations can yield microturbulent velocities (e.g., Edvardsson et al. 1993).

Associated with the errors in each of these parameters are abundance errors. The commonly used spectral features for each of the three elements Li, Be, and B have different sensitivities to different parameters. For F and G dwarfs, for example, the Li abundance from Li I λ6707 is sensitive to $T_{\rm eff}$, but insensitive to log g and [Fe/H]. A change of +100 K in temperature gives +0.09 dex in A(Li), while a change of 0.5 in log g is $<$0.01 dex, and a change in [Fe/H] of 0.10 is only 0.02 dex.

The Be II features are more sensitive to changes in log g than in temperature in the 5500–6500 K range where Be goes from dominant Be I to Be II. A change of +100 K results in a change of only +0.01 dex in A(Be), but a change in log g of 0.2 gives a change in A(Be) of 0.07 to 0.10, increasing with decreasing temperature. For Be an increase in [Fe/H] of +0.10 gives an increase in A(Be) of 0.04 dex near solar metallicities.

For the B I λ2497 resonance line, the abundance of B is sensitive to temperature, gravity and metallicity. For 100 K in $T_{\rm eff}$ the value of A(B) changes by 0.10 dex; for a change in log g of 0.2 there is a change in A(B) of 0.10 dex; a change in [Fe/H] of 0.10 results in a change in A(B) of 0.03 dex.

There can be small differences in the abundances due to the class of models used (e.g., Kurucz vs. OSMARCS). The potential effects of three-dimensional hydrodynamical vs. one-dimensional models are still being investigated (see, for example, Asplund et al. 1999; Asplund 2000). In addition, there can be differences in the abundances derived in LTE compared to NLTE. Calculations to make corrections for these effects have been done for Li by Carlsson et al. (1994) and for B by Kiselman (1994) and Kiselman & Carlsson (1996). Interestingly, the effects due to NLTE cancel out for Be (García López, Severino, & Gomez 1995; Kiselman & Carlsson 1995).

1.4.3 Spectrum Synthesis to Derive Abundances

Early work and some current work on Li and Be involved determining abundances from measured equivalent widths of Li I λ6707 and Be II λ3131. With more sophisticated

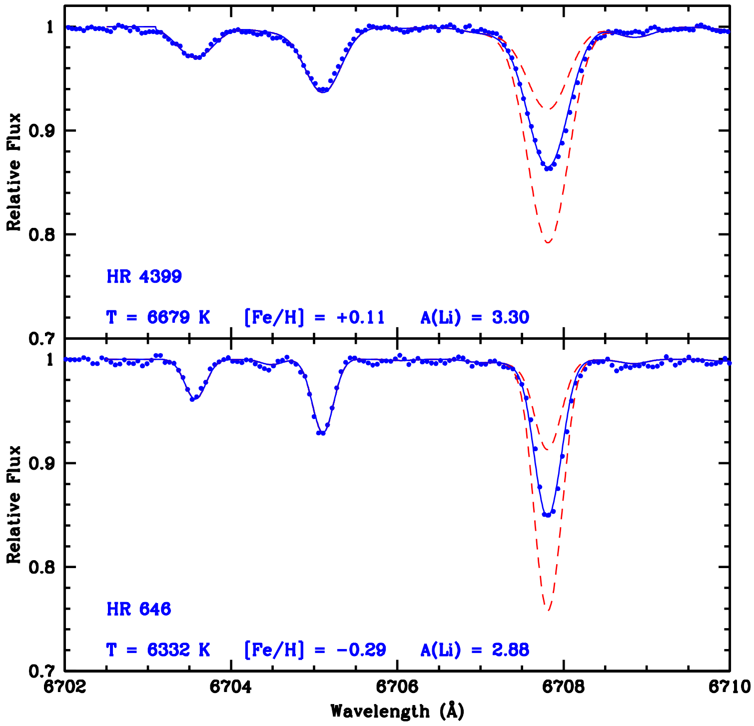

Fig. 1.6. Spectrum synthesis fits for the region of the Li I resonance doublet in two stars. The observed points are the dots from a Keck I HIRES spectrum of HR 4399 (*upper panel*) and from a McDonald spectrum of HR 646 from the 107-in telescope with the coudé cross-dispersed echelle spectrograph (*lower panel*). The solid line represents the best fit for Li abundance, while the dashed lines are a factor of 2 higher and lower in A(Li). The stellar parameters and Li abundances are given for each star. (Adapted from Boesgaard et al. 2004.)

routines such as MOOG (Sneden 1973) and SYNTHE (Kurucz 1993) spectrum synthesis methods can be used readily now. Examples of synthesized spectra for all three elements are given in Figures 1.6–1.8, adapted from Boesgaard et al. (2004). They show observed spectra and synthetic fits for three different abundances for two stars for each element. This technique is especially important for the badly blended features of Be II and B I. The Li doublet is blended and has hyperfine structure; it is therefore asymmetric, so the synthesis technique is preferable for the analysis of this element also.

1.5 Some Recent Results on Li

In the past five years there have been over 500 papers, reviews, and conference proceedings on the topic of lithium. A complete review is not possible, so only a few results are presented here. In IAU Symposium 198, "The Light Elements and their Evolution" (da Silva, de Medeiros, & Spite 2000) a section on lithium abundances is 131 pages long, and lithium appears throughout the 590-page volume.

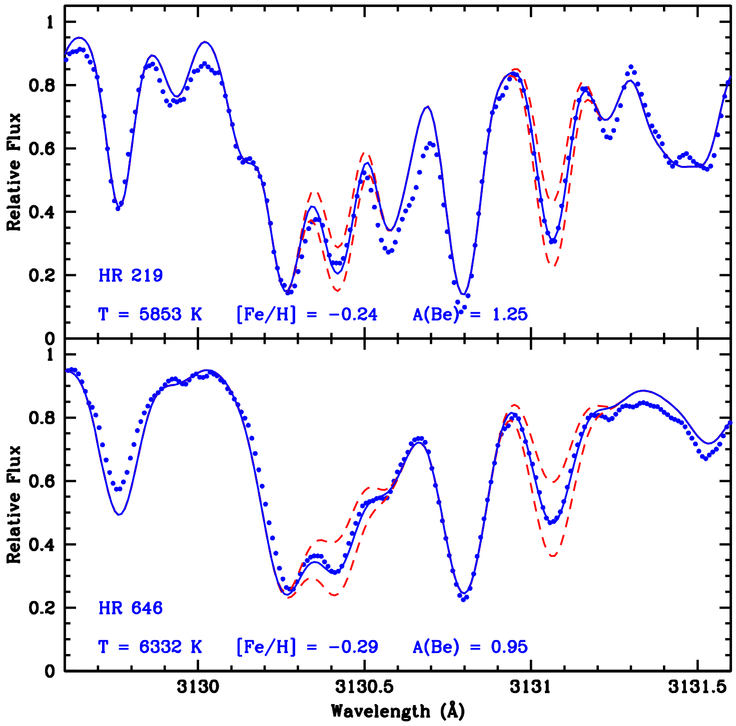

Fig. 1.7. Spectrum synthesis fits for the resonance doublet of Be II for two stars observed with CFHT and the gecko spectrograph. The dots are the observations, and the solid line represents the best fit for the Be abundance. The dashed lines are a factor of 2 higher and lower in Be abundance. The stellar parameters and Be abundances are given for each star. These two stars have similar metallicities, but differ in Be abundance by a factor of 2. (Adapted from Boesgaard et al. 2004.)

1.5.1 A Second Li Feature

Most of the abundance work on Li has been done on the Li I λ6707 resonance doublet. The Li I λ6104 subordinate line was detected in red giant stars by Merchant (1967) and Wallerstein & Sneden (1982). It was found by Duncan (1991) to give a more reliable Li abundance than Li I λ6707 in the T Tauri star BP Tau. The line is weak and appears at the long wavelength edge of a blend of Fe I, Ca I, and Fe I. This feature was detected in the metal-poor halo star, HD 140283, by Bonifacio & Molaro (1998). This star has [Fe/H] = −2.5, so the other lines in the blend are very weak. They derive a similar Li abundance from the resonance line and from the subordinate line, which is formed at deeper layers in the stellar atmosphere.

More recently, Ford et al. (2002a) studied the Li I λ6104 triplet feature in several halo stars. They have firm detections in seven of their 14 stars. The Li abundances determined from the λ6104 feature are slightly higher than those from the resonance line. However, the abundances found provide a good confirmation of the presence and abundances of Li from

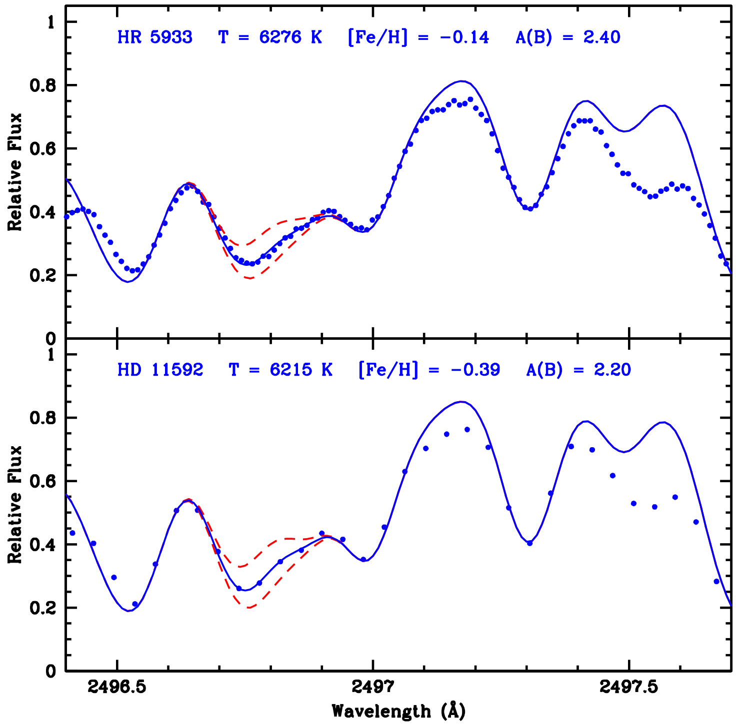

Fig. 1.8. Spectrum synthesis of B for two stars observed with *HST* and STIS. The star in the upper panel, HR 5933, was observed at high resolution and that in the lower panel, HD 11592, was observed at medium resolution. The dots are the observations. The solid line is the best fit, while the dashed lines are a factor of 2 higher and lower in B abundance. The stellar parameters and B abundances are given for each star. These stars have similar temperatures, but HD 11592 is lower in metallicity and in B. (Adapted from Boesgaard et al. 2004.)

the λ6707 doublet. In a similar study Ford, Jeffries, & Smalley (2002b) used the spectrum synthesis technique to determine Li abundances from both λ6707 and λ6104 in several cool Pleiades stars. Of the 11 stars four had detectable Li features at 6104 Å, four had marginal detections, and in three λ6104 was undetectable. The four definite detections gave A(Li) values higher on average by 0.42 dex compared to A(Li) from λ6707. They discuss possible causes of this difference, including the use of one-dimensional model atmospheres and the presence of star spots in these young stars.

1.5.2 Li-poor Halo Stars

As can be seen in Figure 1.1 there are some stars with [Fe/H] < -1.0 that have upper limits only on A(Li); the upper limits indicate Li depletions, as they are clearly outliers in the plateau distribution, having abundances only half (or less) the plateau value. Ryan et al. (2002) propose that these stars are the halo field star counterpart to globular cluster blue stragglers. In their sample of 18 stars the Li-normal stars have sharp lines, while three of the four Li-poor stars have rotational broadening and are spectroscopic binaries. They suggest that there has been mass and angular momentum transfer and that the Li was destroyed before or during the transfer of mass. A similar phenomenon was found by Pritchett & Glaspey (1991) in their study of Li in blue stragglers in the old open cluster M67: the blue stragglers have no detectable Li. They suggest that blue stragglers are caused by binary mergers, mass transfer, or deep mixing.

An interesting suggestion for the Li-poor halo stars comes from Pinsonneault et al. (2002) who suggest that the strongly Li-depleted stars belong to a very small subset of very rapidly rotating stars. The Li depletion results from rotationally induced mixing, which destroys more Li in these rapid rotators. Similarly, the spread in Li in the globular clusters shown in Figure 1.2 could be due to a spread in initial rotation, as suggested by Boesgaard et al. (1998a).

1.5.3 New Li Cluster Work

The study of Li in open clusters dates to the major paper on Li by Herbig in 1965, where several cluster stars are included along with field stars. In 1965 the paper by Wallerstein, Herbig, & Conti focuses on Li in the main sequence Hyades stars. They showed clearly the drop-off in Li with cooler surface temperatures in the G dwarfs. For some F dwarfs they could determine only Li upper limits; in retrospect, this was the first prognostication of the now well-studied Li gap in cluster F stars, first revealed by Boesgaard & Tripicco (1986) in the Hyades some 20 years later. Several subsequent studies of the Hyades have resulted in the Li-temperature profile shown in Figure 1.9. Subsequently, there have been Li studies in several other open clusters; this literature is too plentiful to review here, and instead only two recent cluster Li papers will be mentioned.

Jeffries et al. (2002) have determined Li abundances in 29 F, G, and K dwarfs in NGC 6633, a slightly metal-poor open cluster ([Fe/H] = -0.10 ± 0.08) with an age similar to the Hyades. They make careful comparisons with four other young clusters and find that the mid-F stars have Li depletions similar to those at the same temperature in the Hyades (see Fig. 1.9), Praesepe, and Coma Ber. The cooler stars (late-G and K dwarfs) show less Li depletion than the Hyades stars of similar temperatures but similar depletions with respect to the Coma cluster stars of similar metallicity to NGC 6633. They suggest that the severity of the Li destruction in the coolest stars may be related to metallicity. One of the stars they observed in NGC 6633 is extraordinarily rich in Li. It is a *bona fide* member of the cluster with an effective temperature of 7086 ± 85 K. Deliyannis, Steinhauer, & Jeffries (2002) derive A(Li) = 4.29 ± 0.07 for J37 and suggest that this overabundance of Li results from radiatively driven upward diffusion, as predicted by Richer & Michaud (1993).

Randich, Sestito, & Pallavicini (2003) have found Li abundances for 11 G dwarfs in the oldest open cluster, NGC 188; three of the stars were also in the eight-star sample of Hobbs & Pilachowski (1988). They compare their results from NGC 188 with an age of 6–8 Gyr with those from M67 at 4–5 Gyr and the Hyades at 700 Myr. The Li depletions are only slightly larger than those in the Hyades. For the early-G stars they are similar to the upper envelope for M67, but do not decline as much toward cooler temperatures. They suggest some explanations for these results, including different initial Li abundance in different clusters, different Li depletions rates, and a cessation in Li depletion after an age of $\sim$2 Gyr.

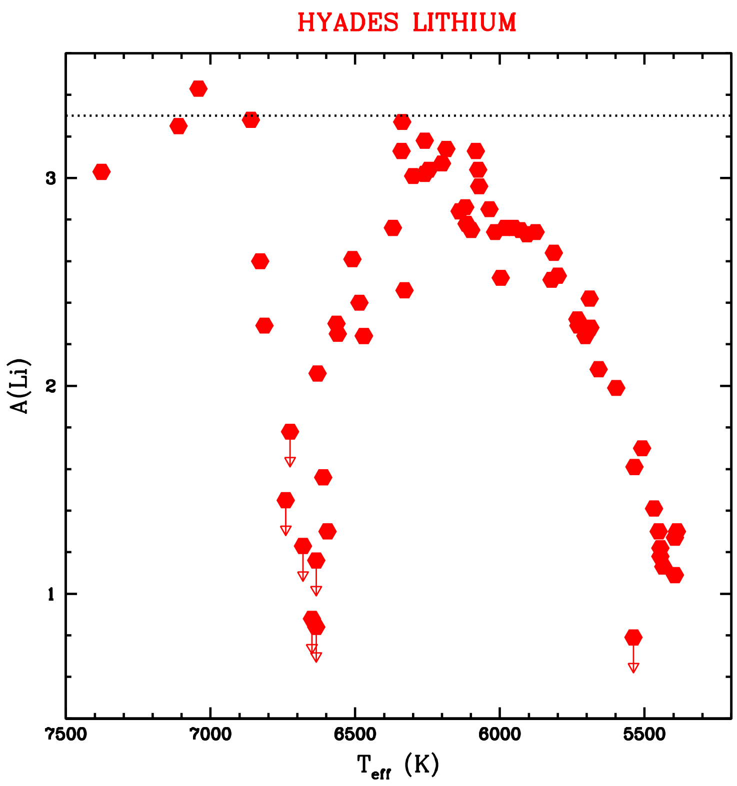

Fig. 1.9. Abundances of Li vs. temperature in the Hyades, showing the Li gap between $\sim 6450-6850$ K and the steep drop in A(Li) with decreasing temperature below 6000 K. The data are from Boesgaard & Budge (1988) and Thorburn et al. (1993).

1.5.4 Summary

Interesting new Li results continue to appear on a range of topics. The problem of low-metal stars with very depleted Li appears to be solved by the work of Ryan et al. (2002) who suggest that they are rotating binaries and the low-mass counterparts of blue stragglers.

New work has been done to determine Li abundances from the subordinate Li feature λ6104. In general, reasonable agreement is found with A(Li) from λ6707, but in some cases λ6104 gives values higher by 0.5 dex.

There are new Li results in open clusters. In a large study of the properties of NGC 6633, Jeffries et al. (2002) compare the results from this Hyades-age cluster with those from several other young clusters and discuss the differences and similarities. One early-F star in that cluster has A(Li) an order of magnitude larger than the meteoritic value, possibly caused by upward diffusion.

The Li results for the old open cluster NGC 188 show less depletion and less scatter than the slightly younger M67 in the G dwarfs. The amount of depletion is only slightly greater than the much younger Hyades. Randich et al. (2003) discuss the implications of those findings.

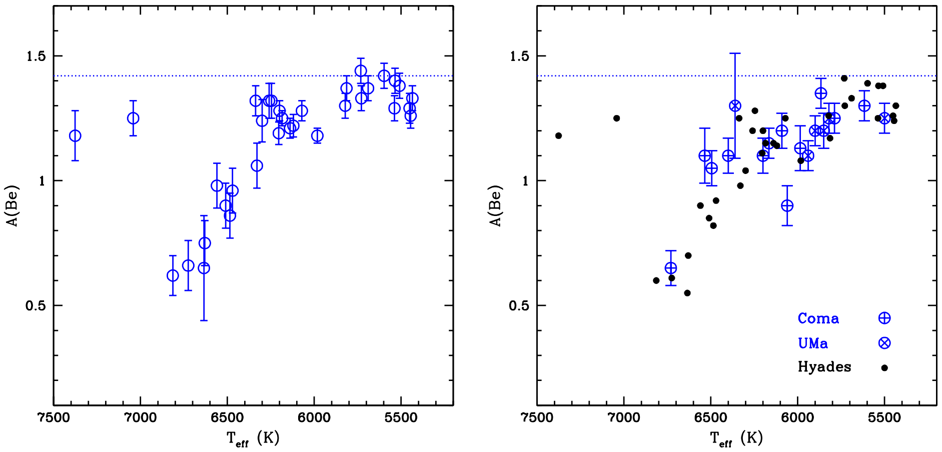

Fig. 1.10. *Left panel:* The Be dip in the Hyades, adapted from Boesgaard & King (2002). *Right panel:* The Be dip in Coma and UMa clusters shown with the Hyades data from Boesgaard et al. (2003b).

1.6 Some Recent Results on Be

1.6.1 Halo Be

As shown in Figure 1.3 there are only a few Be detections in stars with [Fe/H] values as low as −3.0. Three of these are new observations from the VLT with UVES (Primas et al. 2000a, b). The trend shown in Figure 1.4 of Boesgaard (2000) was an ever-decreasing A(Be) with decreasing [Fe/H]. The three new points change this perspective. There is the possibility that the slope is shallower than it seemed in the earlier data. Or possibly there is a plateau in A(Be) near −1.3. This would not necessarily imply the formation of Be by inhomogeneities in the Big Bang.

1.6.2 Be in Clusters

Boesgaard & King (2002) reported a major study of Be in 34 Hyades dwarfs well spaced in temperature from 5450 K to 7400 K. This covered the hot side of the Li dip, the Li dip itself, the Li plateau, and the cool star Li decline (see Fig. 1.9). They found a strong Be dip at the same temperature as the Li dip where Be is detected but depleted. In this dip Be is not as depleted as Li; this was not unexpected, inasmuch as Be is more robust with respect to destruction than Li. They found little or no Be depletion in the 13 stars cooler than 6000 K in spite of the large Li depletions (0.5 to >2.5 dex). This part of the work confirmed and expanded the results of García López, Rebolo, & Pérez de Taoro (1995) on four Hyades G stars. The left panel in Figure 1.10 shows the Hyades Be results of Boesgaard & King (2002).

Observations of Be were made in other young open clusters: the Coma Bernices cluster and UMa moving group by Boesgaard, Armengaud, & King (2003b) and Pleiades and α Per by Boesgaard, Armengaud, & King (2003a). Coma is a little younger than the Hyades (500 Myr vs. 700 Myr for the Hyades), but also shows both a Li and, now, a Be dip. There is no Be depletion in the G stars in any of the clusters even though they show large Li depletions

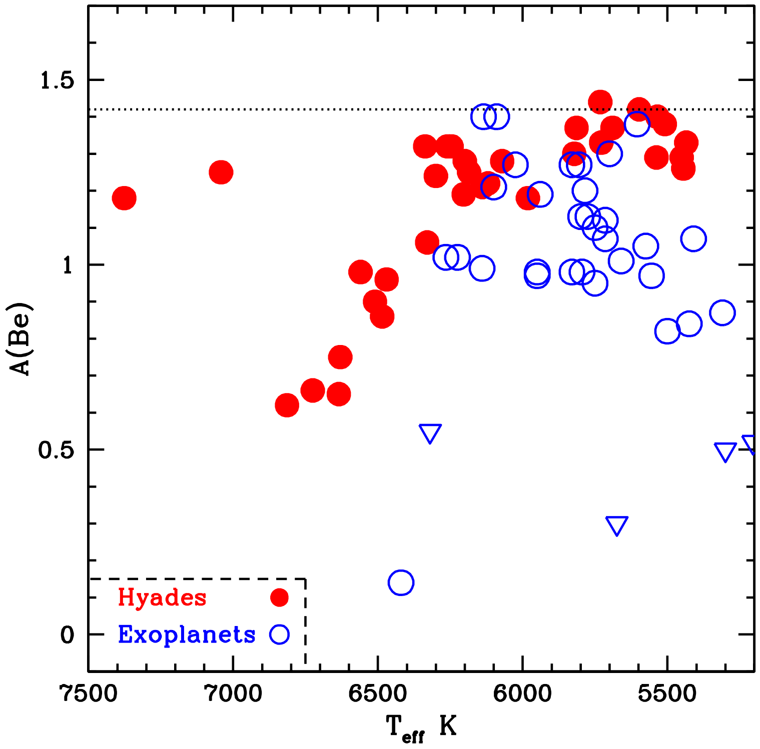

Fig. 1.11. Be abundances in stars with planets (open circles and triangles; Santos et al. 2002) compared with Be in the Hyades stars (filled circles; Boesgaard & King 2002). Inverted triangles represent upper limits.

with decreasing temperature. The Be results for Coma and UMa are shown in the right panel of Figure 1.10. The Pleiades and α Per are still younger at 50–70 Myr. There is only a mild Li dip in the Pleiades F dwarfs and only a weak decline in Li with decreasing temperature in the G dwarfs. The Be abundances in 14 Pleiades stars showed some possibly real scatter, but no trends with temperature. Like the Li depletion, the Be depletion does not reveal itself until an age of >300 Myr in the Li-Be dip in F dwarfs.

Another study of both Li and Be in clusters was done by Randich et al. (2002) with excellent data from the VLT + UVES on faint main sequence stars in M67. At 4–5 Gyr M67 is too old to have any F stars left on the main sequence in the Li-Be dip region. They observed five early-G dwarfs and found little or no Be depletion even though the stars were depleted in Li, concluding that the mixing process does not go to deep enough layers to destroy Be.

1.6.3 Be in Stars with Planets

A study of Be in 32 stars that harbor planets was made by Santos et al. (2002). Such stars have been found to be metal rich when compared to typical field stars, with an average [Fe/H] = +0.17 ± 0.20 (Gonzales et al. 2001). The enrichment could have enabled the stars to form protoplanetary disks and then planets, or the enrichment might be the result of accretion of metal-rich material. They find no clear differences in the distribution of Be (or Li) abundances compared to a set of non-planet stars. Figure 1.11 shows the comparison in A(Be) of the exoplanet stars with the Hyades, which also has an enhanced metallicity, near [Fe/H] = +0.13. Whereas Be in the Hyades is undepleted, several stars with planets have small to major Be depletions, perhaps due to their greater average age.

1.6.4 Correlation of Li and Be

Deliyannis et al. (1998) determined Li and Be abundances in 24 F disk dwarfs in the temperature range 6000–6700 K. Five stars were undepleted in both Li and Be, nine stars showed that the depletions were correlated, while the rest showed only upper limits of one or both elements. They examined several mixing mechanisms to try to explain the correlation and were able to rule out microscopic diffusion and surface mass loss. Rotationally induced mixing seemed best able to account for the observations; possibly gravity waves could contribute. This work was continued by Boesgaard et al. (2001), who made high-resolution observations of Be at CFHT of 46 stars, along with Li observations for 40 of them from Keck I and the UH 2.24-m telescope. In the temperature range from 5850–6680 K, which defines the Li-Be correlation, there are 27 stars with detectable and correlated Li and Be. There is a possibility of a slightly different relation between Li and Be for stars with $T_{\rm eff}$ = 5850–6300 K and those with $T_{\rm eff}$ = 6300–6680 K.

The recent work by Boesgaard & King (2002) and Boesgaard et al. (2003a, b) on Be in open clusters extends the field-star relation to cluster stars. The Hyades A(Li) vs. $T_{\rm eff}$ plot (see Fig. 1.9) gives a context for the Li-Be relation. The cool side of the Li dip is between about 6300 to 6650 K. Figure 1.12 shows the Li-Be correlation in field and cluster stars in this restricted temperature range. The slope of this relation is 0.44, so as Li declines by a factor of 10, Be is reduced by a factor of 2.75. The stars in the youngest clusters (e.g., Pleiades) are in the upper right with low depletions. The other clusters and the field stars are spread along the line. It is thought that the mixing to deeper regions in stellar interiors results from internal angular momentum transfer as the stars age.

1.6.5 Summary

The VLT/UVES results for three very metal-poor stars shows that Be is lower by a factor of 400 relative to the meteorites. According to the observations at low metallicities, it is possible that there is a Be plateau below [Fe/H] of −2.8 at a level of A(Be) = −1.3. This needs to be addressed through additional, but difficult, observations of Be in low-metallicity stars.

Observations of Be in open clusters have led to some interesting new results. The Hyades, Praesepe, and Coma clusters with ages of $(5-8) \times 10^8$ yr show a Be dip like the Li dip in the mid-F stars with temperatures about 6300–6800 K. The Be dip is not as deep as the Li dip. No Be dip is found for younger clusters like Pleiades and α Per at $(5-7) \times 10^7$ yr; clusters this young do not have a significant, if any, Li dip. For the G dwarfs, which show Li depletions of more than 100 times, there are no Be depletions. This is true in all the G stars observed including the old cluster M67.

A survey of Be in stars which have planets revealed a normal distribution in Be. These planet-harboring stars generally have higher than solar [Fe/H]. A primordial origin for the high metallicity may be implied by the Be results.

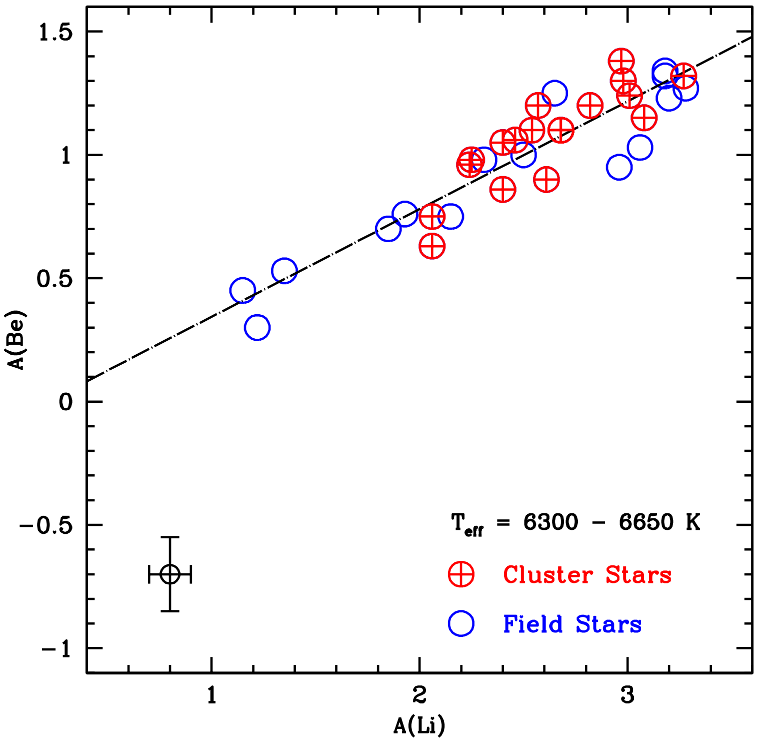

Fig. 1.12. The correlation of Li and Be on the cool side of the Li-Be dip for field and cluster stars. A typical error bar is shown in the lower left. The slope of the dashed line (least squares fit) is 0.44. The stars in the youngest clusters are in the upper right.

In the temperature range from 5900–6650 K there is a correlation between Li and Be. Stars on the cool side of the Li-Be dip (6300 K $< T_{\rm eff} <$ 6650 K) show a strong correlation in both field stars and cluster stars at all ages. This correlation is well matched by predictions of mixing induced by stellar rotation (e.g., Chaboyer, Demarque, & Pinsonneault 1995; Deliyannis & Pinsonneault 1997; Pinsonneault et al. 1999).

1.7 Some Recent Results on B

1.7.1 B Depletions

Although B is less prone to destruction than Li or Be, some stars do show the results of apparent nuclear destruction of B. The stars plotted in Figure 1.4 are those with B determinations from B I; some of those disk-metallicity stars show decreased B. Cunha, Smith, & Lambert (1999) have found a G star in the Orion Association to be B deficient and O rich. Cunha et al. (2000) show the trend, and anti-correlation, between B and O from three G stars and four B stars. Since Li in the G stars is independent of O, it seemed to them unlikely that the ν-process is a significant source of Li and B. They present a simple model that has spatial variations in the light element enrichments in the Orion cloud.

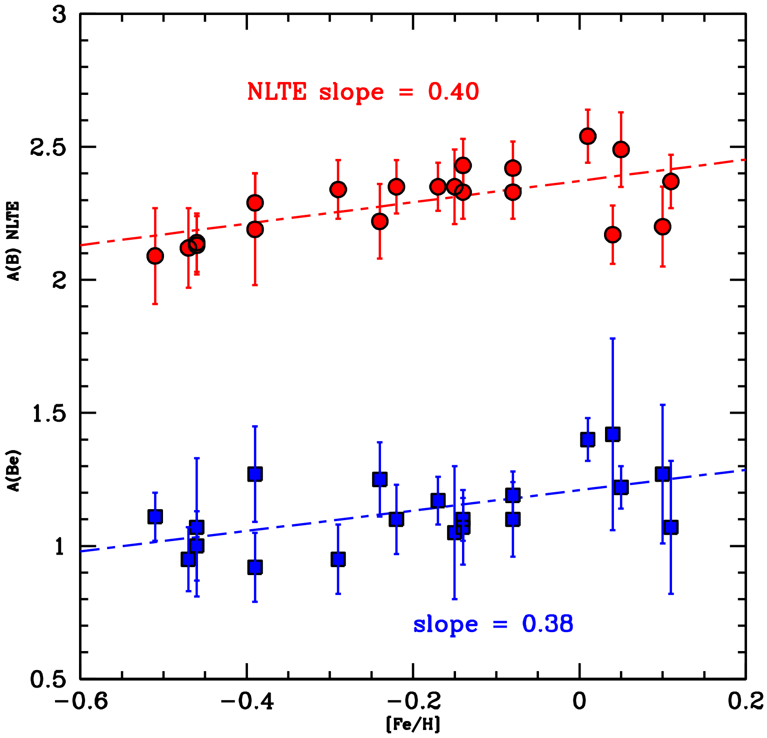

Fig. 1.13. Abundances of B and Be vs. [Fe/H] in Galactic disk stars that are undepleted in Be. Filled circles are the B results; filled squares are Be. These stars are from the upper envelope of disk stars in Figs. 1.3 and 1.4. The slopes are similar, and shallower than the slopes in the halo stars.

There are F and G field stars with apparent B deficiencies. Two examples are Procyon (Lemke, Lambert, & Edvardsson 1993) and ζ Her (Boesgaard et al. 1998b), both of which are very depleted in Li and Be. Procyon is in the Li-Be dip, while ζ Her is a fairly evolved subgiant. A newly identified Li-Be-B deficient star in the Li-Be dip region is HR 107. These stars have huge Li deficiencies—factors of 600 and more—and large Be deficiencies, up to 2 orders of magnitude.

Abundances of B in B-type stars have been determined by Venn et al. (2002) from the B III λ2066 resonance line. In their sample of seven main sequence stars they find two with undepleted B, one with B depleted but detectable, and four where they could only determine upper limits on the B abundance. Of the latter four, three are N rich. They include data on other hot stars from *HST*+GHRS (six stars) and *IUE* (20 stars, predominantly from Proffitt & Quigley 2001) with C, N, and (usually) O abundances in order to understand the B deficiencies and trends. The spread in B in this enlarged sample is 2 orders of magnitude, from A(B) = 2.9 to 0.9. The stars with the lowest B tend to have the highest N. They discuss the role of rotationally induced mixing and its influence on both B and N.

1.7.2 B in the Galactic Disk

Figure 1.4 shows NLTE B abundances in halo and disk F and G stars. In that plot the points represented by crosses are 20 Galactic disk stars from Boesgaard et al. (2004) that are undepleted in Be and, presumably therefore, in B. Although the trend with [Fe/H] is consistent for the halo and disk stars, examination of the disk stars alone indicates a shallower slope. Abundances of both B and Be for those 20 stars alone are shown in Figure 1.13. The slopes of the relationship with [Fe/H] are similar for both B and Be, which indicates a common origin in the disk, presumably spallation. Over a factor of 5 increase in [Fe/H], B and Be gradually increase by nearly a factor of 2. For these stars the B/Be ratio at [Fe/H] is about 14, whereas for the halo stars this ratio is $\sim 15-20$ (Duncan et al. 1998; García López et al. 1998).

1.7.3 Summary

Even though B is the least susceptible to destruction of the three light elements, there are some stars with apparent B deficiencies. Examples of this can be found among the N-rich B stars, F stars in the Li-Be dip, and in the Orion G dwarfs. There is a general increase in B with [Fe/H] with a slope near 0.7. Depending on the reliability of the corrections for NLTE effects in B, there may be some B-rich but metal-poor stars. The ratio of B/Be in the halo is about 15, close to the predictions of Galactic spallation. Disk stars that are undepleted in Be should be undepleted in B; a sample of 20 stars with [Fe/H] between −0.6 and +0.2 have similar relationships between A(B) vs. Fe and A(Be) vs. Fe, with slopes near 0.35 compared to halo stars with steeper slopes.

1.8 Concluding Remarks

We see that Li has an extraordinarily "complex" life with many possible "sources," from the Big Bang to several present-day production mechanisms. Both ^{6}Li and ^{7}Li are fragile elements, and there are many known "sinks" where they can be destroyed. Although there are departures from LTE for Li, the corrections are small, usually less than a few hundredths of a dex.

One the other hand, Be is the most "straightforward" of the light elements. (1) It has only one known source: Galactic cosmic ray spallation. (2) Only the isotope ^{9}Be is stable. (3) It is less susceptible to depletion than Li in stellar interiors. (4) There are minimal effects due to NLTE.

Boron can be characterized as "tough." (1) It is more robust against nuclear destruction. (2) It is difficult to observe because the resonance lines of B I, B II, and B III all occur in the satellite ultraviolet. (3) There seem to be at least two sources of production. (4) Substantial corrections for NLTE effects need to be made.

The abundances of these three elements, separately and in combination, have produced a great wealth of insights into a diverse array of astrophysical matters.

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