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THE EVOLUTION OF GALACTIC BORON AND THE PRODUCTION SITE OF THE LIGHT ELEMENTS[1]

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ABSTRACT

The Goddard High Resolution Spectrograph (GHRS) of the *Hubble Space Telescope* (*HST*) has been used to obtain spectra of the 2500 Å region in eight stars with metallicities ranging from [Fe/H] = −0.4 to −3.0, including the most metal-poor star ever observed for boron. Spectrum synthesis utilizing latest Kurucz model atmospheres has been used to determine the B abundance for each star, with particular attention paid to the errors of each point, to permit judgment of the quality of the fit of models of Galactic chemical evolution. Previous observations were combined with new ones, bringing the number of stars analyzed to 11.

A straight line of slope ≈1 gives an excellent fit to a plot[4] of log $\epsilon(B_{LTE})$ versus [Fe/H], and if NLTE B abundances are used, the slope is ≈0.7. Plotting B versus [O/H] rather than [Fe/H] increases the slope of either plot by about 0.2. The observed relation suggests that the production of light elements such as B and Be is directly related to the production of heavier elements.

Our data do not show a change in slope between halo and disk metallicities, but the number of stars near the disk-halo transition is small, and a modest change is not precluded. The NLTE B/Be ratio is typically ≈15 throughout the lifetime of the Galaxy, a ratio naturally produced by cosmic-ray (CR) spallation. Our data support a model in which most light-element production comes from low-energy CR spallation of C and O nuclei onto protons and α-particles, probably in the vicinity of massive supernovae in star-forming regions. Until recently, most models have emphasized light-element production in the general ISM from the spallation of high-energy protons and α-particles onto CNO nuclei. Especially during the Galaxy's early history, when the metallicity of the ISM was low, the spallation of protons and α-particles onto CNO nuclei cannot account for as much B as we observe, unless the CR flux was sufficiently high for compensation. The observed relation also constrains any direct production of B by the ν-process in supernovae to be at most a small part of total B production.

It is possible that the gamma rays recently detected from the Orion Nebula region are the signature of spallation by energetic C and O nuclei. Nevertheless, B, Be, and Fe data alone give the strongest evidence of the importance of spallation by C and O for producing light elements.

Subject headings: gamma rays: observations — nuclear reactions, nucleosynthesis, abundances — stars: abundances — ultraviolet: stars

1. INTRODUCTION

In their seminal paper on the origin of the elements, Burbidge et al. (1957) attributed the origin of the light elements Li, Be, and B to the "x process," the least certain of the nucleosynthetic processes they discussed. They suggested cosmic-ray (CR) spallation of heavier elements as the source, but the site of such a process was unknown. High-energy flares on the surfaces of young T Tauri stars were suggested, as well as gaseous nebulae, possibly near a supernova (SN). The stellar process was initially favored, but later calculations showed that it was energetically impossible (Ryter et al. 1970).

Reeves, Fowler, & Hoyle (1970) appeared to have solved the problem when they demonstrated that most light-element formation can be accounted for by Galactic cosmic rays (GCR) impinging on the interstellar medium (ISM).

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[4] In the usual notation log $\epsilon(B) = 12.00 + \log N(B)/N(H)$ and $[X/H] = \log N(X)/N(H) - [\log N(X)/N(H)]_{\odot}$.

The suggestion was immediately developed in more detail by Meneguzzi, Audouze, & Reeves (MAR; 1971), and then by Reeves et al. (1973). MAR were able to fit present-day light-element abundances by assuming a constant flux of GCRs through the life of the Galaxy and making reasonable assumptions about CR confinement by the Galactic magnetic field. Several problems were identified, however. Li was underproduced, compared to Be and B, if the large values of Li seen in the youngest stars needed to be matched. The isotopic ratio ^{7}Li/^{6}Li produced by spallation is ≈ 1.5, but the observed meteoritic value is ≈ 12. Finally, the ^{11}B/^{10}B ratio produced by spallation is 2.4, while the observed meteoritic value is close to 4.0. MAR therefore introduced the idea of a large (up to 3 orders of magnitude) increase in the low-energy (≈ 5–40 MeV nucleon^{-1}) CR flux. Since CRs in this energy range are mostly shielded from the solar system by the solar wind, they are not detectable. This additional CR flux increased the production of all light elements and matched the ^{11}B/^{10}B ratio to the accuracy available at the time. The ^{7}Li/^{6}Li was still too low; it has gradually become clear that additional ^{7}Li must come from another Galactic source, such as AGB stars. This dominates the ^{7}Li content of the youngest objects. It also is now clear that a certain amount of ^{7}Li is produced in the big bang, dominating the ^{7}Li content of the oldest stars.

Reeves & Meyer (1978) emphasized the fact that models could be much better constrained if they were required to match not only present-day abundances but also the evolution of light elements throughout the life of the Galaxy. Their conclusions were similar to those of MAR, except that they had to introduce infall of light-element–free matter into the Galactic disk to match the evolution with time. In retrospect, it can be seen that the data they were fitting were sparse and not very precise.

The last few years have seen an enormous increase in the quantity and quality of data on B, spurred by the launch of the *Hubble Space Telescope* (*HST*), and of data on Be, because of the availability of UV-sensitive CCD detectors. (Boron is observed at a wavelength of 2500 Å and Be at 3130 Å.) Data can be gathered on stars of low metallicity, and abundances can be traced from the epoch of formation of the Galactic halo until the present day. The evolution of Li, Be, and B has therefore come to be regarded as a powerful discriminant between different models of the chemical and dynamical evolution of the Galaxy, and the models have become more detailed. As calculated by Vangioni-Flam et al. (1990), Ryan et al. (1992), Prantzos, Cassé, & Vangioni-Flam (PCV; 1993), and Lemoine, Vangioni-Flam, & Cassé (1997), light-element production depends on the intensity and shape of the GCR spectrum, which in turn depends on the SN and massive star formation rates. The production rate also depends on the rise of the (progenitor) CNO abundances and the decline of the gas mass fraction, which is affected by rates of infall of fresh (unprocessed) material and outflow, e.g., by SN heating. Other things being equal, at early times when target CNO abundances were low, light-element production would be much lower for a given CR flux than presently, when the ISM abundances are higher. PCV found that even with these numerous adjustable parameters, no time-independent CR spectrum can reproduce the evolution of light-element abundances. By assuming a very particular form of time variation of the CR flux, they were barely able to fit the evolution of the abundances. They could have done a better job of fitting the data if the primordial production of Li was higher and the "Spite plateau" stars depleted in Li (cf. discussion in Deliyannis et al. 1996). The ^{11}B/^{10}B ratio could not be fitted by any of these models.

The aforementioned models generally attempted to match the observed light-element evolution by adjusting the CR flux and spectrum and concentrating on the "forward" process of proton and α-particle spallation onto CNO targets. We refer to such models as following the "standard" paradigm.

The present investigation suggests a substantially different solution to the problem of the origin of the light elements. Combining 5 yr of *HST* observations of B in stars covering 3 orders of magnitude in metallicity ([Fe/H] ≈ -3.0–0.0), we find that B follows Fe in direct proportion from the earliest times to the present, with little change of slope between halo and disk metallicities. Be data taken from the literature follow a similar trend. Plots versus [O/H] show similar results, although with increased scatter, caused by the lower accuracy of O abundances. A straightforward interpretation of these results is that the net rate of production of B and Be does not depend on the CNO abundances in the ISM. We suggest that the CR spallation most important for light-element production is not primarily protons and α-particles colliding with CNO nuclei in the interstellar medium. Rather, it is C and O nuclei colliding with ambient protons and α-particles, probably in regions of massive star formation. This decouples light-element production from the metallicity of the ISM and results in the approximately linear relationship observed. It also results in a ^{11}B/^{10}B ratio close to that which is observed. This "reverse" spallation process was dominant early in the Galaxy's history, and it remains important at the present epoch. It is possible that recent *Compton Gamma-Ray Observatory* (*CGRO*) observations of gamma rays from the Orion Nebula (Bloemen et al. 1994; Bykov & Bloemen 1994; but see Murphy et al. 1996) provide direct evidence of this process, a possibility presciently suggested in Reeves, Fowler, & Hoyle (1970). Whether the *CGRO* detection is confirmed or not, the light-element data alone strongly constrain the mechanism by which the elements are produced. Details are presented in the § 5.

2. OBSERVATIONS AND DATA REDUCTION

The Goddard High-Resolution Spectrograph (GHRS) of the *HST* was used with the G270M grating to obtain spectra of resolution 26,000 in the B I region (2500 Å) of seven stars ranging in metallicity from [Fe/H] $= -0.35$ to -2.75. Signal-to-noise (S/N) ratios of 50 per diode or 25 per pixel (0.026 Å) were typically achieved. The data are oversampled by a factor of 2 (by substepping), and the resolution corresponds to about 3.7 pixels. To this were added the data for BD $-13°3442$; at a metallicity of [Fe/H] $= -3.0$, this is the most metal-poor star ever observed for B, and it is the subject of a separate investigation (Duncan et al. 1997). Abundances for the three stars previously analyzed by Duncan, Lambert, & Lemke (DLL; 1992) were redetermined with the same spectrum synthesis as the new data, in order to confirm that there were no systematic differences resulting from the analysis procedure (differences were insignificant). The sample presented here thus includes all halo stars in which B has been detected so far.

Data reduction followed the standard *HST* procedure, using the IRAF STSDAS package, combining the quarterstepped, FP-SPLIT data with the tasks POFFSETS and SPECALIGN, which perform a generalized least-squares solution for the photocathode granularity and the true spectrum. Two stars, HD 76932 and HD 184499, were observed twice because of *HST* failures that caused lower S/N spectra to be obtained the first time. Their final spectra are the result of a weighted sum of the two different observations. Comparison of the separate spectra provided an external check of the accuracy of our S/N estimates. More extensive testing of the actual S/N ratios achieved in GHRS spectra of still higher quality is given in the investigation of α Cen A and B (Primas et al. 1997). Spectra of a representative sample of the program stars appear in Figure 1.

3. ABUNDANCE ANALYSIS

Spectrum synthesis, using the latest Kurucz model atmospheres, was used to determine log ϵ(B) for each star, with particular attention paid to the errors. An accurate determination of the uncertainties associated with each B abundance is required in the subsequent discussion of the results to permit judgment of the quality of the fit of models of Galactic chemical evolution and to discriminate among the different proposed mechanisms of light-element formation.

3.1. *Spectrum Synthesis*

Spectrum synthesis was done using the SYNTHE program distributed by Kurucz (1993) on CD-ROM. This program assumes local thermodynamic equilibrium (LTE) in determining level populations and calculating the emergent spectrum. Scripts written by S. Allen (University of California, Santa Cruz) were used to run the program on unix sparc stations. The grid of model atmospheres was that distributed by Kurucz on CD-ROM 13, which included in its computation the blanketing of almost 60 million lines, both atomic and molecular. We used the line list compiled by Duncan et al. (1997) in a study of B in the Hyades giants, which consists almost entirely of laboratory-measured lines. It has been carefully tested in order to fit both the Hyades giants and various metal-poor stars in the B λ2500 region. This list was constructed by starting with Kurucz's LOWLINES list (CD-ROM 1), adjusting (reducing) some *gf*-values where necessary, and adding a minimum number of predicted Fe I lines in order to achieve a good match to the absorption features near the B I lines. At our resolution, the shorter wavelength B component is blended with the Co I λ2496.708 line. The higher resolution study of HD 140283 by Edvardsson et al. (1994) mostly resolves the lines, and the *gf* value we use for the Co line is the same as in their study.

In our line list, the *gf*-values and wavelengths of the B I resonance doublet were selected from O'Brian & Lawler (1992). They differ by only 0.03 dex and are less than 0.01 Å from the values given by Kurucz. Our abundances are derived by fitting the shorter wavelength, less blended component of the B doublet. We do not try to fit the spectrum in detail at wavelengths shorter than 2496.4 Å or longer than 2497.4 Å, since the line list has not been completed there.

The Kurucz solar boron abundance of log $\epsilon(B) = 2.60$ is used as our solar B value. We are aware of slightly higher solar B abundances determined from carbonaceous chondrites, log $\epsilon(B) = 2.88 \pm 0.04$ (Anders & Grevesse 1989), more recently revised to log $\epsilon(B) = 2.78 \pm 0.05$ by Zhai & Shaw (1994), and from solar photospheric resonant lines,

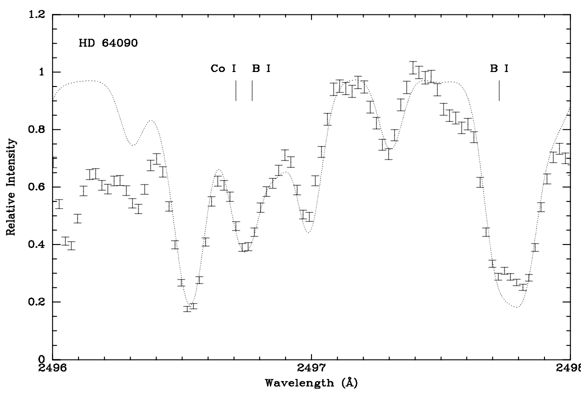

FIG. 1*a*

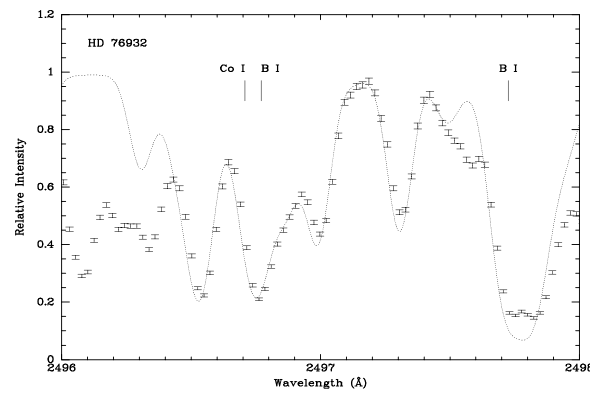

FIG. 1*b*

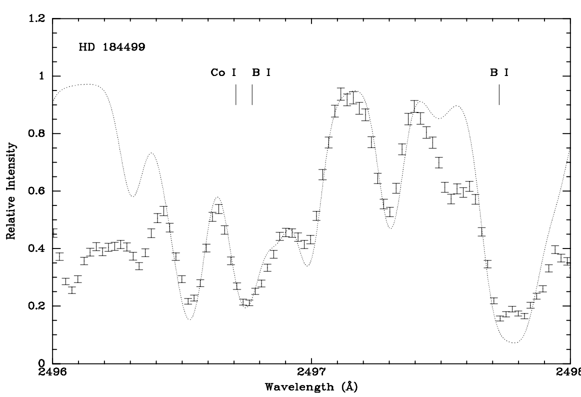

FIG. 1*c*

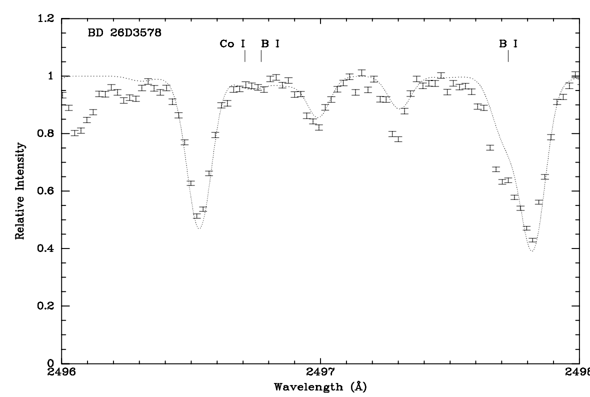

FIG. 1*d*

FIG. 1.—(*a*)–(*d*) Spectra of a representative sample of the program stars and adopted synthetic spectrum fit

log ϵ(B) $= 2.60 \pm 0.30$ (Kohl, Parkinson, & Withbroe 1977). This decision affects the choice of the zero point of the abundance scale and therefore of ratios such as B/Be but does not affect the interpretation of trends in the B data discussed in the present paper. The Kurucz value of the solar B abundance is included in our data set when we describe the Galactic evolution of boron.

The most important systematic error influencing the B/Be ratio may well be the model atmospheres used, since systematic errors in the the latter may affect B and Be differently. Both Primas (1996) and Ryan, Norris, & Beers (1996) have questioned the treatment of convection in the Kurucz atmospheres used here, and demonstrated that these can alter abundances by $0.1-0.2$ dex, and differently for different elements.

We took the physical parameters and their uncertainties for the program stars from an extensive search of the literature. The present investigation did not attempt to derive these fundamental parameters, since our spectral coverage is very limited. Within the range of values determined from the literature, the models that best fit our entire UV spectrum were chosen. The Kurucz model grid is given in steps of 250 K in $T_{\rm eff}$, 0.50 in log g, and 0.50 dex in [Fe/H] for halo stars, and we performed calculations at the nearest grid points. Linear interpolation was then used to calculate spectra for the exact stellar parameters.

The Kurucz models we used assume that all metals scale together, whereas it is known that α-elements are enhanced at low metallicities. Testing showed that the effect of α enhancement on the structure of the model atmosphere produces very small effects on the calculated B abundances. In particular, DLL analyzed three stars using atmospheres with α-enhanced composition from Gustafsson et al. (1975). Although, while refining our best fits, we adjusted the metallicity of all three stars slightly (by -0.05, $+0.04$, and -0.09 dex in HD 19445, HD 140283, and HD 201891 respectively), the largest difference in B abundance we found was -0.04 dex, which is much lower than other errors associated with each determination.

All the models used here were calculated with a microturbulent velocity of 2 km s^{-1}. We did not find it necessary to change to the commonly accepted value of 1.5 km s^{-1} for halo stars (Magain 1989) because the analysis of several curves of growth showed that the dependence of B abundances on this stellar parameter is negligible.

Figure 2 presents spectrum synthesis fits for a representative sample of the stars we analyzed. Table 1 presents stellar parameters and B abundances for the program stars.

3.2. *Uncertainties*

Considerable care was taken in determining the error of each abundance determination. Sources of error we considered included uncertainties in stellar $T_{\rm eff}$, log g, and [Fe/H] (all of which change the atmosphere used in the analysis), continuum placement, photon statistics in the points defining the line itself, and the effect of metal lines that blend with the B features.

In more metal-poor stars, the continuum is easier to define, but the B line is weaker and less certain. At disk metallicity, continuum errors are larger but make less difference, since the line is deep, so the combined effects are relatively constant over the whole range of metallicity inves-

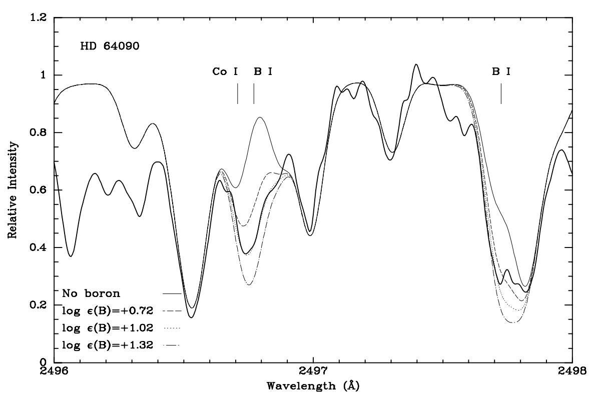

FIG. 2*a*

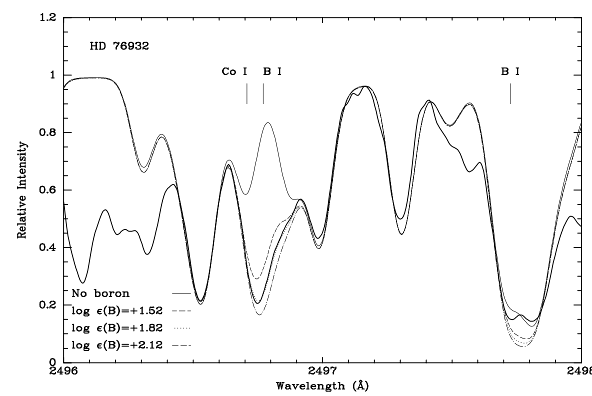

FIG. 2*b*

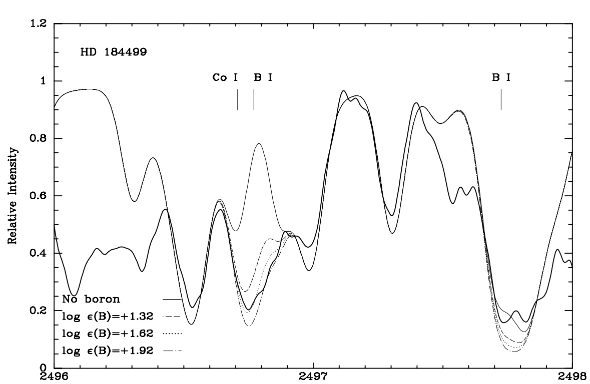

FIG. 2*c*

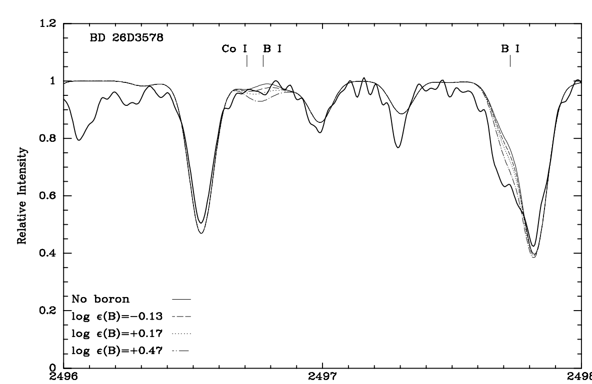

FIG. 2*d*

FIG. 2.—(*a*)–(*d*) LTE spectrum synthesis fits for a representative sample of the program stars

TABLE 1

ADOPTED STELLAR PARAMETERS AND B ABUNDANCES

Star	T_{eff}	log g	[Fe/H]	log ϵ (B_{LTE})	log ϵ(B_{NLTE})
HD 19445[a]	5870	4.5	−2.20	0.32	0.67
HD 64090	5350	4.5	−1.80	1.02	1.20
HD 76932	5900	3.5	−1.00	1.82	1.99
HD 140283[a]	5640	3.5	−2.60	−0.10	0.35
HD 142373	5900	4.0	−0.45	2.05	2.13
HD 184499	5700	4.0	−1.00	1.62	1.75
HD 194598	6000	4.0	−1.30	1.45	1.73
HD 201891[a]	5870	4.5	−1.15	1.62	1.80
BD 3°740	6125	3.5	−2.75	0.22	1.04
BD 26°3578	6150	4.0	−2.35	0.17	0.80
BD −13°3442...	6250	3.75	−3.00	0.01	0.93

[a] Stars from DLL, but reprocessed with Kurucz model atmospheres.

tigated. Table 2 presents, in order, effects due to uncertainties in stellar T_{eff}, log g, [Fe/H], continuum location and photon statistics in the B line, as well as the total (net) error. It can be seen that the total errors do not vary much from star to star. We quantified the dependence of the B abundance on changes in the main stellar parameters by running multiple syntheses and curves of growth, although curves of growth are less reliable, since the B lines are blended. Looking at the literature determinations available for this sample of stars, we considered ±75 K, ±0.25/0.30, and ±0.10 dex to be the typical uncertainties associated with T_{eff}, log g, and [Fe/H], respectively. The more conservative uncertainty of ±0.30 in log g was used for the three most metal-poor stars, for which a larger range of values is found.

Uncertainty in stellar metallicity causes error in two ways. The indirect way is through changing the stellar atmosphere. This is a small effect (less than that caused by log g uncertainties), and it is ignored in Table 2. The direct effect is due to lines that blend with the B features. At our resolution, the Co I λ2496.708 feature blends with B I λ2496.772, and the lines are of comparable strength. The assumption of a higher metallicity attributes more of the blend to Co, decreasing the derived B abundance, and vice versa. The column [Fe/H] in Table 2 gives the amount of this direct effect when the metallicity is uncertain by ± 0.1 dex.

McWilliam et al. (1995) studied Co in their spectrosopic analysis of the most metal-poor stars. They present evidence that its abundance remains scaled-solar to [Fe/H] ≈ −2.5, but that it increases by ≈0.5 dex as [Fe/H] decreases to −3.0. Since our spectra do not resolve the Co-B blend, if Co is overabundant in the way McWilliam et al. describe, the B abundances of our two most metal-poor stars would be systematically overestimated. In such a case they should be decreased, which would tend to eliminate the slight flattening or plateau seen at the lowest metallicity in Figures 3–6. This possibility is studied quantitatively in a separate paper on BD −13°3442, which shows that the decrease in B abundance is unlikely to exceed ≈ 0.1 dex (Duncan et al. 1997). The Edvardsson et al. (1993) higher resolution study of HD 140283, the third most metal-poor star of the present study, partially resolves the Co-B blend and derives a B abundance that is in good agreement with that found here. This argues against the importance of the Co overabundance in that star or in any of the other (more metal-rich) stars.

A significant source of error is the placement of the continuum. Random errors arise from choosing the proper continuum normalization, and systematic errors arise from the adequacy of the model atmospheres in calculating the spectrum and continuum. By choosing different spectral regions for normalization to the models, we estimated the random

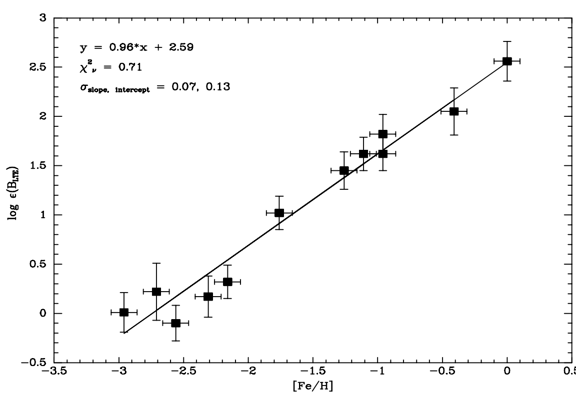

FIG. 3.—log ϵ(B_{LTE}) vs. [Fe/H]. A least-squares fit to these data (see text) yields a slope of 0.99 and $\chi_\nu^2 = 0.77$.

TABLE 2

UNCERTAINTIES AFFECTING B ABUNDANCES[a]

Star	T_{eff} ± 75 K	log g ± 0.25	[Fe/H] ± 0.10 dex	Continuum ± 1.5%	Photon Statistics	Net Error[b]
HD 19445	±0.09	±0.03	±0.10	±0.10	±0.06	±0.18
HD 64090	±0.04	±0.07	±0.14	±0.04	±0.05	±0.17
HD 76932	±0.11	±0.05	±0.15	±0.04	±0.04	±0.20
HD 140283	±0.08	±0.05	±0.10	±0.10	±0.06	±0.18
HD 142373	±0.11	±0.05	±0.10	±0.10[c]	±0.15	±0.24
HD 184499	±0.11	±0.05	±0.10	±0.03	±0.05	±0.17
HD 194598	±0.11	±0.05	±0.10	±0.04	±0.10	±0.19
HD 201891	±0.11	±0.05	±0.10	±0.04	±0.06	±0.17
BD 3°740	±0.08	±0.05[d]	±0.10	±0.10	±0.23	±0.29
BD 26°3578	±0.09	±0.02[d]	±0.07	±0.10[e]	±0.15	±0.21
BD −13°3442......	±0.09	±0.03[d]	±0.10	±0.10[f]	±0.10	±0.20

[a] All units dex.
[b] Excluding NLTE corrections.
[c] For ±5% in the continuum.
[d] For ±0.30 in log g.
[e] For ±1% in the continuum.
[f] For ±0.5% in the continuum.

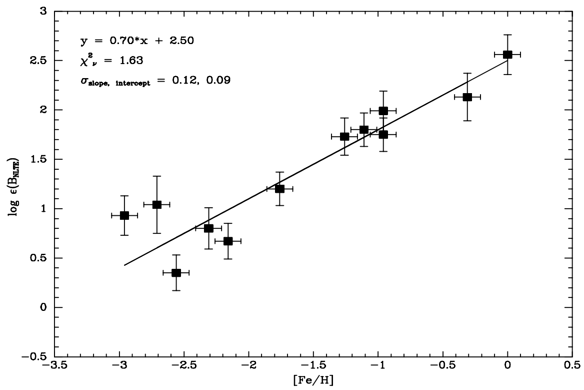

FIG. 4.—NLTE-corrected log ϵ(B) vs. [Fe/H]. A least-squares fit to these data (see text) yields a slope of 0.71 and $\chi^2_\nu = 1.77$.

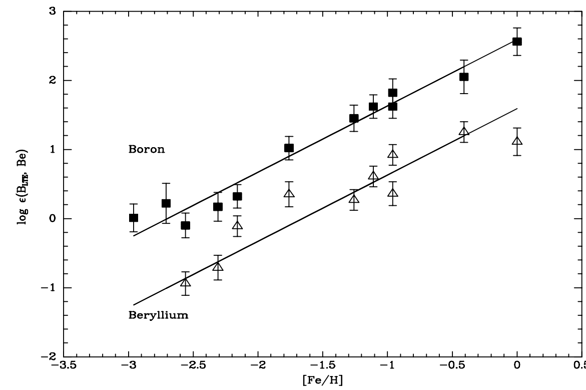

FIG. 5.—log $\epsilon(B_{LTE})$ and log ϵ(Be) vs. [Fe/H]. Fit to Be data is that of B data reduced 10 times.

uncertainty in fitting the continuum level to be $\simeq$1.5% for the more metal-rich stars, $\simeq$1.0% in the metal-poor spectra, and $\simeq$0.5% in the particularly well-observed, very metal-poor star BD $-13°3442$.

3.3. *NLTE Abundances*

A significant source of systematic errors in our B abundances could be due to NLTE effects. As calculated by Kiselman (1994) and Kiselman & Carlsson (1996), NLTE effects increase B abundances most significantly in the most metal-poor stars. The relatively hot UV radiation fields in these stars drive the detailed balance of the B resonance lines away from statistical equilibrium. Overionization and optical pumping tend to weaken the B I 2500 Å doublet, which leads to an underestimate of the B abundance. NLTE calculations are difficult, being limited both by the incomplete understanding of the atomic physics involved and, especially, by the uncertainties in the UV flux values at the precise absorption wavelengths. The Kiselman & Carlsson (1996) study improves upon Kiselman (1994) in that it models the effects of large numbers of lines in the background radiation field, which tend to decrease NLTE effects. Results of the two studies differ by approximately 0.1 dex; present NLTE calculations are necessarily less accurate than this amount. NLTE corrections for our stars range from 0.0 at solar metallicity, to about +0.5 dex for HD 140283 ([Fe/H] = -2.6), to a maximum of +0.9 dex for the two most metal-poor stars. We present both LTE and NLTE abundances in Table 1 and show below that our conclusions concerning the primary nature of the production process for B is not changed whether LTE or NLTE abundances are used.

HD 140283 has been carefully analyzed in a higher resolution study by Edvardsson et al. (1993). Their choice of atmospheric parameters for this metal-poor star is very similar to that of DLL, and if we apply the NLTE correction factor of +0.54 dex they used to our data, we obtain an abundance that is in good agreement with theirs ($\Delta = 0.10$ dex). The NLTE correction factors actually used in the present investigation are those of Kiselman & Carlsson (1996), described previously. For HD 140283, these differ by only 0.10 dex from the value used by Edvardsson et al. (1993).

Similar NLTE calculations for Be have been made by García-López, Severino, & Gomez (1995). They find the corrections to Be (which arises from ionized Be II) to be much smaller than that those to B and less than 0.1 dex in all six metal-poor stars they analyzed.

4. RESULTS

Table 1 summarizes our final results, giving the stellar parameters (T_{eff}, log g, and [Fe/H]) adopted in our best-fit syntheses, along with the derived LTE and NLTE B abundances. Eight new determinations have been added to the three stars initially analyzed by DLL. Uncertainties are summarized in Table 2. The stellar parameters chosen in this analysis are fully consistent with previous determinations in the literature, except for HD 184499. For the latter, in spite of the very similar T_{eff} and log g, our best synthesis indicates a metallicity of around -1.00 dex, while all previously reported values range between [Fe/H] = -0.80 dex and -0.51 dex.

5. DISCUSSION

Figure 3 immediately shows the main result of this investigation: log ϵ(B) is approximately linear with [Fe/H] over both disk and halo metallicities. A least-squares fit to these data (allowing for errors in both coordinates)[5] yields a slope of 0.96 and a reduced χ^2, χ^2_ν, of 0.71, indicating an excellent fit. If NLTE abundances are used, as shown in Figure 4, the slope is 0.70 and $\chi^2_\nu = 1.63$.

If Be abundances (taken from the literature and listed in Table 3) are plotted for the same stars, a similar slope is seen. In Figure 5, the linear fit to the B data in Figure 3, reduced exactly by a factor of 10, is seen to fit the Be data reasonably well. This is precisely what would be expected from CR spallation, in which the cross section ratios of B to Be are approximately 10 at all energies—except close to threshold at a few tens of MeV nucleon^{-1}, where the ratio rises to approximately 30 (DLL). More detailed fitting, for NLTE B abundances and Be included, is discussed below.

5.1. *Comparison to Standard Models and a New Model for Light-Element Production*

The slope of 0.7 to 1.0, suggesting a primary process, is not expected from standard models of CR spallation in the ISM, which predict a secondary process and thus a steeper relation. The steeper relation can be demonstrated schematically. Let $N_A(t)$ be the number abundance of a light element (Li, Be, or B), $N_k(t)$ the abundance of target species

[5] See Appendix for a discussion of line fitting.

TABLE 3

BERYLLIUM ABUNDANCES FROM THE LITERATURE[a]

Star	log ϵ(Be)	Reference	log ϵ(Be)$_{\rm adopted}$
HD 19445........	0.30	1	−0.11
	< −0.30	2	
	−0.14	3	
	−0.11	4	
HD 64090........	0.23	3	0.35
	0.44	4	
	−0.15	5	
HD 76932........	0.66	2	0.36
	0.96	3	
	0.55	4, 5, 7	
	0.36	6	
HD 140283	−1.12	2	−0.94
	−0.78	3	
	−1.02	4	
	−1.07	5	
	−0.94	6	
	−1.05	7	
HD 142373	1.25	3	1.25
HD 184499	0.97	3	0.92
HD 194598	0.30	1	0.27
	0.37	3	
	0.41	4	
	0.05	7	
HD 201891	0.40	1	0.61
	0.67	3	
	0.62	4	
BD 26°3578......	< −0.71	4	−0.71

[a] Be abundances from the referenced studies have been adjusted to take into account the stellar parameters used in the present investigation.

REFERENCES.—(1)Rebolo et al. 1988; (2) Ryan et al. 1990, 1992; (3) Boesgaard & King 1993; (4) Deliyannis et al. 1996; (5) García López et al. 1995; (6) Primas 1996; (7) Thorburn & Hobbs 1996.

k in the ISM, $\sigma_k(E)$ the cross section for spallation onto species k at energy E, and $\phi(t)$ the GCR flux. The rate of production of a light element is then

$$\frac{dN_A}{dt} = \sum_k N_k(t) \int_{E_{\rm Th}}^{\infty} \sigma_k(E)\phi(t) dE \ , \qquad (1)$$

where the integral is taken from the threshold energy, $E_{\rm Th}$. Both the abundance of target nuclei and the CR flux vary with time. If SNs are the source of the target nuclei N_k, and the ISM is well mixed, $N_k(t)$ is proportional to $N_{\rm SN}$, the number of SNs that have occurred up to time t in the life of the Galaxy. If, as is commonly supposed, SNs also seed the acceleration mechanism that produces CRs, ϕ is proportional to the SN rate, $dN_{\rm SN}/dt$. Consequently,

$$\frac{dN_A}{dt} \propto N_{\rm SN} \frac{dN_{\rm SN}}{dt} \ , \qquad (2)$$

which leads to light-element abundances $N_A \propto N_{\rm SN}^2 \propto N_k^2$, or a logarithmic slope of 2, which is inconsistent with our data.

The most detailed model of light-element production under the standard paradigm was probably that of PCV. To fit available data, PCV's model required two zones, one for the halo, with gas outflow, and one for the disk, with inflow. They included $\alpha + \alpha$ reactions, the importance of which was emphasized by Steigman & Walker (1992), which can produce Li but not the other light elements, and found that no time-independent CR spectrum can reproduce the evolution of light-element abundances. By assuming the GCR escape length in the early Galaxy was 100 times longer than in the present Galactic disk, thus creating a much greater CR flux, and incorporating a time-dependent CR spectrum, they were just able to fit all the observations available. Model parameters were chosen to minimize the slope and the differences in light-element production between the halo and disk, as the data required. As PCV stated themselves, these assumptions were somewhat ad hoc and needed further theoretical justification. If the primordial Li abundance was significantly higher than that observed on the Spite plateau because of depletion, as has been argued by the Yale group (e.g., Deliyannis et al. 1996), it becomes easier to fit the data. However, the ^{11}B/^{10}B ratio still cannot be fit.

A possible resolution to all these problems was discussed by DLL when they noted that data for the first three metal-poor stars observed for B seemed to show a linear (in the log) relationship with [Fe/H], suggesting some primary production mechanism rather than the secondary mechanism in the ISM, described above. This idea was originally mentioned by Reeves, Fowler, & Hoyle (1970) and discussed by Walker et al. (1993), and it has subsequently been modeled in detail by Cassé, Lehoucq, & Vangioni-Flam (1995) and Ramaty, Kozlovsky, & Lingenfelter (1995). In the new scenario, B and Be are primarily produced by the spallation of C and O onto protons and α-particles. One could imagine such a process occurring near massive-star SNs, where the particle flux would be very nonsolar in composition, being depleted in H and He and especially enriched in O and C. Cassé et al. (1995) and Ramaty et al. (1996) find that a composition matching either winds from massive (Wolf-Rayet; W-R) stars in star-forming regions or massive-star SNs produces a flux of O and C, which, through collisions with protons and α-particles, can reproduce both the magnitude and slope of B production seen in Figure 3. In addition, a particularly attractive feature of the new models is its natural solution to the ^{11}B/^{10}B problem. Meteoritic ^{11}B/^{10}B is observed to be 3.84–4.25 (Chaussidon & Robert 1995), but the value predicted by standard models of light-element spallation in the ISM is closer to 2.5. The new spallation mechanism produces ^{11}B/^{10}B slightly greater than 4.0, which, when combined in the model with the lower yields of the still operating, traditional GCR spallation, predicts ^{11}B/^{10}B $\sim$ 4. The enhancement of C and O, compared to N, is important in making the good isotopic fit because of differences in the cross sections. The new model

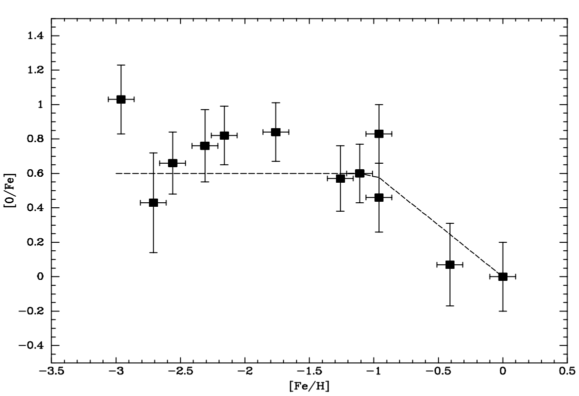

FIG. 6.—[O/Fe] vs. [Fe/H], with the errors on [O/H] determined from the scatter in Table 3. Dashed line is mean galactic [O/Fe] vs. [Fe/H] relation determined from the literature.

also avoids producing too much Li at low metallicity. Since overproduction of Li occurs due to $\alpha + \alpha$ reactions when the metallicity of the ISM is low, a CR spectrum enriched in heavy elements relative to H and He fits the data much better. It is interesting to note that spallation near SNs was one of the original suggestions of Burbidge et al. (1957) for light-element production.

An effect that is more important for spallation by CNO nuclei than that by protons and α-particles is the resultant products' escape from the Galaxy. However, Meneguzzi & Reeves (1975) and Yoshii, Kajino, & Ryan (1997) show that for reasonable values of the escape path length, $\Lambda \approx 10$ g cm^{-2}, the loss is not significant, and uncertainties in Λ have no significant effect on light-element production rates. Equation (1) assumes full thermalization without the loss of light-element products.

A key point of the new models is that the CR abundances are not solar but enriched in metals and depleted in H and He. Likely sites for the process would be near SNs or W-R stars. Walker et al. (1993) note that in CRs of solar composition, spallation by protons and α-particles accounts for $\sim 80\%$ of light-element production, and spallation by the CNO component accounts for the rest. In CRs significantly enriched in C and O, relative to H and He, it is likely that spallation by C and O becomes the dominant process. It is also worth noting that not only is our direct measurement of CR composition limited to CRs of high enough energy for avoiding significant solar modulation, but it is also limited to those created very recently in the life of the Galaxy.

Woosley et al. (1990) have suggested another mechanism for B production, that of the ν-process in SNs. Such direct production also naturally produces a linear relation between B and [O/H] and also leads to a slope close to 1 for B versus [Fe/H]. However, as presently understood, the ν-process should not produce significant amounts of Be, and there is no reason why it should produce a B/Be ratio close to that expected from the spallation cross sections. This argues against the majority of B being produced in the ν-process.

If the production of the light elements is indeed closely tied to the O abundance as just described, one would prefer to plot the abundances versus [O/H] rather than versus [Fe/H]. O abundances gathered from the literature are presented in Table 4. Unfortunately, values for a given star show considerable scatter, as has often been discussed in the literature on O determinations (e.g., King 1993). This can be seen in Figure 6, where [O/Fe] versus [Fe/H] is plotted for each star, with the errors on [O/Fe] determined from the scatter in Table 3. The mean relation (*dashed line*), or one close to it, is that which is found from studies of larger numbers of halo stars (e.g., Tomkin et al. 1992). We have plotted B versus [O/H] with O abundances determined in both ways: adopted from the data for each star in Table 3, $[O/H]_{adopted}$, or taken from the mean relation for [O/H] in halo stars shown in Figure 6, $[O/H]_{mean}$. Figure 7 shows the

TABLE 4

OXYGEN ABUNDANCES TAKEN FROM THE LITERATURE[a]

Star	[O/H]	References	$[O/H]_{adopted}$	$[O/H]_{mean}$
HD 19445	−1.25	1	−1.34	−1.56
	−1.34	2		
	−1.42	3		
	−1.20/−1.70	5		
HD 64090	−1.14	1	−0.92	−1.16
	−0.92	2		
	−1.10	4		
HD 76932	−0.50	3	−0.50	−0.38
	−0.95/−0.66	5		
	−0.53	6		
	−0.50	7		
HD 140283	−1.78	1	−1.90	−1.96
	−1.90	2		
	−1.79	3		
	−1.80/−2.05	5		
	−2.10	6		
	−1.60	7		
HD 142373	−0.34	6	−0.34	−0.12
HD 184499	−0.02	1	−0.13	−0.38
	−0.13	3		
HD 194598	−0.69	2	−0.69	−0.71
	−0.66	3		
	−0.80	7		
HD 201891	−0.26	1	−0.51	−0.51
	−0.51	3		
	−0.58	4		
BD 3°740	−2.28	2	−2.28	−2.11
	−2.42, −2.09	4		
BD 26°3578	−1.23	1	−1.55	−1.71
	−1.55	2		
BD −13°3442......	−1.93	4	−1.93	−2.32

[a] Abundances have been adjusted to take into account the stellar parameters used in the present investigation.

REFERENCES.—(1) Abia & Rebolo 1989 (OI); (2) Tomkin et al. 1992 (OI); (3) Boesgaard & King 1993 (OI); (4) King 1993, 1994 (OI); (5) Bessell, Sutherland, & Ruan 1991 (OI/OH); (6) Nissen et al. 1994 (OH); (7) Thorburn & Hobbs 1996 (OH).

TABLE 5

LINEAR LEAST-SQUARES FITS TO B DATA

y	x	Slope	σ_{slope}	Intercept	$\sigma_{\mathrm{intercept}}$	χ^2_ν	Probability[a]
log $\epsilon(B_{LTE})$	[Fe/H]	0.96	0.07	2.59	0.13	0.71	0.71
log $\epsilon(B_{NLTE})$	[Fe/H]	0.70	0.07	2.50	0.12	1.63	0.09
log $\epsilon(B_{LTE})$	$[O/H]_{adopted}$	1.21	0.13	2.25	0.16	0.97	0.47
log $\epsilon(B_{NLTE})$	$[O/H]_{adopted}$	0.90	0.11	2.27	0.13	1.67	0.08
log $\epsilon(B_{LTE})$	$[O/H]_{mean}$	1.10	0.11	2.24	0.14	0.57	0.84
log $\epsilon(B_{NLTE})$	$[O/H]_{mean}$	0.82	0.10	2.27	0.13	1.39	0.18

[a] Probability that the observed value of χ^2_ν is due to chance.

TABLE 6

LINEAR LEAST-SQUARES FITS TO Be DATA

y	x	Slope	σ_{slope}	Intercept	$\sigma_{\mathrm{intercept}}$	χ^2_ν	Probability[a]
log ϵ(Be)......	[Fe/H]	0.85	0.08	1.49	0.12	2.17	0.03
log ϵ(Be)......	$[O/H]_{adopted}$	1.18	0.16	1.25	0.15	0.67	0.72
log ϵ(Be)......	$[O/H]_{mean}$	1.07	0.14	1.22	0.14	1.02	0.42

[a] Probability that the observed value of χ^2_ν is due to chance.

LTE B versus $[O/H]_{mean}$ plot. Fits to both sets of [O/H] abundances, using both LTE and NLTE B abundances, are summarized in Table 5. Table 5 summarizes all the B plots, and Table 6 does the same for Be.

We also experimented with least-squares linear fits to the original B versus [Fe/H] data using two line segments joined at any intermediate metallicity, looking for a possible change of slope between disk and halo metallicity. Deliyannis et al. (1996) have presented evidence for such structure in a plot of Be versus [Fe/H]. We found that a break at any intermediate metallicity worsens the fit to the B data. However, our errors are large enough and the number of stars involved small enough that a subtle break could have been missed. A plateau at the lowest metallicities, with a break at [Fe/H] $= -2.5$, slightly improves the fit. The gathering of more B data for stars of metallicity near the disk-halo transition is clearly indicated. Table 7 summarizes these results, and the Appendix presents more details on the broken-line fits.

5.2. *Gamma Rays from Orion and Light-Element Production*

Bloemen et al. (1994) report the detection of γ-rays from the Orion Nebula region using the COMPTEL instrument of *CGRO*. Flux is detected at between 3 and 7 MeV, and they decompose the spectrum into the nuclear de-excitation lines of $^{12}C^*$ and $^{16}O^*$ at 4.44 MeV and 6.13 MeV respectively. The signal is stronger than would be expected from the spallation of solar-composition cosmic rays, and greatly enhanced O and C abundances relative to solar are required to explain the observed emissivity. Bykov & Bloemen (1994) suggest that overabundances of O and C could arise very naturally if ejecta from massive SNs are the source of the low-energy CRs causing the spallation that produces the excited C and O. The nuclei could be accelerated up to the required energies (tens of MeV nucleon^{-1}) in Orion by strong stellar winds and shocks from previous SNs.

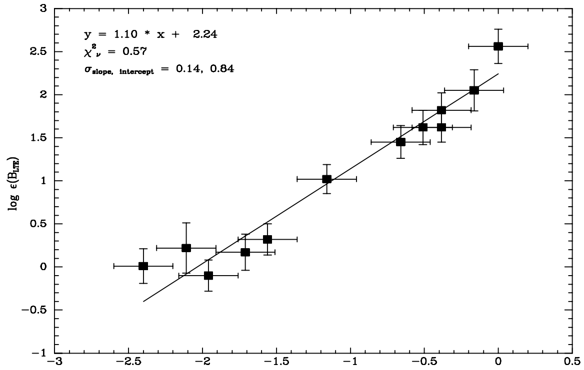

FIG. 7.—log $\epsilon(B_{LTE})$ vs. $[O/H]_{mean}$ (mean [O/H] taken from the mean Galactic [O/Fe] vs. [Fe/H] relation).

Cassé et al. (1995) then showed that the Orion observations suggest a significant effect on the creation of the light elements. If the observed γ fluxes are used to infer the collision rate of $^{12}C^*$ and $^{16}O^*$ with the ambient Orion ISM, the amount of light elements produced would match observed abundances if production continued for about 10,000 yr. They also note that the reactions are not very different if the C and O collide with solar system composition material or pure H and He, which shows that this process could operate throughout the life of the Galaxy—at all values of Galactic metallicity—leading to a linear relationship between B, Be, and O. The low H and He abundances in the CRs minimize $\alpha + \alpha$ reactions in the early Galaxy, avoiding the production of quantities of Li, which would disturb the "Spite plateau" of Li abundance independent of metallicity at low [Fe/H]. Ramaty et al. (1996) made similar calculations in more detail. They showed that either winds from W-R stars or SN ejecta,

TABLE 7

BROKEN-LINE FITS TO B VERSUS [Fe/H]

Break Location	χ^2_ν	Probability[a]
−2.5 (LHS)......	0.52	0.84
(RHS)......	0.52	0.84
−2.0 (LHS)......	1.49	0.15
(RHS)......	1.23	0.27
−1.5 (LHS)......	1.18	0.30
(RHS)......	0.95	0.48
−1.0 (LHS)......	0.86	0.55
(RHS)......	0.85	0.56
−0.5 (LHS)......	0.88	0.53
(RHS)......	1.11	0.35

[a] Probability that the observed value of χ^2_ν is due to chance.

accelerated to energies up to ≈ 30 Mev nucleon^{-1}, can both account for observed light-element abundances and produce a $^{11}B/^{10}B$ ratio equal to or exceeding the meteoritic value. They also demonstrated that the energetics of the process are reasonable.

Before placing too much emphasis on the COMPTEL Orion detection, it should be noted that the OSSE instrument on the same spacecraft has not detected γ-ray emission when observing the same region of sky (Murphy et al. 1996). If the COMPTEL source was pointlike or a few degrees in angular extent, it should have been easily detected. If the emission followed the CO distribution in Orion, it should have been seen at the 3 σ level. Unless the emission is much more extended, this nondetection is difficult to explain. At present, therefore, it is not certain whether direct evidence of the production of light elements is at hand. However, in the present context, we point out that the evolution of the light-element abundances provides the strongest evidence that the traditional theory of production by GCRs is, by itself, insufficient for explaining the abundances.

5.3. *Relative Contributions of Different Light-Element Production Mechanisms*

Vangioni-Flam et al. (1996) assess the relative importance of light-element production by Galactic CR protons and α-particles, the method of energetic C and O spallation, and direct production by the ν-process in SNs. They confirm that CR spallation by O and C from either W-R stars or SNs can explain essentially the entire evolution of B and Be throughout the life of the Galaxy (i.e., at all metallicities). Only a small contribution from GCRs and none from the ν-process is required. Vangioni-Flam et al. (1996) used the same CR energy spectrum as Ramaty et al. (1996) and the latest ν-process yields from S. E. Woosley & T. A. Weaver (1995, private communication). They then attempted to put limits on the relative contributions of the other processes by adjusting the CR energy spectrum to *maximize* possible contributions from GCRs and the ν-process. The result was that roughly comparable (30%) contributions from all three processes might be accommodated. Even in this case, the Woosley & Weaver yields had to be reduced by a factor of 5 in order to avoid overproducing ^{11}B. Since the ν-process yields are quite sensitive to the physical parameters of the SN explosion, such uncertainty is not unexpected.

Because the different light-element production mechanisms operate on different timescales, it is possible to use our data to distinguish observationally between scenarios in which the ν-process does or does not play a major role. Massive SNs and W-R stars are very short-lived, and production from them should start almost immediately in the Galaxy, at the lowest metallicities. The ν-process, involving SNs of all types, should make a maximum relative contribution at intermediate metallicities, near [Fe/H] ≈ -2. As the metallicity of the ISM continues to increase, GCRs should make their maximum contribution at near-solar metallicity. Since the ν-process produces only ^{11}B and not Be, the Vangioni-Flam et al. (1996) models that maximize the ν-process predict a peak in the B/Be ratio near [Fe/H] $= -2$. The B/Be ratio should rise from ≥ 20 to a peak of ≈ 35, and then fall to ≈ 20. Figure 8 plots the B/Be ratio determined from our data. No peak at all is seen at [Fe/H] $= -2$. This suggests at most a minor role (much less than 30%) for the ν-process in producing light elements. GCRs account for ≤ 30%, and the dominant production mechanism is spallation by O and C in a low-energy CR spectrum that is poor in protons and α-particles.

The average NLTE B/Be value for all our stars is 15 ± 3 (1 σ random error). It is not clear if this low value (below the ≈ 20 predicted by Vangioni-Flam et al.) is significant. It could be that the NLTE corrections are somewhat underestimated, but there is no other reason to believe this. The NLTE corrections mostly affect the more metal-poor stars, and use of the Kiselman & Carlsson (1996) corrections makes the B/Be ratio nearly independent of metallicity (Fig. 8*b*). If no correction (Fig. 8*a*), or a stronger correction is used, that independence is no longer obtained. However, as discussed in § 3.1, systematic errors in the model atmospheres used could produce systematic errors that would affect B and Be abundances differently, thereby systematically shifting the B/Be ratio. Effects of 0.1–0.2 dex have been noted for other elements, and such possible effects should be investigated for B and Be.

6. SUMMARY

The present investigation has presented an analysis of B in 11 stars ranging in metallicity from [Fe/H] $= -0.4$ to -3.0. Spectrum synthesis was performed using the latest Kurucz model atmospheres and both B abundances and their uncertainties were carefully derived to permit judgment of the quality of fit of models of Galactic chemical evolution. NLTE corrections to the abundances were considered.

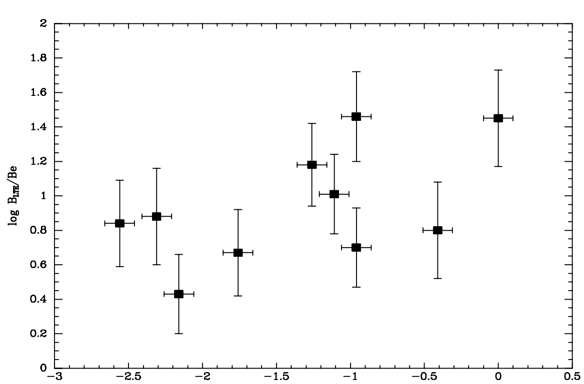

FIG. 8*a*

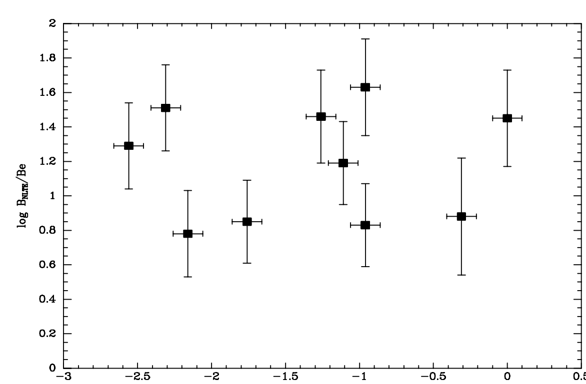

FIG. 8*b*

FIG. 8.—(*a*) LTE and (*b*) NLTE B/Be vs. [Fe/H]

We find that a straight line of slope 0.7–1 gives an excellent fit to a plot of log ϵ(B) versus [Fe/H] or log ϵ(B) versus [O/H], suggesting that the production of light elements such as B and Be is directly related to the production of heavier elements. There is no indication of a change in slope between halo and disk metallicities, although a small change is not precluded by our data, and more data are needed for stars near the disk-halo transition. Be abundances taken from the literature follow a similar trend. The NLTE B/Be ratio is 15 ± 3 (1 σ), close to (slightly less than) that expected from production by spallation at relatively low energies.

The constancy of the NLTE B/Be ratio at a value close to that of the corresponding spallation cross sections may provide the most direct evidence yet obtained for the production of light elements by spallative processes throughout the life of the Galaxy, as originally suggested by Burbidge et al. (1957) and modeled by Reeves et al. (1970) and Meneguzzi et al. (1971). In these canonical models, spallation is a secondary process that occurs in the general Galactic ISM. One generation of SNs is required to produce CNO nuclei that populate the ISM. Later, a flux of CRs, mostly protons and α-particles, splits these nuclei to form Li, Be, and B. The canonical theories predict a slope close to 2 in a plot of log ϵ(B) versus [Fe/H] or log ϵ(B) versus [O/H], and they are contradicted by our data. Even allowing several additional parameters, including very different CR behavior in the halo and the disk (e.g., Prantzos et al. 1993) does not allow theories based on such a secondary process to fit our data well. Also, these theories could not explain the observed ^{11}B/^{10}B ratio in a natural way. Spallation via the reverse process of energetic C and O nuclei onto protons and α-particles does much better. This reverse process was usually discarded as a minor effect (20% according to the calculations of Walker et al. 1993), since the canonical theory used a CR composition similar to that of the solar system. If a population of low-energy ($\approx$20–30 MeV nucleon^{-1}) CRs enriched in C and O and depleted in H and He existed, it could directly produce light elements by spallation of C and O onto the ambient medium. The metallicity of the medium would have little effect, and the process would operate in a similar fashion throughout the life of the Galaxy, leading to the slope of close to 1 that we observe. The original speculation of Burbidge et al. (1957) that spallation near SNs could be a key site of light-element production seems to be a prescient one.

A model in which most light-element production comes primarily from CR spallation of C and O nuclei onto protons and α-particles in the vicinity of massive SNs in star-forming regions fits our data well. If particle compositions are taken from calculations of either massive-star SNs or W-R stars, spallation can reproduce both the magnitude and slope of the B evolution we observe. This model also avoids producing too much Li at low metallicity, which would be inconsistent with the so-called "Spite plateau," the Li abundance produced by the big bang and observed to be the same in most stars of $[\mathrm{Fe/H}] \leq -1$. Overproduction of Li occurs in standard models because of $\alpha + \alpha$ reactions when the metallicity of the ISM is small, and a CR spectrum enriched in heavy elements and depleted in protons and α-particles fits the data better.

Our data can be used to place limits on the relative contributions of the different possible mechanisms for light-element production. We find that spallation of C and O nuclei onto protons and α-particles plays the major role, spallation by Galactic CRs in the general ISM a lesser role, and direct production by the ν-process in SNs at most a minor role.

A particularly attractive feature of the new model is that it provides a natural solution to the long-standing ^{11}B/^{10}B problem. Meteoritic ^{11}B/^{10}B is observed to be 3.84–4.25 (Chaussidon & Robert 1995), but the value predicted by standard models of spallation in the Galactic ISM is closer to 2.5. The new spallation mechanism produces ^{11}B/^{10}B of slightly greater than 4.0, which, when combined with smaller amounts of the still-operating traditional GCR spallation, predicts $^{11}\mathrm{B}/^{10}\mathrm{B} \sim 4$.

It is possible that the γ-rays recently detected from the Orion Nebula region by *CGRO* are the signature of this process in action. Nevertheless, the light-element data alone give the strongest evidence of their formation mechanism.

We would like to thank Michel Cassé, Elizabeth Vangioni-Flam, Reuven Ramaty, and Stan Woosley for their comments, Kim Coble for contribution to the data analysis, David Lambert for initial ideas that eventually led to this paper, and F. Spite for his reference comments. D. K. D. would like to thank his inspiring physics instructor R. Vogt for suggesting many years ago that all good physicists eventually study cosmic rays. This research was 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 NAS 5-26555. C. P. D. and J. R. K. gratefully acknowledge support for this work provided by NASA through grants HF-1042.01-93A and HF-1046.01-93A, awarded through the Space Telescope Science Institute. This research has made use of NASA's Astrophysics Data System Abstract Service.

APPENDIX A

LINE FITTING

A1. LEAST-SQUARES LINEAR FITS

The linear fits reported here used an algorithm that incorporates errors in both coordinates, discussed in Press et al. (1988), implemented by F. Varosi in 1992, and submitted to the (public domain) IDL Astronomy User's Library. This algorithm minimizes χ^2 and is given by

$$\chi^2 = \sum_{i=1}^{n} \frac{(y_i - b - mx_i)^2}{\sigma_{yi}^2 + m^2\sigma_{xi}^2} , \tag{3}$$

where there are n data points and the linear fit is given by $y(x) = mx + b$.

We also tried the standard technique (see Bevington & Robinson 1992) of using the slope of the line to map the direct measurement errors in x into "indirect" errors in y (σ_{yI}) using

$$\sigma_{yI} = \sigma_x \frac{dy}{dx}, \tag{4}$$

where dy/dx is the slope of the line. The value σ_{yI} for the indirect errors in y is combined in quadrature with the direct measurement errors, yielding a total error in y to be used in the evaluation of the χ^2_ν. Results from this fit were very similar to the one above.

Finally, we also tried fitting a line for which the perpendicular distance between the line and the point was minimized. We did not calculate errors on the fit parameters.

The calculated parameters of these fit attempts are all consistent with each other.

A2. BROKEN-LINE FITS

There is some expectation that there should be a break in the B versus [Fe/H] line delimiting the disk-halo transition, analogous to that of [O/H]. We therefore made trial fits to the B data that consisted of two line segments joined at various values of metallicity and investigated whether a better fit was obtained by allowing these further degrees of freedom. The criterion of the quality of the fit we used was the reduced χ^2 statistic, χ^2_ν.

The actual algorithm used shifts the data such that the location of the break is at $x = 0$, least-squares fits a line to the data to the left of the break, uses the y-intercept from that line as the intercept for a line fitting the data to the right, and adjusts the slope of the line on the right to minimize the least-squares deviations. The χ^2_ν for four fit parameters or eight degrees of freedom is calculated, and the data are shifted back onto the original scale. This is then repeated, but with the data to the right fitted first, constraining the fit of the data on the left. We use the notation "LHS" when the left-hand side was anchored first, and "RHS" in the other case. A variety of break locations was tried, as seen in Table 7. Errors were treated with the technique of mapping σ_x into σ_y.

Broken-line fits were generally worse than the unbroken linear fit. However, χ^2_ν indicates that, for our limited number of stars, small changes of slope are not precluded, and, in fact, there is very weak evidence for a plateau at [Fe/H] $= -2.5$. It is clearly important to obtain more data for more stars, especially ones near the disk-halo transition.

REFERENCES

Abia, C., & Rebolo, R. 1989, ApJ, 347, 186
Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Bessell, M. S., Sutherland, R. S., & Ruan, K. 1991, ApJ, 383, 71
Bevington, P. R., & Robinson, D. K. 1992, Data Reduction and Error Analysis for the Physical Sciences (New York: McGraw-Hill)
Bloemen, H., et al. 1994, A&A, 281, L5
Boesgaard, A. M., & King, J. R. 1993, AJ, 106, 2309
Burbidge, E. M., Burbidge, G. R., Fowler, W. A., & Hoyle, F. 1957, Rev. Mod. Phys., 29, 547
Bykov, A., & Bloemen, H. 1994, A&A, 283, L1
Cassé, M., Lehoucq, R., & Vangioni-Flam, E. 1995, Nature, 373, 318
Chaussidon, M., & Robert, F. 1995, Nature, 374, 337
Deliyannis, C. P., Boesgaard, A. M., King, J. R., & Duncan, D. K. 1996, ApJ, in press
Duncan, D. K., Lambert, D. L., & Lemke, M. 1992, ApJ, 401, 584 (DLL)
Duncan, D. K., Peterson, R. C., Thorburn, J. A., Pinsonneault, M. H., & Deliyannis, C. P. 1997, ApJ, submitted
Duncan, D. K., Rebull, L. M., Primas, F., Boesgaard, A. M., Deliyannis, C. P., Hobbs, L. M., King, J. R., & Ryan, S. 1997, A&A, submitted
Edvardsson, B., Gustafsson, B., Johansson, S. G., Kiselman, D., Lambert, D. L., Nissen, P. E., & Gilmore, G. 1994, A&A, 290, 176
Edvardsson, B., Gustafsson, B., Kiselman, D., Lambert, D. L., Nissen, P., & Gilmore, G. 1993, A&A, 290, 176
García-López, R. J., Severino, G., & Gomez, M. T. 1995, A&A, 297, 801
Gustafsson, B., Bell, R. A., Eriksson, K., & Nordlund, A. 1975, A&A, 42, 40
King, J. R. 1993, AJ, 106, 1206
———. 1994, ApJ, 436, 331
Kiselman, D. 1994, A&A, 286, 169
Kiselman, D., & Carlsson, M., 1996, A&A, 311, 680
Kohl, J. L., Parkinson, W. H., & Withbroe, G. L. 1977, ApJ, 212, L101
Kurucz, R. L. 1993, CD-ROM 1, 13, 18
Lemoine, M., Vangioni-Flam, E., & Cassé, M. 1997, ApJ, in press
Magain, P. 1989, A&A, 209, 211
McWilliam, A., Preston, G. W., Sneden, C., & Searle, L. 1995, AJ, 109, 2757
Meneguzzi, M., Audouze, J., & Reeves, H. 1971, A&A, 15, 337 (MAR)
Meneguzzi, M., & Reeves, H. 1975, A&A, 40, 99
Murphy, R. J., Share, G. H., Grove, J. E., Johnson, W. N., Kurfess, J. D., Purcell, W. R., McNaron-Brown, K., & Ramaty, R. 1996, ApJ, 473, 990
Nissen, P. E., Gustafsson, B., Edvardsson, B., & Gilmore, G. 1994, A&A, 285, 400
O'Brian, T. R., & Lawler, J. E. 1992, A&A, 255, 420
Prantzos, N., Cassé, M., & Vangioni-Flam, E. 1993, ApJ, 403, 630 (PCV)
Primas, F. 1996, Ph.D. Thesis, University of Trieste
Primas, F., Duncan, D. K., Pinsonneault, M. H., Deliyannis, C. P., & Thorburn, J. T. 1997, ApJ, 480, 784
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1988, Numerical Recipies in C (Cambridge: Cambridge Univ. Press)
Ramaty, R., Kozlovsky, B., & Lingenfelter, R. E. 1996, ApJ, 456, 525
Rebolo, R., Molaro, P., Abia, C., & Beckman, J. E. 1988, A&A, 193, 193
Reeves, H., Audouze, J., Fowler, W. A., & Schramm, D. N. 1973, ApJ, 179, 909
Reeves, H., Fowler, W. A., & Hoyle, F. 1970, Nature, 226, 727
Reeves, H., & Meyer, J.-P. 1978, ApJ, 226, 613
Ryter, C., Reeves, H., Gradsztajn, E., & Audouze, J. 1970, A&A, 8, 389
Ryan, S. G., Bessell, M. S., Sutherland, R. S., & Norris, J. E. 1990, ApJ, 348, 57
Ryan, S. G., Norris, J. E., Bessell, M. S., & Deliyannis, C. P. 1992, ApJ, 388, 184
Ryan, S. G., Norris, J. E., & Beers, T. C. 1996, ApJ, 471, 254
Steigman, G., & Walker, T. P. 1992, ApJ, 385, L13
Thorburn, J. A., & Hobbs, L. M. 1996, AJ, 111, 2106
Tomkin, J., Lemke, M., Lambert, D. L., & Sneden, C. 1992, AJ, 104, 1568
Vangioni-Flam, E., Audouze, J., Oberto, Y., & Cassé, M. 1990, ApJ, 364, 568
Vangioni-Flam, E., Cassé, M., Fields, B. D., & Olive, K. A. 1996, ApJ, 468, 199
Walker, T. P., Steigman, G., Schramm, D. N., Olive, K. A., & Fields, B. D. 1993, ApJ, 413, 562
Woosley, S. E., Hartmann, D. H., Hoffman, R. D., & Haxton, W. C. 1990, ApJ, 356, 272
Yoshii, Y., Kajino, T., & Ryan, S. G. 1997, ApJ, 485, 605
Zhai, M. & Shaw, D. M. 1994, Meteoritics, 29, 607

Note added in proof.—While preparing this paper, we became aware that work to be published by Ramaty et al. (R. Ramaty, B. Kozlovsky, R. E. Lingenfelter, & H. Reeves, ApJ, 488 [1997]) supports many, though not all, of our conclusions.