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THE ABUNDANCE OF BORON IN THREE HALO STARS[1]

DOUGLAS K. DUNCAN
Space Telescope Science Institute, Baltimore, MD 21218
AND
DAVID L. LAMBERT AND MICHAEL LEMKE
Department of Astronomy, University of Texas, Austin, TX 78712
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ABSTRACT

The Goddard High Resolution Spectrograph of the *Hubble Space Telescope* has been used to obtain spectra of three halo dwarfs at a resolution of 25,000 for a region centered on the B I resonance lines near 2497 Å. The weaker component of the B I doublet is detected in all three stars, but the stronger component is irretrievably blended with strong Fe lines. The stars observed are HD 19445, 140283, and 201891, with metallicities of [Fe/H] = −2.15, −2.64, and −1.06 and B abundances of log ϵ(B) = 0.4, −0.1, and 1.7, respectively, on the scale where log ϵ(H) = 12.0 and log ϵ(Fe) = 7.50 for the Sun. Using recent determinations of the Be abundance in HD 140283, we find B/Be = 10^{+5}_{-4} for this star and infer similar ratios for HD 19445 and HD 201891. This ratio is equal to the *minimum* value of 10 expected from synthesis of B and Be by high-energy cosmic-ray spallation reactions in the interstellar medium. It is shown that the accompanying synthesis of Li by α on α fusion reactions is probably a minor contributor to the observed "primordial" Li of halo stars. It is noted that the observed constant ratios of B/O and Be/O are expected if the principal channel of synthesis involves cosmic-ray CNO nuclei from supernovae colliding with interstellar protons. The relations are also the expected result if cosmic rays in the halo were provided by a source, possibly external to the Galaxy, other than halo stars.

Subject headings: Galaxy: halo — nuclear reactions, nucleosynthesis, abundances — stars: abundances — ultraviolet: stars

1. INTRODUCTION

A variety of sites and nuclear processes have been proposed for the nucleosynthesis of the two stable isotopes (^{10}B and ^{11}B) of the rare light element boron. Most attention has been given to spallation by cosmic rays in the interstellar medium. Recently primordial (big bang) nucleosynthesis has been suggested. These theoretical proposals have yet to be critically tested against observations because astronomical measurements of the boron abundance are limited to the Sun and local young stars. This limitation arises in large part because B being a trace element is detectable spectroscopically only through its ultraviolet resonance lines. With the advent of the *Hubble Space Telescope* (*HST*), the B I resonances lines near 2497 Å may be examined in disk and halo stars in order to trace the evolution of the abundance B/H with metallicity ([Fe/H]).

In this paper, we present B abundances for three halo stars: HD 140283, HD 19445, and HD 201891 with [Fe/H] = −2.64, −2.15, and −1.06, respectively, where, as usual, [Fe/H] = log $(\mathrm{Fe/H})_{\mathrm{star}}$ − log $(\mathrm{Fe/H})_{\mathrm{Sun}}$. Throughout this paper we adopt log ϵ(Fe) = log (Fe/H) and log $(\mathrm{Fe/H})_{\mathrm{Sun}}$ = 7.50 on the usual scale where log ϵ(H) = 12.0. The trio have the Li abundance [log ϵ(Li) ≃ 2.0—see Deliyannis, Demarque, & Kawaler 1990] now expected of unevolved halo stars where the heavier of the two stable isotopes, ^{7}Li, is much more abundant than ^{6}Li. HD 140283 and HD 201891 are known to contain ^{9}Be, the sole stable isotope of Be; HD 19445 presumably contains ^{9}Be, but has yet to be examined. Retention of Li and Be strongly implies that all of the initial B has been preserved in the stars' outer envelopes. We examine whether the B and Be abundances are consistent with the idea that Be and B are products of spallation reactions. The only previous attempt to determine the B abundance in an extreme halo star was by Molaro (1987) who set an upper limit log ϵ(B) < 1.0 for HD 140283. For the high-metallicity end of the halo's range, Molaro (1988) gave log ϵ(B) < 2.3 for HD 76932 with [Fe/H] = −1.1. Our measurements are considerably more accurate and substantially below Molaro's limits. Boron in the solar system has an abundance log ϵ(B) = 2.88 ± 0.04 in carbonaceous chondrites (Anders & Grevesse 1989), a value consistent with the photospheric abundance, log ϵ(B) = 2.6 ± 0.3 (Kohl, Parkinson, & Withbroe 1977), derived from the B I resonance lines. Boesgaard & Heacox (1978) give log ϵ(B) = 2.3 from their observations of the B II 1362 Å line in a sample of 16 local A and B stars.

2. OBSERVATIONS

Observations were made with Goddard High Resolution Spectrograph (GHRS) of *HST*, used in its medium-resolution mode. Use of the small (0″.25 square) spectrograph aperture provided a resolution slightly better than 25,000 or 0.1 Å per 2 pixels. The GHRS uses holograph medium-resolution gratings and a very low noise photon-counting Digicon detector. Scattered light and background are negligible in the data. More details about the instrument may be found in Duncan (1992).

Two independent observations were made of each of the target stars, allowing an internal estimate of observational accuracy. Each observation was made using the "FP-SPLIT" technique which provides spectra taken at four different places on the photocathode to reduce instrumental noise. We find

[1] Based on observations obtained with the NASA/ESA *Hubble Space Telescope* through the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

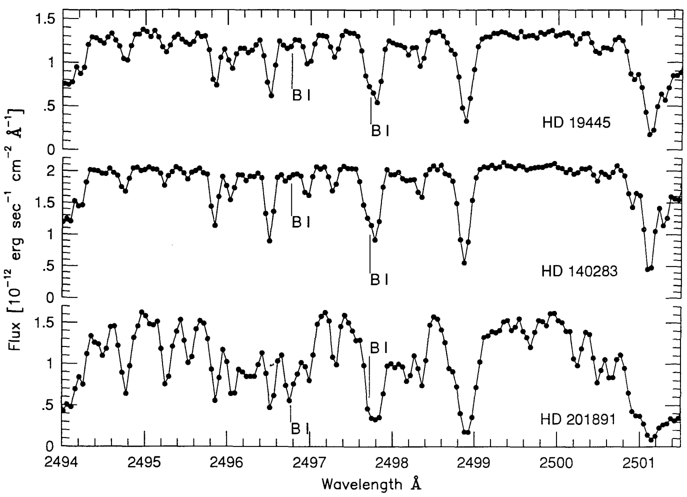

FIG. 1.—Observed spectra of HD 19445, HD 140283, and HD 201891 in the region of the B I resonance lines.

repeatability at slightly less than the photon statistics level, or a S/N per pixel of about 60 for HD 140283, which has a mean of just over 10,000 counts pixel^{-1}. The observations of HD 19445 and HD 201891 collected about 3000 photons pixel^{-1}, and examination of the independent spectra of each star indicates a S/N of 30–40 per 0.047 Å pixel. Figure 1 shows an interval around the B I 2496.6 Å line in the three stars.

Placement of the continuum is an additional source of uncertainty. Examination of the 45 Å bandpass for HD 140283 and HD 19445 reveals several prospective windows, including an extended one ($\delta\lambda \simeq 0.8$ Å) at 2499.5 Å and near the B I lines. We cite three reasons for believing that these windows define closely the true continuum. First, the smooth variation of the continuum across the bandpass was later seen to be almost precisely that defined by observations of two standard line-free stars (μ Col and BD +75°325); the variation is largely set by vignetting within the GHRS. Second, several of the windows in HD 140283 and HD 19445 contain only weak lines in HD 201891. Third, spectrum synthesis using the extensive R. L. Kurucz (1991, private communication) line lists shows average absorption in the windows to be very low. We suggest that the local continuum at the B I lines may be defined such that the photon statistics, not the continuum location, is the more important factor in determining the intensity of weak absorption lines in each of the stars. Location of the continuum is slightly more problematical in HD 201891, the most metal-rich star of the trio, but with a much stronger boron line, the placement of the local continuum is not a major contributor of uncertainty to the B abundance.

Although several very strong lines of Si I and Fe I are present in the bandpass, none of these lines seriously affects the local continuum at the B I line—see Figure 1 where the strong Fe I resonance line is present at 2501.1 Å. By contrast with the spectrum near 2497 Å, we cite the region 2512–2519.5 Å where HD 140283's local continuum shows several narrow intervals where the relative intensity is 90% or greater of the interpolated continuum. In this region containing several strong lines, the maximum flux in HD 201891's spectrum is only about 50% of the expected continuum, and the stretch from 2513.5 to 2519.5 Å is at or below 30%. By happy circumstance, the B I line is not located in such a depressed region.

3. ANALYSIS

Our analysis is based on model atmospheres and a comparison of predicted and observed spectra. Such a comparison calls for basic data on the B I resonance lines and the atmospheric parameters that define a model atmosphere.

3.1. *The* B I *Resonance Lines*

Basic data for the B I resonance lines and neighboring lines were provided by Kohl et al. (1977). The stronger B I line at 2497.7 Å is seriously blended with a Fe II and other lines. Our estimates of the B abundance are obtained from the weaker line at 2496.7 Å with an accurate *gf*-value ($\log gf = -0.81 \pm 0.03$) provided by a measurement of the radiative lifetime of the upper ($3s\,^2S_{1/2}$) state by laser-induced fluorescence (O'Brian & Lawler 1992). The isotopic wavelength shift is 8.6 mÅ, and the wavelengths of the ^{11}B and ^{10}B lines are $\lambda(^{11}\mathrm{B}) \equiv 2496.773$ Å and $\lambda(^{10}\mathrm{B}) = 2496.765$ Å (Burke 1955; Edlén et al. 1970). The hyperfine splitting of these lines may be ignored.

Lines in the immediate vicinity of the B I are a Co I line at 2496.707 Å and a previously unidentified line at 2496.870 Å. At the resolution of the grating employed for our observations, the B I line is not resolved from these neighboring lines. The unidentified line at 2496.870 Å, which is present in the solar spectrum, is also present in our GHRS echelle spectra of the disk F dwarfs α CMi, ι Peg, and θ UMa. We believe the unidentified line to be a Fe I transition from the level $a\,^3G_3$ to an unclassified level. This transition was listed by S. E. Johansson (1991, private communication) in a compilation of potential blends from among iron group neutral atoms. The *gf*-values of the blending Co I and Fe I lines are determined, as we describe below, from a fit to the observed spectrum of HD 140283. Customary procedure in the absence of reliable experimental or theoretical *gf*-values is to derive the *gf*-values by a fit to the solar spectrum. Unfortunately these lines are badly blended and very strong in the solar spectrum, and reliable *gf*-values cannot be extracted.

Moore, Tousey, & Brown (1982) have suggested that an unassigned line of iron coincident with the B I line was overlooked by Kohl et al. (1977), but Learner & Harris (1987) show that Moore et al.'s suggestion is unfounded. Nonetheless, there remains a possibility that there is an unidentified line essentially coincident with the B I line. Some relevant information is provided from our GHRS spectra of ι Peg and θ UMa. This pair have a near-solar Be abundance ([Be/H] = 0.18 (ι Peg), and 0.20 (θ UMa)) according to Boesgaard (1976). Analysis of the echelle spectra of ι Peg and θ UMa with the line list adopted here gives $\log \varepsilon(\mathrm{B}) = 2.3$, that is, the same abundance as obtained by Boesgaard & Heacox (1978) from the B II 1362 Å line in local A and B stars. This correspondence suggests that any unidentified blends make a small contribution to the B I line.

3.2. *Model Atmospheres*

The adopted model atmospheres were computed using the MARCS code (Gustafsson et al. 1975). Improved MARCS models computed with a much more complete representation of the atomic line blanketing were kindly supplied by B. Edvardsson. Analyses made using the original and improved MARCS models give very similar boron abundances.

The principal defining parameters—T_{eff}, $\log g$, and [Fe/H]—are taken from recent discussions of the three stars. The

TABLE 1

ATMOSPHERIC PARAMETERS AND ABUNDANCES

Star	T_{eff} (K)	log g (cgs)	ξ (km s^{-1})	[Fe/H][a]	log ε(B)
HD 19445........	5880	4.4	1.5	−2.15	0.4
HD 140283.......	5640	3.3	1.5	−2.64	−0.1
HD 201891.......	5870	4.5	1.1	−1.06	1.7

[a] [Fe/H] = log ε(Fe) − 7.50.

literature on HD 19445 and HD 140283 is extensive, and we restrict discussion to LTE abundance analyses based on high-quality high-resolution CCD spectra. We adjust published [Fe/H] estimates, as appropriate, to the solar value log ε(Fe) = 7.50. Magain (1989) analyzed blue spectra using MARCS models to obtain (T_{eff}, log g, [Fe/H]) = (5880, 4.10, −2.16) for HD 19445 and (5640, 3.35, −2.60) for HD 140283. Zhao (1990) analyzed green spectra by Magain's precepts to obtain almost identical results: (5880, 4.10, −2.1) for HD 19445 and (5640, 3.10, −2.6) for HD 140283. Tomkin et al. (1992) analyze a set of weak Fe I and Fe II lines to obtain the following parameters: (5880, 4.4, −2.15) for HD 19445 and (5640, 3.28, −2.64) for HD 140283. The effective temperatures were not determined independently by these investigators but are all based on Magain's (1989) discussion. We adopt Tomkin et al.'s parameters (Table 1) as they reproduce the Fe I/Fe II ionization balance best. Our preliminary non-LTE analysis of the optical Fe I and Fe II lines using a model Fe atom constructed by Steenbock (1985; see also Gigas 1986) suggests that the appropriate non-LTE models are (5880, 4.6, −2.0) for HD 19445 and (5640, 3.8, −2.4) for HD 140283. These two models are more similar in log g and [Fe/H] than their LTE counterparts.

The published analyses agree that the microturbulence, assumed depth independent, is 1.5 km s^{-1} for both stars. For HD 201891, we take the atmospheric parameters from Edvardsson et al. (1992): (T_{eff}, log g, [Fe/H]) = (5870, 4.5, −1.06), and a microturbulence of 1.1 km s^{-1}.

Analyses of ultraviolet spectra are potentially plagued by line blanketing from a host of overlapping unidentified lines that simulate a quasi-continuous opacity and depress the continuous flux. There are two reasons for supposing that the blanket is not effective in the two extreme halo stars HD 19445 and HD 140283. First, the line density of the observed spectrum is not very high, and, as noted above, "windows" do exist, and the inferred continuum in the raw spectrum very closely follows that expected from the vignetting introduced by the spectrometer. Second, an incomplete accounting for line blanketing would mean that the observed flux at 2500 Å is less than that predicted. The models for HD 140283 and HD 19445 pass this latter test with flying colors.

This test (see also Bell 1986) was applied with the stellar K magnitudes used to fix the stellar angular diameters. If we write the flux observed at Earth as f_λ (in ergs cm^{-2} s^{-1} $Å^{-1}$) and the flux at the stellar surface as F_λ (in the same units), we may write the predicted flux at 2500 Å as

$$F_{2500} = \frac{F_K}{f_K} f_{2500} ,$$

where we ignore the interstellar reddening for these nearby stars. The observed flux f_K was calculated from the K magnitude and the calibration that $f_K = 4.07 \times 10^{-11}$ ergs s^{-1} cm^{-2} $Å^{-1}$ for a star with $K = 0$ (D. F. Lester 1992, private communication). The adopted K magnitudes were $K = 5.74$ (HD 140283; Simbad data base), 6.65 (HD 19445; Elias et al. 1989), and 5.96 (HD 201891; Fernley 1989). The surface flux F_K was computed from the adopted models. Elias et al. argue that their MARCS-like models are for reasons unknown brighter than the real stars by 13% at K. Since our models are quite similar, we reduce the computed F_K by this amount. The observed fluxes at 2500 Å were obtained from the calibrated *HST* spectra and *IUE* spectra: $10^{12} f_{2500} = 1.3 \pm 0.1$, 2.0 ± 0.1, and 1.2 ± 0.1 for HD 19445, 140283, and 201891, respectively. With this input, we find the ratio of the observed and predicted surface fluxes at 2500 Å to be 1.06, 1.04, and 0.85 for HD 19445, 140283, and 201891, respectively. Differences of 5% are less than the uncertainties in the flux calibrations. Hence, we conclude that the chosen models correctly reproduce the 2500 Å flux and that the local continuum is not depressed by a plethora of unidentified overlapping lines. The apparent small discrepancy between the predicted and observed flux for the stronger-lined star HD 201891 could be eliminated by a very minor increase of the adopted continuous opacity at 2500 Å.

3.3. *Boron Abundances of HD 19445 and HD 140283*

Since the B I line is blended in our spectra with primarily the Co I line and secondarily the Fe I line at 2496.9 Å, its W_λ could be obtained from a deconvolution of the blend into its components. One of the basic premises of the deconvolution procedure is that the contributions of the individual lines are additive. This premise is valid for HD 19445 and HD 140283 in whose spectra the lines being considered are weak and effectively fully resolved in the intrinsic spectrum: it is the finite resolution of the spectrometer in its selected configuration that degrades the spectrum and blends the lines into a single feature. In the case of the stronger-lined star HD 201891, the Co I and B I lines are strong and quite severely blended in the intrinsic spectrum, and the deconvolution procedure is a questionable approach to the definition of the B I line. Therefore, we analyzed the spectra through spectrum synthesis using the model atmospheres discussed earlier. A cautionary note must be sounded in that it is still possible that the B I line may be blended with a weak unidentified line. Although we shall refer to the B abundance, the result should strictly be referred to as an upper limit.

Synthetic spectra and the observed spectrum for HD 140283 are compared in Figure 2. In examining this and other comparisons, it should be remembered that only the region from the strong line Fe I at 2496.5 Å to the Fe II line at 2497.3 Å was considered in detail. The basic line list was compiled from a list of predicted transitions of iron-group atoms and ions by R. L. Kurucz (1991, private communication) and from the earlier compilation of lines by Kurucz & Peytremann (1975). Several predicted lines were obviously much too strong, and these lines were either omitted or retained in the list, but with a greatly reduced *gf*-value. A similar result was found by Leckrone, Johansson, & Wahlgren (1992) in their analysis of GHRS spectra of the chemically peculiar star χ Lupi. They point out that other lines are observed but are predicted to have very small *gf*-values; both effects are easily attributable to configuration interaction. The *gf*-values of the five lines around the B I line were established in one of two ways. An accurate *gf*-value for the strong Fe I line at 2496.5 Å was provided by O'Brien et al. (1991). The *gf*-values of the Co I, Fe I, and Fe II lines were set

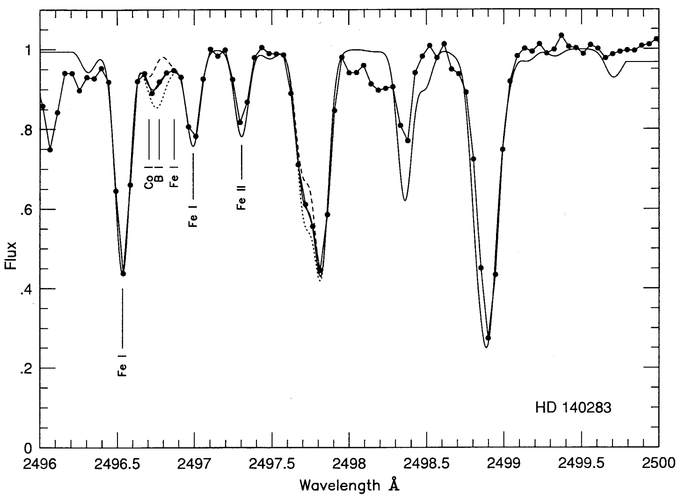

FIG. 2.—Observed and synthetic spectra of HD 140283. Synthetic spectra are shown corresponding to boron abundances log ε(B) = 0.2, −0.1, and −3.0 (no boron).

from a fit to the spectrum of HD 140283. The *gf*-values of lines blended with the stronger B I line at 2497.7 Å were adjusted so that HD 140283's blended feature is synthesized with the B abundance indicated by the weaker B I line. Van der Waals broadening was accounted for by Unsöld's (1955) recipe without any enhancement factors. An accurate estimate of C_6 (units: $cm^6\ s^{-1}$) is essential for HD 19445 and especially HD 201891, whereas due to relatively weak lines and a low gravity, HD 140283's spectrum is only marginally affected in the region of interest. Radiative damping was included with Γ_{rad} (units: s^{-1}) taken from R. L. Kurucz (1991, private communication) or estimated from the classical formula ($\Gamma_{rad} = 2.2 \times 10^{15}/\lambda^2$, where λ is in Å). Stark broadening was ignored. Table 2 gives the line list for the interval that includes the B I lines.

Synthetic spectra of HD 140283 are shown in Figure 2 for three B abundances: log ε(B) = 0.2, −0.1, and −3.0 (no boron). By inspection, the B abundance is seen to be close to log ε(B) = −0.1. The Fe I line at 2496.5 Å with an accurate laboratory *gf*-value is reproduced without manipulation of the atmosphere's defining parameters. Synthetic and observed spectra of HD 19445 are compared in Figure 3. The three synthetic spectra correspond to log ε(B) = 0.7, 0.4, and −3.0 (no boron). A boron abundance log ε(B) = 0.4 fits the Co I–B I blend. The B abundance is confirmed by the fit to the blend containing the stronger B I lines. In general, the synthetic spectrum is an acceptable reproduction of HD 19445's observed spectrum. The model atmospheres suggested by our preliminary non-LTE analyses of the Fe I and Fe II lines in HD 19445 and HD 140283 would provide a closer match to HD 19445's observed spectrum.

We discuss next the probable uncertainties of the B abundances. We are primarily concerned with the two extreme subdwarfs HD 19445 and HD 140283 whose B abundances may possibly betray the presence of primordial B from the big bang. For HD 140283, the sensitivity of the B abundance to the defining parameters is Δ log ε(B) = +0.10, +0.06, and 0.00 for the changes ΔT_{eff} = +100 K, Δ log g = +0.40 dex, and Δ[Fe/H] = +0.4 dex, respectively, where $\Delta X = X_{new} - X_{standard}$ and "new" and "standard" refer to the new model and the adopted model, respectively. Similar changes are found for the slightly hotter model representing HD 19445: Δ log ε(*B*) = +0.09, +0.09, and 0.00 for the same ΔT_{eff}, Δ log g, and Δ[Fe/H]. The B I line in both stars is too weak to be sensitive to the uncertainty of the adopted microturbulence.

Discussion of the uncertainty in the T_{eff} was provided by Hobbs & Duncan (1987) in their determination of lithium abundances in these three stars. In an attempt to get the most accurate stellar temperatures, they examined $R-I$, $V-K$, and Strömgren colors for each star, as well as low-resolution spectral scans. The temperatures from these four sources indicate that the *random* error in temperature for each of our three stars is about 50 K. The *absolute* error in the temperature includes the zero-point errors in the color-temperature and scan-temperature scales, which results in a total uncertainty of approximately 100 K. Effective temperatures derived by

TABLE 2

THE LINE LIST

Species	λ(Å)	χ(eV)	log *gf*	log C_6	$10^{-8}\Gamma_{rad}$
Fe I	2496.533	0.91	−0.66	−32.35	0.87
Co I	2496.707	0.51	−0.70	−31.39	0.76
B I	2496.772	0.00	−0.81	−30.81	3.56
Fe I	2496.870	2.76	−1.40	−30.39	3.56
Fe I	2496.992	2.56	−0.62	−31.39	3.56
Fe I	2497.153	2.56	−3.09	−31.39	3.63
Co I	2497.261	3.25	−0.02	−31.39	3.63
Fe II	2497.303	3.22	−1.45	−32.28	4.57
Fe I	2497.420	2.20	−3.90	−31.36	1.74
Co II	2497.483	3.08	−0.47	−31.58	3.16
Co I	2497.488	2.54	−0.17	−31.39	3.80
Fe I	2497.491	2.20	−2.59	−31.39	1.62
Mn I	2497.595	2.95	−1.09	−30.08	0.85
Fe I	2497.636	3.63	−1.60	−31.39	0.62
Fe II	2497.683	2.81	−2.10	−32.51	2.75
Fe II	2497.703	2.64	−3.83	−31.07	3.09
Fe I	2497.704	2.20	−2.00	−31.39	0.54
Fe II	2497.716	3.27	−1.63	−31.64	5.62
B I	2497.723	0.01	−0.50	−30.81	3.56
Fe I	2497.738	3.27	−2.36	−31.39	0.76
Ni I	2497.801	1.86	−2.59	−31.91	3.80
Fe II	2497.820	2.84	−3.26	−31.61	4.47
Fe II	2497.820	3.23	0.00	−32.58	4.07
Cr II	2497.903	0.96	−1.44	−31.25	1.95

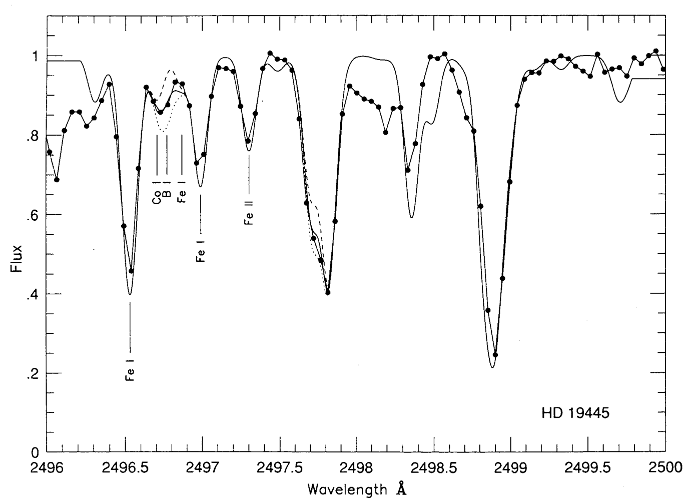

FIG. 3.—Observed and synthetic spectra of HD 19445. Synthetic spectra are shown corresponding to boron abundances log ε(B) = 0.7, 0.4, and −3.0 (no boron).

Hobbs & Duncan (1987) are very similar to our adopted values: our values of $T_{\rm eff}$ are 60 K hotter for HD 19445, identical to Hobbs & Duncan's for HD 140283, and 30 K hotter for HD 201891.

Surface gravities of subdwarfs are customarily determined from the requirement that lines of a neutral atom and the singly charged ion of the same element yield the same abundance. In practice, iron is used, but titanium is an occasional supporting element. For a predetermined Fe abundance from many Fe I lines and a model at a given $T_{\rm eff}$, the few available Fe II lines may match the Fe abundance to about ± 0.1 dex when errors in the equivalent widths and the Fe II *gf*-values are considered. This uncertainty corresponds to ± 0.3 dex in log g. The uncertainty $\Delta T_{\rm eff} \simeq 100$ K translates to $\Delta \log g = \pm 0.16$ dex. Then, we suppose that an uncertainty $\Delta \log g = \pm 0.4$ dex is representative of the accuracy now attainable from this exploitation of ionization equilibrium. Certainly, a comparison of recent applications of this method to HD 19445 and HD 140283 (see § 2) confirms our assessment. Recent applications adopt the assumption of LTE. Our preliminary non-LTE analysis of Fe I and Fe II lines suggests that the LTE analyses underestimate the gravity by about 0.2 dex for HD 19445 and, perhaps, as much as 0.5 dex for HD 140283. Magain (1985) showed that other spectroscopic indicators of the surface gravity provide results concordant to within ± 0.4 dex or better with those from the Fe (and Ti) LTE ionization equilibrium. The alternatives include the damping wings of strong Ca I and Fe I lines, the Ca II K line profile, and the Balmer discontinuity. The mean gravity provided by these alternatives, which are likely to be less sensitive to departures from LTE than the ionization equilibrium of Fe, is, according to Magain's (1985) results, systematically higher than his results from (LTE) ionization equilibrium. Our calculations suggest that a non-LTE analysis of ionization equilibrium would remove the systematic difference. It would be of great interest to make a comprehensive reanalysis of all the indicators of surface gravity.

The surface gravity may also be estimated from the stellar radius and mass. One may assume $M \simeq 0.8\ M_\odot$ for these old subdwarfs. The stellar radius is obtainable from the trigonometrical parallax (π), and either the angular radius as estimated from the infrared flux method or the bolometric magnitude. Published measurements of HD 140283's trigonometrical parallax appear generally consistent; for example, $\pi = 0''.043 \pm 0''.006$ is quoted by Bessell, Sutherland, & Ruan (1991; see also Magain 1985 and Laird, Carney, & Latham 1988). This parallax is equivalent to the surface gravity $\log g = 4.6$ of a main-sequence subdwarf. At this gravity, ionization equilibrium demands $T_{\rm eff} \simeq 6300$ K, but this $T_{\rm eff}$ is quite inconsistent with the observed colors and the excitation temperatures of Fe I and other species. The above parallax and the spectroscopic gravity imply a mass of $m \simeq 0.03\ M_\odot$ (Magain 1985) for HD 140283, but the star is not a brown dwarf! C. C. Dahn (1992, private communication) has resolved the issue with a new determination of the absolute parallax: $\pi = 0''.0147 \pm 0''.0023$ which corresponds to $\log g \simeq 3.7$. The measured parallax of HD 19445 ($\pi = 0''.021 \pm 0''.006$; see Magain 1985), the angular diameter inferred by Arribas & Martinez Roger (1989), and an assumed mass $m = 0.8\ M_\odot$ correspond to $\log g \simeq 4.3$, which is consistent with the spectroscopic estimates (see § 3.2).

The uncertainty in the B abundance of HD 140283 is dominated by the contributions from the equivalent width and the effective temperature. The former contributes ± 0.10 dex, and the latter is unlikely to exceed the ± 0.10 dex that corresponds to $\Delta T_{\rm eff} = \pm 100$ K. The surface gravity contributes ± 0.06 dex for $\Delta \log g = \pm 0.40$ dex. The combination of these three uncertainties amounts to ± 0.14 dex which we round off to ± 0.20 dex to cover additional uncertainties from the several minor sources, such as the *gf*-value. This estimate is also appropriate for HD 19445. These estimates do not, of course, include possible systematic errors: an unidentified blend coincident with the B I line, departures from local thermodynamic equilibrium, failure of the stars to recognize other basic assumptions behind the model atmosphere (i.e., presence of stellar granulation). We comment briefly on these systematic errors when we discuss the conclusions to be drawn from the B/Be abundance ratio.

3.4. *Boron and HD 201891*

Inspection of the observed spectrum (Fig. 1) shows that it is rich in lines with Fe I resonance and some other lines providing deep broad cores and extended wings. Synthetic spectra show that many lines are intrinsically very saturated with cores formed in the atmospheric boundary layer. The B I line makes a major contribution to a strong blended feature; a predicted intrinsic spectrum shows the B I line at a depth of nearly 90% of the continuum and just resolved from the Co I line to the blue and partially resolved from the Fe I line just to the red. At the resolution of the grating, the Co I–B I–Fe I lines comprise a broad feature. The other Fe I line to the red is just resolved, and the Fe II line at 2497.3 Å is well resolved and "black" in the line core. All of these lines as well as many others in the spectral interval would normally be discarded by a spectroscopist seeking to derive elemental abundances. The blending imposed on the spectrum by the moderate resolution of the grating is certainly unhelpful, but the echelle would merely betray more starkly the unsuitability of the lines. These very strong lines are presumably sensitive to non-LTE effects, the structure of the upper photosphere (where is the chromosphere?), the details of the microturbulent velocity field, the local continuum as provided by the pressure broadened wings of the strong lines, and a picket of many weak, mostly unidentified lines. This litany of real problems must be remembered when matching synthetic to observed spectra in order to extract the B abundance.

The first task was to establish the appropriateness of the selected model atmosphere and the completeness of our representation of the continuous opacities in the ultraviolet. Optical spectroscopy and photometry has shown that HD 201891 is well represented by a MARCS model with ($T_{\rm eff}$, log g, [Fe/H]) = (5870, 4.5, -1.1) and a microturbulence of 1.1 km s^{-1} (Edvardsson et al. 1992). Since the Fe I and Fe II lines near the B I line are so strong, we decided to check predicted and observed strengths of several weaker lines, Co I, Cr I, and Fe II. The *gf*-values of these lines were derived using the spectrum of HD 140283. For some lines, *gf*-values were available from laboratory experiments, and the line's predicted strength in HD 140283 was generally close to the measured value. When *gf*-values based on HD 140283 were adopted, the predicted and observed strengths of HD 201891's weaker lines are in fair agreement. The match to the strong lines around the B I line is also satisfactory. A synthesis of the region around the B I lines is shown in Figure 4 for B abundances of log ε(B) = 2.0, 1.7, and -3.0 (no boron). In order to achieve the good fit to the Fe I and Fe II lines, an adequate choice for van der Waals

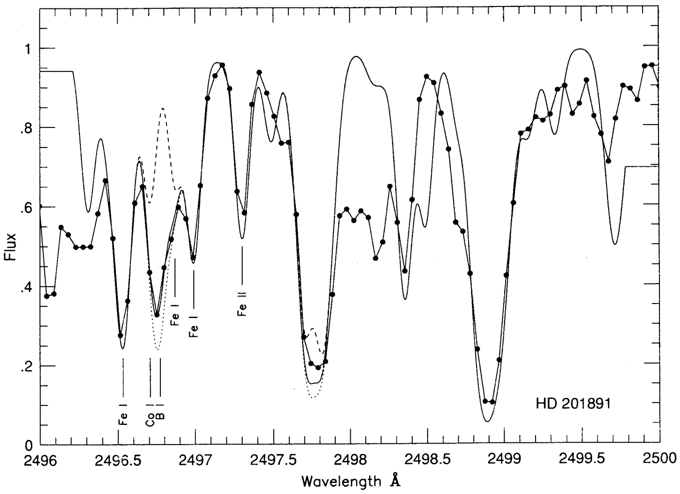

FIG. 4.—Observed and synthetic spectra of HD 201891. Synthetic spectra are shown corresponding to boron abundances log ε(B) = 2.0, 1.7, and −3.0 (no boron).

damping parameters was essential. According to Simmons & Blackwell (1982) only moderate enhancement factors to Unsöld's approximation are required, which was confirmed by our syntheses. Both orbital quantum number and the energy of the parent term have to be properly taken into account when calculating C_6, however.

In conclusion, we note that HD 201891's B abundance is necessarily uncertain because the blend containing the B I line is strong. The B abundance provided by the synthetic spectrum is log ε(B) = 1.7 and is uncertain by about ±0.4 dex.

4. DISCUSSION

Theoretical views on the synthesis of boron may be divided into the orthodox view and a collection of alternative views ranging from the mildly unorthodox to the radical. We discuss first whether our estimates of the B abundance are compatible with the orthodox view in which boron was synthesized by spallation reactions between cosmic rays and interstellar nuclei, and in which the big bang provided truly insignificant amounts of boron: log $\varepsilon(B)_{BB} \simeq -5$ (Kajino & Boyd 1990) for that standard (homogeneous) big bang indicated by the inferred primordial abundances of D, ^{3}He, ^{4}He, and Li. This orthodox view and our observations of boron are most directly compared by reference to observed abundances of beryllium which like B is, in the orthodox view, a product of spallation and not synthesized in observable amounts in the big bang: log $\varepsilon(Be)_{BB} \simeq -3.6$ (Kajino & Boyd 1990) also for the standard (homogeneous) big bang model.

4.1. *The* B/Be *Ratio: Observations*

Recent observations and analysis of the Be II 3131 Å resonance doublet have led to estimates of the Be abundance in metal-poor stars. In particular, independent analyses of the Be abundance of HD 140283 are in good agreement. Gilmore et al. (1992) give a weighted mean abundance log ε(Be) = −0.97 ± 0.25 based on spectra obtained in 1990 and 1991; the 1990 spectra, as reported by Gilmore, Edvardsson, & Nissen (1991) gave log ε(Be) = −0.8 ± 0.3, and the 1991 spectra of higher quality gave log ε(Be) = −1.03. Ryan et al. (1992) obtained log ε(Be) = −1.25 ± 0.4 from independent spectra. The quoted Be abundances refer to different model atmospheres, and the error estimates include the authors' assessment of the contribution from the defining parameters. Ryan et al.'s model atmosphere is quite similar to ours. Gilmore et al. (1992) adopt a higher gravity (log g = 3.5) by using theoretical isochrones and the assumption that HD 140283 is a subgiant. When the published Be abundances are corrected to what would be obtained with our adopted model, they differ by 0.2 dex: log ε(Be) = −1.05 (Gilmore et al.) and −1.23 (Ryan et al.). The difference between Gilmore et al.'s and Ryan et al.'s adjusted abundances may reflect the uncertainty in fitting synthetic spectra to observed spectra of differing quality. The spectra were obtained with the same spectrometer, but Gilmore et al. observed at the slightly higher resolution. Since Gilmore et al. report two independent observations and analyses, we assign their result twice the weight of Ryan et al.'s. We adopt the weighted mean of the two adjusted abundances [log ε(Be) = −1.1] in estimating the B/Be ratio for HD 140283. Uncertainties arising for $T_{\rm eff}$ and log g partially cancel when B/Be is computed: we estimate that Δ log ε(B)/ε(Be) = +0.05, −0.14, and +0.07 for $\Delta T_{\rm eff}$ = 100 K, Δ log g = +0.4, and Δ[Fe/H] = +0.4. In light of our earlier discussion of the defining parameters, these estimates show that the surface gravity is the principal source of uncertainty with respect to the contributions from the model atmosphere. The defining parameters nominally contribute about ±0.15 dex to log ε(B)/ε(Be). The B I line's contribution to the uncertainty is ±25% which we increase to ±30% (or 0.11 dex) to allow for a contribution from the *gf*-value. We take the equivalent estimate for the Be II lines as ±0.15 dex in light of the difference of 0.2 dex between the adjusted independent analyses cited above and from inspection of the published fits of the synthetic to the observed spectra. The combination of these independent errors amounts to ±0.20 dex. Then, we obtain for HD 140283, log ε(B)/ε(Be) = 1.0 ± 0.2 or B/Be = 10 (+5, −4) for the ratio by number of atoms. If the higher gravity (log g = 3.5) preferred by Gilmore et al. (1991) is adopted, the Be abundance increases, and B/Be = 7 is found. Bessell et al. (1991) argue that the appropriate model for HD 140283 has $T_{\rm eff}$ = 5800 K and log g = 4.5. This model, which would give B/Be ≃ 4, is, however, not consistent with the observed colors and violates the requirement of ionization equilibrium for iron (see § 3.2).

Unfortunately, we cannot as yet obtain a direct estimate of the B/Be ratio for HD 19445 because its Be abundance has not been determined. Gilmore et al. (1992) report Be abundances for a sample of subdwarfs including six with −2.3 < [Fe/H] < −1.9. The Be abundance declines smoothly with metallicity with a scatter about a mean trend that is apparently consistent with the measurement errors. These recent Be measurements imply log ε(Be) = −0.6 for HD 19445, which corresponds to B/Be = 10 (+5, −4). Rebolo et al. (1988a) found the Be abundance of HD 201891 to log ε(Be) = 0.4 (+0.3, −0.4) which with our B abundance corresponds to B/Be ≃ 20.

There remain, of course, potential sources of systematic errors. First, if the absorption identified as due to B I in the two extreme subdwarfs is partially contributed by an unidentified line, our results are to be considered upper limits, that is, B/Be < 10 for HD 140283. Second, the analyses of the B I and Be II lines are based on the assumption of LTE. One may surmise that the dominant departure from LTE may be the overionization of the neutral atoms. In this case, Be^+ being the common form for Be will be little affected, but overionization may deplete the density of B atoms, and, hence, we may have underestimated the B abundance. The correction to the LTE abundance is possibly slight because the weak B I lines are formed deep in the atmosphere. Third, the atmospheres may contain granulation (i.e., hot and cold streams). A model atmosphere consisting of homogeneous plane parallel layers fitted to certain observational quantities may fail to represent the B I and Be II lines with equal precision. Such a failure seems likely to affect differently the neutral and ionized lines of elements with comparable ionization potentials. The effective temperature of the model atmosphere is chosen primarily on the basis of an observed continuous spectrum at visible or longer wavelengths. Since the relative contribution of the hot streams is likely to be greater in the ultraviolet, neglect of granulation has possibly resulted in the underestimate of the B abundance. This concern is alleviated by the fact that the predicted and observed fluxes at 2500 Å are in good agreement for HD 19445 and HD 140283. Since the ultraviolet flux for cool objects is sensitive to small changes in temperature, it would seem unlikely that the agreement between the fluxes is fortuitous and such that the higher flux from the hot streams is offset by their smaller surface area.

4.2. *The B/Be Ratio: Predictions*

On the assumption that Be and B are solely products of spallation, the B/Be ratio is predictable with few additional assumptions. Of course, a demonstration that the observed B/Be ratio is equal to that expected from spallation is a necessary, but not a sufficient, condition for spallation to be identified as the principal mode of synthesis of Be and B. The expected B/Be ratio is influenced by the unknown shape of the energy spectrum for the cosmic-ray protons and α-particles in the early Galaxy and by the rather well-determined energy dependent spallation cross sections. Observations show that Galactic cosmic-ray protons and α-particles now have very similar spectra when energy per nucleon is considered. The ratio of protons to α-particles is approximately the Galactic abundance ratio (i.e., $n_p/n_\alpha \approx 10$). More importantly, the energy spectra peak at about 400 MeV nucleon^{-1} which means that production of Be and B by spallation is primarily influenced by proton and α-particle impacts at energies far above the threshold energies for production of the Be and B isotopes: approximately 80% of current production of Be and B is contributed by cosmic rays with energies greater than 100 MeV nucleon^{-1} (Austin 1981). This is an important result because the cross sections for production of these isotopes are almost independent of energy at $E \gtrsim 100$ MeV nucleon^{-1}, and, hence the predicted B/Be ratio is insensitive to the adopted form of the cosmic-ray energy spectrum above 100 MeV nucleon^{-1}.

Our estimates of the B/Be ratio are based on the spallation cross sections compiled by Read & Viola (1984) for protons and α-particles on ^{12}C, ^{14}N, and ^{16}O targets. We ignore the small loss of B and Be as these products are slowed to thermal velocities in the interstellar medium. We comment below on the contribution from cosmic-ray CNO nuclei on interstellar protons and α-particles. Since the energy spectrum of cosmic rays in the early Galaxy is unknown, we begin by estimating the production rates for monoenergetic cosmic rays.

For B, we write the rate as

$$P(\mathrm{B}) = \frac{d\varepsilon_\mathrm{B}}{dt} = \phi_p^\mathrm{CR} \sum_i \varepsilon_i^\mathrm{ISM} \sigma_{p,i}(\mathrm{B}) + \phi_\alpha^\mathrm{CR} \sum_i \varepsilon_i^\mathrm{ISM} \sigma_{\alpha,i}(\mathrm{B}) , \quad (1)$$

where ϕ_p^CR and ϕ_α^CR are the flux of cosmic-ray protons and alphas, $\varepsilon_i^\mathrm{ISM}$ is the abundance of species i in the ambient gas, and $\sigma_{m,i}$ is the spallation cross section between cosmic-ray particle m and the ambient gas particle i. There is an equivalent equation for Be.

The summation over i involves i = C, N, and O. At present, the ratio of the cosmic-ray fluxes ϕ_p/ϕ_α (at the same energy per nucleon) in the cosmic rays is about equal to the local H/He (=10) ratio. We assume that this was also true in the early Galaxy. Observations of halo dwarf stars show that the interstellar gas had a composition corresponding to [O/Fe] = 0.5, [C/Fe] = [N/Fe] = 0.0 for [Fe/H] $\lesssim -1$ (Lambert 1989), and, hence, oxygen was the most abundant element of the CNO trio: C/O = 0.15 and N/O = 0.05. With these relative CNO abundances, we may rewrite equation (1) in terms of the oxygen abundance O/H and an effective cross section σ_eff:

$$P(\mathrm{B}) = \phi_p^\mathrm{CR} \sigma_\mathrm{eff}(\mathrm{B}) \left(\frac{\mathrm{O}}{\mathrm{H}}\right)_\mathrm{ISM} , \quad (2)$$

where

$$\sigma_\mathrm{eff} = \sum_{j=p,\alpha} a_j [\sigma_{j,O}(\mathrm{B}) + 0.15\sigma_{j,C}(\mathrm{B}) + 0.05\sigma_{j,N}(\mathrm{B})] , \quad (3)$$

in which $a_j = 1$ for $j = p$ and $a_j = 0.1$ for $j = \alpha$.

The energy dependences of σ_eff(B) and σ_eff(Be) are shown in Figure 5. At $E \lesssim 30$ MeV nucleon^{-1}, σ_eff is dominated by spallations caused by cosmic-ray α-particles and at $E \gtrsim 30$ MeV nucleon^{-1} by protons on oxygen. We expect the abundance ratio B/Be to be very similar to the production ratio P(B)/P(Be) = σ_eff(B)/σ_eff(Be) shown in Figure 5. At $E < 8$ MeV nucleon^{-1}, P(B)/P(Be) increases steeply as B production from collisions with α's has a lower threshold than Be production. At the high-energy limit, $E \gtrsim 100$ MeV nucleon^{-1}, the production ratio has its minimum value P(B)/P(Be) = 10. The minimum value is insensitive to the adopted relative abundances of CNO nuclei in the interstellar medium and to the ratio $\phi_\alpha^\mathrm{CR}/\phi_p^\mathrm{CR}$. At $E \sim 200$ MeV nucleon^{-1}, B/Be = 21, 6, 9 for p on C, N, and O nuclei, respectively, and 15, 15, and 9 for

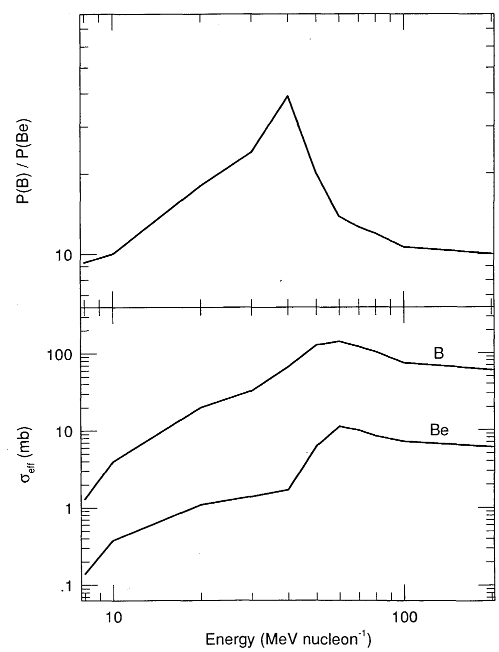

FIG. 5.—The effective cross sections (σ_eff[mb]) for production of B and Be (*lower panel*) and the ratio of the production rates of B and Be (*upper panel*).

α-particles on CNO nuclei, respectively. Therefore, $B/Be \simeq 6$ would be possible only if N is the dominant species of the CNO trio, but abundance analyses of subdwarfs show O atoms outnumber N atoms by about 20 to 1. Some observers have suggested that [C/Fe] may exceed zero for extreme halo stars; for example, Ryan, Norris, & Bessell (1991) obtain $[C/Fe] = 0.4 \pm 0.2$ for HD 140283. Tomkin et al. (1992) in an analysis of C I and CH lines suggest $[C/Fe] = -0.1$ for the halo but obtain $[C/Fe] = 0.2$ for HD 140283. We find that $P(B)/P(Be) = 10$, 11, and 12 at the high-energy limit for $[C/Fe] = 0.0$, 0.2, and 0.4, respectively. Steigman & Walker (1992) compute the B/Be ratio for cosmic rays having the energy spectrum observed locally. For the halo gas ($[O/Fe] = +0.5$, and $\alpha/p = 0.08$), they predict $B/Be = 14.5$ also from the cross-sections compiled by Read & Viola (1984).

In summary, spallation reactions yield a ratio $B/Be \gtrsim 10$ where the lower limit is appropriate for any form for the spectrum of the high-energy cosmic rays (say, $E/A \gtrsim 100$ MeV nucleon^{-1}). Inspection of the uncertainties assigned by Read & Viola (1984) to the cross sections suggest the minimum values for the high-energy limit is about 7 when the uncertainties on the cross section for B and Be production are put at their maximum and minimum values, respectively.

Our estimates (also those by Steigman & Walker 1992) of the production rates $P(Be)$ and $P(B)$ omit the contributions from cosmic-ray C, N, and O nuclei impacting interstellar protons and α-particles. This omission is commonly accepted on the grounds that cosmic-ray C, N, and O nuclei produce high-velocity Be and B nuclei that are largely destroyed through further collisions before they can be slowed to join the interstellar gas; according to Audouze & Reeves (1982) only 30% of the current production of Be and B is provided by the C, N, and O nuclei in the cosmic rays. The estimate of 30% reflects not only the low rate of survival for high-velocity Be and B nuclei, but also the fact that the abundance of C and O nuclei relative to protons in the local cosmic rays is approximately equal to that in the local interstellar medium. (Nitrogen is overabundant in cosmic rays in part because it is a product of spallation.) Omission of the contributions by cosmic-ray C, N, and O nuclei to the halo production of Li, Be, and B is based on the assumption that the CNO abundances scale with interstellar abundances. Meyer (1985a, b, 1988) has shown the composition of local Galactic cosmic rays at their source is the same as that of the coronae of ordinary main-sequence stars, and, hence, these normal stars are identified as the principal source of cosmic rays. Supernovae are, in this picture, a minor contributor of cosmic rays. If main-sequence stars were also the dominant contributor of cosmic rays in the halo, we may continue to omit the contributions of cosmic-ray CNO nuclei to the production of Be and B because the abundance of CNO in the cosmic rays probably paralleled their low abundances in the stars. If, on the other hand, supernovae dominated the injection of cosmic rays into the halo, one expects a high abundance of CNO, and, then, production of Be and B may be dominated by the contributions of the CNO in the cosmic rays. In the next section we show that this dominance may account for the evolution of the Be and B abundances with metallicity.

4.3. *Synthesis of* Li *by Cosmic Rays*

Before commenting on whether the observed B/Be ratio is consistent with the hypothesis that cosmic-ray-induced spallation reaction produced these light elements, we discuss the synthesis of Li that is an inevitable concomitant of spallation reactions. Production of Li in the early Galaxy may differ from B and Be production in one key way: ^{6}Li and ^{7}Li are synthesized by collisions between α-particles in addition to p (and α) collisions with CNO nuclei, and, hence, the ratio of production rates of Li/B and Li/Be in the halo may have been very high. We must therefore consider the possibility that attribution of Be and B as spallation products may imply an excessive production of ^{6}Li and ^{7}Li from α on α collisions. The contribution of the α on α fusion reactions to the synthesis of ^{6}Li and ^{7}Li has been discussed often before; see, for example, the review by Austin (1981). Steigman & Walker (1992) redirected attention on the α-on-α reactions and to the possibly high values for $P(Li)/P(B)$ and $P(Li)/P(Be)$ in the halo.

Cross sections for production of ^{6}Li and ^{7}Li in α-on-α collisions are shown in Figure 6 from Read & Viola (1984). The cross sections for $E > 50$ MeV nucleon^{-1} are an extrapolation of the measurements available in 1984. For ^{7}Li , the recommended curve at 100–300 MeV nucleon^{-1} passes through experimental upper limits to the cross section. At the high-energy limit, $E \gtrsim 100$ MeV nucleon^{-1}, the production rates for our assumed conditions in the early Galaxy are

$$P(^6\mathrm{Li}) = \left[0.0019 + 19\left(\frac{\mathrm{O}}{\mathrm{H}}\right)_{\mathrm{ISM}}\right]\phi_p^{\mathrm{CR}} \qquad (4)$$

and

$$P(^7\mathrm{Li}) = \left[0.0003 + 28\left(\frac{\mathrm{O}}{\mathrm{H}}\right)_{\mathrm{ISM}}\right]\phi_p^{\mathrm{CR}} . \qquad (5)$$

The corresponding rates for Be and B are

$$P(\mathrm{Be}) = 6\left(\frac{\mathrm{O}}{\mathrm{H}}\right)_{\mathrm{ISM}} \phi_p^{\mathrm{CR}} \quad \text{and} \quad P(\mathrm{B}) = 60\left(\frac{\mathrm{O}}{\mathrm{H}}\right)_{\mathrm{ISM}} \phi_p^{\mathrm{CR}} .$$

The relative abundance of Li to B (or Be) is, unlike the

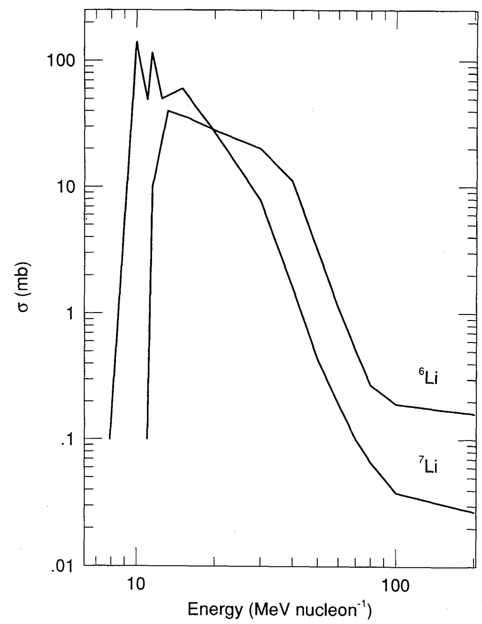

FIG. 6.—The cross sections for production of ^{6}Li and ^{7}Li from α-on-α collisions.

abundance of B to Be, dependent on the temporal evolution of the O abundance in the interstellar medium and of the flux ratio $\phi_\alpha^{CR}/\phi_p^{CR}$. If we assume that $\phi_\alpha^{CR}/\phi_p^{CR}(=0.1)$ at high energies was constant in the halo's development, we predict for the stellar abundances that

$$\frac{\varepsilon(\mathrm{Li})}{\varepsilon(\mathrm{B})} \cong \left(\frac{\mathrm{Li}}{\mathrm{B}}\right) \simeq \frac{0.0022 + 47\langle \mathrm{O/H} \rangle}{60\langle \mathrm{O/H} \rangle} \qquad (6)$$

where $\langle$O/H$\rangle$ is the O/H in the interstellar medium weighted by the cosmic-ray flux at high energies and averaged over the life of the halo prior to the formation of the star. There is a similar equation for ε(Li)/ε(Be). Equation (6) does not take into account that there may be other sources of the light elements such as the big bang and that the stellar surface abundances may be depleted by internal destruction or diffusion. If the interstellar O/H ratio increased linearly with time, Li/B $\simeq$ 15 is predicted. If the B and Be in HD 140283 are entirely due to spallation, the Li synthesized by cosmic rays is predicted to be log ε(Li) $\simeq$ 1.2. The Li from the cosmic rays increases with increasing B and Be abundances (i.e., the metallicity) of the halo star: for [Fe/H] $\simeq -1$, the metallicity of the transition from halo to disk, equation (6) with the observed B abundance predicts log ε(Li) $\simeq$ 1.7. Since the atmospheric ^{6}Li is almost certainly destroyed by the stars on their approach to the main sequence, the relevant predictions are those of the ^{7}Li abundance or log ε(Li) $\simeq$ 0.4 (HD 140283) and 0.9 ([Fe/H] = −1). The predicted Li abundances are higher if the O/H in the interstellar medium increased slowly at first and then more rapidly just prior to the formation of HD 140283. Evolutionary models of rotating halo stars predict substantial depletion of even ^{7}Li. Pinsonneault, Deliyannis, & Demarque (1992) find a factor of 10 depletion for rotating models that reproduce the constant Li abundance of halo stars. The surviving fraction of the cosmic-ray-synthesized Li is then equivalent to log ε(Li) $\simeq -0.6$ (HD 140283) and -0.1 ([Fe/H] $\simeq -1$). These are negligible contributions to the observed abundance [log ε(Li) $\simeq$ 2.1] which is the remnant of an initial (big bang) abundance of log ε(Li) $\simeq$ 3.1.

Low-energy cosmic rays lead to much higher Li/B and Li/Be ratios. This increase occurs in part because the cross sections for Li production through α-on-α collisions increase by factors of 100 (^{6}Li) and 1000 (^{7}Li) as the energy is reduced from 100 MeV nucleon^{-1} or greater to about 20 MeV nucleon^{-1} (Fig. 6). These increases are in sharp contrast to the modest increases (factors of about 3) for the proton on CNO cross sections as the energy drops from above 100 MeV nucleon^{-1} to around 60 MeV nucleon^{-1}. Note also the lower thresholds for the α-on-α reactions. These differences between α-on-α and *p*-on-CNO collisions at low energies in conjunction with our total ignorance about the low-energy spectrum and composition of cosmic rays in the early Galaxy ensure that all calculations of relative rates of Li to B or Be production are bounded only by an investigator's imagination and observational constraints. Production ratios for ^{6}Li/^{7}Li and Li/B as a function of energy are shown in Figure 7 for interstellar gas having the O abundance of HD 140283. Steigman & Walker (1992) adopt the spectrum of local cosmic rays and estimate a ratio of production rates for ^{6}Li to ^{7}Li of 0.9 for α-on-α collisions which contrasts with the ratio of 5 at $E \gtrsim 100$ MeV nucleon^{-1}. Steigman & Walker's prediction of Li/B = 66 for gas of HD 140283's metallicity is an order of magnitude larger than the limiting high-energy value.

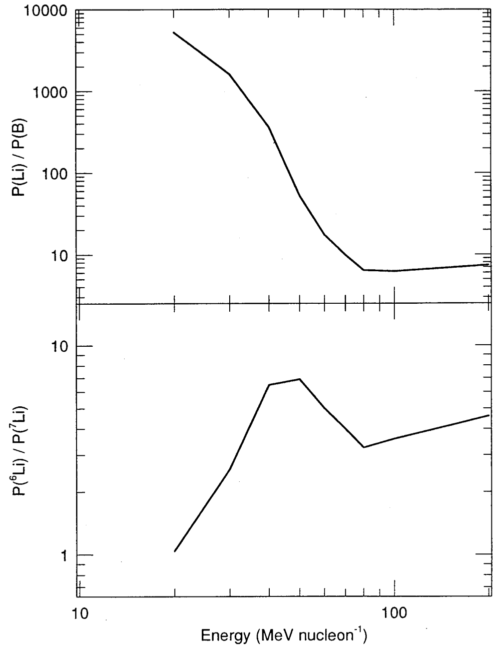

FIG. 7.—Ratios of the production rates $P(^6\mathrm{Li})/P(^7\mathrm{Li})$ and $P(\mathrm{Li})/P(\mathrm{B})$ from the α-on-α fusion reactions and the *p* (and α) on interstellar C, N, and O nuclei for halo gas with the composition of HD 140283.

Once low-energy cosmic rays are introduced, the observations and the predictions of Li, Be, and B in HD 140283 and HD 19445 are not reconciled so straightforwardly as for the high-energy predictions just discussed. Steigman & Walker (1992) discuss Li, Be, and B synthesis on the assumption that the cosmic rays have the observed local spectrum and the composition of the interstellar (halo) gas and noted the possibility that cosmic rays, not the big bang, may have made the dominant contribution to Li in the early Galaxy. If the interstellar oxygen abundance increased linearly with time, Steigman & Walker's production ratios with the observed B and Be abundances predict that HD 140283 and HD 19445 should have a ^{7}Li abundance of about 1.7 when we assume, as is very likely, that the ^{6}Li is destroyed and not now present in the stellar atmospheres. If ^{7}Li is depleted according to the predictions for rotating models (Pinsonneault et al. 1992), the prediction is lowered to log ε(Li) ~ 0.7. However, the production ratios $P(\mathrm{Li})/P(\mathrm{B})$ and $P(\mathrm{Li})/P(\mathrm{Be})$ for the local spectrum are in no sense probable values, and much higher (or lower) values are possible for other choices of the energy spectrum.

The Li/Be and Li/B ratios depend too on the assumption that cosmic-ray CNO nuclei do not produce significant amounts of Li, Be, and B. If the cosmic rays were spawned by supernovae, it is likely in at least the immediate environs of a supernova that the abundance of CNO nuclei in the cosmic rays exceeded their abundance in the ambient halo gas. Then, equation (6) shows that if the ratio of oxygen nuclei to protons in the cosmic rays exceeds about one-tenth of the solar O abundance, the oxygen on proton collisions dominate the Li production; a 50% loss of the Li is included to account for breakup of the high-velocity Li nuclei as they are decelerated in the interstellar medium. When the cosmic-ray CNO nuclei are the leading contributors to spallation, Li/B $\lesssim$ 1 is possible (see eq. [6]) and the observed halo Li abundance must result entirely from the big bang or production in the protogalaxy.

This survey of the Li synthesis that is a concomitant of Be and B synthesis by cosmic rays shows that no certain predictions of the Li yields (scaled to the observed Be and B abundances) can be made at present owing to our lack of knowledge about the energy spectrum and composition of the cosmic rays in the halo. Fortunately Deliyannis, Pinsonneault, & Duncan (1992) show that any systematic differences in the observed Li abundances over the range [Fe/H] = −1.4 to −3.5 are very small, certainly less than 10%. This observational result implies that Li in the halo was not a product of cosmic rays. The implication is compatible with the observed B and Be abundances provided that the production of B and Be was dominated by high-energy cosmic rays. The associated yield of Li may be suppressed further if the CNO nuclei were overabundant in the cosmic rays.

4.4. *Synthesis by Cosmic-Rays: Observations and Predictions*

In the preceding discussion of light element synthesis by cosmic rays we examined predicted and observed *ratios* of the abundances of Li, Be, and B. Ultimately, the hypothesis of synthesis by cosmic rays must pass two additional tests: (1) Can the cosmic rays account for the *absolute* elemental abundances? (2) Can the hypothesis explain the observed growth of the B and Be abundances with metallicity of the halo and disk (i.e., [B/H] vs [Fe/H] or [O/H])?

The yield of B or Be from cosmic-ray spallation depends on the cosmic-ray flux. Steigman & Walker (1992; see also Steigman 1992) who adopt the local energy spectrum show that, when the halo gas has the composition of HD 140283, boron is synthesized at a rate such that HD 140283's B abundance is reached with a *minimum* exposure equivalent to $\phi_p^{\rm local}$ for 7 Gyr, where $\phi_p^{\rm local}$ is the Galactic cosmic-ray flux now observed in the solar neighborhood. If the dominant mode of synthesis was from cosmic-ray protons on interstellar oxygen nuclei, the mean P(B) applicable to HD 140283 is lower than assumed; the rate is halved if the cosmic-ray flux $\phi_p^{\rm local}$ were constant and the interstellar oxygen abundance increased linearly with time. In addition, the rate P(B) was smaller if the actual cosmic-ray flux was limited to high-energy particles. Perhaps the required exposure is 15–30 Gyr at a flux $\phi_p^{\rm local}$. If the CNO nuclei were more abundant (relative to protons) in the cosmic rays than in the ambient halo gas, the exposure times would be shortened. The time available for synthesis depends on the adopted model for the formation of the Galaxy's halo (rapid collapse of a protogalaxy vs. accretion of dwarf galaxies), but presumably the time should be much shorter than the Hubble time, that is, the yields from cosmic-ray spallation were most probably higher than estimates. One surmises that either the cosmic-ray flux was more intense or the interactions more efficient (i.e., local overabundances of CNO nuclei).

The similar evolution of the Be and B abundances contrasts sharply with that of Li. In Figure 8 we show our B abundances and Be abundances of halo stars taken from the literature. We represent the Li abundances by the upper envelope to the run of the observed abundances with metallicity (Rebolo, Molaro, & Beckman 1988; Lambert, Heath, & Edvardsson 1991). One remarkable and well-known feature of Figure 8 is "the Li plateau," that is, the Li abundance is constant for [Fe/H] $\lesssim$ −1.5; HD 19445, HD 140283 and HD 201891 have the Li abundance of the plateau. A second feature is the absence of a plateau in either the Be or B abundances. If the plateau, which is generally regarded as a signature of primordial nucleosynthesis, exists for either Be or B, it must be below their abundance in HD 140283. A third feature of Figure 8 is that the evolution of the Be and B abundance is directly proportional to the Fe abundance. Since the O/Fe ratio is constant for halo stars, the Be and B increase is also proportional to the O abundance. (Accurate results for disk stars are too sparse to determine the transition of the Be and B abundances from the halo to the disk. At [Fe/H] $\simeq$ −1, [O/Fe] changes from [O/Fe] $\simeq$ +0.4 in the halo to [O/Fe] $\simeq$ 0.5 [Fe/H] in the disk.)

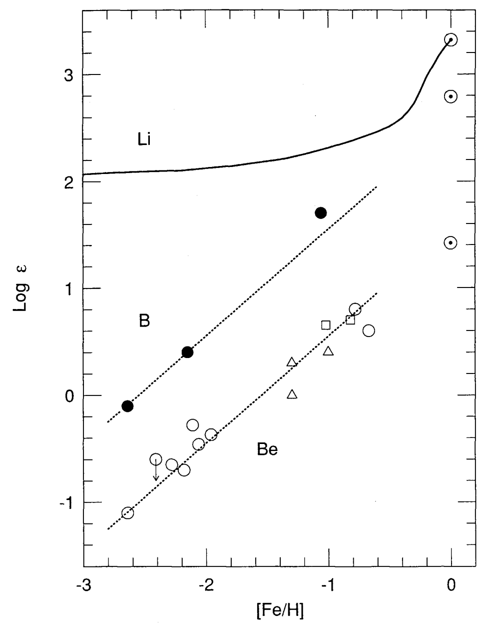

FIG. 8.—Abundances of Li, Be, and B vs. metallicity for halo dwarfs. Be abundances are taken from Edvardsson et al. (1992, *open circles*), Rebolo et al. (1988a, *open triangles*), and Ryan et al. (1992, *open squares*). The mean adjusted Be abundance is shown for HD 140283 (*see text*). The dashed lines fitted by eye to the B and Be data points correspond to [X/H] = [Fe/H] where X = B or Be. The separation between the lines corresponds to B/Be = 10. Meteoritic abundances of Li, and B are shown from Anders & Grevesse (1989).

Evolution of the abundance of Be has been discussed in several papers (Vangioni-Flam et al. 1990; Ryan et al. 1992) and recently by Gilmore et al. (1992). The rate of increase of the oxygen abundance depends on the frequency of Type II supernovae: $d\varepsilon({\rm O})/dt \propto dn^{\rm SN}/dt$ where we neglect contributions from the infall of unprocessed material. Supernovae are widely identified as the source of cosmic rays. If the primary process of spallation involves cosmic-ray protons (and α-particles) on interstellar oxygen nuclei, the rate of increase of B (and, similarly, Be) will involve the supernova rate and the current oxygen abundance. Since the oxygen abundance depends also on the supernova rate, one expects the evolution to follow approximately the relations [Be/H] = [B/H] = 2[O/H] (Vangioni-Flam et al. 1990). The relation is clearly not satisfied by halo stars. On the other hand, if the spallation is dominated by cosmic-ray CNO nuclei colliding with interstellar protons and α-particles, the evolution of a product of spallation may follow the observed relations [Be/H] = [B/H] $\simeq$ [O/H]; the flux of cosmic-ray CNO nuclei may be roughly proportional to the supernova rate, but the abundance of the target protons and α-particles is obviously independent of the present and past supernova rates. Gilmore et al. (1992) note that the observed relations may also be explained if B and Be production is dominated by spallation between supernova-produced cosmic-ray protons and the CNO nuclei in the same supernova's ejecta. Another way to produce a linear relationship between [B/H] or [Be/H] and [O/H] would be if the source of cosmic rays was not the supernovae which produced the metals in the early Galaxy. An early generation of massive objects (Silk 1991) or even extragalactic cosmic rays are speculative possibilities.

5. CONCLUDING REMARKS

The high accuracy of spectra obtainable with the Goddard High Resolution Spectrograph on the *Hubble Space Telescope* have permitted an unprecedented precise measurement of B abundances in three metal-poor stars (see Table 1). The B/Be ratio derived from our result and the published Be abundances for the most metal-poor star HD 140283 is in agreement with the minimum predicted ratio for spallation, but several qualifications may be noted. First, if an unidentified line is nearly coincident with the B I line, our result is an upper limit, that is, B/Be < 10. Second, the prediction (B/Be = 10) assumes that low-energy cosmic-ray protons are a negligible contributor to spallation in the halo; if present in quantity, the predicted B/Be is raised (Fig. 5). Third, Pinsonneault et al.'s (1992) favored (rotating) models of halo stars predict a mild surface depletion of Be by a factor of 1.5 but no depletion of B, that is, the observed B/Be ratio may exceed the initial ratio. Each of these considerations would impair the agreement between our observation and the orthodox prediction of B and Be synthesis. In addition, published alternatives to our adopted model atmosphere also result is a lower B/Be ratio. On the other hand, as we noted earlier, corrections for non-LTE effects and the presence of stellar granulation might increase the observed B/Be ratio. If the observed B/Be ratio of HD 140283 is shown to lie below the minimum predicted value, the discrepancy will suggest that some Be, and perhaps a lesser amount of B, was not synthesized by spallation.

Stellar nucleosynthesis can most probably be excluded as a possible contributor. Light element synthesis in Type II supernovae of about Population I metallicity has been considered by Woosley et al. (1990) and Brown et al. (1991). Woosley et al. investigated synthesis by neutrino-induced reactions within the helium and carbon shells and predicted that supernovae are major suppliers of ^{11}B to the Galaxy. These supernovae produce very little Be (Hartmann 1990). Brown et al. (1991) reexamine earlier calculations by Dearborn et al. (1989) on the synthesis of light elements by the passage of a shock through the hydrogen-rich envelope of a Type II supernova. This mode of synthesis leads to ^{11}B, but not Be. Brown et al. conclude, however, that the shocks do not produce significant amounts of the light elements. Thus, an allowance for a contribution from supernovae necessarily introduces a discrepancy between the observed B/Be ratio and that predicted from spallation. There is a suspicion that the B/Be ratio for HD 201891 exceeds the ratio of 10. It is tempting to identify the excess as due to ^{11}B from supernovae and to suppose that such a contribution is also the explanation of the high solar ^{11}B/^{10}B ratio. Malaney (1992) has examined neutrino-induced production of ^{9}Be in Type II supernovae of very low metallicity. He predicts that substantial amounts of ^{9}Be are synthesized in the He-shell from the reaction ^{7}Li(^{3}H, n)^{9}Be with the tritium produced by neutrino spallation of ^{4}He [i.e., ^{4}He (ν, $\nu' p$)^{3}H]. Large quantities of ^{7}Li but not ^{6}Li are also produced. Production of ^{11}B occurs in the He-shell via ^{7}Li(α, γ)^{11}B and by neutrino spallation on ^{12}C in the C-shell. Unfortunately the predicted B/Be ratio is, as yet, uncertain.

In the past few years a large number of "nonstandard" big bang models have been made (e.g., Malaney & Fowler 1989; Kajino & Boyd 1990 and references therein). These models suggest that density perturbations and chemical separation occurred in the early universe, leading to neutron-rich and neutron-poor regions. The nonuniform density is found to have a strong effect on light element nucleosynthesis, and much effort has been expended to see if models with a baryon-to-photon ratio large enough to reach critical density ($\Omega_b = 1$) can be found which are still consistent with observed ^{7}Li abundances. Although the models fail to reach $\Omega_b = 1$, all of these models produce much larger amounts of Be and B than the "standard" uniform big bang, even with $\Omega_b = 1$. Since they necessarily introduce new free parameters (e.g., the usual filling factor and density contrast ratio between two different kinds of regions), they cannot make a definitive prediction of Be and B abundances in the absence of the other information. Nonetheless, the range of predictions are of interest. Fractional abundances of ^{9}Be approaching 10^{-12} are produced by many models; the ^{10}B and ^{11}B produced is generally 1–2 orders of magnitude lower (Kajino & Boyd 1990). However, Malaney & Fowler (1989) find cases in which the ^{9}Be production is much lower. The B/Be ratio of HD 140283 and the inferred ratio for HD 19445 do not demand primordial contributions to the Be and B. We have, however, noted that our observed ratio (B/Be = 10) might be an overestimate and that the prediction B/Be = 10 is a minimum value appropriate to high-energy cosmic rays. There is as yet no independent evidence that the cosmic rays in the halo were exclusively high-energy particles.

Additional observations of HD 140283, and observations of even more metal-poor stars, both of which are feasible, will clarify the level of agreement with orthodox predictions. In particular, observations of HD 140283 (and other stars) with the GHRS echelle will provide a factor of 4 increase in spectral resolution and with an exposure of several hours will give a spectrum in which the 2496 B I line, if present, will be clearly resolved from the presently known adjacent blends. In Figure 9 we show the best-fitting synthetic spectra from Figure 2, 3, and

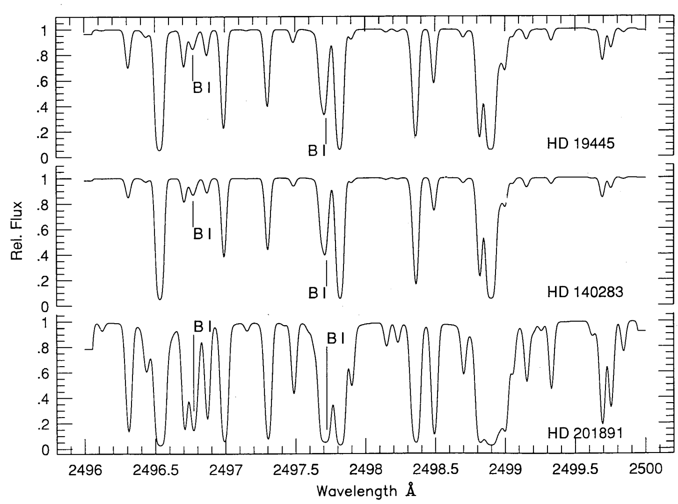

FIG. 9.—Synthetic spectra of HD 19445, HD 140283, and HD 201891 at the resolution of the GHRS echelle spectrometer (100,000) with the B abundance set to current best estimates [log ε(B) = 0.4, −0.1, 1.7]. No macroturbulence/rotation was included.

4 at the higher resolution provided by the echelle. Clearly, echelle spectra will show whether the absorption that we attribute to B I is indeed due to this light trace element. A more challenging series of observations in needed to identify the primordial contribution to Be and B: the search for the Be and B plateaus (i.e., Be and B abundances independent of [Fe/H]) demands observations of stars much fainter than HD 140283.

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