BORON DEPLETION IN F AND G DWARF STARS AND THE BERYLLIUM-BORON CORRELATION

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ABSTRACT

Boron provides a special probe below the stellar surface since it survives to greater depths than do Li and Be. To search for B depletions we have observed B in 13 F and G dwarfs with large Be depletions; for comparison we have also obtained spectra of five stars that are undepleted in Li and Be. We have used HST with STIS to obtain spectra of the B resonance line at 2497 Å. The spectral resolution is 30,000 or 114,000, and the median signal-to-noise ratio is 70 pixel^{-1}. New Be and Li spectra have been obtained at Keck I with HIRES of four of the five standard stars at \( \sim 48,000 \) resolution. Abundances have been determined by the spectrum synthesis method with MOOG. A comparison between the standard stars and those with severe Be depletions shows a distinct difference in the B abundances between the two groups of 0.22 dex. We have discovered a correlation between the Be and B abundances. The slope between \( A(\text{Be}) \) and \( A(\text{B})_{\text{NLTE}} \) is \( 0.22 \pm 0.05 \) [where \( A(\text{element}) = \log N(\text{element})/N(\text{H}) + 12.00 \)], which, as expected, is shallower than the slope between \( A(\text{Li}) \) and \( A(\text{Be}) \) of 0.38. We have normalized the light-element abundances to account for the observation that the initial abundances are somewhat lower in lower metallicity stars by employing recently published empirical relations between Be and [Fe/H] and between B and [Fe/H]. The correlation between the normalized \( A(\text{Be}) \) and \( A(\text{B})_{\text{NLTE}} \) has a slope of 0.18 ± 0.06. The star with the largest Be depletion, HR 107, a main-sequence Ba star, also has the largest B depletion, with the B abundance lower by a factor of 3.5 relative to the standard stars.

Subject headings: stars: abundances — stars: evolution — stars: late-type

Online material: color figures

1. INTRODUCTION

Each of the three light elements, lithium (Li), beryllium (Be), and boron (B), survives to different depths in models of cool stars. Boron is destroyed at temperatures higher than \( 5 \times 10^6 \) K and so provides a probe into deeper layers than do Li (destroyed at \( T > 2.5 \times 10^6 \) K) and Be (destroyed at \( T > 3.5 \times 10^6 \) K). The amount of each element on the surface of a star is decreased if the stellar surface material is circulated down inside the star to its individual critical temperature. Although standard stellar models of F and G dwarfs indicate that there would be no such circulation and thus no depletions of Li, Be, and B, observations show substantial element deficiencies. Several mechanisms that would give rise to additional mixing below the surface convection zones of such stars have been proposed to explain the observed depletions.

The most dramatic observational conflict with the model predictions is the pronounced Li deficiencies in the narrow region where stellar effective temperatures (\( T_{\text{eff}} \)) are between 6300 and 6850 K. This “Li dip” is especially well delineated in the Hyades star cluster, first found by Boesgaard & Tripicco (1986a). A similar “Be dip” has recently been found for the Hyades by Boesgaard & King (2002; see also Boesgaard et al. 2004a). Several studies have been made of this phenomenon in other star clusters. One key result is that there is little or no Li dip in the young (70 Myr) Pleiades cluster (Pilachowski et al. 1987; Boesgaard et al. 1988), and no Be dip (Boesgaard et al. 2003). Thus we understand that the depletions of Li and Be in the dip stars occur during main-sequence evolution, not during the pre–main-sequence phase. The effect of the additional depletion shows up in Li and Be deficiencies in the surface abundances by stellar ages of a few hundred million years.

For both cluster stars and field stars, we see that the depletions of Li and Be are correlated in the temperature regime of \( 5900 \)–\( 6650 \) K, corresponding roughly to the range from the bottom of the Li-Be dip (\( \sim 6650 \) K) to the Li-Be peak (\( \sim 5900 \) K) in the early G dwarfs (see, e.g., Boesgaard et al. 2004b). The slope of the linear relation between \( A(\text{Li}) \) and \( A(\text{Be}) \) is elegantly matched to the predictions of rotationally induced mixing models of Deliyannis & Pinsonneault (1997), as can been seen in Figure 12 of Boesgaard et al. (2004b). [This is in our usual notation of \( A(\text{element}) = \log N(\text{element})/N(\text{H}) + 12.00 \).] As shown by Deliyannis et al. (1998), the proposals to explain the Li dip by mass loss (e.g., Schramm et al. 1990) and by diffusion (e.g., Michaud 1986) can be ruled out. Wave-driven mixing (e.g., García López & Spruit 1991; Talon & Charbonnel 2003)

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occurs closer to the surface than does rotationally induced mixing. It is because these two mixing mechanisms differ in their effectiveness with depth that we were able to distinguish between them with Li and Be measurements (Deliyannis et al. 1998). Analogously, B offers a unique opportunity to examine whether this slow mixing extends to deeper depths, 10%–30% by mass.

The inclusion of B in these light-element studies allows us to (1) probe deeper into stars, (2) search for B depletions in individual stars, and (3) look for a Be-B correlation, which could occur in the same temperature regime and be similar in nature to the Li-Be correlation. All of this will provide new constraints for stellar models. Our previous Hubble Space Telescope (HST) B study provided the provocative hint that B is depleted in the severely Li- and Be-depleted star ζ Her A (= HR 6212 = HD 150680). Here we present B results for 13 newly observed late-F echelle grating with a 0″ 9 aperture on the NUV-MAMA detector (k″/C30 = 2,700, and the effective pixel size is 0.085″). Results for B in the fifth standard star, HR 8888 = HD 220242, had been observed with the University of Hawai‘i 2.2 m telescope and coude spectrograph at a spectral resolution of ~7,000 (Deliyannis et al. 1998; Boesgaard et al. 2001). We also observed the Li-Be depleted star HR 107 (= HD 2454) anew at Keck/HIRES at high S/N to try to obtain a Li detection, or at least a smaller upper limit for A(Li).

The same four standards were also observed at the Be resonance lines (3130 and 3131 Å) with Keck/HIRES. The spectral resolution for these is ~48,000, and the effective pixel size is 0.022″. Results for Be in the fifth standard star, HR 8888, are from a Canada-France-Hawaii Telescope (CFHT) spectrum described in Boesgaard et al. (2001); it has a spectral resolution of 120,000 or a reciprocal dispersion of 0.010 Å pixel⁻¹.

The spectra were reduced using standard IRAF routines. There were typically 13 flat-field files and 13 bias frames used to create the master flat and master bias for each night. Reference Th-Ar spectra were taken to calibrate the wavelengths and determine the dispersion curve. The log of the observations, including exposure times in seconds and S/N ratios, is given in Table 2.

3. ABUNDANCES

Abundances were determined for Li, Be, and B through the spectrum synthesis mode of MOOG, the 2002 version (Sneden 1973). This version contains the UV opacity edges of the metals from Kurucz.

See http://verdi.as.utexas.edu/moog.html.
All of our stars had been observed previously for Be; it was those observations that provided the selection criterion (severely depleted Be) for the stars observed for B. The parameters of those observations that provided the selection criterion (severely as described in those papers. The microturbulent velocities, \( \xi \), the other four standard stars were determined in the same manner and two from Deliyannis et al. (1998). The stellar parameters for adopted from those papers: 12 stars from Boesgaard et al. (2001) are given in column (9) of Table 4. Corrections to LTE abundances for the effects of NLTE have been calculated by Kiselman factor of 11 lower than in HR 860. This shows that these stars have experienced different degrees of mixing. than that in HR 860, while the Be abundance in HR 761 is a best value. The B abundance in HR 761 is a factor of 2 lower than-usual errors). Although the spectra of HR 2264 and HR 6489 are not as sharp-lined as those of HR 6394 and HR 8888, they could yield reliable Li and Be abundances. The Be abundances in Boesgaard et al. (2001) were redetermined from the original spectra with MOOG2002, which has the UV opacity

### TABLE 1
**Observations of Boron**

| STAR ID | HR   | HD   | \( V \) | DATE OBSERVED | SPECTRAL RESOLUTION | EXPOSURE TIME (s) | S/N |
|---------|------|------|--------|--------------|-------------------|------------------|-----|
| 107     | 2454 | 6.06 | 2001 Oct 30 | 30,000 | 1929 | 88 |
| 638     | 13456 | 6.01 | 2002 Feb 10 | 30,000 | 1929 | 97 |
| 761     | 16220 | 6.25 | 2002 Feb 6 | 30,000 | 1975 | 72 |
| 860     | 17948 | 5.59 | 2002 Aug 24 | 114,000 | 3960 | 81 |
| 988     | 20395 | 6.14 | 2002 Jan 25 | 30,000 | 1929 | 90 |
| 2233    | 43318 | 5.65 | 2002 Feb 16 | 30,000 | 1929 | 85 |
| 2264    | 43905 | 5.36 | 2001 Nov 16 | 114,000 | 2144 | 52 |
| 4803    | 109799 | 5.45 | 2002 Jul 19 | 114,000 | 1956 | 48 |
| 6394    | 155646 | 6.65 | 2002 Sep 11 | 30,000 | 1927 | 51 |
| 6489    | 157856 | 6.44 | 2001 Sep 20 | 30,000 | 1927 | 68 |
| 7454    | 184985 | 5.47 | 2001 Sep 15 | 30,000 | 1929 | 81 |
| 7658    | 190009 | 6.45 | 2001 Sep 18 | 30,000 | 1934 | 57 |
| 7697    | 191195 | 5.85 | 2001 Oct 12 | 30,000 | 2141 | 99 |
| 7955    | 198084 | 4.51 | 2001 Nov 28 | 114,000 | 3960 | 64 |
| 8077    | 200790 | 5.94 | 2001 Oct 17 | 30,000 | 1929 | 61 |
| 8250    | 205420 | 6.47 | 2001 Nov 7  | 30,000 | 1934 | 53 |
| 8792    | 218261 | 6.30 | 2001 Nov 3  | 30,000 | 1927 | 51 |
| 8888    | 220242 | 6.62 | 2001 Nov 29 | 30,000 | 1951 | 75 |

### TABLE 2
**New Keck/HIRES Observations of Lithium and Beryllium**

| STAR ID | HR | HD | LITHIUM DATE | EXPOSURE (s) | S/N | BERYLENIUM DATE | EXPOSURE (s) | S/N |
|---------|----|----|--------------|--------------|-----|-----------------|--------------|-----|
| 107     | 2454 | 2003 Jan 11 | 840 | 790 | ... | ... | ... | ... |
| 2264    | 43905 | 2003 Jan 11 | 120 | 435 | 1995 Mar 14 | 300 | 90 | 55 |
| 4803    | 109799 | 2003 Jan 11 | 120 | 575 | 2001 Feb 1 | 600 | 37 | 37 |
| 6394    | 155646 | 2003 Feb 11 | 240 | 505 | 2001 Feb 1 | 600 | 41 | 41 |
| 6489    | 157856 | 2003 Feb 11 | 240 | 505 | 2001 Feb 1 | 600 | 41 | 41 |
edges included; this procedure puts those spectra on the same standard as the new ones for the standard stars. The only significant changes were in $A(\text{Be})$ for HR 2233, which increased from $0.08$ to $0.22$, and for HR 761, which increased from $0.60$ to $0.40$.

### 3.3. Error Estimates

There are several potential sources of error in the abundances determinations. Those associated with the errors in the stellar parameters are the most straightforward to estimate. A typical uncertainty in the value of $T_{\text{eff}}$ of 80 K results in an uncertainty of 0.08 dex in $A(\text{Be})$. An uncertainty in $\log g$ of 0.2 produces an uncertainty in $A(\text{Be})$ of 0.02 dex. If the metallicity is uncertain by 0.1 in $[\text{Fe/H}]$, the resultant error in $A(\text{Be})$ is 0.03 dex. These three parameters and their associated uncertainties are not completely independent of each other nor are they closely interlinked; the combined uncertainty would be between 0.09 (summed in quadrature) and 0.13 (addition of the errors). Other sources of error include the S/N of the observed spectrum, the details of the line list used in the fits, and what could be called the “goodness of fit” estimate between the observed and synthesized spectra. The final estimates of the uncertainties are given in the last column of Table 4.

In all cases the corrections for NLTE effects increase the B abundances. They range from +0.06 dex (for the metal-rich stars) to +0.22 dex (for the metal-poorest stars in our sample). We have applied these corrections as the best available to us and use the NLTE results, but note that the corrections can be sizeable.

The errors on Li and Be have been made in the papers from which those data are drawn. For the new observations of Li and Be in the standard stars, here is a synopsis of the effects of the uncertainties from the errors in the stellar parameters for our range in temperatures, $\log g$ values, and metallicities: for Be, $\Delta T = 80$ K gives $\Delta A(\text{Be}) = 0.01$ dex, $\Delta \log g = 0.1$ gives
TABLE 4

ABUNDANCE RESULTS

| HR (1) | HD (2) | T$_{\text{eff}}$ (3) | $\Delta$(Li) (4) | Reference (5) | $\Delta$(Be) (6) | $\sigma$ (7) | Reference (8) | $\Delta$(B)$_{\text{LTE}}$ (9) | $\Delta$(B)$_{\text{NLTE}}$ (10) | $\sigma$ (11) | $\Delta$(Be), Normalized (12) | $\Delta$(B)$_{\text{NLTE}}$, Normalized (13) |
|--------|--------|---------------------|-----------------|---------------|-----------------|-------|---------------|-----------------|-----------------|-------|-----------------|-----------------|
| Be-depleted Stars
| 107...... | 2454   | 6393               | $<$0.81         | 1              | $<$-1.00 0.16   | 2     | 1.50          | 1.72 0.15       | $<$-0.86        | 1.87  |
| 638...... | 13456  | 6578               | $<$1.13         | 2              | -0.10 0.16     | 2     | 1.95          | 2.17 0.15       | $<$-0.01        | 2.26  |
| 761...... | 16220  | 6199               | $<$0.67         | 2              | -0.40 0.13     | 2     | 1.90          | 2.06 0.16       | $<$-0.27        | 2.19  |
| 860...... | 17948  | 6400               | $<$0.82         | 2              | 0.65 0.17      | 2     | 2.21          | 2.38 0.15       | 0.76            | 2.50  |
| 988...... | 20395  | 6589               | $<$1.36         | 2              | 0.32 0.15      | 2     | 2.18          | 2.36 0.15       | 0.36            | 2.40  |
| 2233...... | 43318  | 6229               | $<$0.86         | 2              | 0.22 0.13      | 2     | 2.06          | 2.25 0.15       | 0.28            | 2.31  |
| 7454...... | 184985 | 6329               | $<$1.17         | 2              | -0.20 0.14     | 2     | 2.08          | 2.19 0.15       | $<$-0.21        | 2.17  |
| 7658...... | 190009 | 6275               | $<$0.96         | 3              | 0.40 0.25      | 2     | 2.19          | 2.28 0.18       | 0.40            | 2.28  |
| 7697...... | 191195 | 6588               | $<$0.83         | 2              | $<$-0.30 0.15  | 2     | 2.03          | 2.19 0.19       | $<$-0.30        | 2.19  |
| 7955...... | 198084 | 6171               | $<$0.56         | 2              | 0.24 0.14      | 2     | 2.10          | 2.15 0.20       | 0.18            | 2.09  |
| 8077...... | 200790 | 6095               | $<$0.58         | 2              | 0.00 0.15      | 2     | 2.02          | 2.10 0.16       | 0.03            | 2.13  |
| 8250...... | 205420 | 6250               | $<$0.72         | 2              | 0.57 0.13      | 2     | 2.16          | 2.26 0.17       | 0.60            | 2.29  |
| 8792...... | 218261 | 6114               | $<$0.96         | 3              | $<$0.31 0.25   | 3     | 1.90          | 1.99 0.18       | $<$0.29         | 1.96  |
| Standard Stars
| 2264...... | 43905  | 6696               | 3.18           | 1              | 1.37 0.16      | 1     | 2.56          | 2.62 0.18       | 1.27            | 2.51  |
| 4803...... | 109799 | 6910               | 3.15           | 1              | 1.09 0.27      | 1     | ...           | ...             | ...             | ...   |
| 6394...... | 155646 | 6171               | 3.05           | 1              | 1.15 0.11      | 1     | 2.06          | 2.17 0.17       | 1.21            | 2.23  |
| 6489...... | 157856 | 6361               | 2.88           | 1              | 1.06 0.18      | 1     | 2.18          | 2.32 0.24       | 1.13            | 2.39  |
| 8888...... | 220242 | 6722               | 3.30           | 1              | 1.44 0.13      | 2     | 2.41          | 2.57 0.17       | 1.44            | 2.57  |

REFERENCES.—(1) New (see Table 2); (2) Boesgaard et al. 2001, as redetermined from MOOG2002; (3) Deliyannis et al. 1998.

For Li the influence of NLTE effects is to decrease the derived LTE abundance. For our sample of stars we have upper limits on $\Delta$(Li) for all the Be-depleted stars. The NLTE corrections for the Li abundances in the five standard stars are $-0.10, -0.10, -0.09, -0.07, and -0.12$, in the order given in Table 4. According to Kiselman & Carlsson (1996) and García López et al. (1995), various effect of NLTE cancel each other for the Be $\lambda\,\lambda$ resonance lines, so no corrections have been applied to $\Delta$(Be).

4. RESULTS AND DISCUSSION

4.1. Boron Abundances and Depletions

We can examine the degree of light-element depletion by comparing the B and Be abundances for our sample of stars. The range in Be abundances (detections) in our Be-depleted stars spans a factor of 11, while the range in B in these same stars spans a factor of 5. The difference in $\Delta$(B) between the highest and lowest value is 0.66 dex, well in excess of the individual errors, typically 0.12 dex. We can now look for a correlation between $\Delta$(B) and $\Delta$(Be) with the expectation that the larger Be depletions will correlate with the larger B depletions. This is shown in Figure 4, where the left panel corresponds to the LTE values of $\Delta$(B) and the right panel to the NLTE values. The slopes for $\Delta$(B) versus $\Delta$(Be) in LTE and NLTE are virtually identical at 0.231 and 0.217, respectively, but there is a vertical offset of +0.16 dex in $\Delta$(B) due to the corrections for NLTE effects. Although the points with upper limits on $\Delta$(Be) are plotted (as small open circles with left-leading arrows), they are not included in the least-squares fit. The relationship is between depleted, but detected, Be and B abundances.

This indicates the discovery of a correlation between the Be and B abundances, similar to the correlation between Li and Be. The slope between Be and B of 0.22 is shallower than that between Li and Be, which is 0.38 (from Fig. 9 of Boesgaard...
et al. 2004a). This can provide clues about how the mixing changes with depth. The B atoms have to be circulated to greater depths to be destroyed, and therefore B is the less susceptible to destruction.

To demonstrate the reality of the B depletion, we show the spectrum synthesis fit for the star with the largest Be deficiency, HR 107. Figure 5a shows the B i region and the syntheses for HR 107. For comparison, a star of similar metallicity was chosen from the sample of Boesgaard et al. (2004c), HD 11592 (Fig. 5b). The synthesis fit has 5 times less B in HR 107 than in HD 11592, and the difference in the line depth of the B feature is obvious.

Tomkin et al. (1989) describe HR 107 as “an F-type mild barium dwarf star.” It has enhanced s-process products such as Y, Zr, Ba, and Ce relative to HR 366, a star of similar temperature, gravity, and metallicity. The Ba star phenomenon apparently arises from mass transfer from an asymptotic giant branch (AGB) star (which is now a white dwarf) to a less massive companion (e.g., McClure et al. 1980). Although no white dwarf companion has been detected near HR 107, its compositional peculiarities are symptomatic of Ba stars. The mass transfer process, which pollutes the atmosphere with material processed in the interior of the AGB star, could affect the light-element abundances. Its Li and Be are undetectable, and it is deficient in B.

4.2. Correlation of Beryllium and Boron

Figure 4 shows the interesting correlation of Be and B similar to the Li-Be correlation first discovered by Deliyannis et al. (1998) and advanced by the additional observations of Boesgaard et al. (2001, 2004b). To examine this further we decided to (1) restrict the temperature range to 5900–6650 K (as was done for the Li-Be correlation), (2) include the Li-normal stars in Boesgaard et al. (2004c), and (3) normalize the abundances to solar metallicity.

It was found in Boesgaard et al. (2004c) that both \(A(\text{Be})\) and \(A(\text{B})\) increase with \([\text{Fe/H}]\) in the Galactic disk. This result is based on HST/STIS observations of B in 20 stars with “undepleted” Be abundances from spectra taken at Keck I with HIRES or at CFHT with the Gecko spectrometer. The stars were chosen because they fell on the upper envelope in a plot of \(A(\text{Be})\).
versus [Fe/H] that covered a range of [Fe/H] from −1.0 to +0.2. The light-element abundances in these stars could be well represented by these relationships for stars in the Galactic disk:

\( A(\text{Be}) = (0.382 \pm 0.135) \frac{[\text{Fe/H}]}{} + (1.218 \pm 0.037), \)

\( A(\text{B})_{\text{NLTE}} = (0.402 \pm 0.117) \frac{[\text{Fe/H}]}{} + (2.371 \pm 0.032). \)

In order to estimate the true depletion of Be and B in our stars we need to make an adjustment for the “initial” Be and B, which appears to depend on metallicity (or age). A star that has fewer metals, e.g., [Fe/H] = −0.30, would start with somewhat lower Be and B than a star of solar metallicity. According to the above relationships, a star at [Fe/H] = 0.0 would have \( A(\text{Be}) = 1.22 \) and \( A(\text{B})_{\text{NLTE}} = 2.37 \), while the star with [Fe/H] = −0.30 would start with \( A(\text{Be}) = 1.10 \) and \( A(\text{B})_{\text{NLTE}} = 2.25 \). So the depletion caused by internal slow mixing should be taken relative to that starting value, and so we have “normalized” the Be and B abundances to solar metallicity.

Figure 6 shows the correlation of Be and NLTE B with the normalized values. As expected, the slope is a bit shallower because some component of the lower abundance for Be and B is not real depletion, but caused by a lower initial Be and B. The relationship from this group of stars (taking into account the errors in both coordinate) is

\[ A(\text{B})_{\text{NLTE}} = (0.180 \pm 0.063) A(\text{Be}) + (2.219 \pm 0.060). \]

We note that although the slopes are fairly shallow the errors are small and the result is significant at the 3 σ level. The linear correlation coefficient indicates a correlation significant at the 96.5% level for the above relationships.

Another approach to elucidate the B-Be correlation is via statistics. We can compare the abundances in two groups. One group is composed of the standard stars, or “Li-normal stars,” which have small or no depletion in all three elements from this paper and from Boesgaard et al. (2004a). The other group contains the six stars with large Be depletions of over an order of magnitude. These stars are listed in the two groups in Table 5, along with their mean values of the normalized Be and B abundances. Here the errors are the standard deviation of the mean. The groups were binned by the Be data, and the difference in the mean B abundances is 0.22 dex, well in excess of the standard deviations by at least 4 σ. One of our goals was to ascertain the reality of B depletions by statistical means, but this turns out to be a statistical confirmation of the Be-B correlation. We have not included HR 7697 and HR 8792 in Table 5 because of their upper limit measurements on \( A(\text{Be}) \), but they do have B detections. Including them in the normalized B list at 2.19 and 1.96 gives a mean for the eight Be-deficient stars of 2.16 ± 0.04. This is a

![Figure 6.—Normalized Be and B abundances (see text § 4.2). The filled symbols are from this paper, and the open circles are from Boesgaard et al. (2004c). The slope includes the errors in both coordinates. [See the electronic edition of the Journal for a color version of this figure.]](image)

### TABLE 5

| HR   | HD   | \( T_{\text{eff}} \) | [Fe/H] | \( A(\text{Li}) \) | \( A(\text{Be}) \), Normalized | \( A(\text{B})_{\text{NLTE}} \), Normalized | Reference |
|------|------|---------------------|--------|-------------------|-------------------------------|----------------------------------|-----------|
| Li-normal Standard Stars |
| 2264 | 43905 | 6696 | +0.27 | 3.18 | 1.27 | 2.51 | 1 |
| 6394 | 155646 | 6171 | −0.14 | 3.05 | 1.21 | 2.23 | 1 |
| 8888 | 220242 | 6722 | +0.01 | 3.30 | 1.44 | 2.57 | 1 |
| 7408 | 15798 | 6347 | −0.22 | 3.14 | 1.19 | 2.44 | 2 |
| 7700 | 16399 | 6481 | −0.08 | 3.13 | 1.15 | 2.36 | 2 |
| 4399 | 99028 | 6679 | +0.11 | 3.30 | 1.03 | 2.32 | 2 |
| 5927 | 142640 | 6387 | +0.05 | 3.35 | 1.20 | 2.47 | 2 |
| Mean | ... | ... | ... | 1.22 ± 0.05 | 2.41 ± 0.05 | |

| Be-depleted Stars |
| 638 | 13456 | 6578 | −0.23 | <1.13 | −0.01 | 2.26 | 1 |
| 761 | 16220 | 6199 | −0.33 | <0.67 | −0.27 | 2.19 | 1 |
| 2233 | 43318 | 6229 | −0.16 | <0.86 | +0.28 | 2.31 | 1 |
| 7454 | 184985 | 6329 | +0.04 | <1.17 | −0.21 | 2.17 | 1 |
| 7955 | 198084 | 6171 | +0.15 | <0.56 | +0.18 | 2.09 | 1 |
| 8077 | 200790 | 6095 | −0.07 | <0.58 | +0.03 | 2.13 | 1 |
| Mean | ... | ... | ... | 0.00 ± 0.21 | 2.19 ± 0.04 | |

References.—(1) This paper; (2) Boesgaard et al. 2004c.
difference between the Li-normal group and the Be-depleted group of 0.25 dex, a factor of 1.8.

5. SUMMARY AND CONCLUSIONS

We have conducted a study of B in stars with large Be depletions to ascertain whether the mixing in such stars goes down to great enough depths to destroy B also. Such information is needed to provide new constraints on stellar models because standard models predict no depletion at all and the emerging new set of more sophisticated models requires additional observational information for validation. We have examined the evidence for a possible correlation between Be and B analogous to the correlated depletions of Li and Be.

We selected 13 F and early-G dwarfs with moderate to severe Be depletions and five stars with undepleted Li for comparison. Since Li is the most sensitive to destruction, stars with normal Li are expected to have no Be or B depletion. One orbit of HST was used for each star; the median S/N at the B resonance line was 70. Complementary ground-based observations of Li and Be were made for the standard stars, while results on Li and Be from previous papers by Deliyannis et al. (1998) and Boesgaard et al. (2001) were used for the program stars. Abundances of all three elements were determined by the spectrum synthesis method of MOOG2002.

The program stars show a range in Be depletions of a factor of 11, and B depletions range up to nearly a factor of 5. The abundances of B and Be are correlated, with a slope of 0.22. We have normalized the Be and B abundances to take into account that the initial abundances may have been lower for the low-metallicity stars, using the relationships discovered by Boesgaard et al. (2004c) for Galactic disk stars. This results in a somewhat shallower slope, 0.18 ± 0.06, but a clear trend.

We also approach this issue by binning the stars into two groups and determining mean Be and B abundances. The groups are seven Li-normal stars \( \Delta(\text{Li}) \geq 3.0 \) from this paper and from Boesgaard et al. (2004c) and six stars with \( \Delta(\text{Be}) < 0.3 \). The B abundances in the two groups are \( \Delta(B)_{\text{NLTE}} \) (normalized) = 2.41 ± 0.05 and 2.19 ± 0.04. As expected, the B deficiencies are smaller than the Be deficiencies (which in turn are smaller than the Li deficiencies), but the existence of B depletions is confirmed.

The star with the most severe Be depletion, HR 107 at \( \Delta(\text{Be}) < -1.00 \), has the largest B depletion, a detection of B at \( \Delta(B)_{\text{LTE}} = 1.50 \) and \( \Delta(B)_{\text{NLTE}} = 1.72 \); these values become \( \Delta(\text{Be}) < -0.86 \) and \( \Delta(B)_{\text{NLTE}} = 1.87 \) when normalized to solar [Fe/H]. However, HR 107 is known to be a main-sequence B star with enhanced s-process elements. The light-element abundances would have been altered in the process of the mass transfer that resulted in the characteristic Ba star symptoms. The normalized Be depletion is more than 2 orders of magnitude, and the normalized B depletion is more than a factor of 2.

The correlation of Be and B should be included as a constraint on models of F and G dwarfs—in particular, those including the effects of stellar rotation. Rotationally induced mixing has been successful in reproducing Li and Be abundances and that correlation for stars with \( T_{\text{eff}} \) from 5900 to 6300 K, as seen in Figure 12 in Boesgaard et al. (2004b).

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