THE ASTROPHYSICAL JOURNAL, 388:184–189, 1992 March 20

EVOLUTION OF BERYLLIUM ABUNDANCES IN THE GALACTIC HALO

SEAN G. RYAN[1]
Department of Physics and Astronomy, University of Victoria, P.O. Box 3055, Victoria, BC, Canada V8W 3P6, and Mount Stromlo and Siding Spring Observatories, The Australian National University, Weston Creek Post Office, ACT 2611, Canberra, Australia

JOHN E. NORRIS AND M. S. BESSELL
Mount Stromlo and Siding Spring Observatories, The Australian National University, Weston Creek Post Office, ACT 2611, Canberra, Australia

AND

CONSTANTINE P. DELIYANNIS[2]
Department of Astronomy, Yale University, P.O. Box 6666, 260 Whitney Avenue, New Haven, CT 06511
Received 1991 June 21; accepted 1991 September 24

ABSTRACT

We have used a spectrum synthesis code to measure Be abundances for three halo stars and an upper limit for a fourth. The abundances are discussed considering models for Galactic and primordial synthesis of Be. Computations for inhomogeneous big bang models range over two orders of magnitude, and we can at best place upper limits on possible primordial nucleosynthesis. We compute a new model for the evolution of Be abundances in the halo, using constraints imposed by its overall metallicity distribution. Observations of stars of [Fe/H] ~ -2.0 are required to clarify the enrichment history of this element.

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

1. INTRODUCTION

Beryllium has recently received increased attention in the literature due to two simultaneous developments: the advent of efficient near-ultraviolet detectors coupled to high-resolution spectrographs which permit much improved observations of the only suitable Be feature, a doublet near 3130 Å, and the prediction of possibly significant primordial synthesis of Be if inhomogeneities, perhaps caused by the quark-hadron phase transition, affected nucleosynthesis during the first few minutes following the big bang. In addition to this cosmological relevance, beryllium possesses the ability to constrain models for the evolution of the Galaxy, since its production during the galactic epoch appears to be limited to the interstellar medium. However, beryllium is destroyed in stars at temperatures of a few million kelvin, so stellar abundances cannot be studied without an appreciation of possible depletion within the star under investigation.

We have obtained detections of Be in three halo dwarfs (one of which may more appropriately be termed a subgiant) and place limts on the abundance in a fourth. In § 2 we present the data and derive abundances. We consider in § 3 the possibility that these abundances have been lowered from the levels when the stars in question formed. We discuss primordial nucleosynthesis in § 4, and galactic evolution models in § 5.

2. DATA AND DERIVED ABUNDANCES

2.1. *Data Acquisition*

The coudé échelle spectrograph on the 3.9 m Anglo-Australian Telescope provides spectra at 3130 Å of sufficient resolution and signal-to-noise ratio (S/N) to permit an improved study of Be abundances in suitably bright halo dwarfs. We used the same observational setup as in Ryan et al. (1990, hereafter Paper I) to obtain spectra of the four halo dwarfs listed in Table 1. The resolution was 0.1 Å (FWHM) as measured in the reduced spectra, corresponding to approximately four detector elements of the image photon counting system (IPCS) as configured. The S/N, given in column (10), are based on the Poisson statistics per detector element. The S/N obtained in this study are 1.0–2.5 times higher than those in Paper I; HD 140283 is the only star common to both works. The two-dimensional spectra were reduced with IRAF routines on the University of Victoria's SUN workstations.

2.2. *Spectrum Synthesis*

As in Paper I, a spectrum synthesis technique utilizing code originating with Cottrell (see Cottrell & Norris 1978) was used to determine the Be abundances of the stars. The line list was again that provided by R. L. Kurucz (1989). In the present work we reviewed the oscillator strengths in that list, *not* with the aim of achieving a perfect match to the solar spectrum (since there is ambiguity over which components of a blend should be changed), but primarily to reduce the strengths of a few lines, almost all due to OH, which were identifiably too strong in our preliminary solar synthetic spectrum. Only one modified line, at 3130.365 Å, directly affected the region near the Be lines, which are at 3130.420 and 3131.065 Å. The model atmospheres for which we computed spectra were from a grid of dwarfs provided by Bell (1981). The model for the solar spectrum synthesis was drawn from the same grid, using parameters $T_{\rm eff}$/log g/[Fe/H]/ξ = 5770/4.44/0.0/1.0 for the solar integrated flux spectrum. We adopted the following values: log $n({\rm Fe})/n({\rm H})_\odot = -4.33$ and log $n({\rm Be})/n({\rm H})_\odot = -10.85$ (Anders & Grevesse 1989); and log $gf = -0.174$ and -0.471 for the shorter and longer wavelength Be lines, respectively (Wiese & Martin 1980). For the program stars we used [Ti/Fe] = +0.35 and [O/Fe] = +0.50, in line with approximate halo overabundances (e.g., Wheeler, Sneden, & Truran 1989; but see also Abia & Rebolo 1989).

[1] Postal address: Astronomy Department, RLM 15.308, University of Texas, Austin, TX 78712.

[2] Postal address: Institute of Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822.

TABLE 1

ATMOSPHERIC PARAMETERS, BERYLLIUM ABUNDANCES, AND OBSERVING LOG

Star (1)	$B-V$ (2)	$b-y$ (3)	c_1 (4)	T_{eff} (5)	log g (6)	[Fe/H] (7)	Refs. (8)	log n(Be)/n(H) (9)	S/N (10)	Observation date (1990) (11)
HD 76932	0.52	0.363	0.289	5800	3.6	−1.05	1, 2, 3, 4, 5	−11.30	16	Mar 11, 12
HD 84937	0.39	0.303	0.367	6250	4.0	−2.20	1, 4, 6	< −12.85	23	Mar 11, 12
HD 134169	0.54	0.376	0.305	5750	3.9	−1.00	1, 2, 3, 4, 5	−11.35	13	Mar 11, 12
HD 140283	0.48	0.377	0.311	5700	3.2	−2.70	1, 7	−13.25	29	Feb 10, 11[a]

REFERENCES.—(1) Carney 1983; (2) François 1986; (3) Spite & Spite 1982; (4) Magain 1987a; (5) Gratton & Sneden 1987; (6) Bell & Oke 1986; (7) Ryan, Norris, & Bessell 1991 (Table 7, references, and discussion therein).

[a] Service request satisfied by R. D. Cannon and B. Croke.

The parameters for the stellar atmospheres were selected from the literature, with attention also given to color temperatures rederived from the $B-V$ calibration of Buser (1987, discussed by Ryan, Norris & Bessell 1991) and the $b-y$ calibration of Magain (1987b). There is not complete agreement between these values; rather than tabulate all possible choices we list instead the adopted values and a range of references on which we based our choice. We have used microturbulence values of 1.0 km s^{-1} for all stars except HD 140283, for which we have adopted 1.5 km s^{-1} to reflect its more evolved status. The Be lines themselves are not very sensitive to microturbulence since the Doppler velocities of light elements are dominated by thermal motions, but the surrounding features due to heavier species are sensitive to microturbulence. Higher weight was given to the less blended, longer wavelength Be line when fitting the synthetic spectra. We compare the synthesized solar spectrum against the solar flux spectrum from Kurucz et al. (1984) in Figure 1. The observed and synthesized program star spectra are shown in Figures 2*a–d*. The derived Be abundances are given in column (9) of Table 1. In Figure 3 we plot these abundances and limits, along with data from the literature. Notes on specific stars are provided below. The model lines will be discussed in § 5.

The ranges in the accuracies (including systematic effects) of the stellar parameters are probably of order ± 100 K in T_{eff}, ± 0.5 dex in log g (possibly larger for HD 140283, as discussed below), and ± 0.2 dex in [Fe/H]. For HD 140283, a decrease in T_{eff} by 100 K lowers the derived Be abundance by 0.05 dex, and an increase in the gravity by 0.5 dex increases the Be abundance by 0.2 dex. Errors in the parameters may therefore contribute approximately 0.2 dex on top of the spectrum-fitting errors, which we estimate are unlikely to exceed 0.2 dex, giving a total of 0.4 dex.

2.2.1. *HD 76932*

For the observation by Budge, Boesgaard, & Varsik (1988), Boesgaard (1990) gives log (Be/H) = −11.2. Our value (−11.3 ± 0.4) is in very good agreement.

2.2.2. *HD 84937*

Bell & Oke (1986) studied this star as a spectrophotometric standard, and we have adopted their atmospheric parameters without modification. It is approximately 500 K hotter than the three other stars in our sample, at a temperature at which its Be line is expected to be weaker than in the others at a given Be abundance. For this reason, we cannot place its abundance limit as low as the detection in HD 140283, despite comparable S/N.

2.2.3. *HD 134169*

There is a considerable range in [Fe/H] values given for this star in the literature. Sneden (1974) and Spite & Spite (1982) give −1.6, whereas François (1986) gives −0.86, and Magain (1987a) and Gratton & Sneden (1987) give −1.02. We have followed the more recent determinations, and assume [Fe/H] = −1.00. The derived beryllium abundance is sensitive to the iron abundance mostly through the impact the latter has on the strength of the absorption adjacent to the Be lines. HD 84937 and HD 140283 are much less affected by this than are the other two stars, due to the less crowded spectra of the more metal-deficient stars.

2.2.4. *HD 140283*

Analyses abound of this classical halo star. We discussed choices of temperature and iron abundance for this star elsewhere (Ryan et al. 1991). Its gravity is a matter of disagreement among astronomers, since the ionization ratios point toward a value near log g = 3.2 (Peterson 1976; Magain 1987a), whereas the trigonometric parallax implies genuine dwarf status, from which log g = 4.5 might be inferred (Laird, Carney, & Latham 199a; Bessell, Sutherland, & Ruan 1991). The Strömgren c_1 value (Carney 1983) places this star on the subgiant branch in Schuster & Nissen's (1989) calibration, and weights the arguments 2:1 in favor of a lower gravity, which we adopt, but uncertainty remains. The implications of an incorrect choice are significant, since the adoption of log g = 4.5 would increase the derived Be abundance by 0.5 dex. This possibility should be

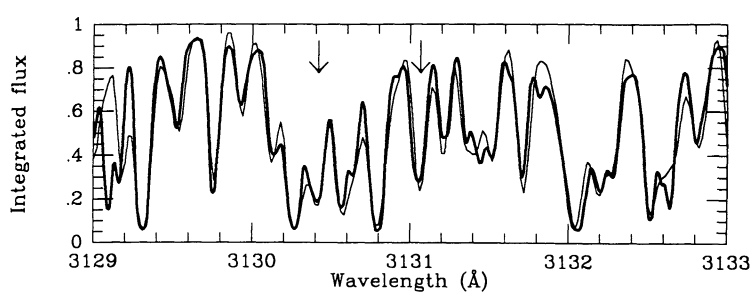

FIG. 1.—Synthetic and observed spectrum for Sun. *Fine line*: synthesis; *thick line*; flux spectrum from Kurucz et al. 1984. Arrows indicate the two Be lines.

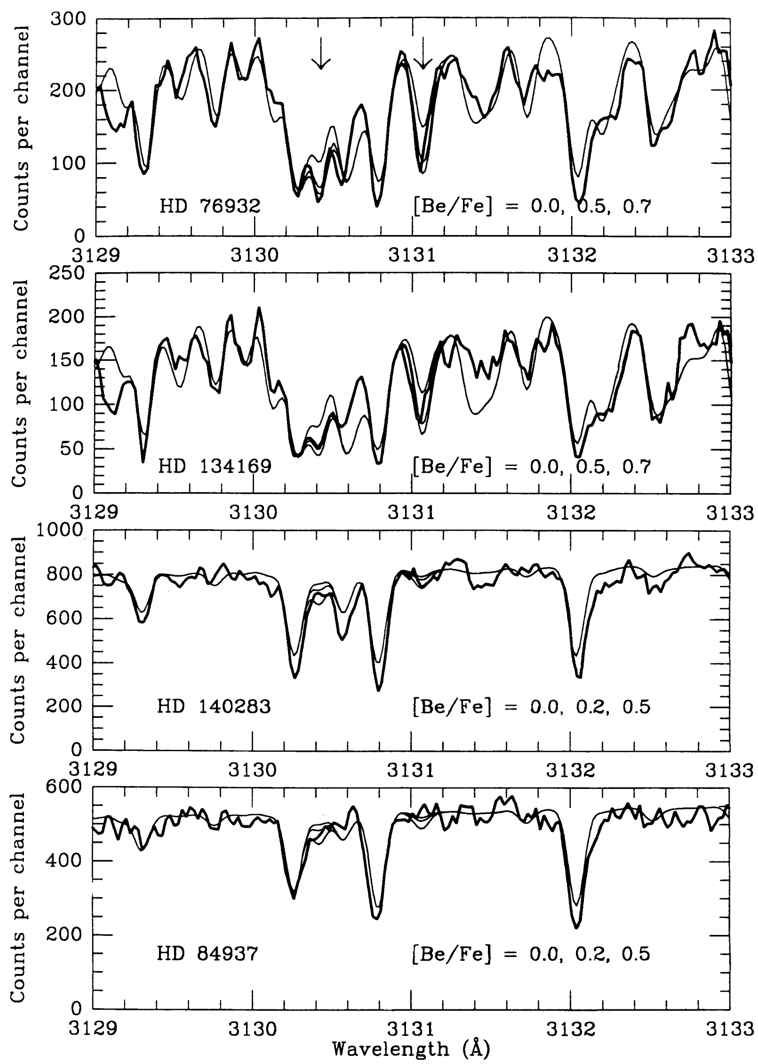

FIG. 2.—Synthetic and observed spectra for program stars. Three synthetic spectra are shown for each star, with the beryllium abundances indicated. *Fine line*: synthesis; *thick line*: observations. Arrows indicate the two Be lines. (*a*) HD 76932. Adopt [Be/Fe] = 0.6; (*b*) HD 134169. Adopt [Be/Fe] = 0.5; (*c*) HD 140283. Adopt [Be/Fe] = 0.3; (*d*) HD 84937. Adopt [Be/Fe] < 0.2.

borne in mind when interpreting the value reported here. Earlier we gave ± 0.5 dex as typifying the range of gravity errors, but for HD 140283 we have adopted a gravity near the lower limit of acceptability, and the error distribution is skewed toward higher rather than lower values.

The abundance we derive from the new spectrum is just 0.05 dex lower, within the errors, than the upper limit given in Paper I. It appears that our earlier observation was on the verge of detectability, but the superior S/N of the present observation was required to determine this with confidence. The stronger of the two Be lines, at 3130.420 Å, is not resolved from the blend in our data, and the line at 3131.065 Å is weak, but the spectrum fit is consistent with an abundance of log $n(\mathrm{Be})/n(\mathrm{H}) = -13.25 \pm 0.4$ dex, including systematic errors. Gilmore, Edvardsson, & Nissen (1991) have recently reported a clear detection of Be in this star. Their spectrum, taken with the same instrumentation, has a slightly higher resolving power but slightly lower S/N. They derive log $n(\mathrm{Be})/n(\mathrm{H}) = -12.8 \pm 0.4$ dex, based on a model with T_{eff}/log g/[Fe/H]/ξ = 5640/3.6/−2.6/1.5. The derived Be abundance is quite sensitive to the assumed gravity, and 0.2 dex of the difference between the two results comes from this alone. The remaining difference is consistent with the other sources of error, especially perhaps the different choices in placement of the pseudocontinuum. Boesgaard (1991) has also observed this feature, not only in HD 140283 but also in other halo stars; quantitative abundances are awaited with interest.

3. DEPLETION OVER STELLAR LIFETIMES

Li and Be are fragile nuclei, destroyed by (p, α) reactions at temperatures of only 2×10^6 K and 3.5×10^6 K, respectively. The base of the surface convection zone in low-mass stars reaches such temperatures during evolution, which leaves the potential for the surface abundance to be depleted. Other physical effects, such as microscopic diffusion and rotationally induced mixing below the convection zone, may further affect the surface abundances.

Li is more fragile than Be and has been used in the past to assess possible depletion of the latter. The uniformity of Li in Population II stars lying within the range 5500 K < T_{eff} <

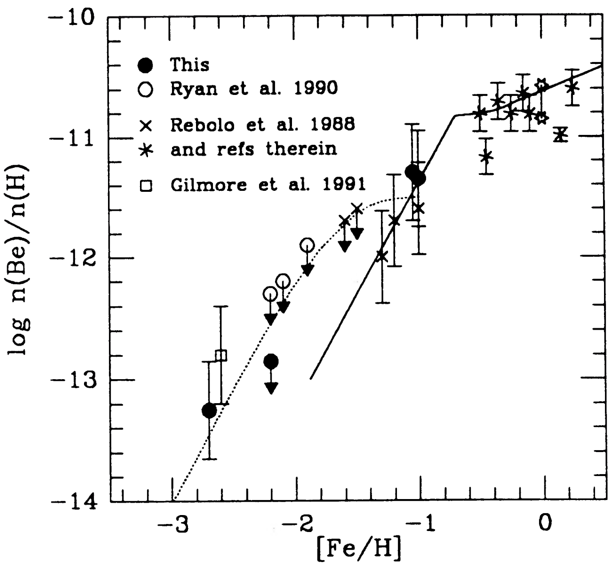

FIG. 3.—Detections and upper limits on Be abundances. Observations: *filled symbols*: this study; *open circles*: Ryan et al. 1990; *crosses*: Rebolo et al. 1988; *asterisks*: references in Rebolo et al. 1988; *box*: Gilmore et al. 1991; *stars*: meteoric (upper) and solar photospheric (lower) abundances from Anders & Grevesse 1989. The two lowest abundance points are different observations of the same star, HD 140283. Errors are not shown for the upper limits. Models: *solid curve*: model from Vangioni-Flam et al. (1990, Fig. 2); *dotted curve*: model for synthesis in the halo computed in this paper, allowing for a decline in halo-star-formation rate which lowers the cosmic-ray flux.

6300 K (encompassing the present program stars) has been used to argue that these stars have not been subject to depletion over their lifetimes. Indeed, standard evolutionary stellar models indicate that Li is depleted by only ~0.1 dex in these stars (Deliyannis, Demarque, & Kawaler 1990). Since, however, rotationally induced mixing could reduce the Li abundance uniformly by an order of magnitude (Pinsonneault, Deliyannis, & Demarque 1991), it is necessary to consider the possibility of rotationally induced Be depletion, especially since some Population I, F stars are known to be significantly Be-depleted (Boesgaard 1976).

Deliyannis & Pinsonneault (1990) present a study dedicated to Be in Population II stars. Their evolutionary stellar models consider three classes of progressively more complex physics that might affect the surface Be: standard models, models with diffusion, and models with rotation. In all three cases, subgiants do not begin dilution until $T_{\rm eff} \sim 5500$ K, similar to the observations of Boesgaard & Chesley (1976) for Population I subgiants. We are satisfied that even our stars in which log g has decreased toward 3.0 will be free from depletion due to *dilution*. For the dwarfs, standard models produce negligible depletion for $T_{\rm eff} > 4900$ K. The magnitude of diffusion depends sensitively on the depth of the surface convection zone, which itself depends sensitively on uncertain parameters (e.g., opacities, mixing length); furthermore, diffusion can be inhibited by turbulence. Nevertheless, diffusion causes preferential Li depletion toward the hotter portion of the Li plateau (Deliyannis et al. 1990), and thus its effects can be observationally constrained by the remarkable flatness in the Li plateau (Deliyannis & Demarque 1991). Deliyannis & Pinsonneault give 0.1 dex as the upper limit on Be diffusion. Finally, their *rotational* models give yet larger Be depletion, possibly 0.2 dex for stars in our study, but they take the conservative position that this depletion could be an overestimate because of current uncertainties in our knowledge of rotational mixing.

In the comparison of observed abundances with models for Galactic and cosmological evolution, it is necessary to keep in mind that the surface abundances may have decreased by between 0.0 and 0.3 dex (the sum of diffusive and rotational effects) over the stellar lifetimes, depending on current uncertainties in the model physics.

4. PRIMORDIAL SYNTHESIS OF BERYLLIUM

Although earlier computations had shown that the primordial synthesis of Be in the standard big bang was almost negligible [log n(Be)/n(H) = −22.7], Boyd & Kajino (1989) showed that the previously neglected ^{7}Li(^{3}H, n)^{9}Be reaction would, when included, raise this by seven orders of magnitude (to a still unobservable abundance). [The recent experimental determination of the ^{3}H(^{7}Li, n)^{9}Be cross section by Coc et al. (1991) suggests a reduction in the earlier predicted abundances, calculated using a theoretical cross section value, by about 0.4 dex.] A more observationally interesting computation, however, is for Be synthesis in inhomogeneous big bang models which incorporate inhomogeneities during nucleosynthesis, such as may have arisen earlier due to the quark-hadron phase transition. The parameters which govern nucleosynthesis in this scenario are not well determined, so it is necessary to explore a large range of parameter space.

Malaney & Fowler (1989) and Kajino & Boyd (1990) have reinvestigated standard and inhomogeneous nucleosynthesis, and we now summarize some of their findings for production of Be in inhomogeneous models. For intermediate values of the volume fraction occupied by high-density zones, $f_v \sim 0.5$, and for high values of the density contrast between high and low-density regions, $R > 20$, they find that Be synthesis is almost independent of R. Synthesis falls by several orders of magnitude at lower values of the contrast, tending toward the standard model at $R = 1$. Synthesis is also largely independent of R for small values of the baryon density, $\Omega_B < 0.04$. Currently considered variations of Ω_B over the range 0.04 to 1.0 produce a range in Be production of only a factor of 10, small (!) in comparison to the variation due to other uncertain parameters.

Kurki-Suonio et al. (1990) and Reeves et al. (1990) argue from the comparison of computations and observations of ^{7}Li and ^{4}He that Ω_B is not permitted to exceed 0.2 or 0.3 even in the inhomogeneous big bang, and they further discuss the constraint of R to lie probably below 100. Even with these restrictions, the computations of Kajino & Boyd still permit a large range in possible primordial synthesis levels, from log n(Be)/n(H) = −16.0 to −13.5. We discuss how the present observations might be interpreted in § 5, but we first note that Terasawa & Sato (1990) have questioned the high levels of primordial synthesis predicted by the model used by Kajino & Boyd. Specifically, Terasawa & Sato find that the neglect of neutron diffusion during nucleosynthesis cannot be ignored, and with its inclusion they derive primordial synthesis levels lower by two orders of magnitude. Kajino & Boyd had not overlooked this matter, but argued for its neglect; work is continuing. (It is not possible to reference all relevant work in this brief discussion. For a more detailed review, see Malaney & Mathews 1991.)

5. GALACTIC EVOLUTION OF BERYLLIUM

The Galactic production of Be is simpler to model than the evolution of elements which form in the interiors of stars. Assuming that Be is indeed produced by cosmic rays, the production rate of Be is proportional to the product of the abundance of C, N, O targets in the interstellar medium (ISM) and the cosmic-ray flux (e.g., Vangioni-Flam et al. 1990). The number ratio of C, N, O elements in the ISM increases with time due to the synthesis of these elements in stars, but the gas mass falls due to star formation. The cosmic-ray flux is assumed to be proportional to the supernova rate, which for halo stars is proportional to the star-formation rate since this determines the number of high-mass stars which evolve quickly into Type II supernovae prior to the evolution of lower mass stars into Type I supernovae. A detailed model has been published by Kajino & Boyd (1990).

The models referenced above predict a slope of approximately 2 for halo stars in the [Be/H], [Fe/H] plane. The abundance of spallation targets increases linearly with metallicity, and the cosmic-ray flux is assumed proportional to the star-formation rate, which is almost constant with time during halo formation in these models. Thus the production *rate* of Be is linearly proportional to metallicity, and its integral over the time since the formation of the Galaxy runs as the second power of metallicity, giving rise to a slope of 2 in the logarithmic abundance plane.

The preferred model VIIb from Vangioni-Flam et al. (1990), which has a time varying star-formation rate *after* 2 Gyr, is shown as a solid curve in Figure 3, along with data from Table 1. Although it fits the data well for [Fe/H] > -1.5, it does not come close to the data for HD 140283. We have no reason to believe that this star is unusually enriched in Be, and the high abundance could be the signature of primordial synthesis of Be, lying within the range computed for inhomogeneous big bang models by Kajino and Boyd. However, in the absence of additional data for halo stars, a firm conclusion would be premature. In keeping an open mind on the explanation for the elevated Be abundance in HD 140283, we present below an alternative analysis of galactic enrichment of this element.

The departure of HD 140283 from the galactic enrichment models may be due to the use of inapplicable models for halo enrichment rather than it being indicative of primordial synthesis. The models discussed above treat enrichment of Be in halo stars as the lead up to enrichment in disk stars. It is known, however, that in order to fit the metallicity distribution of the halo by a simple model for galactic chemical evolution, it is necessary to reduce the yield by a factor of ~ 10 from that inferred from disk stars (e.g., Hartwick 1976; Laird et al. 1988b; Ryan & Norris 1991). The reason for the lower effective yield is not clear, but in the absence of any reason for invoking radically different nucleosynthetic yields in metal-poor stars, Hartwick (1976) proposed that the reduced yield was due to the loss of mass from the halo-star–forming process at a rate proportional to the star-formation rate, caused presumably by supernova heating. This has the effect of reducing the star-forming gas mass faster than is expected from star-formation alone, and hence star formation terminates before all of the original gas has been turned into stars.

The mass loss scenario envisaged by Hartwick would influence the production of Be in the following way. The abundance of relevant spallation targets (C, N, O), the most abundant of which is O, increases proportional to the iron abundance in the halo (e.g., Wheeler et al. 1989, Fig. 2, but see also the caveat at the end of our § 5), so there is no change in this contribution to the slope of the model in Figure 3. However, since the star-formation rate falls more quickly in Hartwick's scenario the supernova rate (and hence cosmic-ray flux) will have a different dependence on abundance. The new model for Be production is described below.

The time rate of Be production is proportional to the time-dependent quantities: the abundance by number of C, N, O targets, which we call $X_{\rm CNO}$ (in units normalized to the solar C, N, O abundance); the gas mass fraction (ratio of nonstellar mass to total mass) $\mu(t)$, where $\mu(0) = 1$; and the star-formation rate SFR:

$$\frac{d}{dt} Z_{\rm Be} = {\rm const}\, Z_{\rm CNO}\, \mu\, {\rm SFR} .$$

We assume that the ratios of the yields for Fe, the CNO group, and the overall metallicity are constant over the period of halo formation. (This would not be true if we attempted to simultaneously include the disk, in which iron production is higher relative to the CNO group.) The abundance Z and effective yield p (without subscripts) will be used to refer to iron, which is what is commonly measured. Since the ratio $Z_{\rm CNO}/Z$ is constant in our assumption, we will replace $Z_{\rm CNO}$ by Z and absorb the factor into the constant of the equation. Following the simple model (see, e.g., Pagel & Patchett 1975), we assume that SFR is proportional to the gas fraction μ, and have $\ln \mu = -Z/p$, where p is the effective yield (in solar abundance units). It follows then that

$$\frac{d}{dt} Z_{\rm Be} = {\rm const}\, Z \exp\left(\frac{-2Z}{p}\right),$$

where we accumulate all constants in one term. Since $d\mu/dt$ (including mass loss) is proportional to SFR, which is in turn proportional to μ, we find $\ln \mu = {\rm const}\, t$, which with the result above shows that the metallicity increases linearly with time. We then have

$$Z_{\rm Be}(t) = {\rm const} \int_0^{Z(t)} Z \exp\left(\frac{-2Z}{p}\right) dZ$$

which gives, as a function of Z,

$$\log_{10} Z_{\rm Be} = {\rm const} + \log_{10}\left\{1 - \left(\frac{2Z}{p} + 1\right) \exp\left(\frac{-2Z}{p}\right)\right\}. \tag{1}$$

Ryan & Norris (1991) determined the effective yield in the halo to be $p = 10^{-1.6}$. We are considering only halo production so we normalize not to the solar system meteoric value but to the value ([Fe/H], $\log_{10} n({\rm Be})/n({\rm H})) = (-1.0, -11.5)$, which represents the higher abundance halo data. With this boundary condition the constant in equation (1) is found to be -11.5. The model is shown as the dotted curve in Figure 3 and is found to give better agreement between the data for HD 140283 and the higher abundance halo points. We emphasize that we have not introduced any new physics in this computation; we have merely taken the model found to explain the overall halo metallicity distribution, i.e., the synthesis of iron in stars, and applied it to the synthesis of Be in the interstellar gas.

Most upper limits to Be lie just above the model; these points are merely consistent with the model, and currently do nothing to help us decide between the existing alternatives. Clearly, it is observations of stars with [Fe/H] ~ -2.0 which will be most important in this regard. The limit for HD 84937 and some of the data near [Fe/H] $= -1.0$ fall slightly below the model line, but are still within the uncertainties.

Future observations especially of stars in the range $-3 \leq$ [Fe/H] ≤ -2 will hopefully reveal the slope of the halo stars in the [Be/H], [Fe/H] plane, and will indicate whether the extension of the simple model presented here is appropriate. The relative (over-?) simplicity with which Be synthesis appears to proceed permits only a few modifications to be made to a given model to make it "fit the data," i.e., Be observations are unforgiving of poor models. It may be that mass loss from the halo-star–formation process is not the cause of the low halo effective yield, in which case it is incorrect to infer a decreasing star-formation rate (cosmic-ray flux) as we have done. Also, the ratio Z_{CNO}/Z may require more thorough treatment once [O/Fe] is reliably known, since we have utilized the earlier but now challenged result that [O/Fe] is uniform for stars over the range of [Fe/H] in the halo (see Abia & Rebolo 1989; Bessell et al. 1991).

6. RELATIONSHIP TO OTHER LIGHT ELEMENTS

Earlier works on Be (Rebolo et al. 1988; Paper I) have discussed the limit set by this element on the spallative contribution to halo Li. Steigman & Walker (1991) have computed, however, that $\alpha + \alpha$ fusion reactions contribute substantially to the production of Li in a Population II environment. Their inclusion of this mechanism raised the predicted halo Li/Be ratio, according to which the Be abundances are consistent with a significant proportion of the Population II Li being of cosmic ray origin, not just at the few percent level. With our upper limit for Be in HD 84937, the model of Steigman & Walker (their eq. [20]) predicts a cosmic ray induced Li(6 + 7) component $\log \epsilon(\mathrm{Li}) < 1.65$.[3] Since only half of this is the observed isotope, ^{7}Li, the model predicts $\log \epsilon(^7\mathrm{Li}) < 1.35$ from cosmic rays, and an additional $\log \epsilon(^7\mathrm{Li}) > 2.0$ is still required to account for the observed abundance in this star, $\log \epsilon(^7\mathrm{Li}) \sim 2.1$. This additional contribution, if primordial, would also be present in the other lithium plateau stars. The cosmic ray contribution to Li borders on being excessive in some stars, e.g., HD 76932, for which equation (20) (without ^{6}Li) would raise $\log \epsilon(^7\mathrm{Li})$ from primordial 2.0 up to 2.2, compared with the observed 1.95. Future work on both elements should clarify this issue.

The measurement of boron abundances (Duncan, Lambert, & Lemke 1991) using *Hubble Space Telescope* ultraviolet spectra will provide additional insight into the relative roles of spallation and possible primordial synthesis of the light elements. The latter mechanism, however, is not yet well constrained in parameter space (see the references discussed in § 4), and the B/Be ratio expected from spallation is sensitive to assumptions regarding the low-energy cosmic-ray proton flux. Interpretation of the observational data will not, it seems, be a trivial exercise.

[3] $\log \epsilon(\mathrm{Li}) = \log [n(\mathrm{Li})/n(\mathrm{H})] + 12.00$.

7. CONCLUSIONS

We have obtained Be abundances for three halo stars and an upper limit for a fourth, using spectra at 3130 Å with a resolution of 0.1 Å (FWHM). Abundances were determined using a spectrum synthesis code (Cottrell & Norris 1978) to allow for blending, especially with OH lines. It is possible that the Be surface abundances in these stars have been depleted by 0.0 to 0.3 dex, depending on the treatment of uncertain stellar physics (Deliyannis & Pinsonneault 1990).

The abundances were discussed considering models for galactic and primordial synthesis of Be. Computations of primordial synthesis of Be in inhomogeneous big bang models vary by two orders of magnitude (Kajino & Boyd 1990; Terasawa & Sato 1990), and we can at best place upper limits on possible primordial nucleosynthesis. Models for galactic production of Be in the halo differ by ~ 1 dex depending on whether synthesis in the halo is treated as the lead up to synthesis in the disk, or whether the halo is treated differently, as we have done following requirements imposed by the overall metallicity distribution of the halo. Observations of stars of $[\mathrm{Fe/H}] \sim -2.0$ are required to clarify the enrichment history of this element, and to utilize it as a constraint on various production mechanisms with implications for Galactic evolution and big bang cosmology.

We are grateful to R. D. Cannon and B. Croke of the Anglo-Australian Observatory for obtaining the spectrum of HD 140283 as a Service Observation. S. G. R. acknowledges financial support from the Australian National University and an operating grant awarded to D. A. VandenBerg from the Natural Science and Engineering Council of Canada.

REFERENCES

Abia, C., & Rebolo, R. 1989, ApJ, 347, 186
Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Bell, R. A. 1981, private communication
Bell, R. A., & Oke, J. B. 1986, ApJ, 307, 253
Bessell, M. S., Sutherland, R. S., & Ruan, K. 1991, ApJ, 383, L71
Boesgaard, A. M. 1976, ApJ, 210, 466
———. 1990, in Cool Stars, Stellar Systems, and the Sun (ASP Conf. Ser. 9) ed. G. Wallerstein, p. 317
———. 1991, CFHT Bulletin, 25, 14
Boesgaard, A. M., & Chesley, S. E. 1976, ApJ, 210, 475
Boyd, R. N., & Kajino, T. 1989, ApJ, 336, L55
Budge, K., Boesgaard, A., & Varsik, J. 1988, in IAU Symposium 132, The Impact of Very High S/N Spectroscopy in Stellar Physics, ed. G. Cayrel de Strobel & M. Spite (Dordrecht: Reidel), 585
Buser, R. 1987, private communication
Carney, B. W. 1983, AJ, 88, 623
Coc, A., et al. 1991, preprint
Cottrell, P. L., & Norris, J. 1978, ApJ, 221, 893
Deliyannis, C. P., & Demarque, P. 1991, ApJ, 379, 216
Deliyannis, C. P., Demarque, P., & Kawaler, S. D. 1990, ApJS, 73, 21
Deliyannis, C. P., & Pinsonneault, M. H. 1990, ApJ, 367, L67
Duncan, D., Lambert, D. L., & Lemke, M. 1991, private communication
François, P. 1986, A&A, 160, 264
Gilmore, G., Edvardsson, B., & Nissen, P. E. 1991, ApJ, 378, 216
Gratton, R. G., & Sneden, C. 1987, A&A, 178, 179
Hartwick, F. D. A. 1976, ApJ, 209, 418
Kajino, T., & Boyd, R. N. 1990, ApJ, 359, 267
Kurki-Suonio, H., Matzner, R. A., Olive, K. A., & Schramm, D. N. 1990, ApJ, 353, 406
Kurucz, R. L. 1989, private communication
Kurucz, R. L., Furenlid, I., Brault, J., & Testerman, L. 1984, Solar Flux Atlas from 296 nm to 1300 nm (National Solar Observatory Atlas No. 1)
Laird, J. B., Carney, B. W., & Latham, D. W. 1988a, AJ, 95, 1843
Laird, J. B., Rupen, M. P., Carney, B. W., & Latham, D. W. 1988b, AJ, 96, 1908
Magain, P. 1987a, A&A, 179, 176
———. 1987b, A&A, 181, 323
Malaney, R. A., & Fowler, W. A. 1989, ApJ, 345, L5
Malaney, R. A., & Mathews, G. J. 1991, Phys. Rep., submitted
Pagel, B. E. J., & Patchett, B. E. 1975, MNRAS, 172, 13
Peterson, R. C. 1976, ApJ, 206, 800
Pinsonneault, M. H., Deliyannis, C. P., & Demarque, P. 1991, ApJ, 367, 17
Rebolo, R., Molaro, P., Abia, C., & Beckman, J. E. 1988, A&A, 193, 193
Reeves, H., Richer, J., Sato, K., & Terasawa, N. 1990, ApJ, 355, 18
Ryan, S. G., Bessell, M. S., Sutherland, R. S., & Norris, J. E. 1990, ApJ, 348, L57 (Paper I)
Ryan, S. G., & Norris, J. E. 1991, AJ, 101, 1865
Ryan, S. G., Norris, J. E., & Bessell, M. S. 1991, AJ, 102, 303
Schuster, W. J., & Nissen, P. E. 1989, A&A, 222, 69
Sneden, C. 1974, ApJ, 189, 493
Spite, F., & Spite, M. 1982, A&A, 115, 357
Steigman, G., & Walker, T. P. 1991, ApJ, submitted
Terasawa, N., & Sato, K. 1990, ApJ, 362, L47
Vangioni-Flam, E., Casse, M., Audouze, J., & Oberto, Y. 1990, ApJ, 364, 568
Wheeler, J. C., Sneden, C., & Truran, J. W. Jr. 1989, ARA&A, 27, 279
Wiese, W. L., & Martin, G. A. 1980, in Wavelengths and Transition Probabilities for Atoms and Atomic Ions (NSRDS-NBS 68) (Washington, DC: GPO), 359