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THE BORON-TO-BERYLLIUM RATIO IN HALO STARS: A SIGNATURE OF COSMIC-RAY NUCLEOSYNTHESIS IN THE EARLY GALAXY

T. P. Walker,[1] G. Steigman,[1,2] D. N. Schramm,[3] K. A. Olive,[4] and B. Fields[3]

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ABSTRACT

We discuss Galactic cosmic-ray (GCR) spallation production of Li, Be, and B in the early Galaxy with particular attention to the uncertainties in the predictions of this model. The observed correlation between the Be abundance and the metallicity in metal-poor Population II stars *requires* that Be was synthesized in the early Galaxy. We show that the observations and such Population II GCR synthesis of Be are quantitatively consistent with the big bang nucleosynthesis production of ^{7}Li. We find that there is a nearly model independent lower bound to B/Be of ~ 7 for GCR synthesis. Recent measurements of B/Be ~ 10 in HD 140283 are in excellent agreement with the predictions of Population II GCR nucleosynthesis. Measurements of the boron abundance in additional metal-poor halo stars is a key diagnostic of the GCR spallation mechanism. We also show that Population II GCR synthesis can produce amounts of ^{6}Li which may be observed in the hottest halo stars.

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

1. INTRODUCTION

The lithium abundances observed in metal-poor ([Fe/H] $\lesssim -1.3$)[5] halo stars with $T_{\rm eff} \gtrsim 5500$ K, $({\rm Li/H})_{\rm OBS} = (1.2 \pm 0.2) \times 10^{-10}$ (Spite & Spite 1982, 1986; Hobbs & Duncan 1987; Rebolo, Molaro, & Beckman 1988), are in excellent agreement with the prediction of standard big bang nucleosynthesis (BBN): $1.0 \leq 10^{10}({\rm Li/H})_{\rm BBN} \leq 2.0$ (Walker et al. 1991). The lack of any significant correlation of the observed Population II lithium with surface temperature or metallicity indicates the lack of substantial production or destruction of lithium in the early Galaxy or in the earliest stars (assuming the lack of a conspiracy wherein lithium depletion is masked by production so as to produce a plateau). Indeed, standard models of depletion (Deliyannis et al. 1989, hereafter DDKKR) suggest no more than 0.1 dex decrease from the pre-stellar ^{7}Li to the ^{7}Li observed in metal-poor halo stars.[6]

Until recently, the absence of beryllium and/or boron in these stars was taken as evidence that the Galactic cosmic-ray (GCR) nucleosynthesis contribution to their observed lithium was negligible. Cosmic rays incident on the ambient ISM can produce Li, Be, and B and in fact these reactions are believed responsible for the observed Population abundances of ^{6}Li, ^{9}Be, and ^{11}B (Reeves, Fowler, & Hoyle 1970; Meneguzzi, Audouze, & Reeves 1971, hereafter MAR; Mitler 1972; Reeves 1974; Walker, Mathews, & Viola 1985, hereafter WMV). Recent observations of (and bounds to) Be in halo stars at the level of Be/H $\sim 10^{-13}$–10^{-12} (Rebolo et al. 1988, hereafter RMAB; Ryan et al. 1990; Gilmore, Edvardson, & Nissen 1991, hereafter GEN; Ryan et al. 1991, hereafter RNBD) led two of us to consider the production of Li, Be, and B by GCR nucleosynthesis in a Population II environment (Steigman & Walker 1992, hereafter SW). SW showed that cosmic-ray nucleosynthesis on a Population II interstellar medium could produce significant amounts of Li (via $\alpha + \alpha$ fusion reactions which are insensitive to variations in the metallicity of the early Galaxy) while at the same time reproducing the Be observed in these stars. In addition, SW pointed out that the "smoking gun" of a GCR nucleosynthesis origin for Be in Population II halo stars is a potentially detectable abundance of boron. Since that time B has been observed in three halo stars (Duncan, Lambert, & Lemke 1992) at the level of $\sim 10^{-12}$–10^{-11}.

While the uniformity of the lithium abundances in sufficiently warm halo stars points to a non-Galactic (cosmological) origin for a substantial fraction of the observed lithium, the correlation of beryllium with metallicity in halo stars [Be increases with increasing metallicity (see Fig. 1)] *requires* that beryllium be made in the early Galaxy. Any primordial component must be lower than those abundances derived from current observations and would manifest itself as a plateau in the low-metallicity limit. At any rate, neither standard big bang nucleosynthesis [with Be/H $\sim 10^{-17}$ and B/H $\sim 10^{-17}$ (Sato 1967; Thomas et al. 1993)] nor inhomogeneous BBN can account for the amounts of Be and B which are currently observed in metal-poor halo stars.[7] Population II GCR syn-

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[1] Department of Physics, The Ohio State University, Columbus, OH 43210.

[2] Department of Astronomy, The Ohio State University, Columbus, OH 43210.

[3] University of Chicago, IL 60637, and NASA/Fermilab Astrophysics Group, FNAL, Batavia, IL 60510.

[4] School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455.

[5] We use the notation $10^{[A/H]} = y_A(\text{Population II})/y_A(\text{Population I})$ and $[A] = 12 + \log y_A$, where y_A is the abundance by number of the nuclide of mass number A relative to hydrogen.

[6] There has been the suggestion that models of stellar evolution which include rotational mixing predict much larger ^{7}Li depletion (Pinsonneault et al. 1992) than the standard models of DDKKR. In any model of stellar evolution, the depletion of ^{6}Li is always greater than the depletion of ^{7}Li due to its weak binding. The observations of Smith, Lambert, & Nissen (1992) of ^{6}Li in HD 84937 (see the discussion in § 3), made after we first submitted this paper, would seem to pose a test to the substantial Li depletion predicted by the rotational mixing model. We believe it is reasonable to adopt the standard depletion model predictions as representative of the average ^{7}Li depletion along the Spite plateau and remind the reader that models do exist which predict more depletion.

[7] Teresawa & Sato (1990) have emphasized that the ultra-neutron rich environments required to significantly alter the Be and B abundances from their standard BBN values are diluted in inhomogeneous models of sufficient zone resolution. To our knowledge, there are no multizone calculations of inhomogeneous BBN production of Be and B for the parameters consistent with the primordial abundances of D, ^{3}He, ^{4}He, and ^{7}Li as inferred from observation (e.g., see Walker et al. 1991). Preliminary results by Thomas et al. (1993) show that inhomogeneous models which fit the primordial D, ^{3}He, ^{4}He, and ^{7}Li cannot simultaneously produce significant Be and B.

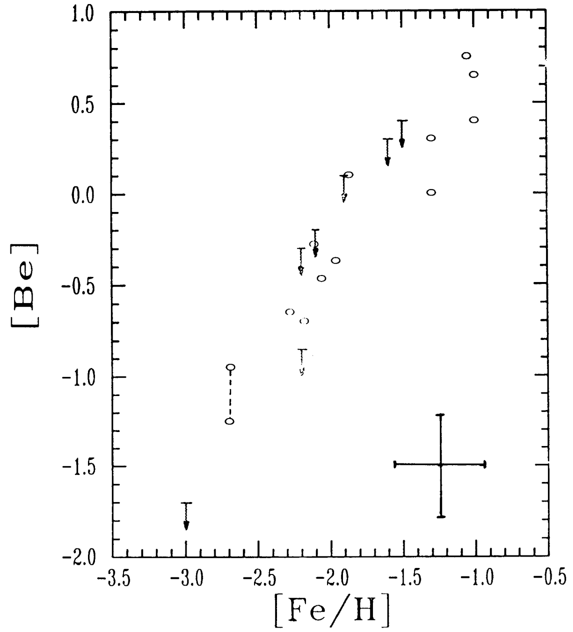

FIG. 1.—Observations of and bounds to beryllium in halo stars as a function of [Fe/H]. Arrows indicate upper limits. The cross hair represents typical error bars as quoted by the beryllium observers. The [Fe/H] values are from the beryllium observations. The two points connected with a dotted line are the observations of HD 140283 cooresponding to RNBD and the average of GEN and GGEN. We also plot the average of the two GGEN measurements of HD 160617 (see Table 1 for further details).

thesis is an unavoidable candidate since there are cosmic rays and some CNO nuclei in the early Galaxy. The rapid increase in the amount of Population II Be and B data led to several detailed chemical evolution models of the early Galaxy (RNBD; Prantzos et al. 1993) which have included the GCR nucleosynthesis model of Steigman and Walker as a component and manage to reproduce not only the Be and B observations, but other features of the early Galaxy as well. With this in mind, this paper investigates testable consequences of Population II GCR nucleosynthesis that are as independent as possible of the details of the evolution of the early Galaxy. This requires, in particular, an examination of the uncertainties in the predicted abundances of Li, Be, and B in a Population II GCR model. We look at acceptable variations in the input physics as well as the relation between the observed stellar abundances of Population II Li, Be, and B and the early Galaxy abundances of these nuclei. In order to eliminate as much of the model dependence as possible, we examine the ratios of Li, Be, and B. We believe our approach leads to values of the ratios of Li, Be, and B which bracket all possible chemical evolution models. Our analysis is broken into several steps: § 2 reviews the model for Population II GCR nucleosynthesis and discusses the different time histories of CNO abundances in the early Galaxy and the destruction of ^{6}Li in halo stars; § 3 summarizes the observational data on Population II stars that have been examined for Be and compares with the predictions of Population II GCR nucleosynthesis; § 4 discusses effects due to acceptable variations in the relative abundance of oxygen in the early Galaxy; § 5 examines the compatibility of standard BBN and Population GCR nucleosynthesis; § 6 discusses possible variations in the cosmic-ray flux and a lower bound to B/Be from any GCR nucleosynthesis model. The correlation of Be and B abundances with metallicity in the early Galaxy is evidence for a Galactic (as opposed to primordial) production mechanism. If the Galactic production mechanism is GCR nucleosynthesis, our conclusions are the following:

1. the lithium observed in Population II halo stars is consistent with standard BBN, and
2. the predicted boron-to-beryllium ratio is always greater than seven and, for any model of Population II GCR synthesis, is confined to the range

$$7 \lesssim \left(\frac{^{10+11}\mathrm{B}}{^{9}\mathrm{Be}}\right) \lesssim 17 .$$

In addition, we point out that the ^{6}Li generated by GCR synthesis is on the verge of detectability in some of the hotter halo stars.

2. CORRECTIONS TO THE ZEROTH-ORDER MODEL WITH FIXED POPULATION II ABUNDANCES

The production rate of a nuclide of mass number A in a medium characterized by cosmic ray fluxes $\phi_i(E, t)$ and ISM densities $N_j(t)$ is (MAR; WMV; SW)

$$\frac{dN_A}{dt} = \sum_{\mathrm{ISM,CR}} N_j(t) \int_{E_T}^{\infty} \phi_i(E, t)\sigma_{ij}^A(E) S_A(E, t)dE . \quad (1)$$

Here the ISM (i) and CR (j) sums are over protons, alphas, and CNO nuclei,[8] the cross sections σ_{ij}^A (Read & Viola 1984) are integrated over the energy per nucleon E from the threshold energy E_T, and we include a dimensionless stopping factor $S_A(E, t)$ which accounts for energy losses in the ISM [hereafter we assume that $S_A(E, t) \approx S_A(E, t_0)$ where t_0 marks the present epoch]. The time dependences of the quantities in the rate equation make any prediction model-dependent. In order to eliminate some of the model dependence, we follow SW and make the following assumptions about the cosmic-ray flux:

1. The shape of the differential cosmic-ray flux remains the same while the overall normalization of the flux can vary. That is, the time evolution of the cosmic-ray flux can be written $\phi(E, t) = f(t)\phi(E, t_0)$ and $\phi(E, t_0) \propto (E + m_p)^{-2.6}$ (the constant of proportionality for cosmic-ray protons[9] is 12.5 cm^{-2} s^{-1} GeV^{-1}). In § 6 we will explore the consequences of relaxing these assumptions about the evolution of the cosmic-ray spectrum.
2. The relative GCR abundances are the same as the relative ISM abundances. If the ISM abundances relative to hydrogen are expressed as $y_i \equiv N_i/N_{\mathrm{H}}$, then this assumption allows us to write $\phi_i(E, t) = [y_i(t)\phi_p(E, t_0)]f(t)$.

With these assumptions we can integrate equation (1) to obtain the relative abundance of nuclide A at any time t_*:

$$y_A(t_*) = \sum_{i,j} R_{ij}^A(t_*)\Delta t_{ij}(t_*) , \quad (2)$$

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[8] This production rate includes the contribution of cosmic-ray CNO on interstellar protons and alphas as well as the production by cosmic-ray protons and alphas on interstellar CNO nuclei. The cosmic-ray CNO component is typically 20% of the total rate.

[9] Since, in most cases, we will restrict ourselves to calculations of ratios of GCR abundances, the overall normalization of the CR spectrum is not relevant. However, in the case of absolute abundances, this normalization is crucial. As an illustrative example we take the Population I cosmic-ray measurement of Jokipii (1979). This number is uncertain by at least a factor of 2 (see, for example, the measurements of Simpson 1982). We comment later on the effects of uncertainties in the cosmic-ray flux.

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where the average production rates are

$$R^{A}_{ij}(t_*) = y_i(t_*)y_j(t_*)\int_{ET} \phi_p(E, t_0)\sigma^{A}_{ij}S_A\, dE\ , \tag{3}$$

and,

$$\Delta t_{ij}(t_*) = \int_0^{t_*} \frac{y_i(t)}{y_i(t_*)}\frac{N_j(t)}{N_j(t_*)} f(t)dt\ . \tag{4}$$

Even with the above assumptions about the cosmic-ray flux and the abundances there remain seven model dependent parameters: Δt_{ij}, where i and j take on all relevant combinations of p, α, and CNO. These seven parameters can be reduced to three with the following assumptions:

1. The abundance of ^{4}He changes little during the early Galaxy and so we can treat it as constant on Population II time scales.
2. The abundances of C and N in the Population II CR and ISM are consistent with those observed in halo stars [C/H] = [N/H] = [Fe/H] (Wheeler, Sneden, & Truran 1989).

The remaining three independent Δt_{ij} (e.g., p–C, p–O, and $\alpha - \alpha$) may be reduced to two by assuming a relationship between Population II oxygen and carbon abundances. SW used the observed relationship for metal-poor ([Fe/H] ≤ -1) halo stars (Barbuy & Erdelyi-Mendes 1989; Sneden, Lambert, & Whitaker 1979): [O/Fe] ≈ 0.5.

We can further minimize the uncertainties by examining the ratios of yields rather than the absolute yields. In particular, the B/Be ratio is the least dependent on the Δt_{ij} since it involves production via CNO interactions only. Since Li can be produced via $\alpha + \alpha$ reactions the predictions for the ratio of Li to Be or B are more model dependent. At any given time t_* the abundance ratios are given by the ratios of the production rates

$$\left(\frac{\mathrm{B}}{\mathrm{Be}}\right)_* = \frac{\sum_{ij} R^{\mathrm{B}}_{ij}(t_*)}{\sum_{ij} R^{\mathrm{Be}}_{ij}(t_*)}\ , \tag{5}$$

$$\left(\frac{\mathrm{Be}}{\mathrm{Li}}\right)_* \approx \left(\frac{\Delta t_{\mathrm{CNO}}}{\Delta t_{\alpha\alpha}}\right)\frac{\sum_{ij} R^{\mathrm{Be}}_{ij}(t_*)}{R^{\mathrm{Li}}_{\alpha\alpha}(t_*)}\ , \tag{6}$$

and

$$\left(\frac{\mathrm{B}}{\mathrm{Li}}\right)_* \approx \left(\frac{\Delta t_{\mathrm{CNO}}}{\Delta t_{\alpha\alpha}}\right)\frac{\sum_{ij} R^{\mathrm{B}}_{ij}(t_*)}{R^{\mathrm{Li}}_{\alpha\alpha}(t_*)}\ , \tag{7}$$

where Δt_{CNO} is shorthand for the exposure time of the dominant CNO nuclide. The approximations in equations (6) and (7) follow from the fact that in sufficiently metal-poor ([Fe/H] $\lesssim -2$) Population II environments the $\alpha + \alpha$ reactions dominate the lithium production (SW). For the detailed calculations we present later we include all Li-production reactions.

The physical interpretation of the Δt_{ij} is clear—the ratio $\Delta t_{\mathrm{CNO}}/\Delta t_{\alpha\alpha}$ is related to the "exposure time" of the CNO nuclei relative to that for ^{4}He. Clearly if the Population II CNO is produced immediately prior to t_*, very little B or Be is produced relative to Li which is created at nearly a constant rate via $\alpha + \alpha$ fusion over the entire interval t_*. This limiting case corresponds to $\Delta t_{\mathrm{CNO}}/\Delta t_{\alpha\alpha} \ll 1$. If on the other hand the CNO abundances come up quickly during the early Galaxy (on time scales $\ll t_*$) the "exposure times" would be comparable ($\Delta t_{\mathrm{CNO}}/\Delta t_{\alpha\alpha} \sim 1$). This is the assumption adopted for the zeroth-order model (SW) and thus yields an upper bound to the Be-to-Li ratio. A more realistic approximation is an intermediate case in which CNO grows uniformly with time for which $\Delta t_{\mathrm{CNO}}/\Delta t_{\alpha\alpha} \sim \frac{1}{2}$. In this scenario, the CNO abundances change on a time scale which is short compared to the $\alpha - \alpha$ exposure time. Since the cosmic-ray produced lithium is dominated by $\alpha + \alpha$ fusion, the gas forming the Population II stars should show little variation of the total lithium (BBN + GCR) with metallicity, while the Be and B abundances of the gas should vary over several orders of magnitude. The Be and B abundances would be directly correlated with the oxygen abundance since their production is dominated by oxygen spallation (due to the enhancement of oxygen relative to carbon and nitrogen). Separate from the issue of relative exposure times, there is a possibility that Be and B are made in the vicinity of supernovae. If this were the case, then we would expect (Be/H) $\propto$ (Fe/H) as is seen in the data (rather than a quadratic dependence as would be expected if both the cosmic-ray abundances and CNO abundances scaled with the supernova rate). In situ production of Be and B in the CNO rich environment of supernova ejecta would lead to a Be/Li ratio which is larger than we calculate here because of the enhanced CNO abundances relative to the ^{4}He nuclei. It may be that the reduction of Be/Li due to different exposure times is cancelled by this in situ enhancement. Because of such uncertainties, most of our comparisons will be restricted to the zeroth-order model. Note that, although the Li to Be or B ratios are sensitive to assumptions about the CNO evolution in the early Galaxy, the B-to-Be ratio is not. Although we can only estimate the uncertainties due to chemical evolution in the early Galaxy, the detailed chemical evolution models of Prantzos et al. (1993), which are constrained to reproduce properties of the early Galaxy other than LiBeB, predict ratios of Li, Be, and B which are in good agreement with our zeroth-order model. In addition, the Prantzos et al. model, as well as the chemical evolution models of Ryan et al. (1991), predict a linear relationship between Be and Fe.

Assuming comparable exposure times for all CNO nuclei, SW have calculated the Population II ([Fe/H] ≤ -1) GCR yields using the CNO abundances discussed above and $y_\alpha = 0.08$ (i.e., a ^{4}He mass fraction of 0.24)

$$[^7\mathrm{Li}] \approx [^6\mathrm{Li}] \approx [\mathrm{Be}] - [\mathrm{Fe/H}]\ , \tag{8}$$

$$[^{11}\mathrm{B}] \approx [^{10}\mathrm{B}] + 0.4\ , \tag{9}$$

and

$$[\mathrm{B}] \approx [\mathrm{Be}] + 1.2\ . \tag{10}$$

Here we supress the isotope label when the quantity represents the sum of the stable isotopes. As was pointed out in SW, the Population II GCR Li/Be ratio can greatly exceed its Population I value [~ 13 (WMV)] and thus the absence of Be cannot be taken as evidence of the absence of GCR synthesized lithium. The less model dependent "smoking gun" for Population II nucleosynthesis is the B/Be ratio. Under the assumptions listed above, SW predicted this ratio to be roughly 14.[10] In following sections we investigate the sensitivity of these predictions to our assumptions about the evolution of the Population II environment.

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[10] It may be worth noting that B/Be is observed to be roughly 14 in the GCRs today where both Be and B are pure spallation products and C/O ~ 1 (Simpson 1982).

TABLE 1

DATA ON HALO STARS SEARCHED FOR BERYLLIUM

Star	[Fe/H][a]	[Be]	[O/H][b]	[Li]
HD 16031	-2.0	-0.37 ± 0.3^{c}	-1.32	2.03 ± 0.2^{d}
HD 19445	-2.2	$< -0.3^{e}$	-1.4	2.07 ± 0.20^{d}
HD 34328	-1.9	$0.1 \pm 0.3^{e,f}$	-1.46	2.07
HD 74000	-2.1	$< -0.2^{g}$	...	2.16 ± 0.20^{d}
HD 76932	-1.1	$0.75 \pm 0.3^{c,h}$	-0.9	1.96
HD 84937	-2.2	$< -0.85^{h}$	$-1.9(-1.6)^{c}$	2.11 ± 0.07^{d}
HD 116064	-2.2	-0.70 ± 0.3^{i}	-1.74	...
HD 134169	-1.0	0.65 ± 0.4^{h}	-0.2^{j}	2.21 ± 0.09^{d}
HD 134439	-1.9	$< -0.1^{e}$	...	...
HD 140283	-2.6	$-0.85 \pm 0.4^{c,i}$	$-2.1(-1.8)$	$2.09 \pm 0.07^{d,k}$
	-2.7	-1.25 ± 0.4^{h}	-2.2	...
	-2.8	-1.03 ± 0.3^{c}	-2.10	...
HD 160617	-2.1	-0.47 ± 0.3^{c}	-1.68	2.20 ± 0.2^{d}
HD 189558	-1.3	0.0 ± 0.4^{e}	...	2.04
HD 194598	-1.6	$<0.3^{e}$	...	2.00 ± 0.20^{d}
HD 200654	-3.0	$< -1.7^{c}$	-2.28^{c}	...
HD 201891	-1.0	0.4 ± 0.4^{e}	-0.26^{j}	1.98 ± 0.07^{d}
HD 213657	-2.3	-0.65 ± 0.3^{c}	-1.65	2.17
HD 219617	-1.5	$<0.4^{e}$	-1.0	2.18 ± 0.07^{d}
BD 23°3912	-1.3	0.3 ± 0.4^{e}	...	2.36 ± 0.2^{d}
CD −30°18140	-2.1	-0.28 ± 0.3^{i}	-1.35	...

[a] Iron abundances as taken from the beryllium references.

[b] Oxygen abundances assumed by beryllium references or as measured.

[c] GGEN.

[d] WSSOK.

[e] RMAB.

[f] Quoted as very uncertain.

[g] RSBN.

[h] RNBD.

[i] GEN.

[j] Abia & Rebolo 1989.

[k] Hobbs & Thorburn 1991.

3. OBSERVATIONS OF Li, Be, AND B IN POPULATION II STARS

The observational data on Population II Li and Be is surprisingly rich considering the very low abundances involved: lithium has been observed (at the level $[\mathrm{Li}] \sim 2.1 \pm 0.1$) in about 40 metal-poor ($[\mathrm{Fe/H}] \lesssim -1.3$) halo stars (Spite & Spite 1982, 1986), and Be has been searched for in about 20 halo stars and detected (at the level of $-1.3 \lesssim [\mathrm{Be}] \lesssim 0.8$) in 12 of them (RMAB; Ryan et al. 1990; GEN; RNBD; Gilmore et al. 1992, hereafter GGEN). We summarize the observational data in Table 1.

We first consider the fate of $^{6}\mathrm{Li}$. The $^{6}\mathrm{Li}/^{7}\mathrm{Li}$ ratio predicted by Population II GCR nucleosynthesis (SW) is relatively insensitive to evolutionary uncertainties; roughly as much $^{6}\mathrm{Li}$ is produced as $^{7}\mathrm{Li}$ ($^{6}\mathrm{Li}/^{7}\mathrm{Li} \sim 0.9$). However, $^{6}\mathrm{Li}$ is the most fragile of the Li, Be, B isotopes and is not expected to survive in Population II stars cooler than ~6300 K (Brown & Schramm 1988; DDKKR) [for comparison, $^{7}\mathrm{Li}$ is only substantially destroyed in stars cooler than ~5500 K (DDKKR)]. $^{6}\mathrm{Li}$ has never been seen in any of the plateau halo stars [the best bound to the $^{6}\mathrm{Li}/^{7}\mathrm{Li}$ ratio is less than 0.1 (Maurice, Spite, & Spite 1984; Pilachowski, Hobbs, & DeYoung 1989)][11] but due to its easy destruction, this absence does not appreciably constrain GCR nucleosynthesis. All of the halo stars observed to contain Be (see Table 1) should have had their original $^{6}\mathrm{Li}$ depleted.

The hottest halo star to be examined for $^{6}\mathrm{Li}$ is the halo subdwarf HD 84937 ($[\mathrm{Fe/H}] = -2.1$, $T = 6200$ K) (Pilachowski et al. 1989) and, as in the cooler stars, $^{6}\mathrm{Li}$ is not seen: $^{6}\mathrm{Li}/^{7}\mathrm{Li} \lesssim 0.1$. Using the observed lithium abundance for HD 84937 ($[\mathrm{Li}]_{\mathrm{OBS}} \approx 2.1$) we conclude that $[^{6}\mathrm{Li}]_{\mathrm{OBS}} \lesssim 1.1$ For this star, the calculations of Deliyannis et al. (DDKKR) imply at least a factor of 3 destruction of any prestellar $^{6}\mathrm{Li}$ [and in fact, older isochrones, which better fit globular cluster data, imply perhaps as much as a factor of 10 destruction of $^{6}\mathrm{Li}$ for this star (Deliyannis, Demarque, & Kawaler 1990)]. If we define f to be the destruction factor so that $[^{6}\mathrm{Li}]_{\mathrm{GCR}} = [^{6}\mathrm{Li}]_{\mathrm{OBS}} + \log f$, then we predict

$$[^{6}\mathrm{Li}]_{\mathrm{OBS}} \approx ([\mathrm{Be}] - [\mathrm{Fe/H}])_{\mathrm{OBS}} - \log f\,, \qquad (11)$$

where we have used equation (8) to estimate the GCR $^{6}\mathrm{Li}$ production. If, consistent with the data in Table 1, we take $([\mathrm{Be}] - [\mathrm{Fe/H}])_{\mathrm{OBS}} = 1.6 \pm 0.2$ (see below) and $\log f \gtrsim 0.5$, then we predict $[^{6}\mathrm{Li}]_{\mathrm{OBS}} \lesssim 1.1 \pm 0.2$, which, for HD 84937 is just on verge of detection. Therefore, an additional, although more model-dependent, test of the GCR mechanism is the prediction of a potentially detectable abundance of GCR produced $^{6}\mathrm{Li}$ in the hottest metal-poor halo stars.[12]

The observations of Be in halo stars, along with a model of GCR nucleosynthesis, can be used to predict the expected abundances of Li and B. Of importance to the GCR

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[11] $^{6}\mathrm{Li}$ was tentatively indentified in the spectrum of HD 211998 ($T \sim 5300$ K, $^{6}\mathrm{Li}/^{7}\mathrm{Li} \sim 0.07$), a cool nonplateau halo star (Andersen, Gustafsson, & Lambert 1984), but these observers caution that this is not a definite detection due to the low quality of the spectrum. Such detection of $^{6}\mathrm{Li}$ would be surprising since $^{7}\mathrm{Li}$ is depleted in this star.

[12] Since we first submitted this paper, $^{6}\mathrm{Li}$ has, in fact, been observed by Smith, Lambert, & Nissen (1993) in HD 84937 at a level of $[^{6}\mathrm{Li}]_{\mathrm{OBS}} = 0.8^{+0.1}_{-0.2}$ in good agreement with our prediction. Beryllium has yet to be detected in this star. Using eq. (11), we would predict from the observed abundance of $^{6}\mathrm{Li}$ that $[^{9}\mathrm{Be}] \gtrsim -0.8^{+0.1}_{-0.2}$ consistent with the observed upper bound. Note that these bounds are based on a lower limit of a factor of 3 destruction of $^{6}\mathrm{Li}$.

synthesis hypothesis are the recent measurements of Be in the extreme halo subdwarf HD 140283. Gilmore et al. (GGEN) find $[\mathrm{Fe/H}] = -2.77$ and $[\mathrm{Be}] = -1.03 \pm 0.3$ in good agreement with the earlier measurement of Gilmore, Edvardson, and Nissen (GEN) who found $[\mathrm{Fe/H}] = -2.6 \pm 0.3$ and $[\mathrm{Be}] = -0.8 \pm 0.3$. Ryan et al. (RNBD) find $[\mathrm{Fe/H}] = -2.7 \pm 0.2$ and $[\mathrm{Be}] = -1.25 \pm 0.4$. Using the average of the GGEN and GEN (RNBD) results allows the following predictions for GCR nucleosynthesis:

$$[{}^7\mathrm{Li}]_{\mathrm{GCR}} = 1.7 \pm 0.4(1.5 \pm 0.4)\ ,$$

and

$$[\mathrm{B}]_{\mathrm{GCR}} = 0.2 \pm 0.3(-0.1 \pm 0.4)\ .$$

For the gas out of which this star formed, the exposure time is large:

$$\Delta t_{\alpha\alpha} = 14(8)\ \mathrm{Gyr}\ .$$

The observations of Be in such a metal-poor star imply that GCR nucleosynthesis, if responsible for the Be present at $[\mathrm{Fe/H}] \sim -2.7$, is very efficient (as evidenced by the large values for $\Delta t_{\alpha\alpha}$).[13] In addition, if the zeroth-order model of GCR nucleosynthesis produces the observed Be, it also produces a non-negligible fraction of the observed lithium. However, we emphasize that the Li/Be ratio expected in GCR nucleosynthesis is sensitive to choices of the relative CNO abundances and to their evolution, a point we discuss further in the next section. Note also that the observation of Be in such a metal-poor Population II star, coupled with the Be abundances observed in more metal-rich Population II stars, establishes direct evidence for the Galactic production of Be: Be *increases with* [Fe/H]. The increase of Be with [Fe/H] *requires* nucleosynthesis in the early Galaxy. It is the absence of the analog of the "Spite plateau" for Be versus Fe that limits (at the level of a part in 10^{-13}) a primordial component to the Be observed in the halo stars.

For the 12 halo stars in which Be has been observed (see Table 1 and Fig. 1), there is a clear correlation (with correlation coefficient 0.96) between [Be] and [Fe/H]. The slope of [Be] versus [Fe/H] is ~1.0 (depending on the actual choices for multiply measured stars). The data are consistent with

$$([\mathrm{Be}] - [\mathrm{Fe/H}])_{\mathrm{OBS}} = 1.6 \pm 0.2\ ,$$

and for the zeroth-order GCR model (SW) (see eqs. [8] and [10]) we then expect

$$[{}^7\mathrm{Li}]_{\mathrm{CR}} \approx [{}^6\mathrm{Li}]_{\mathrm{CR}} \approx 1.6 \pm 0.2$$

and

$$[\mathrm{B}]_{\mathrm{CR}} \approx (2.8 \pm 0.2) + [\mathrm{Fe/H}]\ .$$

These results are consistent with the observations of HD 140283. For more metal-rich halo stars, where CNO contributions to lithium production begin to be of importance, the lithium yields at fixed Be and/or B will increase. We discuss this, along with uncertainties associated with the predictions of the zeroth-order model in the next section.

4. UNCERTAINTIES IN THE PREDICTIONS OF THE ZEROTH-ORDER MODEL

The abundance of lithium derived from observations of metal-poor halo dwarfs provides a test of the predictions of the zeroth-order model of Population II GCR nucleosynthesis. If, indeed, the observed Population II Be has a GCR nucleosynthesis origin, there must be a GCR component to the Li observed in halo stars. In our scenario, the lithium observed in halo stars has a GCR component in addition to the primordial component generated during big bang nucleosynthesis. The GCR nucleosynthesis hypothesis is testable in that the GCR component of lithium which accompanies the GCR produced Be could, when added to the minimum BBN component, exceed the observed abundance of lithium. That is, the observational data on Population II lithium, when combined with the predictions of BBN (Walker et al. 1991), provide an *upper* bound to the GCR component of Li. This, in turn, bounds the GCR Be contribution which may or may not be consistent with the data. Here, we explore this confrontation in more detail, paying particular attention to the uncertainties in the predictions of the zeroth-order model when the various assumptions about the evolution of the CNO abundances are relaxed. Specifically, we examine the sensitivity of the predicted production ratios to the relative excess of oxygen in Population II stars. In § 5 we make a detailed comparison of the GCR and BBN lithium yields with the lithium observations.

For a Population II ^{4}He abundance of $y_\alpha = 0.08$, the production rates (Gyr^{-1}) for ^{7}Li, ^{9}Be, ^{10}B, and ^{11}B as a function of the CNO abundances are

$$\begin{aligned} R(7) = 3.08(1 &+ 0.84 \times 10^{[\mathrm{C/H}]} \\ &+ 0.08 \times 10^{[\mathrm{N/H}]} + 1.13 \times 10^{[\mathrm{O/H}]})\ , \end{aligned} \tag{12}$$

$$R(9) = 0.44 \times 10^{[\mathrm{C/H}]} + 0.09 \times 10^{[\mathrm{N/H}]} + 0.74 \times 10^{[\mathrm{O/H}]}\ , \tag{13}$$

$$R(10) = 3.03 \times 10^{[\mathrm{C/H}]} + 0.30 \times 10^{[\mathrm{N/H}]} + 2.81 \times 10^{[\mathrm{O/H}]}\ , \tag{14}$$

and

$$R(11) = 8.24 \times 10^{[\mathrm{C/H}]} + 0.58 \times 10^{[\mathrm{N/H}]} + 6.34 \times 10^{[\mathrm{O/H}]}\ . \tag{15}$$

Since there is an excess of oxygen (relative to C and N) in Population II stars (Sneden et al. 1979; Barbuy & Erdelyi-Mendes 1989; Wheeler et al. 1989; Abia & Rebolo 1989; Spite & Spite 1991) the Population II GCR production rates of Be and B are, to first order, proportional to the oxygen abundance. GCR production of ^{7}Li and ^{6}Li is, for the more metal-poor stars ($[\mathrm{Fe/H}] \lesssim -2$), dominated by the $\alpha - \alpha$ fusion reactions (SW) but, CNO spallation becomes increasingly important for the more metal-rich halo stars.

If we assume $[\mathrm{C/H}] = [\mathrm{N/H}] = [\mathrm{Fe/H}]$ (and allow [O/Fe] to be unspecified), the Population II production rates become

$$R(7) = 3.08[1 + 1.13 \times 10^{[\mathrm{O/H}]}(1 + 0.81 \times 10^{-[\mathrm{O/Fe}]})]\ , \tag{16}$$

$$R(9) = 0.74 \times 10^{[\mathrm{O/H}]}(1 + 0.71 \times 10^{-[\mathrm{O/Fe}]})\ , \tag{17}$$

$$R(10) = 2.81 \times 10^{[\mathrm{O/H}]}(1 + 1.18 \times 10^{-[\mathrm{O/Fe}]})\ , \tag{18}$$

and

$$R(11) = 6.34 \times 10^{[\mathrm{O/H}]}(1 + 1.39 \times 10^{-[\mathrm{O/Fe}]})\ . \tag{19}$$

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[13] We remind the reader that the exposure time calculated scales directly with the assumed Population II CR flux and also depends on the CR and ISM abundances.

Thus, to first-order, the ratios of GCR produced Be and B to that of Li should scale with the oxygen abundance; in contrast, the B-to-Be ratio should be insensitive to the CNO abundances.

Since the production ratio of Be to Li will vary as O/H (for [C/H] = [N/H] = [Fe/H], the zeroth-order model predicts that $\log\,[R(7)/R(9)] - [\mathrm{O/H}] \approx 0.5$–$0.6$ for $0.3 \leq [\mathrm{O/Fe}] \leq \infty$), an inspection of the available data for such a trend seems appropriate. At present, however, there are several obstacles impeding the analysis of the GCR yields in terms of the oxygen abundances. More serious than the dearth of oxygen determinations for the metal-poor dwarfs is the disagreement between those abundance determinations based on the forbidden line at 630 nm and those derived from the triplet at 777 nm (Abia & Rebolo 1989; Spite & Spite 1991). For the halo giants, $[\mathrm{O/Fe}] \approx 0.5$ for $[\mathrm{Fe/H}] \lesssim -1$ (Barbuy & Erdelyi-Mendes 1989). Although Abia & Rebolo (1989) find the same enhancement *trend*, quantitatively their inferred enhancements are much larger. In contrast, when the forbidden line is used to derive the oxygen abundances in metal-poor dwarfs (Spite & Spite 1991), enhancements similar to those found for the giants are obtained. Though more frequently for more metal-rich stars than considered here, *different* oxygen abundances are derived from the forbidden line and from the triplet (Spite & Spite 1991). Non-LTE effects can apparently account for only a part of this discrepancy (Kiselman 1991). It is likely that the forbidden line measurements are more reliable than the allowed triplet measurements since the allowed triplet transition is sparsely populated and thus quite sensitive to assumptions about the subdwarf atmospheres. In addition, the allowed triplet line is formed near the convection zone in these stars and therefore is sensitive to assumptions about convection in subdwarfs. Thus until this puzzle is resolved (and there are more oxygen abundance determinations in halo dwarfs), we must content ourselves with the correlation between Fe/H and the Li, Be, and B abundances. In terms of [Fe/H] and [O/Fe] the GCR yields can be written

$$R(7) = 3.08[1 + 0.92 \times 10^{[\mathrm{Fe/H}]}(1 + 1.24 \times 10^{[\mathrm{O/Fe}]})]\,, \quad (20)$$

$$R(9) = 0.53 \times 10^{[\mathrm{Fe/H}]}(1 + 1.40 \times 10^{[\mathrm{O/Fe}]})\,, \quad (21)$$

$$R(10) = 3.32 \times 10^{[\mathrm{Fe/H}]}(1 + 0.84 \times 10^{[\mathrm{O/Fe}]})\,, \quad (22)$$

and

$$R(11) = 8.82 \times 10^{[\mathrm{Fe/H}]}(1 + 0.72 \times 10^{[\mathrm{O/Fe}]})\,. \quad (23)$$

First, let us concentrate on the production ratio of Li to Be, $R(7)/R(9)$. Since to leading order this ratio will be proportional to Fe/H, we consider the combination $F = \log\,[R(7)/R(9)] - [\mathrm{Fe/H}]$, which contains the zeroth-order GCR predictions for the relationship between Li/Be and [Fe/H]. F, which is a function of [Fe/H] and [O/Fe], is shown in Figure 2 for $0.3 \leq [\mathrm{O/Fe}] \leq 0.7$. Note that for $[\mathrm{Fe/H}] \lesssim -2$, $F \approx 0.0 \pm 0.2$; for $[\mathrm{Fe/H}] \approx -1$, $F \approx 0.2 \pm 0.1$. If, as in the zeroth-order model, it is assumed that $\Delta t_{\alpha\alpha} = \Delta t_{\mathrm{CNO}}$, then the GCR component of ^{7}Li, for an observed correlation between Be and Fe, is predicted to be

$$[^7\mathrm{Li}]_{\mathrm{GCR}} = ([\mathrm{Be}] - [\mathrm{Fe/H}])_{\mathrm{OBS}} + F\,. \quad (24)$$

Note that with $([\mathrm{Be}] - [\mathrm{Fe/H}])_{\mathrm{OBS}} = 1.6 \pm 0.2$ we predict $[^7\mathrm{Li}]_{\mathrm{GCR}} \approx 1.6 \pm 0.3$ for $[\mathrm{Fe/H}] \lesssim -2$. If to this GCR component we add one from BBN ($y_7^{\mathrm{BBN}} \gtrsim 1.0 \times 10^{-10}$) (WSSOK) then we predict (for $[\mathrm{Fe/H}] \lesssim -2$) that $[^7\mathrm{Li}]_{\mathrm{TOT}} \gtrsim 2.15^{+0.10}_{-0.07}$; this is entirely consistent with $[\mathrm{Li}]_{\mathrm{OBS}} = 2.08 \pm 0.04$ found for 39 halo stars ($[\mathrm{Fe/H}] \lesssim -1.3$) (the sample of WSSOK plus the data of Hobbs & Thorburn 1991). In addition, this is consistent with the recent results of Hobbs & Thorburn (1991) whose analysis of 11 very metal-poor halo stars ($[\mathrm{Fe/H}] \leq -2.6$), yields $[\mathrm{Li}]_{\mathrm{OBS}} = 2.16 \pm 0.07$ using a single set of input parameters. A global average of the same 11 stars yields 2.11 ± 0.08. In particular, the observed lithium abundance of HD 140283 is $[\mathrm{Li}] = 2.09 \pm 0.07$ and $[\mathrm{Fe/H}] = -2.60$ (here we use the correction of earlier measurements of HD 140283 as proposed by Hobbs & Thorburn). Taking our prediction for GCR lithium ($[^7\mathrm{Li}]_{\mathrm{GCR}} \approx 1.6 \pm 0.3$ for $[\mathrm{Fe/H}] \lesssim -2$), the observed Li abundance of HD 140283 implies $y_7^{\mathrm{BBN}} = (0.8^{+0.4}_{-0.6}) \times 10^{-10}$, consistent with the predictions of BBN. Note here that we neglect the contribution of GCR ^{6}Li since it should be significantly depleted in this star.

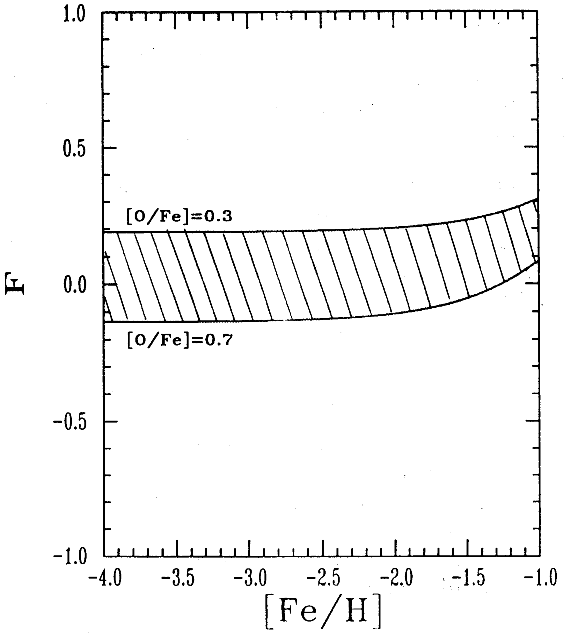

FIG. 2.—Zeroth-order model's predictions for the function $F = \log\,(^7\mathrm{Li}/^9\mathrm{Be}) - [\mathrm{Fe/H}]$ as a function of [Fe/H] for $0.3 \leq [\mathrm{O/Fe}] \leq 0.7$.

Before we turn to a detailed comparison with those stars for which Be has been observed, we discuss here the uncertainties associated with the zeroth-order model. Although the ratios are less sensitive to Galactic evolution uncertainties than are the individual yields, residual model-dependent uncertainties remain nonetheless. As was discussed earlier, the ratios of B or Be to Li depend on the ratio of exposure times $\Delta t_{\mathrm{CNO}}/\Delta t_{\alpha\alpha}$ which depends both on the evolution of the cosmic-ray flux and the CNO abundances. Since the CNO abundances are increasing during the early Galaxy $\Delta t_{\mathrm{CNO}} \leq \Delta t_{\alpha\alpha}$ with the exact ratio determined by the early Galaxy CNO evolution. Thus, the ratios of GCR produced B or Be to Li could be smaller than the production rate ratios (given by eqs. [12]–[15]) by a model-dependent factor which is unknown, but could be 2 or more. As mentioned previously there is at least one possible model-dependent correction with the opposite effect. Production of Be and B in supernova environments will be enhanced relative the Li production (dominated by $\alpha - \alpha$). Thus, although the production rate ratios can be determined reasonably accurately (see Fig. 2), the ratios of GCR produced Be and B to Li are subject to model-dependent enhancement

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and reduction factors. Therefore, in our comparisons between the predictions for GCR synthesized Be and Li with the data summarized in Table 1 and Figure 1, we will use the results of the zeroth-order model (Fig. 2) while keeping in mind that the true uncertainties may well be much larger than those already identified.

Fortunately, both of the above model-dependent corrections are virtually absent if we concentrate on the B-to-Be ratio. This ratio is insensitive to the uncertainties in the abundances and therefore to the details of the evolution of the CNO abundances. To a high degree of accuracy $(B/Be)_{GCR} = R(B)/R(Be)$ where from equations (21), (22), and (23) we see that

$$\frac{R(B)}{R(Be)} = 23.1\left(\frac{1 + 0.75 \times 10^{[O/Fe]}}{1 + 1.40 \times 10^{[O/Fe]}}\right) . \tag{25}$$

For $[O/Fe] = 0.5$, $R(B)/R(Be) = 14.4$ (SW); for $0 \leq [O/Fe] < \infty$, $16.8 \gtrsim R(B)/R(Be) \gtrsim 12.4$. This ratio is the "smoking gun" for GCR nucleosynthesis. As it is based on the nuclear reaction cross sections and on the shape of the CR spectrum, we delay a critical examination of the uncertainties in this ratio until the § 6.

5. CONSISTENCY OF A TWO-COMPONENT MODEL FOR HALO STAR LITHIUM

As we have already noted, the data of Table 1 is consistent with a linear correlation between Be and Fe ($[Be] - [Fe/H])_{OBS} = 1.6 \pm 0.2$ (we compute this relationship for all the metal-poor stars of Table 1 excluding HD 160617 (which is significantly nitrogen overabundant), and treating the average GGEN observations of HD 140283 as one data point). If the observed Be has a GCR origin, then the zeroth-order model predicts that some of the Li observed in Population II stars should also have a GCR component

$$[^7Li]_{GCR} = 1.6 \pm 0.2 + F , \tag{26}$$

where F is shown in Figure 2 as a function of [Fe/H] and [O/Fe]. Observations of some three dozen sufficiently warm ($\gtrsim 5600$ K), sufficiently metal-poor ($[Fe/H \leq -1.3$) halo stars (the "Spite Plateau") have yielded (WSSOK)

$$[Li]_{OBS} = 2.08 \pm 0.02 , \tag{27}$$

where 0.02 is the $1 - \sigma$ deviation of the mean. This error is most likely and under estimated due to systematic effects. Thus we conclude that $(Li/H)_{OBS} > (Li/H)_{GCR}$ since $F \leq 0.25$ for $[Fe/H] \leq -1.3$ (see Fig. 2).

Now we examine the predictions and observations of lithium more closely. Instead of examining the beryllium-bearing halo stars as a whole, an analysis of the individual stars can be done. To test the consistency of the two-component model for halo star lithium on a star by star basis, we use the observed values for [Fe/H] and [O/H] for each halo star with a Be measurement (see Table 1). The production of Galactic ^{9}Be will be accompanied by the production of additional ^{7}Li so that, assuming a primordial ^{7}Li component, the total ^{7}Li can be expressed as a function of ^{9}Be. In this discussion we assume that the observed ^{7}Li is the pre-stellar lithium. Standard models of depletion (DDKKR) indicate no more than 0.1 dex of ^{7}Li depletion. Were we to include 0.1 dex of depletion, the primordial component inferred from the difference of the observed ^{7}Li and the GCR ^{7}Li would be 0.1 dex larger, in slightly better agreement with the predictions of BBN than indicated by the analysis below. In Figure 3 we show this relationship for HD 140283. The two solid curves represent our calculated ^{9}Be abundances assuming the lowest possible ^{7}Li abundance consistent with big bang nucleosynthesis, $[Li] = 2.0$, (*upper curve*) and the $2 - \sigma$ upper limit to the observed Spite plateau, $[Li] = 2.12$, (*lower curve*). If there were no GCR synthesis of ^{9}Be, the observed ^{7}Li for HD 140283 would be the primordial abundance, which by default overlaps the region consistent with BBN. Also plotted is the $1 - \sigma \times 1 - \sigma$ box corresponding to the observed lithium and beryllium for HD 140283. The two-component model is consistent with BBN if the box lies between the curves, as it does. This analysis agrees, as it should, with that presented earlier.

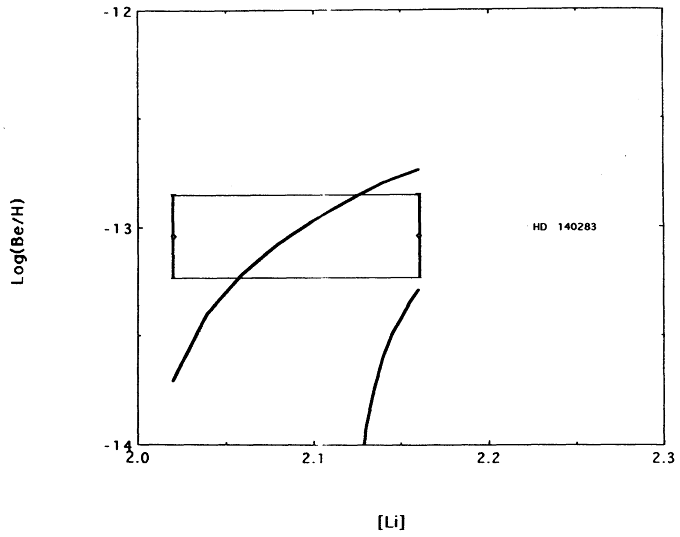

FIG. 3.—Consistency of the two-component Li model for HD 140283. The upper curve represents the predicted ^{9}Be abundance as a function of observed ^{7}Li assuming the minimum primordial component consistent with BBN ($[Li] = 2.0$). The lower curve is the same for an assumed primordial component of $[Li] = 2.12$. The box represents the $1 - \sigma$ errors in the observed ^{9}Be and Li abundances. Overlap of the data with the region bounded by the curves indicates that the Li accompanying the production of the observed ^{9}Be is consistent with BBN Li and observed Li.

Similar consistency for the two-component model is found, at the $1 - \sigma$ level, for all but one (HD 76932) of the remaining halo stars observed to contain Be (note that HD 76932 may be too metal-rich to qualify as an extreme halo star). Although there is agreement with BBN at the $2 - \sigma$ level for HD 76932, we note that the oxygen abundance is uncertain (Barbuy 1988) and that recent measurements of HD 76932 (Bessel, Sutherland, & Ryan 1991) have shown a more standard oxygen enhancement. As we noted earlier, there is strong debate the oxygen enhancements of halo subdwarfs (e.g., in the stars observed by Abia & Rebolo 1989)—a debate that has strengthened with additional evidence for anomously high [O/H] in HD 140238. For example, Bessel & Norris (1987) have also found $[O/Fe] = 0.9$ for this star at a wavelength (314.4 nm) rather than the disfavored triplet line (770 nm). Interestingly enough, note that if one takes the fit of N versus O found for extragalactic H II regions (Olive, Steigman, & Walker 1991), $[N] = 1.56[O] +$ constant (which reasonably extrapolates to solar abundances as well), one finds the standard Population II enhancement for $[Fe/H] = -1.3$ and at much lower metallicities, say $[Fe/H] = -2.5$, we would expect $[O/Fe] = 0.9$. In addition to the uncertainties in our calculation of Be/Li due to uncertainties in the observed oxygen, by assuming the *observed* O abundances for our calculations of the GCR nucleosynthesis

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production of Li, Be, and B, we are implicitly assuming that the C, N, and in particular, the O, had exposure times comparable to the $\alpha - \alpha$ interactions. As discussed earlier, this implies that we have calculated an upper limit to the Be/Li ratio. If instead these elements are introduced over a gradual time period, so that the Be production rate increases with time, the Be yields estimated here would necessarily be reduced.

The above detailed comparisons between the data and the predicted zeroth-order model abundances are remarkably successful (given the uncertainties—at least a factor of 2—discussed earlier). We have found that $[^7\text{Li}]_{\text{GCR}} < [^7\text{Li}]_{\text{OBS}}$ and, that the excess is entirely consistent with ^{7}Li production predicted by standard BBN (assuming that the observed ^{7}Li has been depleted by less than 0.1 dex). GCR nucleosynthesis is therefore a viable candidate for the mechanism responsible for the Be observed in Population II stars. Next we turn to a reeexamination of the GCR production of boron.

6. A LOWER BOUND TO B/Be IN GCR NUCLEOSYNTHESIS

As we have discussed earlier, since B and Be can only be produced by spallation through interactions involving CNO nuclei, the B/Be ratio predicted for Population II GCR nucleosynthesis is relatively insensitive to the evolution of the metallicity of the Population II ISM and thus this ratio provides a good diagnostic for GCR nucleosynthesis. Assuming the CR spectral shape is constant in time, that [C/H] = [N/H] = [Fe/H] (that is that the carbon and nitrogen abundances track the iron abundance), and that oxygen is enhanced by about a factor of 3 relative to iron ([O/Fe] = 0.5), SW predicted B/Be $\sim$ 14. If the observed relative abundance of B-to-Be is the signature of Population II GCR nucleosynthesis, it is imperative to investigate the robustness of this prediction. How do reasonable changes in the composition of the Population II ISM and/or changes to the spectral shape of the CR flux effect the B/Be ratio?

The effect of changes in the relative composition of CNO on the B/Be ratio can be understood by considering the spallation cross sections for the production of B and Be off the individual CNO nuclei. The closer the target nucleus is in nucleon number to boron, the more likely it is that B, rather than Be, is produced by a spallation reaction since the phase space supression is smaller when fewer nucleons are in the final state. As the nucleon number of the target becomes larger, this phase space supression becomes less important so that the spallation production cross sections of B and Be become comparable. Therefore an ISM which is rich in carbon should yield a larger B/Be ratio than one which is oxygen rich. Under the extreme assumption that spallation *only* on oxygen contributes to the GCR yields, the B/Be ratio is reduced to 12.4 in the zeroth-order model.

We can also consider GCR nucleosynthesis in an ISM which is dominated by α-nuclei, such as might be expected in environments associated with the ejecta of Type II supernovae. Relative to oxygen, the typical abundance (by number) of α-nuclei in a Type II SN is similar to the corresponding solar abundances (Cameron 1982; Anders & Grevesse 1989). The spallation cross sections to B and Be off α-nuclei heavier than oxygen are not well measured, however the general features of these spallation cross sections are understood (Rudstam 1966; Silberberg & Tsao 1973):

1. above threshold (roughly 10 MeV nucleon^{-1}) there is some resonance structure and the cross section becomes flat above $\sim$1 GeV nucleon.$^{-1}$
2. ^{11}B production is larger than ^{10}B which is in turn larger than ^{9}Be, and the (10 + 11)/9 ratio decreases as the target mass increases, asymptotically approaching the ratio of particle stable nuclei at each isobar ($\sim$3.9).
3. The total spallation cross section grows (geometrically as $A^{2/3}$) with target nucleon number A, while the cross section for production of B or Be decreases due to the increasing number of final states available (roughly proportional to A^2).

Because of these generic features and the relatively low number densities of nuclei heavier than oxygen, including a Type II SN distribution of α-nuclei in an otherwise pure oxygen environment will only slightly decrease the B/Be ratio below its minimum value of 12.4 in the zeroth-order pure oxygen model.

Note that the zeroth-order model assumes an $E^{-2.6}$ cosmic-ray spectrum. Steeper CR spectra incident on *any* Population II ISM will lead to *larger* values of the B/Be ratio due to two additional features of the spallation cross sections:

1. The resonance structure for B production is more pronounced than that for Be.
2. The threshold for B production is lower than that for Be (fewer nucleons to dislodge).

Thus, we expect that cosmic-ray spectra *flatter* than $E^{-2.6}$ will *decrease* the B/Be ratio compared to the zeroth-order model. Since the spallation cross sections are flat at high energy, flatter spectra tend toward the limit of constant cross sections and a lower bound to B/Be in Population II GCR nucleosynthesis models is easy to obtain. In the flat spectrum limit the yields of B and Be are dominated by high-energy cosmic-ray spallation. In this limit we can write

$$\frac{\text{B}}{\text{Be}} = \left(\frac{\sigma_{16}^{\text{B}}}{\sigma_{16}^{\text{Be}}}\right) \sum_{\alpha_i} \left(1 + \frac{n_{\alpha_i}}{n_{16}} \frac{\sigma_{\alpha_i}^{\text{B}}}{\sigma_{16}^{\text{B}}}\right) \Bigg/ \sum_{\alpha_i} \left(1 + \frac{n_{\alpha_i}}{n_{16}} \frac{\sigma_{\alpha_i}^{\text{Be}}}{\sigma_{16}^{\text{Be}}}\right), \tag{28}$$

where the sums are over all α-nuclei and we have assumed the production to be dominated by CR protons so that the spallation cross sections are those for protons above a few GeV nucleon^{-1}. The only cross sections measured are (in mbar) $\sigma_{16}^{\text{Be}} = 4.2$ and $\sigma_{16}^{\text{B}} = 39.2$ (Read & Viola 1984), $\sigma_{20}^{\text{B}} = 21.9$ and $\sigma_{24}^{\text{B}} = 15.6$ (Gupta & Webber 1989), and $\sigma_{28}^{\text{Be}} = 4.7$ (Raisbeck & Yiou 1977). Using the Silberberg & Tsao (1973) estimates for the remaining cross sections gives a lower bound to B/Be in Population II nucleosynthesis

$$\left(\frac{\text{B}}{\text{Be}}\right) \sim 9.33(0.89) = 8.3 \,. \tag{29}$$

If, instead of the specific semi-empirical analysis of Silberberg & Tsao, we use a simpler "billiard ball" estimate of the unknown spallation cross sections, the B/Be ratio in the flat spectrum limit would be $\sim$7.5. The billiard ball estimation explicitly uses a total cross section which grows as $A_{\text{targ}}^{2/3}$ with the yield to each species decreased by a factor A_{targ}^{-2}. Therefore $\sigma \propto A_{\text{targ}}^{-4/3}$ with the relative yield being the sum over particle stable nuclei (that is, the constant of proportionality is the sum over branching ratios of particle stable nuclei which decay to ^{9}Be, ^{10}B, or ^{11}B), normalized to the measured values of the cross sections.

We therefore conclude that any model for Population II GCR nucleosynthesis must produce Population II boron in excess of beryllium by a factor of at least 7–8, with the uncertainty in this lower bound arising from the estimates of the cross sections. If the B/Be ratio in halo stars is measured to be significantly lower than 7, then, in the absence of some preferential destruction of B reative to Be, the mechanism which dominates the production of beryllium in the early Galaxy cannot be GCR nucleosynthesis. On the other hand, if B/Be is found to be around 10 in halo stars containing Be, then GCR synthesis is a viable mechanism for the production of the Population II abundances of Be and B. If B/Be ratios are observed to be greater than seven but less than 12, then the cosmic-ray spectrum in the early Galaxy should be flatter than the presently observed $E^{-2.6}$. It is to be expected that the cosmic-ray fluxes and spectra change as the Galaxy evolves since supernova rates along with magnetic field strengths and configurations are likely different in the early Galaxy.[14] This flatter spectra would also lead to a decrease in Li/Be relative to the predictions of the zeroth-order model. However, as we have discussed earlier, this ratio is more sensitive to the details of the chemical evolution of the early Galaxy than is B/Be.[15]

7. CONCLUSIONS

We have discussed the Galactic cosmic-ray (GCR) production of Li, Be, and B in the early Galaxy. If such a mechanism is responsible for the observed Be in metal-poor halo subdwarfs, the GCR Li which must accompany the Be is consistent with the Li produced by big bang nucleosynthesis (BBN). In our scenario, the Li observed in halo stars comes from two sources: (1) a primordial baseline from BBN of $(\mathrm{Li/H})_{\mathrm{BBN}} = (1.0\text{–}1.3) \times 10^{-10}$, and (2) a contribution from GCR Population II nucleosynthesis to the BBN component as $[\mathrm{Fe/H}] \rightarrow -1$. Although the zeroth-order model is not a chemical evolution model, we have attempted to isolate the features that any model which produces Be by GCR nucleosynthesis must have. Less model dependent than the GCR Li/Be ratio is the B/Be ratio. In any model of Population II GCR nucleosynthesis we have shown this ratio to be $7 \lesssim \mathrm{B/Be} \lesssim 17$, depending on the CNO content of the early Galaxy and the shape of the cosmic-ray spectrum. Therefore, if GCR nucleosynthesis is responsible for the observed Be in halo stars, these stars should contain detectable abundances of B[16]. If the B/Be ratio is measured to be significantly less than seven, the mechanism which dominates the production of Be in the early Galaxy cannot be GCR nucleosynthesis. However, the correlation of Be with [Fe/H] would still require new Galactic astrophysics and is inconsistent with any type of primordial production, standard or nonstandard. A primordial component of Be would manifest itself as a yet unobserved plateau in the Be versus Fe data. Such a plateau must be at a level greater than 10^{-17} (relative to hydrogen) in order for nonstandard primordial nucleosynthesis to become necessary. In conclusion, Population II GCR nucleosynthesis can account for the observed beryllium in halo stars and still be consistent with BBN production of lithium. As a consequence, observable abundances (at levels roughly an order of magnitude greater than beryllium) of boron should result and the ^{6}Li which is made might be observable in the hottest halo stars.

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[14] Recent evidence from the GRO-EGRET satellite does in fact show flatter spectra (E^{-2}) in extragalactic objects (Fichtel 1992; Michelson 1992).

[15] The detailed chemical evolution models of Prantzos et al. (1993) predict smaller values of Li/Be, consistent with the trend toward flatter cosmic-ray spectra.

[16] Duncan, Lambert, & Lemke (1992) have reported B/Be of roughly 10^{+5}_{-4} in HD 140283, in good agreement with the predictions of the GCR model.

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