Light Elements in Main Sequence Stars: Li, Be, B, C, O

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Abstract. The abundances of the rare light elements, Li, Be, and B, provide clues about stellar structure and evolution, about Galactic evolution and about their nucleosynthesis, including production during the Big Bang. The abundances of the abundant light elements, C and O, reveal information about the chemical history of the Galaxy and the mass spectrum of early generations of stars.

1. The Rare Light Elements

The trio of light elements, Li, Be, and B, offer a special opportunity to discern the structure and processes occurring beneath the surfaces of stars. The three are destroyed by fusion reactions at a few million K. The isotope of $^7$Li fuses with a proton at $T \sim 2.5 \times 10^6$ K and higher which corresponds to the inner 97.5% (by mass) of the solar model. For $^9$Be the temperature is $\sim 3.5 \times 10^6$ K and higher, or 95% (by mass). The relevant figures for the B isotopes ($^{10}$B and $^{11}$B) are near $5 \times 10^6$ K and 18-20% (by mass). Thus the surface zones in which each element is preserved have different dimensions; the amount of each element remaining on the stellar surface indicates how deep the mixing has been. And since the depletion in F and G dwarfs is apparently due to slow mixing, the depletion is a function of the age of a star.

Due to the low abundances of these rare light elements in stellar atmospheres, they are primarily observed in their respective resonance lines. For F and G stars these are 6707.74 and 6707.89 Å of Li I, 3130.42 and 3131.06 Å of Be II, and 2496.77 Å of B I. The Li I resonance doublet occurs in a relatively clean part of the spectrum, but both the Be II and B I features are in spectral regions crowded with other lines. Extracting the abundances requires the use of spectrum synthesis methods. Examples of synthesized spectra of all three elements can be found in Boesgaard et al. (2004c).

1.1. The Li and Be Dips in mid-F Dwarfs

The discovery of the Li dip in the Hyades by Boesgaard & Tripicco (1986) was followed by a series of papers searching for such a dip in other open clusters (e.g., Pilachowski, Booth & Hobbs (1987), Boesgaard, Budge & Ramsay (1988), Hobbs & Pilachowski (1988), Soderblom et al. (1993), and more recently, Steinhauser (2003).) A search for a Be dip in the Hyades was done by Boesgaard & Budge (1989) with the tantalizing hint of such a dip. It has been possible with the Keck telescope and HIRES (Vogt et al. 1994) to re-examine the Hyades and to extend the search for a Be dip to other clusters. One cautionary note, however,
is that many of the young stars with mid-F spectral types (near the center of the dip) are rotating sufficiently to affect the reliability of the Be abundance determination. Therefore we observed stars with $v \sin i < 20$ km s$^{-1}$.

Boesgaard & King (2002) found compelling evidence of a Be dip in the Hyades which is $\sim$700 Myr old; this is shown in the left panel of Figure 1. The comparison of the Li and Be abundance is shown in the right panel of Figure 1. The abundances are on the same scale and are normalized to the meteoritic values of $A$(Li) = 3.30 and $A$(Be) = 1.42 (Grevesse & Sauval 1998). (We define $A$(element) = log $N$(element)/$N$(H) + 12.00.) There are two major differences in the abundance-temperature profile between the two elements. 1) The Be dip in the mid-F stars is not as deep as the Li dip. 2) There is no apparent depletion of Be in the G stars in spite of the large (a factor of 100) depletion of Li. These results are not unexpected as the Be atoms need to be mixed down deeper to higher temperatures within the star to be destroyed. The volume of the region where Be is preserved is larger than that where Li is preserved indicating a larger number of surviving Be atoms initially.

![Figure 1. Left: The Be dip in the Hyades. Abundances of Be are shown as a function of temperature. The horizontal line corresponds to $A$(Be) in meteorites of 1.42. Right: A display of both Li and Be in the Hyades on the same scale with $A$(Be) on the left y-axis and $A$(Li) on the right y-axis. The Li results are shown as hexagons and the Be results as encircled plus signs. The two elements are normalized to their respective meteoritic abundances of 1.42 for Be and 3.30 for Li, shown by the horizontal line. ApJ, 565, 587.](image)

Other young and intermediate age clusters have been investigated for the presence of a Be dip and to check Be in the G dwarfs. Boesgaard, Armengaud & King (2003a) looked at the younger Pleiades and $\alpha$ Per clusters. The left panel of Figure 2 shows the scaled Li and Be abundances in those two clusters. There is no evidence of a Be dip in these clusters which are $\sim$50 - 70 Myr old. This indicates that the Li-Be dip is a phenomenon that occurs on the main sequence, not during pre-main sequence evolution, after an age of 100 Myr or so.

Other young clusters have been studied for Be including Coma and the UMa moving group which are slightly younger than the Hyades at 300 - 500 Myr. Boesgaard, Armengaud & King (2003b) found evidence of Be dip in the Coma
cluster which can be seen in the right panel of Figure 2. It is shown in comparison with the Hyades Be dip and is on the same scale as the left panel of Figure 1. The pattern is similar to the Hyades with perhaps more (intrinsic?) spread in A(Be). The Praesepe cluster was also studied by Boesgaard, Armengaud & King (2004a). They found depleted Be in the Li dip region in Praesepe stars and summarized the results for five young to intermediate age clusters. The correlation between Li and Be in the cluster stars was presented for stars in the temperature range from 5900 - 6650 K. (This is discussed below in §1.3.)

1.2. Beryllium in Field Stars

In addition to the Be studies in cluster stars Boesgaard et al. (2004b) have determined Li and Be in an array of F and G field dwarfs with high S/N spectra primarily from Keck/HIRES (Be) and the UH 2.2-m coudé spectrograph (Li). They have compiled the results from that and other studies, including the cluster work, into plots showing the range and trends of A(Be) with both effective temperature and metallicity. Those results are shown in Figure 3.

It can be seen that there are stars at or near the meteoritic abundance at all temperatures (left), but only at the higher metallicity values, near solar [Fe/H] (right). The field stars can show large Be depletions (two orders of magnitude and more), but the (young) cluster stars in the Be dip region have depletions of no more than a factor of 10. For the cooler stars (\( T < 5700 \) K) field stars show depletions of up to a factor of 4, but the relatively younger cluster stars have little or no Be depletion. The field stars in the Be dip may have no Be depletion while others have depletions larger than a factor of 100. The highly Be-depleted stars may be the older ones or those with higher initial angular momentum.
The right panel of Figure 3 shows that the full range of \( \text{A(Be)} \) is seen at solar metallicity, \([\text{Fe/H}] = 0.0 \pm 0.2\). The full range extends out to stars with metallicities a factor of two less than solar \(([\text{Fe/H}] = -0.3)\). It appears that there is an upper envelope of \( \text{A(Be)} \) as a function of \([\text{Fe/H}]\); that is, the initial amount of Be in stars is correlated with its \([\text{Fe/H}]\). This appears to be the case for halo stars as well (e.g. Duncan et al. 1998).

![Figure 3. Left: Values of A(Be) as a function of temperature. This compilation is from several sources; the crosses are field stars from Boesgaard et al. (2004b), Deliyannis et al. (1998) and Boesgaard et al. (2001). The inverted triangles represent upper limits on A(Be) from those papers. The open circles are cluster stars from Hyades (Boesgaard & King 2002, Boesgaard et al. 2004a) the Pleiades and \( \alpha \) Per (Boesgaard, Armengaud & King 2003a), Coma and UMa (Boesgaard, Armengaud & King 2003b) and Praesepe (Boesgaard, Armengaud & King 2004a). The plus signs are the stars with exoplanets from Santos et al. (2002). Right: Values of A(Be) in F and G dwarfs as a function of [Fe/H]. The symbols are the same as in the left panel. ApJ, 613, 1202.]

1.3. The Correlation of Li and Be

The cluster and field star data on Li and Be can be assembled to investigate the correlation between the abundances of these elements. Boesgaard et al. (2004b) have done this and have found correlations for the 88 field and cluster stars between 5900 - 6650 K. They have divided this into two temperatures ranges corresponding to the cool side of the Li-Be dip, 6300 - 6650 K, where Li and Be are increasing as the temperature decreases and the cooler group of early G stars near the Hyades Li peak, 5900 - 6300 K. The correlations for these two groups are shown in Figure 4, along with the best fit slope for each group. A light line with the slope for the other group is also shown to illustrate differences between the two temperature groups.

For the 35 stars with \( T = 6300 - 6650 \) K the least squares fit gives the relationship: \( \text{A(Be)} = 0.433 (\pm 0.036) \text{A(Li)} - 0.071 (\pm 0.094) \)

For the 54 stars with \( T = 5900 - 6300 \) K the least squares fit gives the relationship: \( \text{A(Be)} = 0.337 (\pm 0.031) \text{A(Li)} + 0.248 (\pm 0.078) \)
Figure 4. Left: The Li and Be abundances in the hotter stars which corresponds to the cool side of the Li-Be dip, 6300 - 6650 K. The dot-dashed line represents the best-fit least-squares slope of 0.43 ± 0.04. The faint dotted line is the slope for the stars in the right panel. The horizontal and vertical dotted lines correspond to the meteoritic Be and Li abundances respectively. Right: The Li and Be abundances in the cooler stars, 5900 - 6300 K. The dot-dashed line represents the best-fit least-squares slope of 0.34 ± 0.03. The faint dotted line is the slope for the stars in the left panel. ApJ, 613, 1202.

The 88 stars in the total sample from $T = 5900 - 6650$ K are shown in the left panel of Figure 5. The least squares solution for this line is:

$$A(\text{Be}) = 0.382(\pm 0.030) A(\text{Li}) + 0.105 \ (\pm 0.078)$$

Figure 5. Left: The Li and Be abundances in the full sample of 88 cluster and field stars with $T = 5900 - 6650$ K. A typical error bar is in the lower right. The horizontal and vertical dotted lines represent the meteoritic Be and Li abundances respectively. Right: Models - see text. ApJ, 613, 1202.

Calculations of Li and Be depletion due to rotationally-induced slow-mixing have been made by Deliyannis & Pinsonneault (1997) for dwarf stars of selected
ages (0.1, 1.7, and 4 Gyr), initial rotation (10 and 30 km s\(^{-1}\)) and specific temperatures (see their Figure 2). Examples of these depletions at the three ages and the two initial velocities are shown in Figure 5, right panel, for specific temperatures between 5900 and 6300 K. The observed slope is shown as the dot-dashed line from Figure 4, right panel. For this comparison the initial A(Be) is taken as 1.28, which corresponds to the mean of the high values in Figure 4, left panel. The observations and predictions are in remarkably good agreement and very supportive of the conclusion that the light element depletion is due to rotationally-induced mixing. Deliyannis & Pinsonneault (1997) argue persuasively against mass loss and diffusion as the source of the depletion.

1.4. Boron in Field Stars

In order to study B in the Galactic disk, Boesgaard et al. (2004c) used HST + STIS to obtain spectra of the B I line at 2497 Å in 20 stars which had no depletion of Be. The stars are from the upper envelope of Figure 3, right panel, and cover a range in [Fe/H]. Since the Be abundance is undiminished in these stars, the B abundances would be unaffected by depletion also.

![Figure 6](image_url)

Figure 6. Left: An example of the spectrum synthesis of the B I line. The upper star is a high resolution spectrum, \(R = 114,000\), while the lower star is at medium resolution, \(R = 30,000\). The dots are the observed points, the solid line is the best fit, and the dashed lines are a factor of two in \(A(B)\) above and below the best fit. Right: The B and Be abundances in the sample of stars with undepleted Be. There is a slope to the relationship with [Fe/H] of about 0.40 for both Be and B. ApJ, 606, 306.

Figure 6, left panel, shows and example of the spectrum synthesis for B I. The results of the research to determine the initial values for B and Be in Galactic disk stars are shown in Figure 6, right panel. Both B and Be increase slowly with Fe such that as Fe increases by a factor of 4, Be and B increase by a factor of \(\sim 1.7\).

Those relationships are:

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

\[
A(B)_{\text{NLTE}} = 0.402 \pm 0.117 [\text{Fe/}H] + 2.371 \pm 0.032
\]
The ratio of B/Be for the 20 stars was found to be 15, with no trend with [Fe/H]. This ratio is consistent with the predictions of spallation reactions as the source of Galactic Be and B.

1.5. The Correlation of Be and B

Another HST/STIS study of B focussed on stars with large Be depletions to try to find stars that were depleted in B. In this work Boesgaard, Deliyannis & Steinhauer (2005) looked at 13 F and G stars with large Be depletions and at five Be-normal stars. The result was the discovery of a correlation between Be and B as shown in Figure 7. The left panel shows the Be and B abundances in our sample of 18 stars and has a slope of 0.20 ±0.05. Those values have been corrected for the differences in the initial values of B and Be that result from the relations seen in Figure 6, right panel. Other Li- and Be-normal stars have been added from the work described in the previous section; those results are seen in Figure 7, right panel, where the slope is 0.18 ±0.06. Predictions for B depletion have not yet been made, but it seems likely that rotational mixing will be a key ingredient in the small B depletions.

2. Li, Be, B Summary

We have presented an amalgamation of several research projects on light elements from spectra obtained primarily with the Keck telescope and HIRES and HST with STIS. In addition to the Li dip in several intermediate age clusters, we have now discovered a Be dip in those clusters. The Be dip is not as deep as the Li dip, that is, Be is not as depleted as Li. Neither Li nor Be is measureably depleted in the younger open clusters, e.g. Pleiades. The depletion of these elements occurs during main-sequence evolution, after an age of ∼100
myr. Although Li is depleted in cooler stars, and the depletion increases with decreasing surface temperature, there is little or no Be depletion in stars cooler than 5900 K.

Many stars in clusters and the field show depleted, but detectable, Li and Be. The abundances of Li and Be are found to be correlated in such stars with Li being more depleted than Be. For stars in the temperature range of 5900 - 6650 K the relationship is:

\[ A(\text{Be}) = 0.382 (\pm 0.030) A(\text{Li}) + 0.105 (\pm 0.078). \]

When Li has decreased by a factor of 10, Be has decreased by only a factor of 2.4. This relationship is very well matched by the predictions of models with rotationally-induced mixing.

Through use of B abundances from HST data we have found that there are stars with depleted, but detected, B. And there is a correlation between the B and Be abundances. That relationship is:

\[ A(\text{B}) = 0.175 (\pm 0.058) A(\text{Be}) + 2.237 (\pm 0.055). \]

This slope is shallower than the Li-Be slope because the B preservation region is larger and B atoms have to be mixed to deeper stellar layers to be depleted.

Li, Be, B all seem to increase at about the same rate with [Fe/H] in Galactic disk stars. The slope for A(B) with [Fe/H] is 0.40 and for A(Be) with [Fe/H] is 0.38. Large depletions have been found for all three elements in our samples of F and G Population I stars.

3. Carbon and Oxygen in Open Clusters

After H and He, the most abundant elements are C, N, O, and Ne. Determining those abundances, however, is a difficult proposition. This is a report on an ongoing project to determine abundances in open clusters, and focuses on the determination of Fe, C, and O abundances in three clusters: the Pleiades at an age of \( \sim 70 \) Myr, the Hyades at \( \sim 700 \) Myr and M 67 at 5 Gyr. The spectra for all were obtained with Keck I + HIRES at high S/N and high spectral resolution of \( \sim 48,000 \). The spectral range covered 5700 - 8120 Å. Abundances were determined from some 40 lines of Fe I, 6 of C I and the 3 of the O I triplet.

3.1. Oxygen Abundances

Although abundances found from the O I triplet at 7771, 7773, and 7774 Å are influenced by the effects of NLTE, the corrections to be applied are complicated to determine and various researchers have found different results, ranging from a few hundredths to a few tenths of a dex. (In particular, there is uncertainty in the size of the collision rates and cross sections for collisions with neutral hydrogen, e.g. Kiselman 2001.) It is possible to take an empirical approach on this issue. First, we can determine O abundances in a number of stars of different temperatures on the main sequence in the same cluster. All unevolved stars in a given open cluster can be expected to have the same O abundance. We have done this for 30 stars in the Hyades cluster in a temperature range of 5700 - 7100 K; the spectra are from the Palomar 5-m condé and Keck + HIRES. The O abundances (on the scale where \( \log (H) = 12.00 \)) from the O I triplet as a function of effective temperature are shown in Figure 8 (left). While the hotter
stars show large O abundances, the values found from Hyades stars cooler than 6200 K are consistent with each other. This suggests that the NLTE effects are small (at least consistent) in the cool stars.

Figure 8. Left: Abundances of O from the O I triplet in Hyades main sequence stars, showing the effect of stellar temperature. All stars in the Hyades should have the same O abundance, but the hotter stars give abundances that are higher than the cooler stars, presumably due to effect of NLTE. The horizontal dotted line corresponds to a uniform value of log N(O)/N(H) + 12.00 = 9.10 for the 15 stars with $T_{\text{eff}} < 6200$ K. Right: Abundances of O from observations of the O I triplet and the [O I] forbidden line in the same stars, all having $T_{\text{eff}}$ less than 6200 K. The diagonal line shows the equivalent abundance from the two techniques. The stars are subdivided into three temperature groups. No differences are found in the three groups. The abundance errors are typically ±0.10.

Another empirical approach is to examine O abundances found from the O I triplet and the forbidden [O I] line at 6300 Å when these features can be measured in the same stars. This can be done with the data set in King & Boesgaard (1995). The result of this is shown in Figure 8 (right) for stars cooler than 6200 K. The diagonal line corresponds to the same abundance from the two different features of O. The two methods give the same result (within the typical error of ±0.10 dex) with no apparent difference in the three temperature groupings shown in the figure.

As a result of these two empirical demonstrations, we have determined O abundances from the O I triplet from observations of main sequence stars cooler than 6200 K. Note that Schuler et al. (2004) find that O abundances from the O I triplet begin to increase again for stellar temperatures below 5400 – 5500 K in their study of O abundances in the Pleiades and M 34. The stars in our samples in the Pleiades and M 67 are all hotter than 5500 K.

### 3.2. Hyades

We have found abundances in some 18 Hyades late-F and early-G dwarfs from Keck HIRES spectra with S/N from 610 to 730. Figure 9 (left) shows the positions of these stars in the Hyades HR diagram. The abundances of Fe were
Figure 9. Left: HR diagram for the Hyades from Hipparcos data. The stars we observed are shown as large open circles. Right: Abundances of Fe in the Hyades stars. The horizontal dotted line shows the cluster mean [Fe/H] = +0.18 ± 0.01.

found from ~40 Fe I lines for each star; those results are shown in the right panel of Figure 9. The mean cluster abundance is [Fe/H] = +0.18 ± 0.01, in good agreement with the recent value of +0.16 ± 0.02 (Yong et al. 2004).

Figure 10. Examples of the spectra of the Hyades in the C I and the O I regions. The top star is one of the hottest in our sample, the middle one is near the solar temperature and the lower one is one of the coolest in the sample.

We have found O and C abundances from the high excitation lines of these elements in the near IR spectrum. The lines used are shown in each of three Hyades stars in Figure 10. The abundances are shown as a function of temperature in Figure 11. The stars studied are all cooler than 6200 K. For the mean cluster [C/H] we find +0.16 ± 0.02 and a mean [C/Fe] = −0.02. For [O/H] we find the mean cluster abundance to be +0.17 ± 0.01 and a mean [O/Fe] = −0.01.
3.3. Pleiades

We have obtained Keck/HIRES spectra of 20 late-F and early-G dwarfs with S/N ratios of 95 – 160. The color-magnitude diagram for the Pleiades is shown in the left panel of Figure 12. The right panel of Figure 12 shows the results for [Fe/H] in these Pleiades stars from ∼40 lines.

The mean value for the cluster is [Fe/H] = +0.06 ± 0.02, which is slightly higher than previous values of +0.02 ± 0.06 (Boesgaard 1989), −0.03 ± 0.02 (Boesgaard & Friel 1990), 0.00 ± 0.05 (Boesgaard, Budge & Ramsay 1988). The abundance results for C and O are shown graphically in Figure 13. For [O/H] we find +0.11 ± 0.02 and thus [O/Fe] = +0.05. Our [O/H] is in good agreement

Figure 11. Abundance results for the Hyades for C (left panel) and O (right panel). The horizontal dotted lines show the cluster means: [C/H] = +0.16 ± 0.02 and [O/H] = +0.17 ± 0.02.

Figure 12. Left: Color-magnitude diagram for the Pleiades with the large crosses indicating the stars observed. Right: Results for the Fe abundances in the Pleiades stars. The cluster mean [Fe/H] = +0.06 ± 0.02 (dotted line).
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with that from [O I] $\lambda$6300 of +0.14 from Schulaer et al. (2004). Carbon is low in the Pleiades with [C/H] = −0.04 ±0.02 and [C/Fe] = −0.10.

![Figure 13](image)

Figure 13. Left: Carbon abundances in the Pleiades. Right: Oxygen abundances in the Pleiades. The horizontal dotted lines show the cluster means: [C/H] = −0.04 ±0.02 and [O/H] = +0.11 ±0.02.

3.4. M 67

The Keck/HIRES spectra of our 14 M 67 stars have S/N ratios ranging from 70 to 140. The stars we selected were similar to the sun and have a range in $T_{\text{eff}}$ of 5600 - 6000 K. Figure 14 (left) shows the color-magnitude diagram for M 67 with our stars as open circles and the cluster represented by a 5 Gyr isochrone from Vanden Berg (1985). The [Fe/H] values for the M 67 stars are shown in Figure 14 (right) where the cluster mean is −0.05 ±0.01.

All of our M 67 stars are cooler than 6200 K (the hottest is 5974 K) and hotter than 5500 K (the coolest is 5716 K). The 14 stars are in good agreement with each other in their values of [C/H] and [O/H]. Those results are shown in Figure 15. The cluster means are [C/H] = −0.02 ±0.02 and [O/H] = +0.01 ±0.03. The abundances of Fe, C, and O are quite close to solar for the old open cluster, M 67.

4. Carbon and Oxygen Summary

The results for the three clusters are summarized in Table 1. Although there are only three clusters discussed here, it seems apparent that there is no evidence of an age-metallicity effect in the disk clusters. The differences found in the composition of the clusters could result from the composition in the local interstellar material from which they were formed, i.e. a “place of origin” effect.

The Hyades is enhanced in Fe, C, and O relative to solar by about +0.17 dex. For M 67 the amount of the three elements is similar to that in the Sun. Although the Pleiades seems slightly enhanced in Fe and O by about +0.05 dex compared to the Sun, it seems to be low in C with [C/H] = −0.04 and [C/Fe] = −0.09.
Figure 14. Left: The color-magnitude diagram for M 67. The line is the 5 Gyr isochrone from Vanden Berg (1985) and the stars we observed are open circles. Right: The [Fe/H] values for each star plotted against its temperature. The cluster mean [Fe/H] = $-0.05 \pm 0.01$ (dotted line).

Figure 15. Left: Carbon abundances in the M 67. Right: Oxygen abundances in the M 67. The horizontal dotted lines show the cluster means: $[C/H] = -0.02 \pm 0.02$ and $[O/H] = +0.01 \pm 0.03$.

Table 1. Open Cluster Abundances

| Cluster | Age  | [Fe/H] | C/Fe | [C/H] | [O/H] | O/Fe | O/C |
|---------|------|--------|------|-------|-------|------|-----|
| Pleiades | 70 Myr | +0.06 | 0.02 | −0.04 | 0.02 | +0.11 | 0.05 | +0.15 |
| Hyades   | 700 Myr | +0.18 | 0.01 | +0.16 | 0.02 | +0.17 | 0.02 | -0.02 | -0.01 | +0.01 |
| M 67     | 5 Gyr | −0.05 | 0.01 | −0.02 | 0.02 | +0.01 | 0.03 | +0.03 | +0.06 | +0.03 |
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References

Boesgaard, A.M. 1989, ApJ, 336, 798
Boesgaard, A.M., Armengaud, E. & King, J.R. 2003a, ApJ, 582, 410
Boesgaard, A.M., Armengaud, E. & King, J.R. 2003b, ApJ, 583, 955
Boesgaard, A.M., Armengaud, E. & King, J.R. 2004a, ApJ, 605, 864
Boesgaard, A.M., Armengaud, E., King, J.R., Deliyannis, C.P. & Stephens, A. 2004b, ApJ, 613, 1202
Boesgaard, A.M., Budge, K.G. & Ramsay, M.E. 1988, ApJ, 327, 389
Boesgaard, A.M. & Budge, K.G. 1989, ApJ, 338, 875
Boesgaard, A.M., Deliyannis, C.P., King, J.R. & Stephens, A. 2001, ApJ, 553, 754
Boesgaard, A.M., Deliyannis, C.P. & Steinhauer, A. 2005, ApJ, submitted
Boesgaard, A.M. & Friel, E.D. 1990, ApJ, 351, 467
Boesgaard, A.M. & King, J.R. 2002, ApJ, 565, 587
Boesgaard, A.M., McGrath, E.M., Lambert, D.L. & Cunha, K. 2004c, ApJ, 606, 306
Boesgaard, A.M. & Tripicco, M. 1986, ApJ, 302, L49
Deliyannis, C.P., Boesgaard, A.M., Stephens, A., King, J.R., Vogt, S.S., & Keane, M. J. 1998, ApJ, 498, L147
Deliyannis, C.P. & Pinsonneault, M.H. 1997, ApJ, 488, 836
Duncan, D.K., Peterson, R.C., Thorburn, J.A., & Pinsonneault, M.H. 1998, ApJ, 499, 871
Grevesse, N. & Sauval, A.J. 1998, Sp. Sci. Rev., 85, 161
Hobbs, L.M. & Pilachowski, C.A. 1988, ApJ, 334, 734
King, J.R. & Boesgaard, A.M. 1995, AJ, 109, 383
Kiselman, D. 2001, NewAR, 45, 559
Pilachowski, C., Booth, J. & Hobbs, L.M. 1987, PASP, 99, 1288
Santos, N.C., García López, R.J., Israeliant, G. Mayor, M. Rebolo, R., García-Gil, A., Pérez de Taoro, M.R. & Randich, S. 2002, A&A, 386, 1028
Schuler, S.C., King, J.R., Hobbs, L.M. & Pinsonneault, M. 2004, ApJ, 602, L117
Soderblom, D.R., Fedele, S.B., Jones, B.F., Stauffer, J.R. & Prosser, C.F. 1993, AJ, 106, 1080
Steinhauer, A. 2003, Ph.D. thesis, Indiana University
Vandenberg, D.A. 1985, ApJS, 58, 711
Vogt, S. S. et al. 1994, Proc. SPIE, 2198, 362
Yong, D., Lambert, D.L., Allende Prieto, C. & Paulson, D.B. 2004, ApJ, 603, 697