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# THE OBSERVED TREND OF BORON AND OXYGEN IN FIELD STARS OF THE DISK

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## ABSTRACT

Oxygen abundances are derived in a sample of 13 field F and G dwarfs or subgiants with metallicities in the range $-0.75 \leq$ [Fe/H] $\leq +0.15$. This is the same sample of stars for which boron abundances have been derived earlier from archived spectra obtained with the *Hubble Space Telescope*. Only the weak [O I] 6300 Å and O I 6157 Å and 6158 Å lines have been used to determine O abundances. It is argued that, over the range of temperature and metallicity spanned by the program stars, these [O I] and O I lines provide accurate oxygen abundances, largely free from non-LTE or one-dimensional model atmosphere effects. The results for oxygen are combined with the boron abundances published previously to define a boron versus oxygen abundance for field disk stars: the relation $\log (B/H) + 12 = \log \epsilon(B) = 1.39 \pm 0.08 \log \epsilon(O) - 9.62 \pm 1.38$ is obtained. The slope of $m_{BO} = 1.39$ (in log-log abundance by number coordinates) indicates that in the disk the abundance of B relative to O is intermediate between primary and secondary production (hybrid behavior). The slope found here for $\log \epsilon(B)$ versus $\log \epsilon(O)$ is identical within the uncertainties to that found by previous investigators for $\log \epsilon(Be)$ versus $\log \epsilon(O)$, where $m_{BO} = 1.45$. The two relations of B and Be versus O result in essentially solar B/Be ratios for field disk stars. A comparison of the results here for B-O in the disk to B-O in the halo (with B abundances taken from the literature) reveals that if [O/Fe] in the halo is nearly constant or undergoes only a gentle increase with decreasing [Fe/H], then boron behaves as a primary element relative to oxygen. In such a case, there is a transition from $N(B) \propto N(O)$ in the halo to $N(B) \propto N(O)^{1.4}$ in the disk. On the other hand, if [O/Fe] increases substantially in the halo (such that [O/Fe] $\propto -0.4$[Fe/H]), as suggested by some studies of the 3100–3200 Å electronic OH lines, then there is no significant difference between the behavior of B-O in the halo compared with that in the disk [i.e., $N(B) \propto N(O)^{1.4}$].

*Key words:* Galaxy: abundances — stars: abundances

## 1. INTRODUCTION

The light elements lithium, beryllium, and boron fall, in mass, between the elements produced primarily as products of big bang nucleosynthesis, H and He, and those produced by stellar nucleosynthesis (elements heavier than $^{12}$C). These three elements consist of the five stable nuclei $^6$Li, $^7$Li, $^9$Be, $^{10}$B, and $^{11}$B. The origins of these isotopes are believed to be understood qualitatively: the big bang produced some $^7$Li (perhaps 10% of the total current Galactic disk abundance). Spallation interactions between cosmic rays and ambient gas in the interstellar medium provide some amounts of all five of these light stable nuclei. A variation of cosmic-ray production includes fusion reactions of the form $\alpha + \alpha$ between cosmic ray $\alpha$-particles and interstellar $^4$He to produce some $^6$Li and $^7$Li. Stellar nucleosynthesis also plays a role in the synthesis of $^7$Li and $^{11}$B; neutrino-induced spallation in core-collapse Type II supernovae (SN II) may produce some $^7$Li and $^{11}$B, while hot bottom burning in asymptotic giant branch (AGB) stars is known to create $^7$Li.

With so many processes involved in light element synthesis, understanding the chemical evolution of Li, Be, and B requires substantial input from both observations and theory. Within the last 5–10 years, the addition of new observations of boron from the *Hubble Space Telescope* and of beryllium from large ground-based telescopes and the

inclusion of stellar and interstellar medium (ISM) observations of $^6$Li have resulted in more emphasis on quantitative comparisons of yields from the various production mechanisms of the theory. In this paper, the focus is on a better definition of the relationship of boron versus oxygen for the more metal-rich regime from [Fe/H] $\sim -0.75$ to $+0.15$.

Most previous studies of boron with metallicity have used iron as the fiducial metallicity indicator. This is due in part to the ease with which Fe abundances can be measured in stars; large numbers of Fe I and Fe II lines are easily measurable over a range of stellar effective temperatures and metallicities. Although easy to observe and analyze, iron is perhaps not the best choice as a benchmark against which to measure boron: the nucleosynthetic origin of Fe, above [Fe/H] $\geq -1.0$, arises both in SN II and SN Ia, as well as the fact that Fe plays essentially no role in the spallative production of the light elements.

Oxygen, on the other hand, is more directly related to B production: boron produced by the *v*-process should scale with oxygen (as both the *v*-process and O-production result from SN II); spallation reactions, which produce $^{10}$B and $^{11}$B, result to a large degree from O, either as energetic protons spallating ISM $^{16}$O or as accelerated oxygen being spalled from ambient ISM H and He, but oxygen is more difficult to observe than iron. The choice of available lines is

more limited and the reliability of these lines remains a topic of active research and discussion. There are basically four ways to measure oxygen abundances in stars with $T_{\rm eff} \leq 7000$ K (which correspond to the main-sequence turnoff for the lower mass old disk or halo stars): (1) the forbidden [O I] lines at 6300 Å and 6363 Å; (2) permitted O I lines, such as the well-known near-IR triplet lines at 7771–7775 Å (which are quite strong at solar-like metallicities and temperatures), or weaker O I lines, such as those found near 6156–6158 Å; (3) OH from electronic transitions in the near-UV region 3100–3200 Å; and (4) OH from vibration-rotation transitions in the IR near 1.6 and 3.4 $\mu$m. All these various oxygen determinants have good and bad points associated with them, and there is an extensive body of literature on this topic; a recent summary of ideas concerning the pros and cons of the different ways to measure oxygen is found in the review by Lambert (2001).

Some of the major points concerning the derivation of oxygen abundances can be summarized as follows: The zero-volt [O I] lines should be reliable O abundance indicators in the cool stars, as most of the oxygen atoms are neutral in the ground state. However, these lines are fairly weak, requiring spectra with relatively high signal-to-noise ratio (S/N) and will not be observable at all for the more metal-poor stars. The permitted O I lines at 7771–7775 Å are strong lines and are thus detectable even in very metal-poor stars; however, they arise from $\chi = 9.14$ eV and thus represent only a small fraction of total O I atoms. It has been argued that these lines may be affected by non-LTE, as well as being sensitive to small-scale temperature inhomogeneities in a star's atmosphere, i.e., granulation (Kiselman 1991, 1993; Kiselman & Nordlund 1995). The size of this effect and its variation with temperature, gravity, and metallicity remain a topic of some controversy. The other permitted lines near 6156–6158 Å are very weak and, although apparently free of substantial effects due to non-LTE or atmospheric structure (Kiselman 1993), require high S/N ($\geq 300$) and are detectable only at relatively high metallicities.

The molecular OH lines remain an option and the near-UV electronic OH lines were studied initially by Bessell & Norris (1987) and Bessell, Sutherland, & Ruan (1991), with more recent and quite extensive surveys by Israelian, Garcia-Lopez, & Rebolo (1998) and Boesgaard et al. (1999b). The region near 3100–3200 Å is not only difficult to observe from the ground, but it is also quite line-blanketed in stars with near-solar metallicities, and there is a recent discussion of missing continuous opacities (in the Sun) by Balachandran & Bell (1998). Presumably, though, the importance of metal opacities lessens as [Fe/H] decreases. There also remains a suspicion that the near-UV OH is sensitive to temperature structure across a stellar disk, as well as non-LTE effects (Lambert 2001). The use of three-dimensional model atmospheres may be required to investigate these possibilities (Apslund 2001). The IR vibration-rotation transitions of OH lie in clean regions of the spectrum and should form in LTE (Hinkle & Lambert 1975). Use of the IR OH lines is still in an early stage (Balachandran & Carney 1996), but with more access to high-resolution IR spectroscopy the number of oxygen abundance determinations based on these lines will increase.

To define better the trend of B versus O at the metal-rich end ([Fe/H] $\geq -0.75$), oxygen abundances have been derived for a sample of field stars in which boron abundances were measured by Cunha et al. (2000). These stars have now been observed with high resolution and high signal-to-noise spectra sufficient to measure either the [O I] 6300 Å line or the weak O I lines at 6157 Å. Based on previous work such as Kiselman (1993) or the ideas summarized by Lambert (2001), these two sets of oxygen lines should provide abundances relatively free from non-LTE or model atmosphere effects.

## 2. OBSERVATIONS

The spectra containing the neutral oxygen lines presented here were taken with two different telescopes and spectrometers, both located at McDonald Observatory at the University of Texas. One subset of program stars was observed with the Sandiford cross-dispersed echelle spectrometer, attached to the Cassegrain focus of the 2.1 m Struve reflector. This spectrometer provides a 2 pixel resolving power of $\lambda/\Delta\lambda = R = 60{,}000$ on a $400 \times 1200$ pixel CCD detector, and spectra cover the wavelength interval 6050–7900 Å. Nine target stars were observed on two runs, in 2000 February and April. In addition, four other stars were observed in 2000 September with the H. J. Smith 2.7 m reflector and cross-dispersed coude echelle spectrometer; these spectra were obtained with a $2048 \times 2048$ pixel CCD at a resolution (5 pixels) of $R = 110{,}000$. These higher resolution data do not have complete spectral coverage, and of the oxygen lines only the [O I] 6300 Å line was visible. Because weak oxygen lines were the primary goal of the spectroscopy, relatively high signal-to-noise ratios were obtained with both instruments: S/N $\sim$ 300–400.

Data reduction utilized the IRAF software from NOAO. Bias CCD frames were subtracted from the raw program CCD images (stars, internal quartz flat fields, and ThAr hollow cathode lamps). The two-dimensional locations of the spectral orders were defined, interorder light was then identified in each frame, and polynomial fits to this light were made in both the dispersion and cross-dispersion directions, with the resultant interorder light subtracted from the image in question. The bias-subtracted and interorder-corrected frames were then divided by the flat-field images, and the defined spectral orders were then summed and extracted to obtain a set of one-dimensional spectra. Wavelength calibrations were set from the ThAr spectra, with typical residuals from a wavelength fit of 5–8 mÅ for the 2.1 m spectra and 2–3 mÅ for the 2.7 m spectra.

In all stars, the final S/N ratios were sufficient to detect the [O I] 6300 Å line and the O I lines near 6157 Å. Because of their weakness and the possibilities of blending with even weaker nearby lines, spectrum synthesis was employed in the analysis of these features. In addition, in the $R = 60{,}000$ spectra the stronger near-IR O I triplet lines, near 7774 Å, were easily detectable and equivalent widths measured for these lines. Fringing occurs in the Sandiford CCD, redward of about 7500 Å, and this fringing on these observing runs was not removed entirely by division either by the flat field or by the hot star. The wavelength scale of the fringing is larger than the spectral line widths, and in particular equivalent widths of the near-IR triplet lines were measured with regard to the fringing (with amplitude $\sim$10%). Comparison with published equivalent widths of these O I lines reveals good agreement (within 1–8 mÅ), indicating that reasonably accurate equivalent widths could be measured from these spectra for these lines.

## 3. ANALYSIS

The stellar parameters ($T_{eff}$, log $g$, and [Fe/H]) for the program stars were the same as those adopted in the study of boron by Cunha et al. (2000). These parameters, in turn, were taken largely from the work of Boesgaard et al. (1998), with some minor modifications in the values of the microturbulent velocities made by Cunha et al. (2000), who found somewhat smaller values. The effective temperatures used here were obtained from an average of eight photometric scales and from the infrared flux method. The log $g$ values for the sample stars were derived from the recipe in Edvardsson et al. (1993), which comes from a comparison of the $c_1$ indices with those from the stellar models. Stellar parameters are listed in columns (1)–(5) of Table 1.

Although it is not expected that the stellar parameters for near-solar metallicity F and G dwarfs and subgiants are seriously in error, consistency checks were made on the adopted effective temperatures, gravities, and metallicities. In the first check, it was found that nine of our program stars were in common with the large abundance study of disk F and G stars from Edvardsson et al. (1993). They derived effective temperatures from theoretical Strömgren colors (primarily $b - y$) computed from opacity-sampled MARCS model atmospheres and obtained metallicities from a sample of Fe I and Fe II lines. A comparison of our adopted values with their $T_{eff}$ values and those of [Fe/H] revealed the following mean differences, in the sense of values of this study minus values of Edvardsson et al.: $\Delta T_{eff} = -85 \pm 34$ K and $\Delta$[Fe/H] $= 0.00 \pm 0.06$ dex. Our adopted surface gravities could also be compared with the values in Edvardsson et al. (1993), although their recipe was used to derive our log $g$ values. The comparison, as expected, is very good, with $\Delta$ log $g = 0.00 \pm 0.04$, and any differences result from the sensitivity of the log $g$ values to the different $T_{eff}$ values and metallicities.

As a further check, our adopted surface gravities were compared with those obtained ultimately from trigonometric parallaxes measured with the *Hipparcos* satellite. Allende Prieto & Lambert (1999) derived fundamental parameters for roughly 17,000 nearby stars from comparison with evolutionary calculations. A direct comparison of the log $g$ values for all stars studied here with the trigonometric log $g$ values listed in their Table 1 indicated very good agreement: a mean difference (values from this study minus trigonometric values) of $-0.04 \pm 0.10$ dex.

Another possibility was to compare the adopted stellar parameters with parameters determined spectroscopically. A sample of Fe I and Fe II lines, with accurate laboratory $gf$-values, were measured in all program stars from the spectra obtained here. A discussion of a selected sample of iron lines and their $gf$-values is found in Smith et al. (2000); using this set of lines in a solar model yields an iron abundance of log $\epsilon$(Fe) $= 7.50$, in agreement with the meteoritic value, and a solar microturbulent velocity of 1.0 km s$^{-1}$. For our $R = 60,000$ spectra, this line list represented 22 Fe I lines and four Fe II lines, while for the $R = 110,000$ spectra (with incomplete wavelength coverage), 5 Fe I and 2 Fe II lines were measured. A simultaneous fit, demanding the same Fe abundances from low- and high-excitation ($\chi \sim 2$–5 eV) and weak and strong ($\sim 5$–120 mÅ) Fe I lines, as well as the Fe II lines, yields spectroscopic values of $T_{eff}$, log $g$, $\xi$, and Fe abundance. In all cases for the program stars, it is found that the Fe I and Fe II lines yield stellar parameters that are extremely close to the adopted ones. The mean differences (and standard deviations) of the spectroscopic parameters minus those from Cunha et al. are $\Delta T_{eff} = -25 \pm 30$ K, $\Delta$log $g = -0.05 \pm 0.07$, and $\Delta\xi = +0.2 \pm 0.2$ km s$^{-1}$. Use of the spectoscopic parameters would have no significant effect on B and O (or Fe), thus to retain consistency with the boron results from Cunha et al. (2000) we adopt the stellar parameters used in that study.

The LTE synthesis code MOOG and Kurucz model atmospheres were used to perform spectrum synthesis for the 6157 and 6300 Å regions, with the line lists constructed using the Kurucz & Bell (1995) compilation of atomic lines and lines other than those from oxygen in these spectral intervals having their respective $gf$-values adjusted to fit the solar flux spectrum (Kurucz et al. 1984). For the rather strong O I near-IR lines, equivalent widths were measured and oxygen abundances derived from these. Imperfect cancellation of telluric $O_2$ rendered the [O I] line questionable

TABLE 1

STELLAR PARAMETERS AND BORON AND OXYGEN ABUNDANCES

| Star (1) | $T_{eff}$ (K) (2) | log $g$ (3) | [Fe/H] (4) | $\xi$ (km/s) (5) | $A(B)$[a] (6) | $A([O\ I])$[a] (7) | $A(O\ I_{6158})$[a] (8) | $A(O\ I_{7774})$[a] (9) | $A(O)$[a] (10) |
|---|---|---|---|---|---|---|---|---|---|
| HD 4813 ......... | 6150 | 4.4 | −0.14 | 1.1 | 2.7 | 8.78 | ... | ... | 8.78 |
| HD 5015 ......... | 6110 | 4.0 | +0.02 | 1.3 | 2.5 | 8.76 | ... | ... | 8.76 |
| HD 19994 ........ | 6130 | 4.1 | +0.15 | 1.3 | 2.8 | 8.98 | 8.89 | 9.11 | 8.94 |
| HD 28033 ........ | 6185 | 4.3 | +0.11 | 1.4 | 2.6 | ... | 8.89 | 8.97 | 8.89 |
| HD 61421[b] ....... | 6560 | 4.0 | −0.02 | 1.2 | 2.3 | 8.92 | 8.87 | 9.32 | 8.90 |
| HD 82328 ........ | 6300 | 4.1 | −0.17 | 1.2 | 2.6 | 8.81 | 8.72 | 9.05 | 8.76 |
| HD 128167....... | 6650 | 4.3 | −0.39 | 1.0 | 2.3 | 8.62 | 8.64 | 8.90 | 8.63 |
| HD 150680[b]...... | 5825 | 3.8 | 0.00 | 1.5 | 2.2 | 8.96 | 8.84 | 8.94 | 8.90 |
| HD 159332....... | 6180 | 3.9 | −0.22 | 1.0 | 2.4 | ... | 8.62 | 9.07 | 8.62 |
| HD 184499....... | 5650 | 4.1 | −0.75 | 1.0 | 2.1 | 8.48 | 8.60 | 8.87 | 8.54 |
| HD 185395....... | 6700 | 4.3 | +0.01 | 1.0 | 2.6 | ... | 8.76 | 9.22 | 8.76 |
| HD 210027....... | 6480 | 4.3 | −0.08 | 1.2 | 2.6 | 8.65 | ... | ... | 8.65 |
| HD 216385....... | 6200 | 4.0 | −0.30 | 1.0 | 2.4 | 8.73 | ... | ... | 8.73 |
| Sun................ | 5777 | 4.44 | 0.00 | 1.3 | 2.7 | 8.91 | 8.84 | 8.84 | 8.88 |

[a] Abundances with $A(x) = \log \epsilon(x)$.
[b] Lithium and beryllium depleted stars (Boesgaard et al. 1998; Cunha et al. 2000).

in three of the 11 stars observed at $R = 60,000$ (this line in these stars was not analyzed), while in the four stars observed at $R = 110,000$, the spectral coverage included only the [O I] line. Oscillator strengths for the permitted O I lines at 7774 Å were taken from Bell & Hibbert (1989) and Butler & Zeippen (1991), while $gf$-values for the O I lines at 6157 Å were from Wiese, Glennon, & Smith (1966). The $gf$-value suggested by Lambert (1978) was used for the [O I] 6300 Å line. In Figure 1 are shown synthetic spectral fits to the weak [O I] and O I lines in HD 184499: this star was chosen as an illustration because of its relatively low metallicity, with the [O I] and O I lines easily detected and well-defined.

The derived LTE oxygen abundances, as well as stellar parameters and boron abundances, are summarized in Table 1. Abundances from all three sets of oxygen lines, the [O I] 6300 Å line and the two O I lines near 6157 Å, as well as the near-IR O I lines near 7774 Å, are listed in columns (7)–(9) of Table 1. Columns (1)–(5) of this table contain the stellar names and parameters, while column (6) lists the non-LTE boron abundances. If both the [O I] 6300 Å and O I 6157 Å sets of lines are used, the final O abundance (listed in col. [10] of Table 1) is the average of both sets, otherwise, either 6300 or 6157 Å is used in the final abundance. A comparison of abundances derived from the oxygen lines is shown in Figure 2, where the O abundances from O I 6157 Å are plotted versus those from [O I] 6300 Å: the solid line shows perfect agreement, while the dashed lines represent $\pm 0.1$ dex. These two weak-line indicators are in good agreement, with ~0.1 dex differences not at all unexpected for such weak lines. The mean difference in abundance from these two sets of lines is ([O I] − O I)
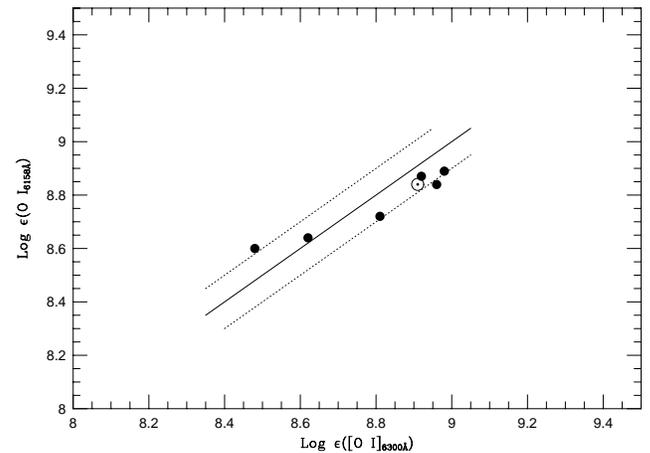


FIG. 2.—Comparison of oxygen abundances derived from the forbidden line at 6300 Å and the weak excited O I lines at 6157 Å and 6158 Å. There are six program stars in which both sets of lines were measured, as well as results for the Sun from the Solar Flux Atlas of Kurucz et al. (1984). The solid line depicts a perfect agreement, while the dashed lines illustrate $\pm 0.1$ dex from perfect agreement. These results demonstrate that together the [O I] 6300 Å line and the O I 6157 Å and 6158 Å lines yield completely consistent results, within ~0.1 dex, over the range of $T_{\rm eff}$ values, gravities, and oxygen abundances spanned by the program stars.

$+ 0.04 \pm 0.08$ dex: this is a reasonable estimate of the uncertainties in the O abundances presented for this sample of stars. In addition, the [O I] line has an excitation potential of $\chi = 0.00$ eV, while the 6157 Å O I lines have $\chi = 10.74$ eV. Such good agreement between lines of quite different excitation potentials suggests that the $T_{\rm eff}$ scale used here is
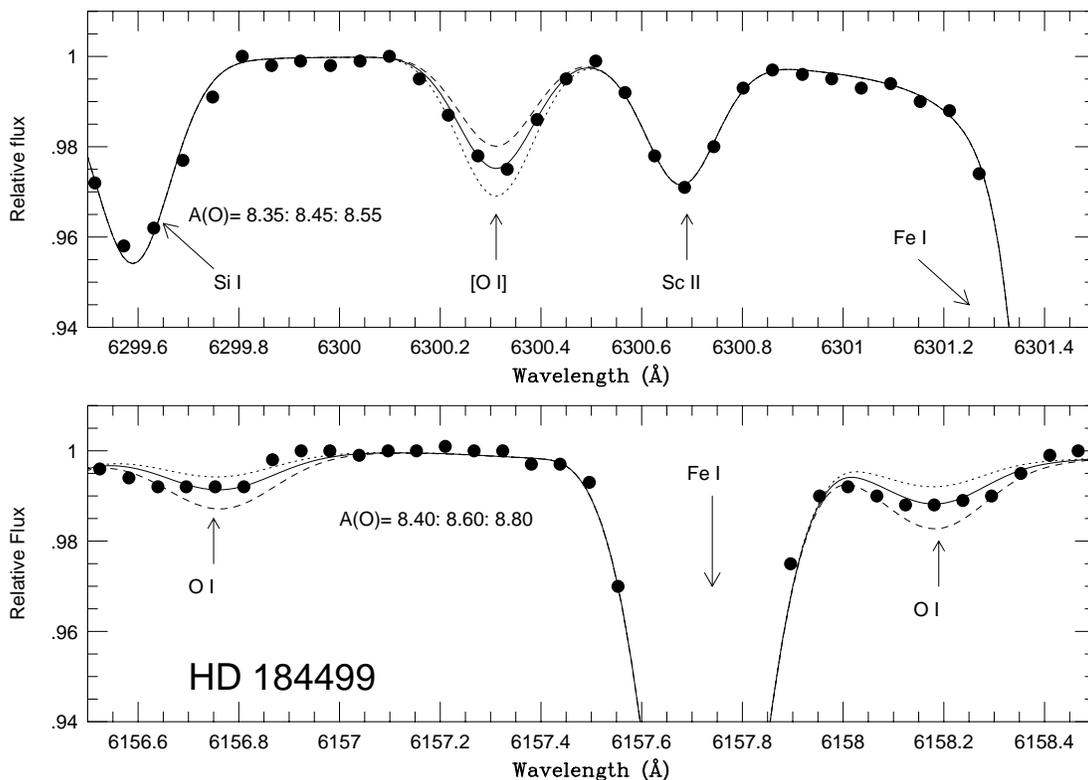


FIG. 1.—Spectra of one of the more metal-poor sample stars: HD 184499, showing the observed points (*circles*) and the synthetic spectra (*solid curves*) and two spectral regions: the forbidden line, [O I] 6300 Å (*top*) and the excited, permitted O I lines near 6157 Å (*bottom*). These weak oxygen lines provide O abundances that are relatively free from non-LTE effects and are the primary oxygen abundance indicators for all studied stars.

adequate. We note that Edvardsson et al. (1993) found trends between abundances derived from the [O I] 6300 Å and O I 6157 Å lines such that $[O/Fe]_{6300} = -0.025 + 0.4657[O/Fe]_{6157}$. The sample here is too small and spans too limited a range in [O/Fe] to test the Edvardsson et al. relation significantly. Our results, however, do fit easily within an Edvardsson-like relation with a slope of 0.60 and an offset from them of 0.09 dex. Again, over the limited range of [O/Fe] spanned by the stars in this sample, the differences between [O I] and O I are less than 0.1 dex.

The good agreement found between [O I] and O I 6157 Å is not found when these weak-line O abundance results are compared with abundances derived from the triplet O I lines near 7774 Å. (See Table 1, as well as Fig. 1, in Cunha, Smith, & King 2001). Attempts to find some order in the sense of the differences between O I 7774 Å and the other two sets of lines do not succeed completely. Although some trend is found with temperature, in the sense that the 7774 Å lines tend to give systematically larger O abundances as $T_{eff}$ increases, there is still considerable scatter at any given $T_{eff}$. King & Boesgaard (1995) found that in nearly solar-metallicity ($[Fe/H] \geq -0.5$) F and G stars the [O I] and O I 7774 Å lines show reasonably good abundance agreements for $T_{eff} \leq 6200$ K, but the O I lines then yield systematically larger O abundances for the hotter stars. This is similar to what is found here, although we have fewer stars (note in Table 1 that the best agreement between [O I] and O I 7774 Å is found for the two coolest stars, HD 150680 and the Sun).

## 4. RESULTS AND DISCUSSION

It has been argued here that the O abundances derived from the combination of [O I] 6300 Å and O I 6157 Å lines in this sample of 13 field F and G stars do not suffer from significant non-LTE or model atmosphere effects. These abundances can be combined with the boron abundances to define a B-O relation for the disk. Figure 3 (top) shows such a relation, a plot of log $\epsilon(B)_{NLTE}$ versus log $\epsilon(O)$; the boron abundances have uncertainties characterized by $\sim \pm 0.2$ dex, while we estimate here (based on the comparison of [O I] with O I 6157 Å abundances in the same stars) that the O abundances have typical uncertainties of $\pm 0.1$ dex, and these error estimates are indicated by the error bars in Figure 3. Two stars, HD 61421 and HD 150680, were excluded from Figure 3 and from the B-O fit because these two stars exhibit extremely large Li depletions, as well as measurable Be depletion, and thus may also have undergone some B astration (Boesgaard et al. 1998; Cunha et al. 2000). The remaining 11 stars in Figure 3 (top) show no evidence of B depletion. There is a well-defined trend of B with O in Figure 3, and in the log-log plane it is fitted by a straight line over this (admittedly limited) range of abundance in oxygen. The slope of this line, derived from a linear least-squares fit that includes the data point error estimates, is $m_{BO} = 1.39 \pm 0.08$ (the intercept of this line is $-9.62 \pm 1.38$). Viewed another way, the number abundances of boron and oxygen vary as $N(B) \propto N(O)^{1.4}$ in field disk stars. Models that include either only direct or only reverse production of B by energetic particles predict secondary or primary behavior of B with O: in log-log space this corresponds to slopes of either 2.0 or 1.0, respectively. At the metal-rich end of the metallicity distribution of stars in the Galaxy, for this sample of field stars these results rule out either pure primary or pure secondary production of B

with O, presumably indicating a combination of processes for B production in the disk.

It is of interest to compare the slope of log $\epsilon(B)$ versus log $\epsilon(O)$ derived here in disk stars with other studies of boron in halo stars. Both Duncan et al. (1997) and Garcia-Lopez et al. (1998) have measured boron in nine halo stars spanning the range of [Fe/H] from $-3.0$ to $-0.4$ (for three other halo stars observed for boron, Garcia-Lopez et al. argue only for upper limits to the B I detection, and we discard these stars in the following discussion). Oxygen abundances are also available for this sample of halo stars from the literature, and both Duncan et al. and Garcia-Lopez et al. include some comments on these literature O abundances in their analyses of the behavior of B. Both papers point to the fact that oxygen abundances in halo stars, which rely almost exclusively on the near-IR O I or near-UV OH, remain uncertain, with large scatter found from various literature values for the same star. In the end, these studies resort to assuming an [O/Fe] versus [Fe/H] relation to estimate how B might vary with O in the halo. It turns out that the evolution of B with O over the entire range of halo to disk hinges critically on the behavior of [O/Fe] with [Fe/H].

As a first step in investigating the possible halo behavior of boron, we used the non-LTE boron results from both Duncan et al. and Garcia-Lopez et al. (for nine stars) and simply averaged their respective values: both studies find excellent agreement between their boron abundances, with only small ($\sim 0.1$ dex) differences. Here, iron abundances are taken from literature values (for which there is little disagreement), and three assumed [O/Fe] relations are used to "derive" the respective runs of boron versus oxygen. This is the same approach as that used by Duncan et al. (1997) and Garcia-Lopez et al. (1998) and is used because of the uncertainty still under discussion about how the abundance of O varies with metallicity in the metal-poor stars. Using this approach allows one to see quantitatively how the different possible behaviors of oxygen in the metal-poor stars will affect the transitional behavior of B versus O from halo to disk. In one case, we use $[O/Fe] = -0.4[Fe/H]$ over the entire range of [Fe/H] values (as found by most of the near-IR O I studies, e.g., Cavallo, Pilachowski, & Rebolo 1997, or near-UV OH studies, e.g., Israelian et al. 1998 or Boesgaard et al. 1999b), while in the second case we assume that $[O/Fe] = -0.4[Fe/H]$ down only to $[Fe/H] = -1.0$, below which [O/Fe] stayed constant (as is found typically by studies that use [O I], e.g., Barbuy 1988; Fulbright & Kraft 1999; Apslund 2001). Use of a simple break point in the [O/Fe] relation at $[Fe/H] = -1.0$ is assumed, although the reality of such a break point has been investigated by King (1994). He suggests that a simple polynomial provides as good a fit to the data as two lines, although the differences between the two ways of parameterizing [O/Fe] versus [Fe/H] will not affect results discussed here. It should also be noted that most of the stars used to define [O/Fe] using the [O I] line are giants, and there remains a possibility that some of these giants have undergone very deep mixing that might mix material that is depleted in O, via the CNO cycles, onto the surface. Such O depletions, however, should also be accompanied by large N enhancements, which have not been observed in samples of field red giants (e.g., Langer, Suntzeff, & Kraft 1992). We also consider the possibility that [O/Fe] follows a gentle but steady increase with decreasing [Fe/H], as advocated
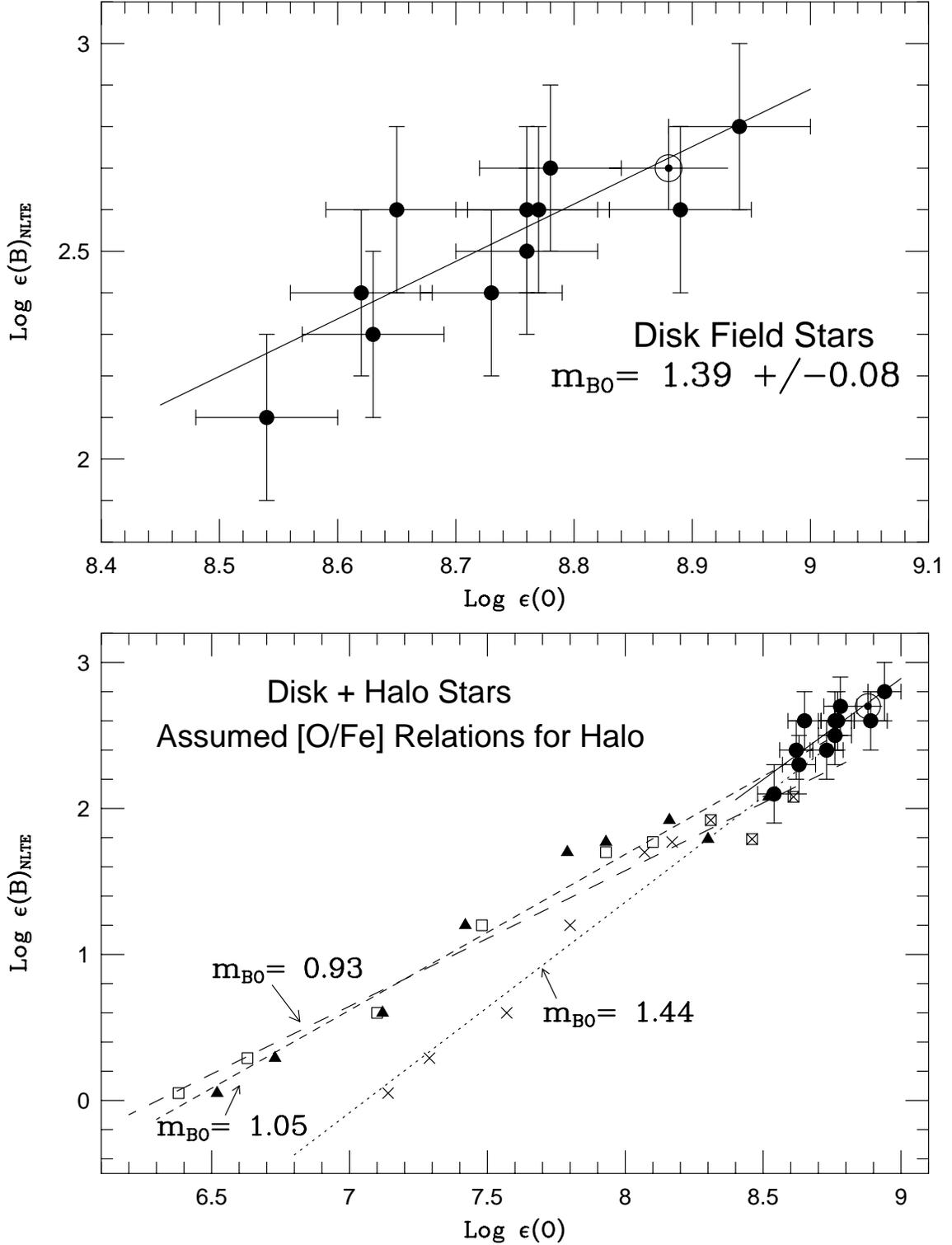
FIG. 3.—*Top*: Metal-rich disk relation between boron and oxygen for stars studied here. All these program stars have undepleted B. The oxygen abundances are based exclusively on the weak [O I] 6300 Å and 6157 Å lines. The non-LTE boron abundances are from Cunha et al. (2000). In the log-log plot of abundances, there is a well-defined "linear" relationship (correlation coefficient of 0.90) with a slope of 1.39 ± 0.08, or $N(B)$ proportional to $N(O)^{1.4}$. We expect this relationship, defined at the metal-rich end, to be free from significant systematic effects. *Bottom*: Comparison of the relation defined for the disk stars with that of boron abundances obtained for halo stars from Duncan et al. (1997) and Garcia-Lopez et al. (1998). Because oxygen abundances from the near-UV OH lines and near-IR O I triplet lines (which are the lines used in the halo stars) remain uncertain, oxygen abundances are estimated from Fe abundances by using three different assumptions about the behavior of O with Fe in the halo. The $m_{BO} = 0.93$ line is derived from an O/Fe relation in which [O/Fe] is constant (at +0.4) below [Fe/H] of −1.0, as suggested in the recent preprint by Apslund (2001; *squares*). The $m_{BO} = 1.05$ line is from a King (2000) relation of [O/Fe] = −0.184[Fe/H] + 0.019 (*triangles*), while the $m_{BO} = 1.44$ line results from [O/Fe] increasing steadily as −0.4[Fe/H], as indicated by the OH results from Israelian et al. (1998) and Boesgaard et al. (1999b; *crosses*).

by King (2000), where [O/Fe] = −0.184[Fe/H] + 0.019. A comparison of the resulting B-O relations are shown along with the disk relation in Figure 3 (*bottom*). It is found that for the case of a continually increasing [O/Fe] ratio, the halo slope of log $\epsilon$(B) versus log $\epsilon$(O) is $m_{BO} = 1.44$. This slope is indistinguishable from the slope we derive for the disk stars, pointing to no evolution in the yields of B/O as the oxygen abundance increases by 2 orders of magnitude. If, on the other hand, the constant value of [O/Fe] = +0.4 is used below [Fe/H] values of −1.0, the slope for the halo B abundances is then $m_{BO} = 0.92$: significantly different than that found for the disk stars (where we argue that the oxygen abundances are secure). In addition, for the steady but gently sloped increase from King (2000) we derive a similar slope of $m_{BO} = 1.05$. For these latter two cases, there would be a clear slope change in log $\epsilon$(B) versus log $\epsilon$(O) near [Fe/H] ∼ −1.0, which would indicate a change in yields of B/O, going from near primary in the halo to intermediate primary-secondary (hybrid) in the disk. Clearly, more work on the oxygen abundances for the halo stars for which boron abundances have been derived is desirable.

In the above exercise, oxygen abundances have been estimated directly from the Fe abundances using three different assumed O-Fe relations. The results obtained above could be incorrect if the literature Fe abundances were in error. Recently, Idiart & Thevenin (2000) have presented calculations that indicate that Fe I may be measurably out of LTE in solar-temperature stars at low metallicities (with the effect increasing as [Fe/H] decreases). We have thus also used the published corrections from Idiart & Thevenin for Fe to rederive O abundances using their non-LTE Fe abundances for the halo program stars. These new oxygen estimates were then compared with those of boron, and the following slopes were obtained: for a steadily increasing [O/Fe] ratio of 0.4[Fe/H], a halo boron-oxygen slope is found to be $m_{BO} = 1.57$, and for the constant [O/Fe] value of +0.4 for the halo, a slope of 1.10 is obtained, while for King's (2000) relation the slope is 1.19. The conclusions from the previous paragraph remain: In one case the slope from disk to halo remains approximately constant, while in the other two cases, there is a transition from an intermediate slope in the disk to primary behavior of B-O in the halo.

Beryllium is an interesting element to compare with boron, and Boesgaard et al. (1999a) have presented an extensive set of results for Be versus O for [O/H] ranging from −2.0 to 0.0. They also find that, in a log-log plot, Be is linearly related to O, with a slope of $m_{BeO} = 1.45 \pm 0.04$. The oxygen abundances from Boesgaard et al. are obtained from the near-UV OH, and the discussion from the previous two paragraphs applies to this slope as well. At the metal-rich end of the distribution ([Fe/H] ≥ −1.0), however, there may be little to no correction to the O

abundances from the near-UV OH (Apslund 2001), thus the results from Boesgaard et al. can be compared directly with the results here for B versus O. The slopes between B and Be, within the uncertainties, are identical. Transformed to the log $\epsilon$ notation the Boesgaard et al. relation for Be-O is log $\epsilon$(Be) = 1.45[log $\epsilon$(O)] − 11.57, which can be compared with our result for boron, log $\epsilon$(B) = 1.39[log $\epsilon$(O)] − 9.62. These two relations of B and Be versus O predict ratios of B/Be of 28 at log $\epsilon$(O) = 8.90 and 26 at log $\epsilon$(O) = 8.40, close to the solar value of B/Be = 23 (meteoritic) and 20 (photospheric),

## 5. CONCLUSIONS

Oxygen abundances have been derived from weak lines of [O I] 6300 Å and O I 6157 Å, which are argued to be reliable indicators for deriving O abundances, in a sample of disk F and G stars. The sample of disk stars for which oxygen was measured are the same stars in which Cunha et al. (2000) have determined boron abundances, and a relation between log $\epsilon$(B)$_{NLTE}$ and log $\epsilon$(O) has been established for these disk F and G stars. A well-defined slope, in log-log coordinates, is found with $m_{BO} = 1.39 \pm 0.08$, which indicates a relation intermediate between primary and secondary production of B with respect to O. This slope is identical to the analogous slope found for Be-O by Boesgaard et al. (1999a) for stars covering the same metallicity range (they find $m_{BO}$ = in a log-log relation to be 1.45).

A comparison of boron abundances derived here to published halo B abundances (from Duncan et al. 1997 and Garcia-Lopez et al. 1998) shows good agreement in the overlap O abundance region, but the relation of B to O in the halo still depends critically on the interpretation of oxygen abundances derived from the near-IR O I lines or the near-UV OH lines, a subject still not completely resolved. It was shown that if the oxygen abundances as found from the near-UV OH lines remain, then the intermediate slope of B versus O continues unchanged (within the uncertainties) from disk to halo. On the other hand, if O abundances, as derived from the near-UV OH, are lowered by approximately −0.25 dex at [Fe/H] = −2.0 and approximately −0.50 dex at [Fe/H] = −3.0 (Apslund 2001) the behavior of B with O in the halo becomes nearly primary, indicating a change in the B-O relation from halo to disk (with the slope increasing from ∼ 1.0 to 1.4).

REFERENCES

Allende Prieto, C., &, Lambert, D. L. 1999, A&A, 352, 555
Asplund, M. 2001, NewA R. in press
Balachandran, S., & Bell, R. A. 1998, Nature, 392, 791
Balachandran, S., & Carney, B. W. 1996, AJ, 111, 946
Barbuy, B. 1988, A&A, 191, 121
Bell, K. L., & Hibbert, A. 1989, J. Phys. B., 23, 2673
Bessell, M. S., & Norris, J. 1987, J. Astrophys. Astron., 8, 99
Bessell, M. S., Sutherland, R. S., & Ruan, K. 1991, ApJ, 383, L71
Boesgaard, A. M., Deliyannis, C. P., King, J. R., Ryan, S. G., Vogt, S. S., & Beers, T. C. 1999a, AJ, 117, 1549
Boesgaard, A. M., Deliyannis, C. P., Stephens, A., & Lambert, D. L. 1998, ApJ, 492, 727

Boesgaard, A. M., King, J. R., Deliyannis, C. P., & Vogt, S. S. 1999b, AJ, 117, 492
Butler, K., & Zeipen, C. J. 1991, J. Phys. IV, Colloque C1, 141
Cavallo, R. M., Pilachowski, C. A., & Rebolo, R. 1997, PASP, 109, 226
Cunha, K., Smith, V. V., Boesgaard, A. M., & Lambert, D. L. 2000, ApJ, 530, 939
Cunha, K., Smith, V. V., & King, J. R. 2001, NewA R. in press
Duncan, D. K., Primas, F., Rebull, L. M., Boesgaard, A. M., Deliyannis, C. P., Hobbs, L. M., King, J. R., & Ryan, S. G. 1997, ApJ, 488, 338
Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P., & Tomkin, J. 1993, A&A, 275, 101
Fulbright, J. P., & Kraft, R. P. 1999, AJ, 118, 527

García López, R. J., Lambert, D. L., Edvardsson, B., Gustafsson, B., Kiselman, D., & Rebolo, R. 1998, ApJ, 500, 241
Hinkle, K., & Lambert, D. L. 1975, MNRAS, 170, 447
Idiart, T., & Thévenin, F. 2000, ApJ, 541, 207
Israelian, G., García López, R. J., & Rebolo, R. 1998, ApJ, 507, 805
King, J. R. 1994, AJ, 107, 350
————. 2000, AJ, 120, 1056
King, J. R., & Boesgaard, A. M. 1995, AJ, 109, 383
Kiselman, D. 1991, A&A, 245, L9
————. 1993, A&A, 275, 269
Kiselman, D., & Nordlund, A. 1995, A&A, 302, 578
Kurucz, R. L., & Bell, B. 1995, CD-ROM 23, Atomic Line Data (Cambridge: Smithsonian Astrophys. Obs.)

Kurucz, R. L., Furenlid, I., Brault, J., & Testerman, L. 1984, Solar Flux Atlas from 296 to 1300 nm (Cambridge, MA: Harvard Univ. Press)
Lambert, D. L. 1978, MNRAS, 182, 249
————. 2001, in IAU Joint Discussion, Oxygen Abundances in Old Stars and Implications to Nucleosynthesis and Cosmology, ed. B. Barbuy (Dordrecht: IAU), in press
Langer, G. E., Suntzeff, N. B., & Kraft, R. P. 1992, PASP, 104, 523
Smith, V. V., Suntzeff, N. B., Cunha, K., Gallino, R., Busso, M., Lambert, D. L., & Straniero, O. 2000, AJ, 119, 1239
Wiese, W. L., Glennon, B. M., & Smith, M. W. 1966, Atomic Transition Probabilities (Washington, D. C.: GPO)