BORON IN THE SMALL MAGELLANIC CLOUD: A NOVEL TEST OF LIGHT-ELEMENT PRODUCTION

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1 INTRODUCTION

Most of the elements in the universe have been created by either big bang nucleosynthesis or stellar nucleosynthesis. There are a few elements, however, that owe their existence, in part or in whole, to another site and other nuclear processes, that is, to spallation (and fusion) reactions involving galactic cosmic rays and ambient interstellar nuclei. Among this minority are lithium, beryllium, and boron (LiBeB). Understanding this trio’s origins requires extensive observations of their abundances in a variety of objects. Detailed understanding of boron’s nucleosynthesis has lagged behind that of the two other light elements, in large part because lithium and beryllium are observable in optical spectra, but detection of boron demands UV spectroscopy. An extensive body of observational data on abundances of lithium and beryllium is available for theoretical considerations (see, e.g., Boesgaard et al. 2001; Deliyannis et al. 1998; Smith, Lambert, & Nissen 1998 and references therein), but little is presently known about boron.

Reeves, Fowler, & Hoyle (1970; with refinements by Meneguzzi, Audouze, & Reeves 1971) proposed that LiBeB are produced by spallation reactions (e.g., \( p + O \rightarrow \alpha Li, Be, or B \)) and a fusion reaction \( (\alpha + \alpha \rightarrow ^6Li \) and \( ^7Li \)) between cosmic rays and ambient nuclei in interstellar gas. In the local Galactic interstellar medium, the dominant contribution to the synthesis of the boron isotopes \(^{10}B \) and \(^{11}B \) is thought to be cosmic-ray protons spallating interstellar \(^{16}O \) nuclei. An alternative source of \(^{11}B \), but not \(^{10}B \), has been proposed by Woosley et al. (1990): neutrino-induced spallation of \(^{12}C \) in the carbon-burning shell of a massive star undergoing a Type II supernova (the \( \nu \)-process).

The relative contributions of galactic cosmic rays and supernovae to boron’s synthesis are ill determined at present. A calibration of these contributions is, in principle, possible by examining the \( B/Be \) ratio, as beryllium production is not predicted by the \( \nu \)-process. Analysis shows that \( B/Be \) ratios are close to that predicted from spallation over a wide range of metallicities (Duncan et al. 1997; García-López et al. 1998). However, the uncertainties in \( B/Be \) ratios are such that a contribution \(( \leq 30\% \) see, e.g.,...
Furthermore, cosmic-ray spallation theory predicts the product of \( ^{12}\text{B} \) and \( ^{10}\text{B} \) reactions, suggesting an additional contribution to the \( ^{11}\text{B} \) abundance, higher ratio, \( ^{11}\text{B} / ^{10}\text{B} = 4.05 \), in meteorites. This result also implies that the cosmic-ray flux in the SMC is no more than determined from both nebulae and stars and is known to be about \( \frac{1}{4} \) as abundant as in the solar neighborhood (see, e.g., Meneguzzi et al. 1971; Prantzos, Cassé, & Vangioni-Flam 1993; Lemoine et al. 1998).

To advance our understanding of the synthesis of boron, it is valuable to measure boron abundances in a diverse set of environments. Here we describe an attempt to measure the boron abundance in the Small Magellanic Cloud, where the history of star formation, present metal abundances, and present cosmic-ray flux differ from the local Galactic values. For example, in the SMC, oxygen has been well determined from both nebulae and stars and is known to be about \( \frac{1}{4} \) as abundant as in the solar neighborhood (see, e.g., Korn et al. 2000; Hill 1999; Venn 1999 and references therein). Furthermore, Sreekumar et al. (1993) found that the cosmic-ray flux in the SMC is no more than \( \frac{1}{4} \) that near the Sun, based on EGRET observations that failed to detect \( \gamma \)-rays at energies \( \geq 100 \) MeV (\( \gamma \)-rays are the main decay product of \( \pi^0 \)’s produced in the collision of cosmic rays with interstellar atoms).

Herein we present boron abundances from the B \( \lambda 2066 \) line from the Hubble Space Telescope Imaging Spectrograph (STIS) spectra of two SMC main-sequence B-type stars, AV 304 and NGC 346-637. Both of these stars have been well studied in the optical by Rolleston et al. (1993, hereafter R93; also W. R. J. Rolleston et al., private communication), so that atmospheric parameters and some elemental abundances are available. These stars show no signs of internal mixing (usually demonstrated through enrichments of surface nitrogen abundances), and Rolleston et al. have found oxygen abundances that are in excellent agreement with other SMC oxygen results. We have also used the HST STIS spectra to determine the iron-group abundances in the two SMC B-type stars, for comparison with analyses of cool SMC supergiants.

2. Target Selection and Observations

Two SMC B-type stars, AV 304 and NGC 346-637, were selected for HST STIS spectroscopy near the B \( \lambda 2066 \) line. These SMC stars are known sharp-lined objects (i.e., low \( v \sin i \)), which is a necessary property to be able to resolve the B \( \lambda \) line in the crowded UV spectrum. Two main-sequence B-type stars in the Galaxy (HD 36591 and HD 34078), with temperatures similar to those of the SMC targets (see Table 1), were also selected as standards for differential analyses.

The SMC observations (see Table 2) were made with the G230M grating \( (R = 30,000) \) and a 52 \( \times \) 0.05 slit to obtain a dispersion of 0.19 A pixel\(^{-1} \), or 28 km s\(^{-1} \) per resolution element. The Galactic data are from Venn et al. (2002, hereafter V02). Spectra were reduced using the STIS pipeline. The spectra were rectified using a low-order Legendre polynomial and offset from vacuum wavelengths (observed) to air wavelengths (line list, discussed below). In addition, the Galactic spectra were smoothed (3 pixel boxcar smoothing). The final signal-to-noise ratio \( (S/N) \) of each spectrum is listed in Table 2. The spectra are shown in Figures 1, 2, 3, and 4.

3. The Abundance Analyses

3.1. Line List

The line list and atomic data originated from the Kurucz (1989, 1993) line list, including all lines in the iron-group, light-elements, and heavy-elements lists, up to barium and through the third ionization state. This line list was updated by including the new wavelengths for eight Fe \( \lambda \) lines reported by Proffitt et al. (1999) from Fourier transform spectrometer (FTS) laboratory measurements. We also updated the atomic data of 172 Fe \( \lambda \) lines listed in Kurucz’s line list by adopting the oscillator strengths and wavelengths from Ekberg (1993). This is similar to the line list used by V02 but over a larger wavelength region (\( \lambda \lambda 2044-2145 \)).

| Star        | Spectral Type | \( T_{\text{eff}} \) (K) | \( \log g \) | \( v \sin i \) (km s\(^{-1} \)) | 12 + log(O/H) (NLTE) | 12 + log(N/H) (NLTE) | Reference |
|-------------|---------------|--------------------------|-------------|-------------------------------|----------------------|----------------------|-----------|
| HD 36591    | B1 IV         | 26,449                   | 4.15        | 11                            | 8.67 ± 0.22          | 7.69 ± 0.10          | 1         |
| AV 304      | B1 V          | 26,330                   | 4.21        | 16                            | 8.54 ± 0.05          | 7.64 ± 0.05          | 2         |
| HD 34078    | O9.5 V        | 33,000\(^a\)             | 4.07        | 14                            | 8.34 ± 0.25          | 7.25 ± 0.09          | 1         |
| NGC 346-637 | B0 V          | 30,500                   | 4.00        | 28                            | 8.0 ± 0.23           | 7.25 ± 0.09          | 4         |

**Notes.**—The atmospheric parameters listed here were adopted for ATLAS9 models and spectral syntheses. Solar metallicity was used for HD 36591 and HD 34078, while \([\text{Fe}/\text{H}] = -1.0\) models were used for SMC stars. The parameters from Gies & Lambert (1992) were adopted for HD 36591, with \( T_{\text{eff}} \) lowered by 3.4%. The O and N abundances have been adjusted to this lower \( T_{\text{eff}} \) scale (see \( \Delta \) in Table 9 of Gies & Lambert (1992) and corrected for the use of Gold, rather than Kurucz, NLTE models (see V02 for a full discussion).

\(^a\) Temperature was raised to 33,000 K from the Gies & Lambert–corrected value of 30,352 K, because we expect that HD 34078 should have near-solar Fe abundances, as it is a runaway Orion star.

\(^b\) While Gies & Lambert (1992) found \( v \sin i \) in this star to be 30 ± 3 km s\(^{-1} \), we found that a lower \( v \sin i \) of 20 km s\(^{-1} \) was required to fit the sharp lines in this spectrum.

**References.**—(1) Gies & Lambert (1992); (2) Cunha & Lambert 1994; (3) W. R. J. Rolleston et al., private communication; (4) R93.
Atomic data for the B\textsc{iii} 2s\textsuperscript{2}S\textsuperscript{2}p\textsuperscript{2}P resonance doublet with lines at $\lambda 2065.8$ and 2067.3 are taken from Proffitt et al. (1999; discussed further by V02). The weaker B\textsc{iii} line at $\lambda 2067.3$ is blended with a strong Fe\textsc{iii} line and a weaker Mn\textsc{iii} line and is not suitable for boron abundance determinations. For all syntheses, an isotopic ratio $^{11}\text{B}/^{10}\text{B} = 4.0$ is assumed, the solar system ratio (Zhai & Shaw 1994; Shima 1963). This is consistent with the estimates given by Proffitt et al. (1999) from their line profile analyses of two sharp-lined B-type stars. Uncertainties in the use of this ratio are discussed below.

Contamination of the spectra by interstellar (IS) lines is considered. Proffitt & Quigley (2001) first noted the importance of IS lines in this wavelength range, particularly one Cr\textsc{ii} interstellar line that can come close to the B\textsc{iii} $\lambda 2065.8$ feature, depending on the stellar radial velocity. Data from Morton (1991) have been used to pinpoint the location of possible IS lines in the spectra, and we note those that appear in all of our spectra. The SMC spectra contain doubles of each IS line, because there is more than one cloud along the line of sight to these stars (presumably a Galactic component and an SMC component). We have identified

| Star            | $V$  | Grating | Slit   | Exposure(s)          | Date        | S/N |
|-----------------|------|---------|--------|----------------------|-------------|-----|
| AV 304          | 14.98| G230M   | 52 x 0.05 | 19950 s at $\lambda 2095$ | 1999 Oct 26 | 50  |
|                 |      |         |        | $+2460$ s at $\lambda 2095$ | 2000 Sep 29 |     |
|                 |      |         |        | $+22680$ s at $\lambda 2095$ |             |     |
| HD 34078        | 5.96 | E230H   | 0.1 x 0.03 | 432 s at $\lambda 2063$ | 2000 Mar 15 | 55  |
| HD 36591        | 5.34 | E230M   | 0.2 x 0.05ND | 3 x 432 s at $\lambda 2124$ | 1999 Feb 9 | 100 |
|                 |      |         |        | $+2 x 434$ s at $\lambda 1978$ |             |     |
|                 |      |         |        | $+2 x 432$ s at $\lambda 2269$ |             |     |
| NGC 346-637     | 14.98| G230M   | 52 x 0.05 | 2376 s at $\lambda 2095$ | 1999 Oct 25 | 30  |
|                 |      |         |        | $+12944$ s at $\lambda 2095$ |             |     |
|                 |      |         |        | $+2376$ s at $\lambda 2095$ |             |     |
|                 |      |         |        | $+9708$ s at $\lambda 2095$ | 2000 Oct 2 |     |

Note.—All observations of AV 304 were in the continuous viewing zone.

![Figure 1](image-url)  
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**Fig. 1.**—Coadded HST STIS spectra (dotted lines) for SMC (AV 304 and NGC 346-637) and Galactic (HD 36591 and HD 34078) stars and their spectrum syntheses (solid lines). Iron-group metallicities in Table 5 were used for each synthesis, i.e., $[\text{M/\text{H}}] = 0.07$, $-0.6$, and $-1.0$ for HD 36591, AV 304, and NGC 346-637, respectively. Solar iron-group abundances are adopted for HD 34078 (see text). All features listed in Table 5 are identified by a line above the feature; features used solely for a differential analysis are marked by an arrow. IS lines are marked below the spectra. Note that the SMC stars have two sets of IS lines (represented by different symbols). Galactic spectra were smoothed for a 3-pixel resolution element.
Fig. 2.—Same as Fig. 1, but for $\lambda \lambda 2070.5-2092.5$

Fig. 3.—Same as Fig. 1, but for $\lambda \lambda 2092.5-2114.5$
The locations of the IS lines are noted in the spectrum figures (see Figs. 1–5). They have different locations in each figure because the spectra are shown in the stellar rest frames.

The final line list includes 6685 features between $\lambda\lambda2044$ and 2145. All were included in the syntheses, but many are negligible contributors. A few, final, fine adjustments were made to the line list; after an examination of a preliminary syntheses of HD 36591, slight wavelength shifts were made to isolated, strong, iron-group lines to improve the line synthesis. These fine adjustments are reported in Table 3. In addition, after the initial iron-group abundance determination was made for HD 36591 from this line list, fine adjustments were made to the oscillator strengths of five lines not previously included because of their grossly inconsistent fits in comparison to the remaining 64 lines, which are also listed in Table 3. These five lines were then included in a differential analysis. The final line list does a remarkably good job at fitting the stellar spectra over this UV range in HD 36591, AV 304, and HD 34078. This is noteworthy, because UV line lists are notoriously incomplete and/or uncertain in their atomic data. Examination of the spectrum figures finds very few missing lines and quite good fits, suggesting that the energy levels and transition probabilities are fairly accurate.

### 3.2. Synthesizing the Spectra

Elemental abundances have been determined from LTE spectral syntheses and ATLAS9 model atmospheres (Kurucz 1979, 1989). The stellar $T_{\text{eff}}$, gravity, and projected rotational velocity ($v \sin i$) values were adopted from the literature; see Table 1. The $T_{\text{eff}}$-values listed for HD 36591 and HD 34078 have been scaled down by 3.4% from those listed in Gies & Lambert (1992, hereafter GL92), in order to remove the increase they applied to their photometric results. Corresponding to this lower $T_{\text{eff}}$, the GL92 non-LTE (NLTE) nitrogen and oxygen abundances have been adjusted by the $\Delta$-values in their Table 9. In addition, the GL92 NLTE abundances are based on calculations made with Gold (1984) model atmospheres, instead of the more heavily line-blanketed Kurucz models. Thus, we have also applied a correction to account for the Gold-Kurucz offsets, as tabulated by Cunha & Lambert (1994, their Table 10).

Other parameters were determined from the syntheses, i.e., microturbulence ($\xi$) and radial velocity (as described by V02), and are listed in Table 4. Macroturbulence ($\xi_M$) was initially set to the instrumental broadening values (28 km s$^{-1}$ for the SMC stars, 15 km s$^{-1}$ for HD 36591, and 4 km s$^{-1}$ for HD 34078). These values were increased for the Galactic stars by 3 km s$^{-1}$ to best fit the smoothed spectral line profiles. ATLAS9 models with 1/10 solar metallicity were used for the SMC stars, while solar-metallicity models were adopted for the two Galactic stars. Spectral syntheses were made using the program LINFOR.5

5 LINFOR was originally developed by H. Holweger, W. Steffen, and W. Steenbock at Kiel University. It has been upgraded and maintained by M. Lemke, with additional modifications by N. Przybilla.
For the two cooler stars, HD 36591 (Galactic) and AV 304 (SMC), the spectrum syntheses fit the observed spectra well. For the two hotter stars, HD 34078 (Galactic) and NGC 346-637 (SMC), the initial spectrum syntheses proved to be unsatisfactory. For HD 34078, a slightly lower \( \sin i \) was required to fit its sharp-line UV spectrum. Also, the preliminary iron abundance result was very low for a solar-neighborhood object: \([\text{Fe/H}] = -1.0\). Since HD 34078 is one of the hottest stars analyzed, the 3.4% reduction to the GL92 temperature (discussed above) significantly affects the iron abundance.\(^6\) Since this star is expected to have a near-solar iron abundance, as it is a former member of the Orion association, we found it is necessary to raise the temperature to 33,000 K to yield this result. Accordingly, we have not completed a differential analysis of NGC 346-637 with respect to HD 34078, because of the uncertainties in the parameters of this hot star. However, HD 34078 is included in Figures 1–4 to show the high quality of our line list, even at hot temperatures.

The analysis of NGC 346-637 also presented some difficulties, beginning with its radial velocity. We found that a radial velocity of 250 km s\(^{-1}\) was necessary to best fit the \( \text{HST} \) STIS data, yet R93 reported a value of \( \sim 100 \) km s\(^{-1}\) for this star. A large radial velocity is unusual; the velocities for SMC stars tend to range from 100 to 180 km s\(^{-1}\) (see, e.g., Venn 1999; R93; Grebel, Roberts, & Brandner 1996). In addition, the spectrum synthesis proved to be quite difficult, with very few clean iron-group lines available to constrain the fitting parameters (see Figs. 1–4). An SMC-like iron-group abundance (discussed below) was found, \([\text{Fe/H}] = -1.0 \pm 0.3\) (see Table 5), but our spectrum fits were not very satisfactory. We examined other spectrum syntheses over a range in atmospheric parameters (i.e., \( T_\text{eff} \), gravity, radial velocity, and \( \sin i \)), but no significant improvements were found. We suspect that this star might be an unresolved binary. Binarity could explain the large, and apparently variable, radial velocity for this star, and it could affect the spectrum synthesis if the companion contributes continuum to the UV spectrum.

\[ \text{Table 3: Iron Group Wavelength Offsets} \]

| Element | \( \lambda \) (Kurucz) | \( \lambda \) (New) | \( \log g/f \) |
|---------|-------------------|-----------------|-----------|
| Mn ii...... | 2048.949 | 2048.918 | \ldots |
| Mn ii...... | 2049.357 | 2049.314 | \ldots |
| Mn ii...... | 2049.682 | 2049.663 | \ldots |
| Mn ii...... | 2063.337 | 2063.397 | \ldots |
| Mn ii...... | 2065.886 | 2065.892| \ldots |
| Fe iii...... | 2050.743 | \ldots | 0.19 |
| Fe iii...... | 2052.271 | b | \ldots |
| Fe iii...... | 2053.524 | b | \ldots |
| Fe iii...... | 2054.492 | b | \ldots |
| Fe iii...... | 2055.863 | 2055.859 | \ldots |
| Fe iii...... | 2056.152 | 2056.156 | \ldots |
| Fe iii...... | 2057.059 | 2057.072 | \ldots |
| Fe iii...... | 2057.928 | 2057.925 | \ldots |
| Fe iii...... | 2058.209 | 2058.205 | \ldots |
| Fe iii...... | 2058.566 | b | \ldots |
| Fe iii...... | 2064.980 | b | \ldots |
| Fe iii...... | 2068.249 | 2068.263 | \ldots |
| Fe iii...... | 2070.539 | 2070.561 | \ldots |
| Fe iii...... | 2070.976 | 2070.996 | \ldots |
| Fe iii...... | 2076.322 | 2076.318 | \ldots |
| Fe iii...... | 2080.220 | \ldots | \ldots |
| Fe iii...... | 2082.384 | 2082.377 | \ldots |
| Fe iii...... | 2084.376 | \ldots | 0.99 |
| Fe iii...... | 2089.093 | 2089.120 | 0.28 |
| Fe iii...... | 2093.505 | 2093.512 | \ldots |
| Fe iii...... | 2096.423 | 2096.417 | \ldots |
| Fe iii...... | 2099.226 | b | \ldots |
| Fe iii...... | 2010.966 | 2100.950 | 0.04 |
| Fe iii...... | 2107.322 | 2107.339 | \ldots |
| Fe iii...... | 2108.679 | 2108.684 | \ldots |
| Fe iii...... | 2116.593 | 2116.583 | 0.24 |

\(^6\) Note that this iron-group abundance result is also lower than that reported by V02 for HD 34078 for two reasons. First, V02 synthesized fewer features (12 in 22 Å, whereas 25 features are synthesized over 70 Å in this paper). Second, the iron abundance is very sensitive to temperature in hot stars (see the temperature sensitivities listed in Table 7 of V02). The 3.4% temperature effect on abundances was applied to the boron and CNO abundances in the discussion by V02 but not to iron, since it was an insignificant effect for the stars in the discussion in that analysis.

### 3.3. Iron-Group and Synthesis Parameters

The iron-group abundances were determined from synthesis of specific features in the spectra, and results from the individual features were averaged. In Table 5, the line abundances are listed relative to the meteoritic abundances from Grevesse & Sauval (1998), e.g., \( \log(\text{Fe}) = 7.50 \) and \( \log(\text{Mn}) = 5.53 \). The mean abundances in Table 5 were calculated by excluding line abundances that fall more than 2 \( \sigma \) from the mean (of the line-to-line scatter).

We estimate an uncertainty of approximately \( \pm 2 \text{ km s}^{-1} \) in the macroturbulence, based on line profile fitting, but only \( \pm 1 \text{ km s}^{-1} \) in microturbulence, based on line strengths. Iron-group uncertainties for HD 36591 and HD 34078 were previously determined by V02. These uncertainties are adopted here for the SMC stars, since the atmospheric parameters and analysis method are similar. NLTE effects are neglected throughout this iron-group analysis. Iron-group abundances are determined primarily from lines of the dominant ionization species of the elements, i.e., Fe ii.

As expected, near-solar mean iron-group abundances are found for HD 36591, \([\text{Fe/H}] = -0.07 \pm 0.10\) from 46 features. The iron-group abundance for AV 304 is \([\text{Fe/H}] = -0.6 \pm 0.2\) from 24 features, which is identical to a differential line-by-line comparison with HD 36591 (including the five additional features with altered oscillator strengths discussed above, for a total of 29 lines). This metallicity is similar to the R93 results for AV 304’s light elements (e.g., Si and Mg), as well as those of a pioneering attempt to determine iron in AV 304 based on GHRS spectra by Peters & Grigsby (1999). It is also in good agreement with iron abundances in cooler supergiants \((-1.0 < [\text{Fe/H}] < -0.5\); Venn 1999; Hill 1997, 1999; Luck et al. 1998; Russell & Bessell 1989).\(^6\)

The mean iron-group abundance for NGC 346-637 is \([\text{Fe/H}] = -1.0 \pm 0.3\), determined from nine features. A differential analysis of these nine features, plus three more with corrected oscillator strengths, with respect to the cooler Galactic star HD 36591 yields \(-1.0 \pm 0.4\) dex (recall that, because of uncertainties in \( T_\text{eff} \) for HD 34078, we do not present a differential analysis of NGC 346-637 with this star,
TABLE 4
BORON ABUNDANCES FROM STIS SPECTROSCOPY

| Star        | $V_{rad}$ (km s$^{-1}$) | $\xi_{Ma}$ (km s$^{-1}$) | $\xi$ (km s$^{-1}$) | $12 + \log(B/H)$ | $12 + \log(B/H)$ | $12 + \log(Mn m)$ |
|-------------|-------------------------|--------------------------|---------------------|------------------|------------------|------------------|
| HD 36591    | 29                      | 18                       | 2                   | $\leq 1.36$      | $\leq 1.27$      | 5.31             |
| AV 304      | 145                     | 30                       | 3                   | $\leq 1.7$       | $\leq 1.6$       | 4.9              |
| HD 34078    | 56                      | 7                        | 3                   | $\leq 2.4$       | $\leq 2.5$       | 4.4              |
| NGC 346-637 | 254                     | 30                       | 2                   | $\leq 1.5$       | $\leq 1.6$       | 4.6              |

Notes.—Abundances have been determined from spectrum syntheses using the model atmosphere parameters listed here and in Table 1. Radial velocities ($V_{rad}$) and $\xi$-values are determined from the group features. Radial velocities have been corrected for vacuum-to-air wavelength offsets. NLTE corrections are from calculations in V02. The B $\lambda$2065.8 and Mn $\lambda$2065.9 abundances were varied together in order to achieve the best fit; thus, we report the best-fit Mn $m$ abundance here in italics.

TABLE 5
IRON-GROUP ABUNDANCE RESULTS

| $\lambda$ (Å) | Element(s) | [M/H] HD 36591 | [M/H] AV 304 | [M/H] NGC 346-637 |
|--------------|------------|----------------|--------------|-------------------|
| 2048.92      | Mn $m$     | $-0.09$        | $-0.6$       | ...               |
| 2049.37      | Fe $ii$ + Mn $m$ | $-0.10$ | ... | $-0.4$         |
| 2049.66      | Mn $m$     | 0.00           | ...          | ...               |
| 2050.74      | Fe $ii$    | Fixed $1.4$    | 0.93         | ...               |
| 2051.85      | Fe $ii$ + Fe $iv$ | +0.05 | ... | ...           |
| 2052.27      | Fe $ii$    | $-0.09$        | ...          | ...               |
| 2053.52      | Fe $ii$    | $-0.24$        | ...          | ...               |
| 2054.56      | Fe $ii$ $\times$ 3 | $-0.08$ | ... | ...           |
| 2055.86      | Fe $ii$    | +0.19          | ...          | ...               |
| 2056.16      | Fe $ii$    | +0.08          | $-0.3$       | ...               |
| 2057.07      | Fe $ii$    | $-0.08$        | $-0.4$       | $-1.3$            |
| 2057.93      | Fe $ii$    | $-0.15$        | ...          | $-1.0$            |
| 2058.21      | Fe $ii$    | $-0.03$        | ...          | ...               |
| 2058.57      | Fe $ii$    | +0.22          | $-0.8$       | ...               |
| 2059.67      | Fe $ii$    | +0.11          | $-1.3$       | ...               |
| 2063.40      | Mn $m$     | $-0.13$        | ...          | ...               |
| 2066.40      | Mn $m$ $\times$ 2 + Ni $m$ | $-0.25$ | $-0.5$ | ...       |
| 2068.26      | Fe $ii$    | +0.26          | $-0.2$       | $-1.4$            |
| 2068.99      | Fe $ii$ + Mn $m$ + Cr $m$ | $-0.25$ | $-0.9$ | ...       |
| 2069.82      | Fe $ii$ + Mn $m$ | 0.00 | ... | ...       |
| 2070.56      | Fe $ii$    | +0.32          | $-1.2$       | $-1.0$            |
| 2070.98      | Fe $ii$ $\times$ 3 | $-0.35$ | 0.0 | ...       |
| 2073.35      | Fe $ii$ + Mn $m$ | $-0.05$ | ... | ...       |
| 2074.23      | Fe $ii$    | $-0.02$        | ...          | $+0.4$            |
| 2076.32      | Fe $ii$    | $-0.54$        | ...          | ...               |
| 2077.36      | Mn $m$ + Co $m$ | $-0.05$ | ... | ...       |
| 2077.74      | Fe $ii$ + Fe $iv$ | +0.22 | ... | ...       |
| 2078.08      | Fe $ii$ + Mn $m$ | $-0.35$ | ... | ...       |
| 2079.00      | Fe $ii$ $\times$ 4 | +0.20 | $-0.7$ | ...       |
| 2080.22      | Fe $ii$    | $-0.07$        | $+0.2$       | ...               |
| 2081.08      | Mn $m$ $\times$ 2 + Co $m$ | $-0.02$ | ... | ...       |
| 2082.38      | Fe $ii$    | $-0.13$        | ...          | ...               |
| 2083.55      | Fe $ii$    | +0.09          | ...          | ...               |
| 2084.36      | Fe $ii$ $\times$ 3 + Mn $m$ $\times$ 2 | Fixed | +1.3 | 2.03       |
| 2084.93      | Fe $ii$ $\times$ 2 | $-0.05$ | $-0.8$ | ...       |
| 2085.84      | Fe $ii$ + Cr $m$ | +0.08 | ... | ...       |
| 2087.15      | Fe $ii$    | +0.16          | ...          | ...               |
| 2087.93      | Fe $ii$    | $-0.16$        | $-0.6$       | ...               |
| 2089.12      | Fe $ii$    | Fixed $0.9$    | ...          | ...               |
| 2090.16      | Fe $ii$ $\times$ 4 + Mn $m$ $\times$ 3 | 0.00 | $-1.3$ | ...       |
| 2091.35      | Fe $ii$ $\times$ 2 | $-0.40$ | $-1.0$ | ...       |
| 2092.97      | Fe $ii$    | 0.00           | ...          | $-0.8$            |
| 2093.51      | Fe $ii$    | $-0.08$        | ...          | ...               |
| 2095.66      | Fe $ii$ $\times$ 3 | $-0.10$ | $-0.3$ | ...       |
| 2096.42      | Fe $ii$    | +0.13          | ...          | ...               |
| 2099.30      | Fe $ii$ $\times$ 2 | $-0.22$ | $-1.0$ | ...       |
| 2101.04      | Fe $ii$ + Mn $m$ | Fixed | 0.7 | 0.83       |
even though they are both hotter stars). The iron-group abundance for NGC 346-637 is somewhat lower than that for AV 304, which could be explained by dilution of the UV continuum by a companion if NGC 346-637 is an unrecognized binary (discussed above). However, NGC 346-637 has an iron abundance that is within the range of the results from young supergiants, and it is in excellent agreement with the iron abundance found for supergiants in the young SMC cluster NGC 330 (Hill 1999; Luck et al. 1998).

### 3.4. Boron Abundances

LTE boron abundances for the SMC stars are listed in Table 4, following the procedures detailed by V02. The spectrum synthesis for HD 36591 is slightly different from that in V02, because $T_{\text{eff}}$ has been lowered 3.4% from the GL92 value here; also, the temperature for HD 34078 is higher, 33,000 K, to yield solar-like abundances (discussed above).

In general, no attempt was made to constrain a priori the abundance of the weak Mn $\lambda$2065.9 line, which is blended with the B $\lambda$2065.8 feature, as described by V02. However, in the case of AV 304, an unfortunate noise spike redward of the boron feature causes the Mn abundance to be indeterminate. Therefore, we have adopted the underabundance suggested by the iron-group analysis. In the analysis by V02, it was found that the Mn $\lambda$2065.9 line abundance was generally in good agreement with the iron-group determination, with $-0.35 \leq [\text{Mn/Fe}] \leq -0.05$. If $[\text{Mn/Fe}] = -0.35$, it does not alter the boron upper limit for AV 304. The iron-group abundance was also adopted for the Mn $\lambda$2065.9 line in NGC 346-637 and HD 34078, as this feature seems to be insignificant at these hotter temperatures (i.e., lowering the Mn abundance further does not alter our boron upper limits).

As noted above, an isotopic ratio of $^{11}\text{B}/^{10}\text{B} = 4.0$ is adopted. Of course, this ratio is undetermined in the SMC, and a purely Galactic cosmic ray spallation model predicts $^{11}\text{B}/^{10}\text{B} = 2.5$. Calculations show that the difference in the boron abundance yielded by using a ratio of 2.5, as opposed to 4.0, is negligible; $\Delta \log(\text{B/H}) \leq 0.05$ for both SMC stars.

To compute the boron abundance uncertainties independent of uncertainties in Mn $\lambda$2065.9, it was found necessary to fix the Mn line abundance a priori. The Mn line abundance was set to the best-fit value (in Table 4). A second method of setting the Mn abundance according to the iron-group uncertainties for each parameter was examined by V02 and found to yield similar boron uncertainties. Table 6 shows that the most significant uncertainty in the boron abundances tends to be the continuum placement (thus, the S/N of the data). The two hottest stars, HD 34078 and NGC 346-637, are also sensitive to the atmospheric parameters, particularly $T_{\text{eff}}$. In general, hot stars are not the best boron indicators. While the result for NGC 346-637 is consistent with a lower boron abundance in the SMC, it is possible that no boron exists in NGC 346-637 to within the errors caused by the low-S/N spectrum. This is shown in Figure 5, where the best-fit upper limit is shown, with $+0.3$
and $12 + \log(B/H) = -10$ for comparison. Finally, in Table 4, the LTE boron abundances are corrected for NLTE effects, using calculations reported in V02.

4. DISCUSSION

4.1. Boron and Oxygen in the SMC and the Galaxy

Boron synthesis, whether controlled by spallation in the interstellar medium or by Type II supernovae, is coupled to the growth of the oxygen abundance. Therefore, it is of interest to establish the relationship between boron and oxygen in the SMC.

At present, our boron upper limits in two young stars are the sole data points on boron in the SMC [12 + log(B/H) $\leq$ 1.6 in both]. The oxygen abundances in our SMC targets are listed in Table 1 and are in excellent agreement with oxygen results from other young SMC stars and H II regions. Oxygen abundances in the SMC have been

![Figure 5](image-url)

Fig. 5.—Boron syntheses for all program stars. The best-fit syntheses are shown, as well as $\Delta \log(B/H) = \pm 0.3$ for comparison, except for NGC 346-637 where the best fit, +0.3, and no boron [12 + log(B/H) = −10] are shown. IS lines are again noted. The spectra of HD 36591 and HD 34078 are shown in V02 for the same wavelength region, but the spectra here are synthesized at different temperatures (that of HD 36591 has been lowered 3.4% and that of HD 34078 has been raised to 33,000 K; see text).
determined from H II regions, hot and cool supergiants, and B-type main-sequence stars. The results are pleasingly consistent; see summary by Venn (1999, their Table 9). More recent results include additional analyses of B-type stars by Korn et al. (2000) and Dufton et al. (2000), who found mean abundances $12 + \log(O/H) = 8.13$ and 8.0, respectively.

A comparison of boron and oxygen can also be made for Galactic stars and the local interstellar medium. In Table 7, we list boron abundances in local Population I stars and nebulae and adopt $12 + \log(B/H) = 2.5$ in the solar neighborhood. Furthermore, we adopt $12 + \log(O/H) = 8.7$ (see Allende Prieto, Lambert, & Asplund 2001) for the present local oxygen abundance. Additional local boron abundances have been determined over a wide range in metallicities, and several studies have reported on the boron-oxygen corelation (see, e.g., García-López et al. 1998; Duncan et al. 1997). Smith, Cunha, & King (2001) provide a reassessment of the relation between boron and oxygen in Galactic F- and G-type dwarfs. The oxygen abundances in stars where the $B \lambda 2497$ line was observed led to a correlation represented by $B/H \propto (O/H)^{m}$, with $m = 1.4 \pm 0.1$ for stars with $-0.4 < [O/H] < +0.2$; see Figure 6. (Note that our adopted initial local Galactic abundances for boron and oxygen lie on this line in Fig. 6). On including results from the literature to extend the relation to lower metallicities, Smith et al. (2001) found $m \approx 1.0$ for stars with $[Fe/H] \leq -1.0$, depending on the adopted set of oxygen abundances in the metal-poor stars. The uncertainties in oxygen in metal-poor stars is an ongoing debate at present (see Lambert 2001). Also, it should be noted that the abundances of beryllium, a product solely of spallation, behave in a very similar way to those of boron and that the $B/Be$ ratio is approximately constant from solar-metallicity stars to the most metal-poor (Boesgaard et al. 1999).

In Figure 6, we show the oxygen abundances and boron upper limits established for the two SMC stars reported here. The solid line shows the Smith et al. (2001) fit to the B-O relation for the Galactic stars with $B \propto O^{1.4}$, while the dashed lines indicate linear and quadratic trends of B with O. If taken at face value, the results for the two SMC stars would suggest that the boron-oxygen relationship in the SMC is in excellent agreement with that of the Galactic disk.

### 4.2. Boron Depletion Mechanisms

A discussion of boron synthesis in the SMC assumes that boron has not been depleted in the stellar atmosphere and should represent the present-day abundance in the interstellar medium. Observations of Galactic B-type stars, however, show that boron depletion is not uncommon (V02; Proffitt & Quigley 2001). Therefore, the possibility of the loss of atmospheric boron must be recognized.

Several processes are capable of reducing the boron abundance while a B-type star is on the main sequence. The most likely process is rotationally induced mixing, although mass loss, or mass transfer from an evolved companion, would also produce the same result. Mass loss from main-sequence B-type stars is not expected to have a significant effect on the surface B abundance (see the discussion in Fliegner, Langer, & Venn 1996 and V02). It would require a mass-loss rate an order of magnitude larger than that observed for Galactic B-type stars (Cassinelli et al. 1994). For SMC stars, we expect the winds to be even weaker, since winds of hot stars are driven by photon momentum transfer through metal line absorption and are thus a function of metallicity (see, e.g., Kudritzki & Puls 2000).

Mass transfer in a close binary system will not affect boron in the mass-receiving (i.e., the observed) star without a considerable enrichment of nitrogen (see, e.g., Wellstein 2000). For AV 304, W. R. J. Rolleston et al. (private communication) find the nitrogen abundance $12 + \log(N/H) = 6.7 \pm 0.2$ from N II lines measured from a VLT UVES spectrum. The fact that this abundance is in very good agreement with those measured in SMC H II regions (Dufour 1984; Russell & Dopita 1990; Kurt et al. 1999) and for other B-type stars (see, e.g., Korn et al. 2000) eliminates the idea that mass transfer could have affected its boron abundance. For NGC 346-637, the picture is unclear.
R93 could determine only an upper limit to the nitrogen abundance: $12 + \log(N/H) \leq 7.2$, which does not entirely exclude the possibility that mass transfer might have affected the surface abundances. Furthermore, we suspect that this star might be an unrecognized binary (see §3.2).

Depletion of boron by rotationally induced mixing cannot be ruled out. Recent models by Heger & Langer (2000) follow the evolution of the angular momentum distribution in intermediate-mass stars from the pre-main sequence through core collapse and find that rotational mixing can affect stellar surface abundances of boron and nitrogen. For rapidly rotating stars, boron can be depleted and nitrogen enriched at the surface. V02 have confirmed that these models do indeed fit the observed abundances of boron and nitrogen in Galactic B-type stars. Boron is predicted to be depleted before detectable nitrogen enrichment. While nitrogen-rich stars are predicted and observed to be boron-depleted before detectable nitrogen enrichment, these elements do indeed fit the observed abundances of boron and nitrogen in Galactic B-type stars. (Proffitt & Quigley 2001; V02), stars showing a nitrogen-rich stars are predicted and observed to be boron-depleted before detectable nitrogen enrichment. While nitrogen in Galactic B-type stars. Boron is predicted to be depleted before detectable nitrogen enrichment. While nitrogen-rich stars are predicted and observed to be boron-depleted (Proffitt & Quigley 2001; V02), stars showing a normal nitrogen abundance can also be boron-depleted by as much as 1 dex! Thus, this is a possibility that we cannot exclude for either AV 304 or NGC 346-637. To reduce this possibility, additional stars would have to be observed to search for stars with a higher boron abundance. (While lithium and beryllium would be depleted too, these elements are not observable in B-type stars.)

4.3. Spallation in the SMC

In the case of the solar neighborhood, the contribution of spallation to the synthesis of boron is assessable from measurements of the beryllium abundance in stars; beryllium owes its origins exclusively to spallation, and the B/Be ratio is predictable with fair certainty. Unfortunately, there are no determinations of the Be abundance in SMC gas or stars, and one must predict the production rate of boron from the ingredients controlling it.

Suppose boron is produced by the process $p_{\text{CR}} + O_{\text{ISM}} \rightarrow B$. The production rate $dn_B/dt$ involves three factors: the cosmic-ray proton flux ($\phi_{\text{CR}}$), the O abundance in the interstellar medium [$n(O)$], and the spallation cross section [$\sigma(O \rightarrow B)$], that is,

$$dn_B/dt = \phi_{\text{CR}} n(O) \sigma(O \rightarrow B),$$

where the energy dependences of the factors are suppressed and an integral over energy is implicit. To this rate must be added contributions from C and N as targets and from $\alpha$-particles as projectiles.

The production rate at present in the SMC would appear to be much less than that in the local regions of the Galaxy, because (1) the oxygen abundance [$n(O)$] in the SMC is a factor of 4 lower than that in the local interstellar medium (see § 4.1), and (2) the upper limit on the cosmic-ray flux in the SMC is at least a factor of 5 less than the local flux (Sreekumar et al. 1993). Taken together, $dn_B/dt$ for the SMC might be a factor of 20 less than the local rate. But the boron abundance at a given time and location is an integral of the production rate; a low rate now does not of itself preclude higher rates in the past. Thus, the history of the cosmic-ray flux can also contribute to predicting the boron abundance.

4.3.1. History of the Cosmic-Ray Flux

The history of the cosmic-ray flux (CRF) must be known in order to calculate the evolution of the boron abundance. The confinement time of Galactic cosmic rays is short (below), and hence the present flux is no guide to the past flux of cosmic rays. Measurements of the abundance of secondary fragments produced in the interstellar medium by nuclear interactions between cosmic rays and ambient nuclei have provided estimates of the confinement time for Galactic cosmic rays. Radioactive $^{10}$Be was the first “clock” to be proposed (Hayakawa, Ito, & Terashima 1958). Now, measurements of $^{10}$Be, $^{26}$Al, $^{36}$Cl, and $^{54}$Mn all indicate a confinement time of about 15 Myr (Yanasak et al. 2001). Clearly, Galactic cosmic rays must be continuously replenished if spallation is to work its magic.

The confinement time for the SMC is probably shorter. The magnetic field lines of the SMC are expected to be highly disrupted as a result of interactions with the Galaxy and the LMC. Mathewson, Ford, & Visvanathan (1986, 1988) and Murai & Fujimoto (1980) suggest that a close encounter between the Magellanic Clouds and the Milky Way occurred about 200 Myr ago, and observations show that it is likely that this disturbance disrupted the magnetic field lines of the SMC (Wayte 1990; Haynes et al. 1991; Goldman 2000). As cosmic rays are highly ionized particles, they are generally trapped by the magnetic field lines within a galaxy; thus, disrupted magnetic field lines in the SMC may lead to shorter lifetimes for cosmic rays in the SMC.

Thus, the present CRF in the SMC is not likely to be the same as the past CRF. For example, a large burst of star formation that began 2–4 Gyr ago enriched the SMC to its present oxygen abundance (see, e.g., Pagel & Tautvaišienė 1998; Mighell, Sarajedini, & French 1998; de Freitas Pacheco, Barbuy, & Idfi 1998; Gardiner 1999), and it should also have produced a higher CRF. However, the star formation rate is thought to have declined since that time, and hence the CRF might also have declined. We expect the present low flux is a recent phenomenon that should have no influence on the boron-oxygen correlation.

4.3.2. Boron-Oxygen Relationship

Although the source of the cosmic rays and the identity of the acceleration mechanism are uncertain, it is assumed that the CRF is linked to the presence of supernovae. Thus, given the short confinement time, $\phi_{\text{CR}} \propto N_{\text{SN}}(t)$ is a plausible approximation. Since oxygen is a product of Type II supernovae, one may suppose that $dN_{\text{SN}}/dt \propto dN(O)/dt$. If it is assumed that the constant of proportionality between the CRF and the number of supernovae is time-independent, equation (1) predicts that $B/H \propto (O/H)^m$, with $m \geq 2$. This result does not depend on an assumption of a time-independent $dn_B/dt$; star formation in bursts (as in the SMC) does not necessarily invalidate the result. As long as the mean lifetime of the cosmic rays is short relative to the durations of the burst and the CRF is tied to that of the O-producing massive stars, the production rate integrated over time will result in the quadratic dependence.

Direct comparison of the boron-oxygen relationship in the Galaxy and in the SMC will be inappropriate if the efficiency of cosmic-ray generation in supernovae is different for the two galaxies. Nonetheless, it is of interest to make such a comparison. In the solar neighborhood, we adopt $12 + \log(B/H) = 2.5$ and $12 + \log(O/H) = 8.7$ (see § 4.1). Adopting $12 + \log(O/H) = 8.1$ for the SMC, the quadratic relation predicts $12 + \log(B/H) = 1.3$ for the SMC, a value that is 0.3 dex below our measured upper limits. If cosmic
rays do escape more easily from the SMC (discussed above), then the boron production rate per oxygen atom produced by supernovae would be smaller in the SMC. Recognition of this fact would result in a predicted boron abundance that is even lower than $12 + \log(B/H) = 1.3$.

While our boron upper limits are in fair agreement with the quadratic prediction, the quadratic approximation is of questionable validity, at least for the solar neighborhood. Observations of boron and oxygen abundances in stars for which boron is undepleted do not show the quadratic dependence (see § 4.1): as noted, $m = 1.4$ for Galactic stars of approximately solar metallicity, and a lower index (e.g., $m \approx 1$) might be required to fit the observations of metal-poor stars (Smith et al. 2001). If $m = 1.4$ is adopted, the predicted SMC boron abundance [$12 + \log(B/H) \sim 1.6$] is in excellent agreement with our upper limits. An index of $m = 1$ predicts a boron abundance 0.3 dex greater than our upper limits for the SMC stars. While a difference of 0.3 dex is within 3 $\sigma$ of our boron upper limits, we note that this agreement worsens for our best-analyzed star, AV 304. For AV 304, $12 + \log(O/H) = 8.2$; thus, a slope of $m = 1$ predicts a boron abundance that is 0.4 dex larger than our upper limit. This result argues against a purely linear relation between oxygen and boron in the SMC, unless we need to consider rotationally induced depletion, and/or the possibility of less efficient production, and/or retention of cosmic rays in the SMC.

Other schemes can also be devised that allow for values of $m$ less than 2. In the context of spallation, a simple way is to consider the “reverse” of the “direct” process introduced above. For the reverse reaction $O_{\text{CR}} + p_{\text{ISM}} \rightarrow B$, a boron-oxygen relation with $m = 1$, that is $B \propto O$, is expected. The reverse rate is often neglected because it produces higher velocity boron nuclei than the direct process, and the escape from the Galaxy before the nuclei are thermalized is greater than for directly produced boron. Furthermore, when the interstellar medium has approximately solar abundances of C, N, and O, the reverse process is much less effective than the direct process. For example, in the early Galaxy, the oxygen abundance in the interstellar medium was lower, but the cosmic rays, if they were accelerated material from supernova ejecta, might have had an oxygen abundance similar to that of contemporary cosmic rays. This circumstance would favor the reverse rate. In the limit that the reverse process was dominant at low metallicities, one expects a switch from $m = 1$ to $m = 2$ as O/H increases in simple galactic models. And, in fact, depending on the choice for the oxygen abundances in metal-poor stars, there is a trend from $m \approx 1$ at low metallicity to a higher value ($m = 1.4$) at solar metallicity (see Smith et al. 2001).

Finally, two other scenarios can be mentioned. First, if cosmic rays are not of galactic origin, their flux would be independent of the supernova rate, which would affect all boron-oxygen relations. However, there is ample evidence that the extragalactic component to Galactic cosmic rays is small (see, e.g., Pannuti 2000; Dickel 1974; Butt et al. 2001), including the fact that the SMC does not have the same CRF as seen in the local Galaxy (Sreekumar et al. 1993). Second, if boron is primarily a product of neutrino-induced spallation in Type II supernovae, then one expects $m \approx 1$. However, the contribution by this process is currently estimated at $\leq 30\%$ in the Galaxy (see, e.g., Lemoine et al. 1998; Vangioni-Flam et al. 1996).

5. CONCLUSIONS

We have analyzed HST STIS observations of the B iii resonance line at $\lambda 2066$ for two SMC B-type stars. The upper limits, corrected for small NLTE effects, are $12 + \log(B/H) \leq 1.6$ for both AV 304 and NGC 346-637. Unless the stars have internally depleted boron by a large factor, we show that the upper limits are plausibly consistent with the hypothesis that boron is a product of spallation induced by cosmic rays. Significant production by neutrino-induced spallation of $^{12}\text{C}$ in Type II supernovae is probably excluded, unless the initial boron abundance was a factor of 2 higher than our upper limits.

The UV line list is quite excellent for spectrum synthesis at Galactic and SMC metallicity in this temperature range. For AV 304, we find $[\text{Fe/H}] = -0.6 \pm 0.2$ from both an absolute and differential analysis with HD 36591. This is consistent with results from the A–F supergiants in the SMC. In comparison, the fewer and weaker iron-group lines in the spectrum of NGC 346-637 result in a less certain abundance, $[\text{Fe/H}] = -1.0 \pm 0.3$. We also suggest that this star might be an unresolved binary.

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