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IMPLICATIONS OF A HIGH POPULATION II B/Be RATIO

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ABSTRACT

The observed boron/beryllium ratio in extreme Population II stars has been interpreted as evidence of Be and B synthesis by early Galactic cosmic rays. However, a recent reanalysis of the boron abundance in the Population II halo star HD 140283 suggests that B/H may be larger than previously reported, by as much as a factor of 4. This would yield a B/Be ratio lying in the range $14 \lesssim \mathrm{B/Be} \lesssim 50$. The possibility of a high Population II B/Be ratio stresses the importance of the upper limit to the B/Be ratio arising from cosmic-ray production. It is found that the limit to cosmic-ray–produced B/Be depends upon the assumed cosmic-ray spectrum. For any Population II comic-ray spectrum that is a single power law in either total energy per nucleon or in momentum, the B/Be ratio is constrained to lie in the range $7.6 \lesssim \mathrm{B/Be} \lesssim 14$. Thus, if the new B/Be ratio is correct, it requires either a bimodal cosmic-ray flux with a large low-energy component, or, for another B source, possibly the proposed ν-process in supernovae, either of which may be helpful in explaining the observed $^{11}\mathrm{B}/^{10}\mathrm{B}$ ratio. Finally, it is noted that the boron reanalysis highlights the uncertainty in our knowledge of the B/Be ratio, and the need for additional data on Be and B abundances.

Subject headings: cosmic rays — nuclear reactions, nucleosynthesis, abundances — stars: Population II

In the last few years, new observations of Population II halo stars have led to the detection of boron (Duncan et al. 1992, hereafter DLL; Edvardsson et al. 1994) and beryllium (Rebolo et al. 1988; Ryan et al. 1990, 1992; Gilmore, Edvardsson, & Nissen 1992a; Gilmore et al. 1992b; Boesgaard & King 1993). It is commonly believed (Reeves, Fowler, & Hoyle 1970; Meneguzzi, Audouze, & Reeves 1971 (MAR); Reeves et al. 1973; Walker, Mathews, & Viola 1985; Steigman & Walker 1992, hereafter SW; Prantzos, Cassé, & Vangioni-Flam 1993, hereafter PCV; Walker et al. 1993, hereafter WSSOF; Steigman et al. 1993, hereafter SFOSW; Fields, Olive, & Schramm 1994, hereafter FOS) that these elements have their origin in early cosmic-ray activity. Spallation of carbon, nitrogen, and oxygen by protons and α-nuclei can for the most part account for the observed abundances of B and Be. Early cosmic rays can also produce some of the observed ^{7}Li as well as all of the now observed ^{6}Li (Smith, Lambert, & Nissen 1992; Hobbs & Thorburn 1994), in part by spallation but predominantly via the accompanying $\alpha + \alpha$ fusion.

A comparison of observed abundance ratios and their theoretical predictions is a good test of models of Galactic cosmic-ray nucleosynthesis (SW; PCV; WSSOF; SFOSW; FOS) and Galactic chemical evolution (PCV); it may have implications for big bang nucleosynthesis as well (WSSOF; Olive & Schramm 1992). The ratios of interest are $^6\mathrm{Li}/^7\mathrm{Li}$, Li/Be, B/Be, and potentially $^{11}\mathrm{B}/^{10}\mathrm{B}$. In the case of $^6\mathrm{Li}/^7\mathrm{Li}$, where the theoretical prediction of about 0.9 (from cosmic-ray nucleosynthesis) is robust, the observation of ^{6}Li (Smith et al. 1992; Hobbs & Thorburn 1994) is a good indication that Li is not strongly depleted in stars (at least not by nuclear burning; Brown & Schramm 1988; Deliyannis et al. 1989). Although caution is still warranted because of the current paucity of data, the $^6\mathrm{Li}/^7\mathrm{Li}$ ratio found by both groups is consistent with standard models of cosmic-ray and big bang nucleosynthesis and standard stellar models which have minimal Li depletion (SFOSW). The Li/Be ratio which can be used to probe the compatibility between cosmic-ray and big bang nucleosynthesis (WSSOF; Olive & Schramm 1992) is much more model-dependent (FOS). There are as yet no data on the $^{11}\mathrm{B}/^{10}\mathrm{B}$ ratio in Population II objects, but such data would be very interesting, as this ratio is anomalous even in Population I objects, a point we will return to below. Finally, the B/Be ratio, like the $^6\mathrm{Li}/^7\mathrm{Li}$ ratio, is largely independent of cosmic-ray models (WSSOF; FOS) and so is an excellent test of these models.

While there are many observations giving the Be abundance in halo stars (Rebolo et al. 1988; Ryan et al. 1990, 1992; Gilmore et al. 1992a, b; Boesgaard & King 1993), there are data on B for only three stars (DLL; Edvardsson et al. 1994), since the B lines reside well into the ultraviolet and thus require satellite observation. The data are summarized in Table 1. In the table we show the observed abundances of Be and B as well as Fe for the three halo stars. For each particular Be measurement we list the Fe abundance used for that measurement. Note that both the Be and the Fe abundances for each star vary among the different measurements.

In the case of HD 140283, there are several independent observations of Be and two observations of B. In the table we show the quoted value of [Be]. For [B], we have averaged the two measurements and, to minimize systematics, we have adjusted the B abundance quoted in Edvardsson et al. (1994) by assuming stellar parameters (temperature and surface gravity) as in DLL. To obtain the B/Be ratios, we use the average B abundance and we have adjusted the Be abundances

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TABLE 1

Observed Population II Abundances of Be and B

Star	[Fe/H]	[Be]	[B]	LTE B/Be	NLTE B/Be	Source[a]
HD 19445	−2.1	−0.14 ± 0.1	0.4 ± 0.2	3.4 ± 1.8	~8	BK
HD 140283	−2.7	−1.25 ± 0.4	−0.16 ± 0.14	12 ± 12	34–50	Ry
HD 140283	−2.8	−0.97 ± 0.25	−0.16 ± 0.14	7 ± 5	23–33	G
HD 140283	−2.7	−0.78 ± 0.14	−0.16 ± 0.14	5 ± 2	14–21	BK
HD 140283	−2.5	< −0.90	−0.16 ± 0.14	>7	>21–30	M
HD 201891	−1.3	0.65 ± 0.1	1.7 ± 0.4	10 ± 10	~14.5	Re, BK

[a] BK = Boesgaard & King 1993; Ry = Ryan et al. 1990, 1992; G = Gilmore et al. 1992a, b; M = Molaro, Castelli, & Pasquini 1993; Re = Rebolo et al. 1988.

in each case to also match the DLL stellar parameters. For HD 19445 we note that there are in addition upper limits of [Be] less than 0.3 (Rebolo et al. 1988) and less than −0.3 (Ryan et al. 1990) giving B/Be > 1.3 and B/Be > 5, respectively, which have not been included in the table, and for HD 201891 the values of [Be] and B/Be given represent an average of the two published measurements.

One should be aware that most observational determinations have been made using different sets of parameters in their stellar atmosphere models. Although one can ascribe some uncertainty to chosen values of these parameters, it is not always clear to what extent these systematic errors have been incorporated into the quoted so-called statistical error, and different authors make divergent assumptions on the uncertainty of their assumed stellar parameters. Thus some care is warranted in using these data. Since systematic errors due to assumed model parameters, etc., are probably not distributed in a Gaussian manner, nor will they be decreased with the square root of the number of observations, one cannot reliably apply standard statistical techniques. (Perhaps future observational papers might consider separating the systematic portion of the stated error from the statistical portion as is now being done in many nuclear and particle physics papers.)

As one can see from the B/Be ratios in Table 1, some of the LTE ratios are in agreement with standard cosmic-ray nucleosynthesis model predictions (B/Be $\simeq$ 12–14), but most of them are on the low side of the prediction. For example, the overall average in the case of HD 140283 gives B/Be = 6 ± 2. (However, recall the caveat regarding systematic errors.) Thus effort has been concentrated for the most part in determining how low the B/Be can be made within the context of cosmic-ray nucleosynthesis. In WSSOF it was argued on the basis of spallation cross sections that the extreme lower limit is B/Be $\gtrsim 7$. Both WSSOF and PCV have noted that a low Population II B/Be ratio (between 7 and 10) would imply a flatter cosmic-ray spectrum in the early Galaxy, which is suggested to have arisen from stronger cosmic-ray confinement.

Recently, Kiselman (1994) has performed a reanalysis of the inferred B in HD 140283 from the DLL data. In the original analysis of DLL, abundances based on the B I and Be II spectral lines were extracted using the assumption of LTE. The beryllium abundance is believed to be relatively insensitive to this approximation. It was recognized by DLL that a non-LTE (NLTE) analysis could be a potentially important correction to the boron abundance. Kiselman (1994) has in great detail attempted to account for the NLTE correction for the specific case of HD 140283. Indeed, he found an overall upward correction to the boron abundance of 0.56 dex or a factor $\gtrsim 3$. To test the reliability of his results, Kiselman perturbed his model and estimates that a reasonable NLTE correction to the boron abundance of HD 140283 should lie between 0.46 and 0.62 dex. Recently the DLL measurement of B in HD 140283 has been confirmed by Edvardsson et al. (1994). Within errors, there is very good agreement in the LTE abundances. Edvardsson et al. (1994) argue for a similar NLTE correction to their derived abundance. In Table 1 we also give Kiselman's corrected B/Be ratio for the range 0.46–0.62 dex. The weighted average of the three positive observations of Be (again corrected for differing surface gravities) is [Be] = −0.93 ± 0.12, giving B/Be = 6 ± 2. After the Kiselman correction, we find that B/Be = 17–25, using the central value of Be. The range here corresponds to the range in the correction factor, not to statistical errors. The correction factors for HD 19445 and HD 201891 were obtained from D. Kiselman (1994, private communication).

The possibility of a high Population II B/Be ratio can have interesting consequences. WSSOF compute an upper bound of B/Be $\lesssim 17$ for cosmic-ray production in Population II. However, whereas the WSSOF lower limit to B/Be is model-independent, their upper limit is not, since it was calculated in their "zeroth-order" model. The question we ask here is, what is the true, model-independent upper bound to the B/Be ratio arising from cosmic rays? In this paper we compute the range of B/Be produced in various models of cosmic-ray synthesis of LiBeB, and we discuss the implications for alternative means of boron production.

There are several factors which affect the maximum B/Be ratio that Population II cosmic rays can produce. Ultimately, the predicted ratios are controlled by (well-measured) nuclear physics, in the guise of spallation/fusion cross sections. The model-dependent feature one may adjust is the Population II cosmic-ray flux spectrum, which one must decide how to parameterize. Given a choice of flux, its LiBeB yields are constrained to be consistent with the observed Population II LiBeB abundances and ratios. To determine the maximum B/Be, then, the game is to choose a range of admissible Population II cosmic-ray spectra, and then, to convolve it with the cross sections, find the highest B/Be ratio these spectra can produce without violating observational constraints.

The rate of LiBeB production by cosmic rays is given for each process by the usual rate equation (see FOS for details on our recent analysis): the product of target abundances with an integral of the cosmic-ray flux times the cross section for the reaction and a factor accounting for the probability of the LiBeB being stopped in the Galaxy before escape. The lower bound for the integral is the threshold energy T^0 for each spallation/fusion process. The thresholds are determined by Q-values for the reactions. Here the most important fact about these thresholds is that for all spallation reactions $T^0_{\rm B} < T^0_{\rm Be}$, i.e., *the threshold for boron production is lower than that for beryllium production.* Thus all of the flux in the energy range

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$T^0_{\rm B} \le T \le T^0_{\rm Be}$ (in our case, 3.13 MeV $\le T \le$ 17.5 MeV) will produce only boron. Clearly, one can make B/Be arbitrarily high by tuning the low-energy cosmic-ray flux to exploit this difference in thresholds. Note as well that for boron isotopic production, we have $T^0_{11} < T^0_{10}$, and so a large low-energy flux will also have the effect of increasing the ^{11}B/^{10}B ratio.

The cosmic-ray spectrum ϕ is propagated (in energy space) from a source spectrum q which one must specify. Today we observe the propagated flux from contemporary sources, from which we can infer a source spectrum. However, observations of the present spectrum are limited by solar modulation to include only cosmic rays with kinetic energy $T \gtrsim 100$ MeV nucleon^{-1}. The observed spectrum is consistent, over this range, with a source law taking the form of a single power law, either in momentum per nucleon, $q(p) \propto p^{-\gamma}$, or in total energy per nucleon, $q(T) \propto (T + m_p)^{-\gamma}$. The observed Galactic cosmic-ray flux today corresponds to such a flux, with a spectral index of $\sim$2.7. The present cosmic-ray confinement is characterized by a path length Λ which varies in energy around ~ 10 g cm^{-2}.

We do not know directly how the cosmic-ray flux behaves at low energy ($\lesssim$100 MeV nucleon^{-1}); this is an unfortunate state of affairs, since the B/Be ratio is very sensitive to the details of the flux at precisely this energy range. We will in this paper assume that we may extrapolate the cosmic-ray flux from the measured high-energy region down to the low-energy regime. We will for the moment also assume that the low-energy flux obtained through this extrapolation is the *only* low-energy component. We remind the reader, however, that while the data we are extrapolating from measures the present, Population I cosmic-ray flux, we wish to model its behavior in the Population II epoch. As several authors have pointed out, in this epoch the flux parameters, namely, the spectral index and escape path length, are not well constrained, and indeed could have been different from those today. We will therefore allow for these parameters to vary within physically allowable ranges as done in FOS.

In choosing the allowed flux parameters, we consider the possibility that a high B/Be might change the outlook on the behavior of early cosmic-ray confinement. Before the Kiselman (1994) result, it was argued that larger early confinement was needed to reproduce a low B/Be. Now we consider the opposite case, and so this motivation for a larger confinement weakens. Thus, we have allowed the escape path length to vary over the range 10 g cm^{-2} $\le \Lambda \le$ 1000 g cm^{-2}, which encompasses the present values and extends up to values at which nuclear inelastic losses dominate the escape losses.

We have calculated LiBeB production rates using cosmic-ray fluxes propagated from different source spectra that are power laws either in momentum or in total energy. For each source type (i.e., power law in momentum or in total energy) we plot the ratio of production rates, ∂_tLi/∂_tBe, as well as ∂_tB/∂_tBe. Our results appear in Figures 1 and 2. As noted in FOS, lacking a model for the Galactic chemical evolution, one can only calculate the ratio of LiBeB production rates rather than the actual abundance ratios, e.g., B/Be or Li/Be. However, FOS note that evolutionary processes will serve to make ∂_tLi/∂_tBe a lower bound for the true Li/Be ratio, while evolutionary effects are unimportant in the B/Be ratio which can be identified with the ∂_tB/∂_tBe ratio.

Note that in the case of the momentum source spectrum (Fig. 1) the ∂_tB/∂_tBe ratio does rise with increasingly steep spectra. This is expected: a featureless power law in momentum has a lot of power at low energies, and so the ∂_tB/∂_tBe ratio should be sensitive to the spectral index (although the steepness of the source law is greatly softened at low energies by ionization losses included in the propagation). However, while the ∂_tB/∂_tBe ratio linearly increases with the spectral index, the ∂_tLi/∂_tBe ratio increases exponentially. But a large Li/Be ratio is constrained by the observational data. If we demand that the cosmic rays do not wash out the Spite plateau, then we may very generously insist that (Li/Be)$_{\rm CR}$ < (Li/Be)$_{\rm OBS}$ $\simeq$ 1000. Bearing in mind that the ∂_tLi/∂_tBe ratio *underestimates* the Li/Be, we see that the spectral index is strongly constrained. Even for a high confinement, the steepest allowed spectrum has $\gamma \lesssim 3.3$. In this range, for all confinement parameters, ∂_tB/∂_tBe $\simeq$ B/Be $\lesssim$ 14. A momentum source that is not otherwise enhanced at low energies cannot produce B/Be in the range of the Kiselman results.

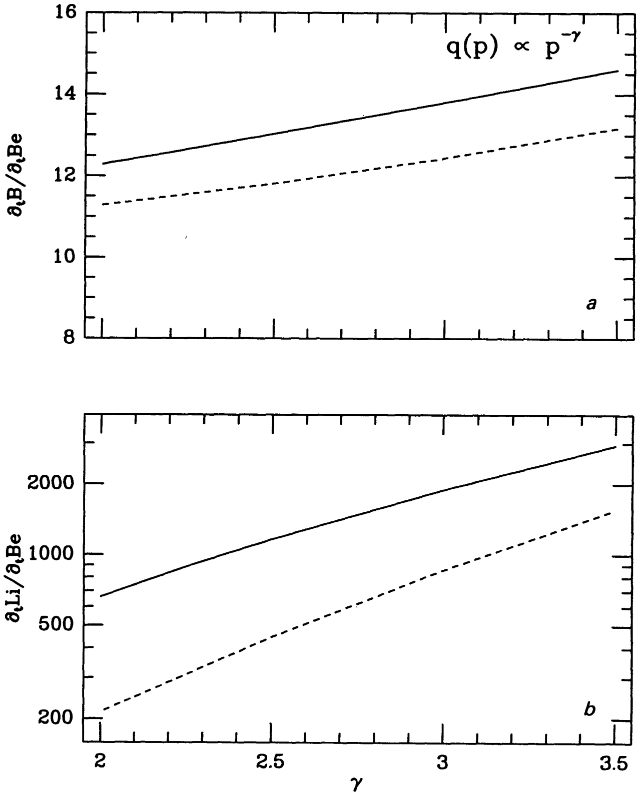

FIG. 1.—Ratios of LiBeB production rates for a source spectrum $q(p) \propto p^{-\gamma}$, plotted as a function of spectral index γ. For both plots we use CNO abundances [C/H] = [N/H] = [Fe/H] = [O/H] $-0.5 = -2.5$, and ^{4}He/H = 0.08. (*a*) The ∂_tB/∂_tBe ratio; the solid curve is for Λ = 10 g cm^{-2}, the broken curve is for Λ = 1000 g cm^{-2}. Note the very restricted, linear scale in the ordinate, showing the insensitivity of ∂_tB/∂_tBe to the spectral index. (*b*) As in (*a*), for the ∂_tLi/∂_tBe ratio. Here we see that ∂_tLi/∂_tBe is exponentially sensitive to the spectral index, in contrast to the results of plot (*a*). As discussed in the text, the observational constraint Li/Be $\ll$ 1000 implies that ∂_tB/∂_tBe $\simeq$ B/Be $\lesssim$ 14.

Similar results for a source spectrum in total energy are shown in Figure 2. Note here that there is much less of a problem with the ∂_tLi/∂_tBe ratio. However, this spectrum is doomed to fail to produce high B/Be. Because the source is a power law in total energy, $q \sim (T + m_p)^{-\gamma}$, the nucleon rest mass m_p introduces a low-energy cutoff which keeps the flux spectrum finite and sets the scale for the peak in the propa-

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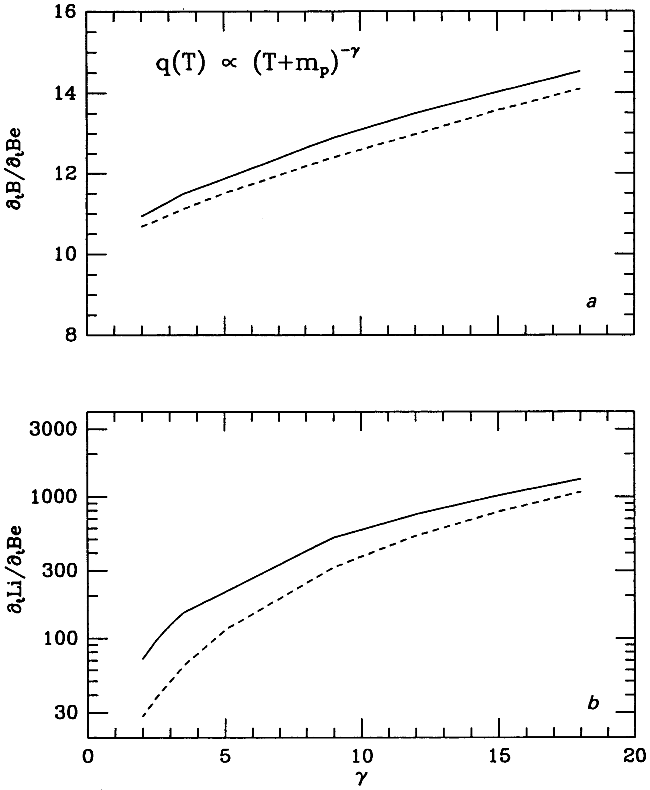

FIG. 2.—As in Fig. 1, for a source spectrum $q(T) \propto (T + m_p)^{-\gamma}$. (*a*) The $\partial_t B/\partial_t Be$ ratio; note the larger range in γ compared to that of Fig. 1, and the even less steep dependence of $\partial_t B/\partial_t Be$ on the spectral index. (*b*) The $\partial_t Li/\partial_t Be$ ratio. Here again $\partial_t Li/\partial_t Be$ is sensitive to γ, but less so than for a source spectrum in momentum (Fig. 1). Note also the $Li/Be \ll 1000$ again gives $\partial_t B/\partial_t Be \simeq B/Be \lesssim 14$.

gated flux to be around m_p, far above the tens of MeV at which one requires a large flux to fit B/Be. This effect is seen in the flatness of the $\partial_t B/\partial_t Be$ curve in Figure 2. One expects a spectral index around $\gamma = 2$–3, and certainly $\gamma < 5$, which gives $B/Be \lesssim 12$. However, to get a feeling for the maximum possible B/Be, we arbitrarily allow the spectral index to increase until the $\partial_t Li/\partial_t Be$ constraint is reached. Even in this poorly motivated case, we have $\partial_t B/\partial_t Be \lesssim 14$, the same constraint as for the momentum spectrum. Thus, for either spectral type, we have an upper bound for

$$\partial_t B/\partial_t Be \simeq B/Be \lesssim 14 , \qquad (1)$$

a limit which is independent of the choice of confinement parameter Λ and allows for variation in spectral index.

If the NLTE correction to the B abundance in HD 140283 is correct, then for this star $B/Be \gtrsim 14$ (see Table 1) and is more likely to be even higher; thus a single–power-law cosmic-ray flux underestimates the observed B/Be ratio. We must therefore conclude that either (1) the cosmic-ray flux is not well described by a single power law; (2) there has been significant stellar depletion in Population II, which would preferentially destroy Be relative to B because of the difference in the Coulomb barriers; or (3) something other than or in addition to cosmic rays produces the observed ratio. We will address point 1, suggesting a possible non–power-law spectrum. Regarding point 2, as it is argued in SFOSW, we do not expect significant depletion in these stars, as is indicated by the positive identification of ^{6}Li in halo stars. Thus we will not consider this line of reasoning further. As for point 3, we note that no proposed source for Be (and for ^{6}Li) other than cosmic rays has stood the test of time, and thus, lacking an alternative, we will continue to assume that these nuclei do arise from cosmic-ray processes. We will consider the possibility of additional sources to the boron abundance.

If we take the observed LTE B/Be ratio to be accurate (i.e., assume that B and Be are undepleted), and we assume that cosmic rays (with a single–power-law spectrum) produced the Be (and inevitably some B as well), then the import of the Kiselman (1994) NLTE calculation is that another source of boron is needed. As mentioned above, one possibility frequently discussed is the superposition of a low-energy component to the cosmic-ray flux. Such a low-energy component to the cosmic rays is not directly observable. However, introduction of a low-energy component to the cosmic-ray flux allows additional tuning of LiBeB production beyond the above considerations of adjusting the cosmic-ray source type, or confinement.

Long before the recent Kiselman (1994) analysis, there was another good reason for an additional source of B, namely, the boron isotropic ratio. It is well known that standard cosmic-ray nucleosynthesis models predict (MAR) a value $^{11}B/^{10}B \simeq 2.5$, whereas the observed ratio (Cameron 1982; Anders & Grevesse 1989) is very close to 4. Interestingly, the same low-energy flux that will make a high B/Be ratio will also make a large $^{11}B/^{10}B$ ratio. Indeed, this point has been noted by MAR as well as in subsequent cosmic-ray nucleosynthesis calculations. MAR first suggested that the cosmic rays might have a low-energy component which could fix the (Population I) boron isotopic problem, and possibly the Population I lithium isotopic ratio as well. Authors since then have followed this lead in trying to reproduce the solar ratios of B and Li, and have been moderately successful in doing so, the most recent model being that of WMV. The low-energy particles were proposed to be similar to those seen in solar flares, which indeed have steep spectra. MAR and subsequent authors have modeled this component with a power law in kinetic energy, with indices between 3 and 7. PCV also have some discussion of Population II synthesis of LiBeB by including a low-energy spectral component. They find that, while addition of this component allows for a felicitous $^{11}B/^{10}B$ ratio, the flare component also leads to Li overproduction at low metallicities. PCV concluded that such a fix to the $^{11}B/^{10}B$ ratio problem, could only be implemented during the disk phase of the Galaxy. As such, it can not account for a high B/Be ratio in halo stars.

WMV and earlier works have calculated the LiBeB yields for the case in which the low-energy flare component dominates the production. For this case of a LiBeB synthesis purely by flares (in a Population I environment), WMV find that such a flux does not reproduce elemental or isotopic ratios. In particular, they find that $B/Be \gtrsim 100$ for a flare spectrum with index $\beta \gtrsim 5$, and they find that in all cases $^{11}B/^{10}B \gtrsim 5$. They also find that $Li/B \gtrsim 80$, an overproduction that only becomes exacerbated in a Population II environment. That these ratios fit the data poorly is an indication that a flare spectrum alone cannot dominate the LiBeB production in a Population I environment. Furthermore, since the Be and B production is insensitive to Galactic evolution, these conclusions hold for a Population II environment as well.

While we cannot observe a low-energy flux directly, there are two indirect observational constraints and signatures that

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have been suggested. One is its ionization of the interstellar medium (ISM), which MAR employ as a constraint on the low-energy flux. Too many cosmic-ray particles would ionize the ISM beyond the observed limits. Also, a low-energy flux creates a distinctive γ-ray spectrum. These γ-rays are produced by inelastic collisions with CNO nuclei that leave the CNO in an excited state. The de-excitation of these states leaves a signature of distinctive lines. Until recently these lines, predominantly from the 4.44 MeV state of $^{12}C^*$, and at 6.13 MeV from $^{16}C^*$, have remained unobserved. However, the COMPTEL group on the *Gamma Ray Observatory* (Bloemen et al. 1994) have observed the Orion complex at 0.75–30 MeV and report a detection of γ-ray emission in excess of background in the 3–7 MeV range (and only in this range).

Bloemen et al. (1994) report a flux of $(1.01 \pm 0.15) \times 10^{-4}$ cm^{-2} s^{-1} (3–7 MeV). This is to be compared with the calculations of Meneguzzi & Reeves (1975), applied to Orion, for which one expects a flux at the $^{12}C^*$ peak of $\phi_\gamma \simeq (2.5\text{–}5) \times 10^{-7}$ cm^{-2} s^{-1} MeV^{-1} for a flare-type spectrum (and significantly less for a spectrum from a single-component momentum or total energy source). Bloemen et al. (1994) suggest that an enhancement in the low-energy cosmic-ray proton flux sufficient to match the observation leads to a large rate for the ionization of the ISM. Consequently, Bloemen et al. argue that these γ-rays are not from energetic protons on interstellar C and O but instead from an enhanced component of low-energy cosmic-ray C and O on ISM hydrogen. Recently, attemps to incorporate this new γ-ray observation into Galactic cosmic-ray nucleosynthesis models have been presented (Cassé, Lehoucq, & Vangiomi-Flam 1994; Reeves 1994). These models may also predict a higher than standard B/Be ratio. In the remaining discussion, we consider other alternatives which predict a high B/Be ratio.

Because of the difficulty in producing the observed isotopic ratio of $^{11}B/^{10}B$ in standard cosmic-ray nucleosynthesis models, it has been suggested that alternative astrophysical sites for the production of ^{11}B must be found. One such site is at the shock front of Type II supernovae, as suggested by Dearborn et al. (1989): when the shock hits the hydrogen envelope, it burns the ambient ^3He and ^4He producing ^7Be. Some of the resulting ^7Be combines with α-particles to produce ^{11}C, which decays to ^{11}B. They noted that significant ^{11}B production might take place. Subsequent calculations (Brown et al. 1991) have shown that these hydrodynamic processes were not sufficient producers of these light elements for currently preferred parameter values.

A potentially more important source for ^{11}B production has been found to result from neutrino-induced nucleosynthesis in Type II supernovae (Woosley et al. 1990). The inelastic scattering of neutrinos leads to unstable excited states which decay by p, n, or α emission. These processes were included in supernova nucleosynthesis calculations by Woosley et al. (1990), where it was found that considerable ^{11}B production can result as the flux of neutrinos passes through the He, C, and Si shells of the stellar envelope, primarily by neutrino spallation of ^{12}C. The dominant product is ^{11}B, since it is favored for ν-spallation to knock out a single nucleon. In addition, some synthesis of ^7Li and ^{10}B takes place by this process but the production rate seems quite low. This process is attractive, as it naturally creates ^{11}B without much ^{10}B and thus provides the needed source of ^{11}B to augment GCR production and so reproduce the $^{11}B/^{10}B$ ratio.

Indeed, the ^{11}B yields from these processes (Woosley, Timmes, & Weaver 1993; Timmes, Woosley, & Weaver 1995) were incorporated in a chemical evolution model (Olive et al. 1994). Respecting the overall constraints imposed by the LiBeB observations in halo stars, they were able to obtain a solar isotopic ratio $^{11}B/^{10}B \simeq 4$. Using the boron isotopic ratio to normalize the ν-process yields, they showed that neutrino process nucleosynthesis leads to a relatively model-independent prediction that the B/Be elemental ratio is large (greater than 50) at low metallicities ([Fe/H] < -3.0), assuming still that Be is produced as a secondary element as is the case in the conventional scenario of Galactic cosmic-ray nuelosynthesis. (Despite earlier conjectures [Malaney 1992], ^9Be is not significantly produced by the ν-process). In particular, at the metallicity corresponding to that of HD 140283, [Fe/H] $\simeq -2.6$, Olive et al. (1994) predicted that the B/Be ratio should be close to 40. Although still on the high side, this is in overall good agreement with the NLTE corrected values shown in Table 1.

To summarize our results, the Kiselman (1994) analysis of the B abundance in HD 140283 suggests that in this star the B/Be ratio is potentially higher than can be accounted for by cosmic-ray nucleosynthesis with a single–power-law source spectrum. This is best understood as arising from a overabundance of boron. If indeed the boron is high, then it must have a source that was active in the Population II epoch, either low-energy cosmic rays in the early Galaxy or an alternative, non–cosmic-ray process. The former might be suggested by the data of Bloemen et al. (1994), while the latter has a promising candidate in the ν-process. These two alternatives should be distinguishable by getting more B/Be ratios, particularly in extremely metal-deficient ([Fe/H] $\lesssim 3$) stars, for which the ν-process should be dominant and hence the B/Be should be much larger than in HD 140283 (Olive et al. 1994).

The NLTE reanalysis of the boron abundance also underscores the difficulty of Population I Be and B abundance measurements. Clearly there is a need for continued scrutiny of these abundances, as well as for further data in more stellar environments, some presumably not having the same NLTE effects and so amenable to a test of the possibility of high B/Be.

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REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Bloemen, H., et al. 1994, A&A, 281, L5
Boesgaard, A. M., & King, J. 1993, AJ, 106, 2309
Brown, L. E., Dearborn, D. S., Schramm, D. N., Larsen, J. T., & Kurokawa, S. 1991, ApJ, 371, 648
Brown, L., & Schramm, D. N. 1988, ApJ, 329, L103
Cameron, A. G. W. 1982, in Essays in Nuclear Astrophysics, ed. C. A. Barnes, D.D. Clayton, & D. N. Schramm (Cambridge: Cambridge Univ. Press), 23
Cassé, M., Lehoucq, R., & Vangioni-Flam, E. 1994, preprint
Dearborn, D. S. P., Schramm, D. N., Steigman, G., & Truran, J. 1989, ApJ, 347, 455
Deliyannis, C. P., Demarque, P., & Kawaler, S. D., Krauss, L. M., & Romanelli, P. 1989, Phys. Rev. Lett., 62, 1583
Duncan, D. K., Lambert, D. L., & Lemke, M. 1992, ApJ, 401, 58 (DLL)
Edvardsson, B., Gustafsson, B., Johansson, S. G., Kiselman, D., Lambert, D. L., Nissen, P. E., & Gilmore, G. 1994, A&A, in press

Fields, B. D., Olive, K. A., & Schramm, D. N. 1994, ApJ, 435, 185 (FOS)
Gilmore, G., Edvardsson, B., & Nissen, P. E. 1992a, AJ, 378, 17
Gilmore, G., Gustafsson, B., Edvardsson, B., & Nissen, P. E. 1992b, Nature, 357, 379
Hobbs, L., & Thorburn, J. 1994, ApJ, 428, L25
Kiselman, D. 1994, A&A, 286, 169
Malaney, R. A. 1992, ApJ, 398, L45
Meneguzzi, M., Audouze, J., & Reeves, H. 1971, A&A, 15, 337 (MAR)
Meneguzzi, M., & Reeves, H. 1975, A&A, 40, 110
Molaro, P., Castelli, F., & Pasquini, L. 1993, Origin and Evolution of the Light Elements, ed. N. Prantzos, E. Vangioni-Flam, & M. Cassé (Cambridge: Cambridge Univ. Press), 153
Olive, K. A., Prantzos, N., Scully, S., & Vangioni-Flam, E. 1994, ApJ, 424, 666
Olive, K. A., & Schramm, D. N. 1993, Nature, 360, 439
Prantzos, N., Cassé, M., & Vangioni-Flam, E. 1993, ApJ, 403, 630 (PCV)
Rebolo, R., Molaro, P., Abia, C., & Beckman, J. E. 1988, A&A, 193, 193
Reeves, H. 1994, talk presented at the ESO/EIPC Workshop on the Light Element Abundances
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
Ryan, S., Bessel, M., Sutherland, R., & Norris, J. 1990, ApJ, 348, L57
Ryan, S., Norris, J., Bessel, M., & Deliyannis, C. 1992, ApJ, 388, 184
Smith, V. V., Lambert, D. L., & Nissen, P. E. 1992, ApJ, 408, 262
Steigman, G., Fields, B. D., Olive, K. A., Schramm, D. N., & Walker, T. P. 1993, ApJ, 415, L35 (SFOSW)
Steigman, G., & Walker, T. P. 1992, ApJ, 385, L13, (SW)
Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1995, in preparation
Walker, T. P., Mathews, G. J., & Viola, V. E. 1985, ApJ, 299, 745
Walker, T. P., Steigman, G., Schramm, D. N., Olive, K. A., & Fields, B. D. 1993, ApJ, 413, 562 (WSSOF)
Woosley, S. E., Hartmann, D. H., Hoffman, R. D., & Haxton, W. C. 1990, ApJ, 356, 272
Woosley, S. E., Timmes, F. X., & Weaver, T. A. 1993, in Nuclei in the Cosmos, ed. F. Käppeler & K. Wisshak (London: IOP)