

NEUTRINO PROCESS NUCLEOSYNTHESIS AND THE $^{11}\text{B}/^{10}\text{B}$ RATIOKEITH A. OLIVE,^{1,2} NIKOS PRANTZOS,^{2,3} SEAN SCULLY,¹ AND ELISABETH VANGIONI-FLAM²*Received 1993 June 4; accepted 1993 October 11*

ABSTRACT

We consider the evolution of the light elements (Li, Be, and B) incorporating the effects of their production by both neutrino process and cosmic-ray nucleosynthesis. We test the viability of the neutrino process to resolve the long standing problem of the $^{11}\text{B}/^{10}\text{B}$ isotopic ratio which amounts to 4 at the time of the formation of the solar system. This hypothesis may be ultimately constrained by the B/Be ratio observed in halo stars. Though we are able to obtain a solar isotopic ratio $^{11}\text{B}/^{10}\text{B} \simeq 4$, the current paucity of data at low metallicity prevents us from making a definitive conclusion regarding the resolution of this problem. We show, however, that neutrino process nucleosynthesis leads to a relatively model independent prediction that the B/Be elemental ratio is large (> 50) at low metallicities ($[\text{Fe}/\text{H}] < -3.0$), if Be is produced as a secondary element (as is the case in the conventional scenario of galactic cosmic-ray nucleosynthesis).

Subject headings: cosmic rays — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

One of the successes of the standard big bang model is the prediction of the primordial abundances of the light nuclei, D, ^3He , ^4He , and ^7Li . In the standard model, the abundances of these isotopes, which span 10 orders of magnitude (by number), are in accordance with observations for a narrow range in the baryon density or, equivalently, a baryon to photon ratio of $(2.8-4) \times 10^{-10}$ (Walker et al. 1991).

The other light nuclei, ^6Li , ^9Be , ^{10}B , and ^{11}B are thought to be produced in the interstellar medium by cosmic-ray spallation and fusion reactions of protons and alpha particles with C, N, O, and He nuclei. Their produced abundances in the standard big bang nucleosynthesis model is four to five orders of magnitude below the observations (Kajino & Boyd 1990; Thomas et al. 1993a). Production by cosmic rays can by and large account for the observed solar abundances of these elements (Reeves, Fowler, & Hoyle 1970; Meneguzzi, Audouze, & Reeves 1971). However, ^7Li is also partly produced by galactic cosmic-ray nucleosynthesis (GCRN), providing a potential constraint on big bang nucleosynthesis (Olive & Schramm 1992). Because ratios of the isotopes produced in GCRN are largely model independent, observations of the Be and B abundances can be an important test in determining what fraction of ^7Li observed in warm halo subdwarfs is primordial. Conventional GCRN models for the production of these elements which assume time-independent spectra and follow the metallicity of the interstellar medium (ISM) were able to explain the limited amount of data available at that time (i.e., for $[\text{Fe}/\text{H}] \geq -1.4$) (Vangioni-Flam et al. 1990). However, these simple models tend to underproduce Be and B at low metallicities. These elements have now recently been observed in low metallicity Population II stars (Rebolo et al. 1988; Ryan et al. 1990; Gilmore, Edvardsson & Nissen 1991; Ryan et al. 1992; Gilmore et al. 1992; Duncan, Lambert, & Lemke 1992; Rebolo

et al. 1993). More recent models which treat the early galaxy as a “closed” rather than a “leaky” box for GCR increase the predicted abundances of Be and B for low metallicities almost to observed levels (Prantzos, Cassé, & Vangioni-Flam 1993a, hereafter PCV).

It should be noted that inhomogeneities present in the early universe may alter the predictions of standard big bang nucleosynthesis (Applegate, Hogan, & Scherrer 1987; Alcock, Fuller, & Mathews 1987) and give rise to increased nucleosynthesis beyond $A = 8$ (Boyd & Kajino 1989; Malaney & Fowler 1989). However, it has been shown (Thomas et al. 1993b) that even under extreme conditions the abundances of ^6Li , Be, and B in inhomogeneous big bang nucleosynthesis remain two to three orders of magnitude below their observed values in halo dwarf stars. Furthermore, when the constraints from the light elements are applied, there is little distinction between standard and inhomogeneous model results for elements with $A < 12$ (Kurki-Suonio et al. 1990; Thomas et al. 1993b; Reeves 1993).

While the abundances of Li, Be, and B predicted by the improved models of galactic cosmic ray (GCR) production of PCV almost match observations, these models cannot solve the long-standing problem of the solar $^{11}\text{B}/^{10}\text{B}$ ratio. Most GCR models predict a ratio of around 2.5 (Meneguzzi, Audouze, & Reeves 1971; Meneguzzi & Reeves 1975; Walker, Mathews, & Viola 1985; Abia & Canal 1988; Steigman & Walker 1992; Walker et al. 1993). The observed ratio is found to be closer to 4 (Shima 1963; see also Cameron 1982; Anders & Grevesse 1989). Meneguzzi & Reeves (1975) suggest as a possible solution to this problem introducing a steeply decreasing spectral component at low energies (less than 80 MeV nucleon⁻¹) in GCR. At these energies, the cross sections of ^{10}B and ^{11}B are somewhat different, leading to a larger isotopic ratio. PCV point out, however, that $\alpha + \alpha \rightarrow ^{6,7}\text{Li}$ reactions were ignored in these studies. PCV find that steepening the GCR spectra of protons and alphas at low energies leads to a solar isotopic ratio of $^{11}\text{B}/^{10}\text{B} \sim 4$ but results in Li production considerably exceeding observed values in halo dwarfs.

PCV also explore a possible solution to this problem by assuming that the more fragile ^{10}B is completely destroyed when ejected by a star of any size, while all of the ^{11}B is allowed to survive. Most previous models assume that all of the Li, Be,

¹ School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455.

² Institut d'Astrophysique de Paris, 98 bis Boulevard Arago, 75014 Paris, France.

³ Service d'Astrophysique, Centre d'Etudes de Saclay, 91191 Gif sur Yvette, France.

and B is destroyed when ejected from stars. The maximum isotopic ratio under these conditions is 2.9. They conclude that this can not account for the observed isotopic ratio.

With the difficulty in producing the observed isotopic ratio of $^{11}\text{B}/^{10}\text{B}$, 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 alpha particles to produce ^{11}C which decays to ^{11}B . The primary goal of that work was to explore an alternative site for the production of ^7Li to reach Population I abundances. They noted however that significant ^{11}B production might also take place. To date, the ^{11}B produced by this process has not been included in chemical evolution models and an isotopic ratio of $^{11}\text{B}/^{10}\text{B}$ including production of ^{11}B by this process has not been determined.

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 core collapse of a massive star into a neutron star creates a flux of neutrinos so great that in spite of the small cross sections involved, it may still induce substantial nucleosynthesis. It is 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 . In addition, some synthesis of ^7Li and ^{10}B takes place by this process but the production rate seems quite low.

In this paper, we include production of ^{11}B , ^7Li , and ^{10}B predicted from neutrino nucleosynthesis in Type II supernova events (Woosley, Timmes, & Weaver 1993; Timmes, Woosley, & Weaver 1993) in galactic chemical evolution models along with GCR spallation production. We investigate the isotopic ratio of $^{11}\text{B}/^{10}\text{B}$ resulting from these models as well as the observational consequences of the increased abundances of B and Li. As we will show, although it is possible to obtain a $^{11}\text{B}/^{10}\text{B}$ isotopic ratio $\simeq 4$, the B/Be ratio is typically high, $\text{B}/\text{Be} \gtrsim 20$, and is only marginally consistent with present data for halo stars. Indeed, the primary source of ^{11}B predicts significantly higher B/Be ratio at low metallicity than in standard models of GCRN and can as such conclusively test this hypothesis.

The importance of the ν -process was previously considered by Malaney (1992) primarily with regard to the production of ^9Be , though a discussion of the effect on B and the B/Be ratio was included. Malaney claimed that ^9Be is produced via the $^7\text{Li}(t, n)^9\text{Be}$ reaction. This rate was included in the recent Timmes et al. (1993) calculations and no substantial amount of ^9Be was found to survive the supernova shock.

2. GALACTIC EVOLUTION FROM THE ν -PROCESS

Before integrating the ν -process yields into a full-blown model of galactic chemical evolution, we make the following, more simplified evaluation. Because we include a new source of B without any accompanying Be, we must be sensitive to the potential danger of an excessive B/Be ratio. In fact, this ratio has the possibility of strongly constraining the ν -process source for B. The Be abundance observed in halo dwarf stars shows an almost linear dependence with metallicity. The observed Be abundance can be fit approximately by

$$[\text{Be}] \equiv 12 + \log(\text{Be}/\text{H}) \simeq 1.7 \pm 0.4 + [\text{Fe}/\text{H}]. \quad (1)$$

Let us consider first the very simple model used in Steigman & Walker (1992) and Walker et al. (1993). There, it was assumed that the Population II abundances of C, N, and O in ISM were simply related to the iron abundance as $[\text{C}/\text{H}] = [\text{N}/\text{H}] = [\text{Fe}/\text{H}]$ and $[\text{O}/\text{Fe}] = 0.5$. Evolution of these elements was not included in the model. Furthermore, it was also assumed that all exposure times for GCRN processes were equal. The overall exposure time then can be fixed by fitting the Be observations. Because the B/Be ratio in this model is relatively fixed at $\text{B}/\text{Be} \sim 14$ (i.e., the ratio of the corresponding spallation cross sections), we can predict the B abundance as a function of $[\text{Fe}]$, $\log(\text{B}/\text{H}) \sim -9.2 + [\text{Fe}/\text{H}]$, which is in good agreement with the fit to the three observations of B when a linear relation is assumed,

$$[\text{B}] \equiv 12 + \log(\text{B}/\text{H}) \simeq 2.7 \pm 0.9 + [\text{Fe}/\text{H}]. \quad (2)$$

The basis for the additional source of ^{11}B are neutrino processes occurring during Type II super-novae. Neutrinos, including also ν_μ and ν_τ , are copiously produced in the hot collapsed core during a supernova (see e.g., Mayle, Wilson, & Schramm 1987). Because of their higher temperature, ν_μ and ν_τ neutral current reactions are dominant. The inelastic scattering of these 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 significant amounts of ^7Li and ^{11}B and lesser amounts of ^{10}B were produced (as well as other heavier isotopes).

An important aspect of the calculation of Woosley et al. (1990) is the full treatment of pre- and postshock nucleosynthesis. Since the duration of the neutrino burst exceeds the timescale for the passage of the shock through the inner layers of the exploding star, ν -process nucleosynthesis can continue after the passage of the shock. In the outer layers, however, the destruction of fragile isotopes is a significant effect and is, for example, responsible for the destruction of ^9Be . Given the nature of the calculation there is a fair amount of uncertainty regarding the yields obtained by this process. The main uncertainty comes from the poorly known neutrino spectrum; indeed, there are indications that the high energy part of it (the most efficient for nucleosynthesis) should be considerably suppressed (Myra & Burrows 1990). In this work, we include the recent results of Timmes et al. (1993) regarding the production of ^7Li , ^{10}B , and ^{11}B over a wide range of initial stellar masses. However, for the purposes of normalization to a solar $^{11}\text{B}/^{10}\text{B}$ ratio we take the liberty of adjusting the neutrino-process yields by an overall factor.

To estimate the effect of the ν -process on the boron isotopic ratio, we first separately integrate the ν -process yields over a simple initial mass function with slope parameter, $x = 1.8$, and a constant star-formation rate. We find, as expected, an approximately linear relationship for ^{11}B versus metallicity, $[\text{B}] = 2.55 + [\text{Fe}/\text{H}]$. When added to the GCRN component for boron, we find that the $^{11}\text{B}/^{10}\text{B}$ isotopic ratio is raised from the canonical GCRN value of ~ 2.5 to 4.5. Furthermore, the B/Be ratio is increased from 14 to $\simeq 22$. When compared with the available data: $[\text{B}] = 0.4 \pm 0.2$ (HD 19445); $= -0.1 \pm 0.2$ (HD 140283); and $= 1.7 \pm 0.4$ (HD 201891) from Duncan et al. (1992) and $[\text{Be}] < -0.3$ (HD 19945) from Ryan et al. (1990); $[\text{Be}] = -1.25 \pm 0.4$ (HD 140283) from Ryan et al. (1992); $= -0.97 \pm 0.25$ (HD 140283) from Gilmore et al. (1992); and $= 0.4 \pm 0.4$ (HD 201891) from Rebolo et al. (1988). Thus the B/Be ratio becomes (propagating the quoted errors): B/

$\text{Be} = 20 \pm 26$ (HD 201891); $\text{B}/\text{Be} = 14 \pm 14$ (HD 140283) based on the beryllium measurement of Ryan et al. (1992) and $\text{B}/\text{Be} = 7 \pm 5$ (HD 140283) based on the measurements of Gilmore et al. (1992); and $\text{B}/\text{Be} > 5$ (HD 19445),⁴ one sees that although the agreement with the data is worsened when the ν -process yield is included, this explanation of the boron isotopic ratio can by no means be excluded.

Notice that in this section we assume a GCR origin for Be, ^{10}B and (part of) ^{11}B , but we adopt the observed B versus Fe and Be versus Fe relationships which are almost linear. It is well known however, that such linearity characterizes the evolution of a primary element (like oxygen), whereas in conventional GCR models B and Be behave as secondaries (see Prantzos et al. 1993b). This discrepancy between theory and the observations is somewhat alleviated, but not completely removed, in PCV, where a more efficient production of B and Be in the early Galaxy is suggested (see next section). Obviously, if the ν -process B is incorporated in such a model, the resulting B/Be ratio at low metallicity is expected to be even larger than previously estimated. In the next section we investigate this effect with a fully developed model of galactic chemical evolution.

3. LiBeB PRODUCTION BY NEUTRINOS AND COSMIC RAYS

We start with a brief description of the PCV model, where an important correction has been incorporated. It is currently thought that GCR are accelerated mainly by supernovae shock waves and propagate in the Galaxy by diffusing on the irregularities of the galactic magnetic field and suffering losses by ionization, nuclear reactions and leakage, in the framework of the “leaky box” model (e.g., Cesarsky 1980). Notice that in this model, leakage takes place perpendicularly to the galactic disk, which has today a confinement volume with thickness $H_0 \sim 0.5$ kpc and a gas fraction $\sigma_{\text{gas},0} \sim 0.10\text{--}0.20$ (Rana 1991). The corresponding *escape length* (a key parameter characterizing the leaky box model and indicating the amount of matter that GCR “traverse” before being lost) is estimated to be $\Lambda_{e,0} \sim 10$ g cm^{-2} , at least up to 3–4 GeV n^{-1} .

In order to explain the recent B and Be observations in halo stars, PCV suggest that during its early evolution the Galaxy was a “closed” rather than a “leaky” box to GCR. According to the PCV analysis, the escape length evolves as $\Lambda_e \propto \sigma_{\text{gas}} H$, i.e., it was much larger in the past due to the larger gas content and the larger dimensions of the young Milky Way. The corresponding GCR spectrum is found to be flatter than the current one, and the associated proton flux above ~ 100 MeV is found to evolve roughly as $F \propto \sqrt{\Lambda_e}$. Using a simplified prescription for the early collapse phase of the Galaxy and a detailed chemical evolution model, the recent Be and B observations are well reproduced with this hypothesis on GCR propagation. Notice, however, that the obtained B versus Fe and Be versus Fe relationships are still nonlinear, i.e., B and Be are clearly produced as secondary elements in that model.

Since that work, Malaney & Butler (1993) noticed that the loss of protons due to π^0 production has been neglected in PCV. This term is insignificant today. Indeed, the *nuclear destruction length* for protons is $\Lambda_N \sim 200$ g cm^{-2} and does not affect the total loss length $\Lambda^{-1} = \Lambda_N^{-1} + \Lambda_e^{-1} \sim \Lambda_e^{-1}$. However, this factor might have been important in the earliest phases of the Galaxy, if GCRs were as efficiently confined as

⁴ To date, only an upper limit for Be is available for this star (Ryan et al. 1990).

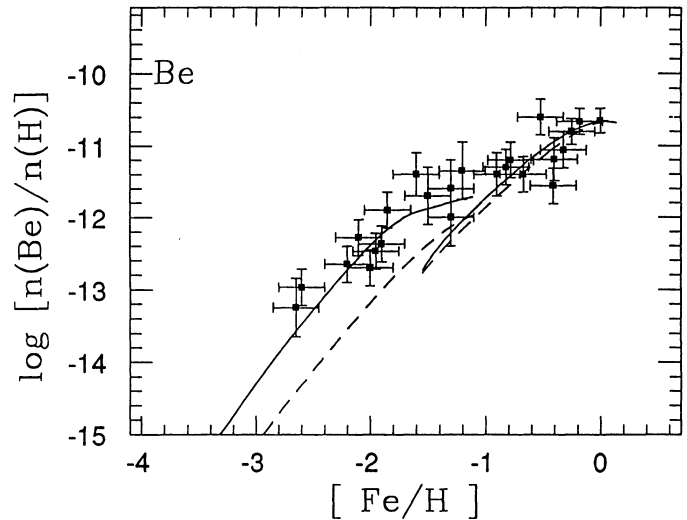


FIG. 1.—Be abundance as a function of $[\text{Fe}/\text{H}]$ with (solid line) and without (dotted line) ν -process nucleosynthesis included. The two curves coincide since ^9Be is not produced by the ν -process. Also shown is the Be abundance in an unenhanced GCRN model (dashed line). The theoretical curves are compared to available data. (See text for references on observational data.)

suggested in PCV. In this work we incorporate the nuclear destruction term in our model. As a result we obtain GCR fluxes lower by a factor of ~ 2 with respect to the previous work at large Λ values (see Fig. 1 in Prantzos & Cassé 1993). In the framework of the galactic evolution model this concerns quite a short period (a few 10^7 yr), in the very beginning of the Galaxy. The resulting Be and B abundances are slightly affected, but still consistent with the observations, as can be seen in Figures 1 and 2. Notice also that the nuclear destruction term is much more important for alpha particles, which have a corresponding length of $\Lambda_N \sim 25$ g cm^{-2} only. For that reason, GCR alphas never develop spectra as flat as GCR protons, even in the case of a good confinement: they are simply “removed” by collisions with the ISM protons for values of $\Lambda \geq 25$ g cm^{-2} . In this modified scenario (i.e., maintaining the efficient GCR confinement in the early Galaxy but

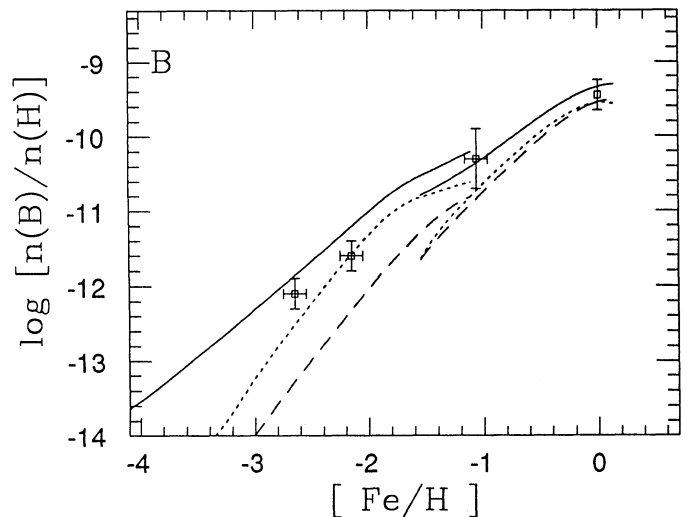


FIG. 2.—B abundance as in Fig. 1

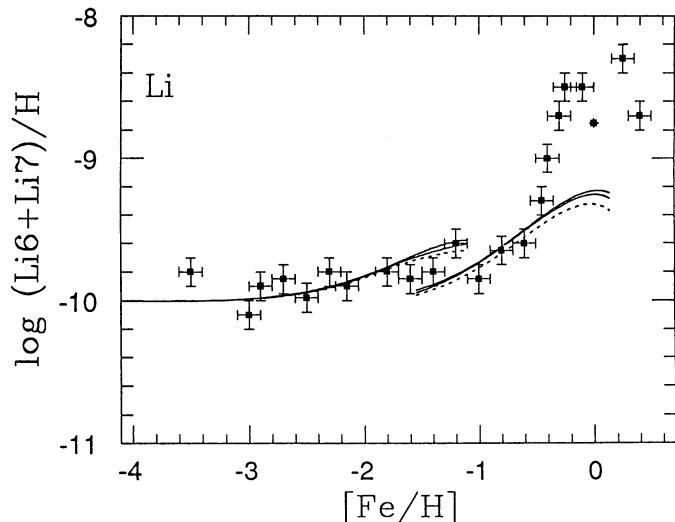


FIG. 3.—Li abundance as in Fig. 1. Data are from Spite & Spite (1991). Only the upper envelope of the data is shown.

incorporating the nuclear destruction term) the early Li abundance is maintained low and consistent with observations (see Fig. 3). The reason, however, is not the flattening of the GCR alpha spectra (as in the original PCV), but the nuclear destruction of alphas at large Λ .

Given the reasonable success of the modified PCV model at explaining the low metallicity observations of Be and B, we now include new isotopic yields of Woosley et al. (1993) and Timmes et al. (1993) of ν -process produced ^7Li , ^{10}B , and ^{11}B . Our goal is to explain the $^{11}\text{B}/^{10}\text{B}$ ratio which is observed to be ~ 4 in the solar system. The PCV model, like almost all models of GCRN, gives a ratio of about 2.5. The additional source of ^{11}B from the ν -process increases this ratio. We have adjusted the overall ν -process yield to give a solar system $^{11}\text{B}/^{10}\text{B}$ ratio of 4. To do so, we found that it was necessary to reduce the neutrino induced yields by a factor ~ 2 to avoid overproducing ^{11}B . A summary of our results is displayed in Table 1. The resulting $^{11}\text{B}/^{10}\text{B}$ ratio as a function of metallicity is shown in Figure 4. This result can be compared directly to the case without a ν -process contribution (*dotted line*) and to the case without an enhanced cosmic-ray spectrum (*dashed line*). As one can see, enhancing the cosmic-ray spectrum has little effect on the $^{11}\text{B}/^{10}\text{B}$ ratio. The large discontinuity is solely due to our treatment of the two (halo and disk) separate components of the galaxy (see PCV for details of the model). A one-zone model and presumably a more comprehensive treat-

TABLE 1

COMPARISON BETWEEN OBSERVED VALUES AT THE BIRTH OF THE SOLAR SYSTEM AT $t = 12.5$ Gyr AND THE MODEL

Parameter	Observed Data	Model Result
$X_{\text{H}}/X_{\text{H}\odot}$	1	1.03
Y/Y_{\odot}	1	0.92
$X_{\text{Be}}/X_{\text{Be}\odot}$	1	1 (Normalization)
$X_{\text{B}}/X_{\text{B}\odot}$	1	1.08
$^{11}\text{B}/^{10}\text{B}$	4.05 ± 0.1	4.11 (ν -Process yield adjusted)
$[\text{O}/\text{H}]$	0	0.13
$[\text{Fe}/\text{H}]$	0	0.011
Z/Z_{\odot}	1	0.94
σ (present value)	0.10–0.20	0.19

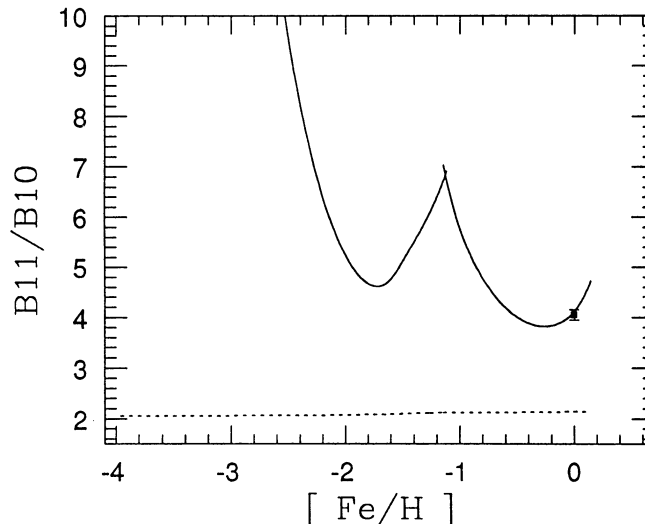


FIG. 4.— $^{11}\text{B}/^{10}\text{B}$ ratio as in Fig. 1

ment of the two zones (including infall in the disk) would show a smoother relationship.

With the $^{11}\text{B}/^{10}\text{B}$ ratio fixed, we can now examine the compatibility of the model with the data on Li, Be, and B. In Figures 1–3, we show the evolution of the LiBeB isotopes as a function of $[\text{Fe}/\text{H}]$. In each of these figures, we compare the abundance of the LiBeB element with (*solid line*) and without (*dotted line*) ν -process nucleosynthesis and without an enhanced cosmic-ray spectrum (*dashed line*). The solar values for B and Be are the same as those adopted in PCV. They are somewhat smaller than the values given by Anders & Grevesse (1989) and are closer to the values adopted in Reeves & Meyer (1978) and Arnould & Forestini (1989). In Figure 1, we show the beryllium abundance as a function of $[\text{Fe}/\text{H}]$. As discussed above, the beryllium is slightly lower than the results of PCV due to the correction in the escape length noticed by Malaney & Butler (1993) but is nevertheless still in acceptable agreement with the data. The ν -process makes very little contribution to Be/H. As shown in Figure 2, the model appears acceptable with respect to the evolution of the boron abundance both with and without the ν -process contribution. For both beryllium and boron, the benefit of the enhanced cosmic-ray spectrum is clear. Finally we see that the lithium abundance shown in Figure 3 is also quite compatible with the data. Here, we have taken a primordial abundance $[\text{Li}] \approx 2.0$ (Olive & Schramm 1992) and have included both the GCRN and ν -process contributions, neither of which is excessive at low metallicities. Notice that since no stellar source of Li is included in the model, the predictions for the disk ($-1 < [\text{Fe}/\text{H}] < 0$) are lower than the observations.

Despite the apparent success regarding the observed abundances of the LiBeB elements, the B/Be ratio is more difficult to reproduce. In Figure 5, we show the B/Be ratio as a function of $[\text{Fe}/\text{H}]$. Though at $[\text{Fe}/\text{H}] \approx -1$ to -2 , the ratio is only slightly higher than standard GCRN predictions and consistent with the data for HD 201891, at lower $[\text{Fe}/\text{H}] < -2$ there is a clear departure from more standard model results. The B/Be becomes very large ($\text{B}/\text{Be} > 50$), for $[\text{Fe}/\text{H}] \lesssim -3$. This is clearly due to the primary nature of ^{11}B produced mostly by the ν -process in the halo versus the secondary nature of Be, produced only by GCRN. As it stands, the model is only mar-

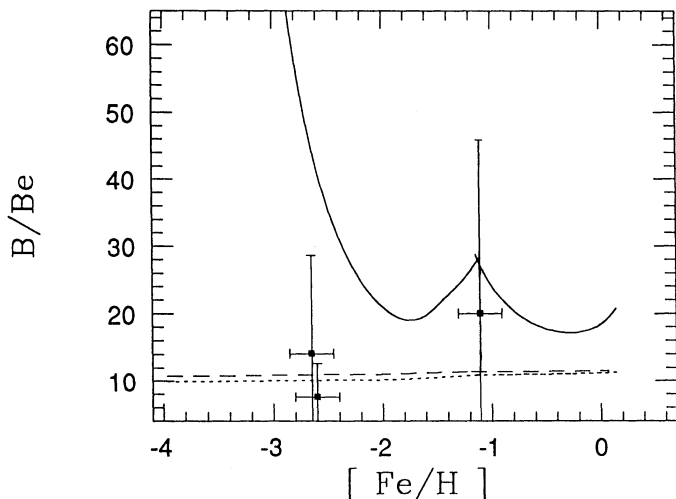


FIG. 5.—B/Be ratio as in Fig. 1

ginally consistent with the data for HD 140283 (at the 2σ level). With regard to HD 140283, we note the following: 1) a recent observation (Molaro, Castello, & Pasquini 1993) has failed to identify beryllium in this star using a potentially more reliable part of the line spectrum and indicate that a lower value for Be/H and hence higher value for B/Be is likely; 2) the oxygen abundance in this star seems perhaps anomalously high. Several measurements indicate a value $[O/Fe] \sim 0.8-0.9$ (Bessel & Norris 1987; Molaro et al. 1993). Such a large oxygen enhancement may also be accompanied by a beryllium enhancement due to cosmic-ray spallation (the boron enhancement would be masked by the ν -process contribution). Thus this star seems particularly incapable of excluding the high value for B/Be we would expect at $[Fe/H] \sim -2.6$ due to the ν -process enhancement of ^{11}B . Future measurements of B and

Be at low metallicity have the clear potential at confirming or rejecting the ν -process contribution as a solution to the $^{11}\text{B}/^{10}\text{B}$ isotopic ratio.

4. CONCLUSION

In summary, we have tested the hypothesis that a primary source of ^{11}B due to ν -process nucleosynthesis in Type II supernovae can explain the observed solar $^{11}\text{B}/^{10}\text{B}$ isotopic ratio. We note at this point that the observed value $^{11}\text{B}/^{10}\text{B} \approx 4$ is due to a relatively old measurement (Shima 1963). Given the attention paid to this number, a new measurement of this ratio is certainly warranted. Though we are able to produce the observed isotopic ratio of 4 as well as a reasonable evolution for the LiBeB elements, we expect a significantly higher B/Be ratio than in more standard models of cosmic-ray nucleosynthesis and galactic chemical evolution. Due to the primary nature of the neutrino-process source for ^{11}B relative to the secondary source for Be, we have found that the ratio $B/Be > 50$ when $[Fe/H] < -3$. Indeed, we think that measurements of the B/Be ratio in halo stars can help clarify the importance of neutrino-process nucleosynthesis (and ultimately confirm or invalidate it).

We would like to thank Frank Timmes and Stan Woosley for generously sharing their most recent results of supernova nucleosynthesis. We would also like to thank Jean Audouze, Michel Cassé, and David Schramm for useful discussions. K. A. O. would like to thank the Institute d'Astrophysique de Paris, where this work was completed, for their hospitality. The work of K. A. O. and S. S. was supported in part by DOE grant DE-AC02-83ER-40105. The work of K. A. O. was, in addition, supported by a Presidential Young Investigator Award. The work of N. P. and E. V.-F. was supported in part by PICS 114, "Origin and Evolution of the Light Elements," CNRS.

REFERENCES

- Abia, C., & Canal, R. 1988, *A&A*, 189, 55
 Alcock, C., Fuller, G. M., & Mathews, G. J. 1987, *ApJ*, 320, 439
 Anders, E., & Grevesse, N. 1989, *Geochim. Cosmochim. Acta*, 53, 197
 Applegate, J. H., Hogan, C. J., & Scherrer, R. 1987, *Phys. Rev. D*, 35, 1151
 Arnould, M., & Forestini, M. 1989, *Nuclear Astrophysics*, ed. M. Lozano et al. (Berlin: Springer), 48
 Bessel, M. S., & Norris, J. E. 1987, *J. Astrophys. & Astron.*, 8, 199
 Boyd, R. N., & Kajino, T. 1989, *ApJ*, 336, L55
 Cameron, A. G. W. 1982, in *Essays in Nuclear Astrophysics*, ed. C. Barnes, D. Clayton, & D. Schramm (Cambridge: Cambridge Univ. Press), 35
 Cesarsky, C. 1980, *ARA&A*, 18, 289
 Dearborn, D. S. P., Schramm, D., Steigman, G., & Truran, J. 1989, *ApJ*, 347, 455
 Duncan, D. K., Lambert, D. L., & Lemke, M. 1992, *ApJ*, submitted
 Gilmore, G., Edvardsson, B., & Nissen, P. E. 1991, *ApJ*, 378, 17
 Gilmore, G., Gustafsson, B., Edvardsson, B., & Nissen, P. E. 1992, *Nature*, 357, 379
 Kajino, T., & Boyd, R. N. 1990, *ApJ*, 259, 267
 Kurki-Suonio, H., Matzner, R. A., Olive, K. A., & Schramm, D. N. 1990, *ApJ*, 353, 406
 Malaney, R. A. 1992, *ApJ*, 398, L45
 Malaney, R. A., & Butler, M. N. 1993, *ApJ*, 407, L73
 Malaney, R. A., & Fowler, W. A. 1989, *ApJ*, 345, L5
 Mayle, R. W., Wilson, J. R., & Schramm, D. N. 1987, *ApJ*, 318, 288
 Meneguzzi, M., Audouze, J., & Reeves, H. 1971, *A&A*, 15, 337
 Meneguzzi, M., & Reeves, H. 1975, *A&A*, 40, 110
 Molaro, P., Castelli, F., & Pasquini, L. 1993, in *Origin and Evolution of the Light Elements*, ed. N. Prantzos, E. Vangioni-Flam, & M. Cassé (Cambridge: Cambridge Univ. Press), 153
 Myra, E., & Burrows, A. 1990, *ApJ*, 364, 222
 Olive, K. A., & Schramm, D. N. 1992, *Nature*, 360, 439
 Prantzos, N., & Cassé, M. 1993, *ApJ*, submitted
 Prantzos, N., Cassé, M., & Vangioni-Flam, E. 1993a, *ApJ*, 403, 630 (PCV)
 ———. 1993b, in *Origin and Evolution of the Light Elements* ed. N. Prantzos, E. Vangioni-Flam, & M. Cassé (Cambridge: Cambridge Univ. Press), 156
 Rana, N. 1991, *ARA&A*, 29, 129
 Rebolo, R., Garcia Lopez, R. J., Martin, E. L., Beckman, J. E., McKeith, C. D., Webb, J. K., & Pavlenko, Y. V. 1993, in *Origin and Evolution of the Light Elements*, ed. N. Prantzos, E. Vangioni-Flam, & M. Cassé (Cambridge: Cambridge Univ. Press), 149
 Rebolo, R., Molaro, P., Abia, C., & Beckman, J. E. 1988, *A&A*, 193, 193
 Reeves, H. 1993, in *Origin and Evolution of the Light Elements*, ed. N. Prantzos, E. Vangioni-Flam, & M. Cassé (Cambridge: Cambridge Univ. Press), 168
 Reeves, H., Fowler, W. A., & Hoyle, F. 1970, *Nature*, 226, 727
 Reeves, H., & Meyer, J. P. 1978, *ApJ*, 226, 613
 Ryan, S., Bessel, M., Sutherland, R., & Norris, J. 1990, *ApJ*, 348, L57
 Ryan, S., Norris, J., Bessel, M., & Deliyannis, C. 1992, *ApJ*, 388, 184
 Shima, M. 1963, *Geochim. Cosmochim. Acta*, 27, 911
 Spite, F., & Spite, M. 1991, *A&A*, 252, 689
 Steigman, G., & Walker, T. P. 1992, *ApJ*, 385, L13
 Thomas, D., Schramm, D. N., Olive, K. A., & Fields, B. D. 1993a, *ApJ*, 406, 569
 Thomas, D., Schramm, D. N., Olive, K. A., Meyer, B., Mathews, G. J., & Fields, B. D. 1993b, *ApJ* (submitted)
 Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1993, *ApJ*, in preparation
 Vangioni-Flam, E., Cassé, M., Audouze, J., & Oberto, Y. 1990, *ApJ*, 364, 568
 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. 1993, *ApJ*, 413, 562
 Walker, T. P., Steigman, G., Schramm, D. N., Olive, K. A., & Kang, H. 1991, *ApJ*, 376, 51
 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: Institute of Physics Publishing), in press