THE ASTROPHYSICAL JOURNAL, 447:184–190, 1995 July 1

BERYLLIUM AND BORON ABUNDANCES OF METAL-DEFICIENT HALO STARS AND ACCRETION OF INTERSTELLAR MATTER

Y. YOSHII,[1] G. J. MATHEWS,[2] AND T. KAJINO[3]

Received 1994 September 14; accepted 1995 January 17

ABSTRACT

We discuss the correlation of light-element abundances with metallicity for metal-deficient dwarfs in the Galactic halo. We show that such stars can experience some metal enrichment after their formation because of accreting interstellar material during repeated encounters with molecular clouds in the Galactic plane. If light-element abundances are produced by the secondary spallation of preexisting heavy elements by cosmic rays, then this accretion affects the light-element abundances and metal abundances differently. We construct an analytic chemical evolution model for the halo and disk which reproduces the observed abundance correlations and the halo metallicity distribution. We show that the introduction of interstellar accretion leads to a low metallicity plateau in the correlation of light elements with metallicity which would mimic the formation of such elements in the big bang. We suggest here that the observation of a constant light-element abundance at low metallicity may not be a signature of primordial origin but rather a measure of the average accretion rate from metal-enriched gas in the Galactic plane.

Subject headings: accretion, accretion disks — Galaxy: halo — stars: abundances

1. INTRODUCTION

Recently there have been a number of reported detections of beryllium and boron abundances in low-metallicity stars (Rebolo et al. 1988; Ryan et al. 1990, 1992; Gilmore, Edvardsson, & Nissen 1991; Gilmore et al. 1992; Duncan, Lambert, & Lemke 1992). Such studies were originally motivated, at least in part, by suggestions (Boyd & Kajino 1989; Malaney & Fowler 1989; Kajino & Boyd 1990) that baryon inhomogeneous big bang nucleosynthesis models might produce large abundances of ^{9}Be and ^{11}B relative to the insignificant production expected from standard homogeneous big bang nucleosynthesis (Wagoner, Fowler, & Hoyle 1967; Wagoner 1973; Thomas et al. 1993). If there were a primordial contribution to the light elements, it would manifest itself as a constant light-element abundance at low metallicity as in the case of the well-known flattening of the primordial lithium abundance for $[\mathrm{Fe/H}] \lesssim -1$ observed in Population II stars (e.g., Rebolo et al. 1988).

Some of the original theoretical motivation for a flattening of the abundance of beryllium and boron at low metallicity has waned, however, largely because of the development of more physical treatments of baryon diffusion during primordial nucleosynthesis (Kurki-Suonio et al. 1990; Terasawa & Sato 1990; Mathews et al. 1990; Jedamzik, Fuller, & Mathews 1994; Thomas et al. 1994). Nevertheless, the observation of beryllium and boron abundances as a function of stellar metallicity remains as an important indicator of cosmic-ray nucleosynthesis in the early Galaxy (Gilmore et al. 1991; Ryan et al. 1992; Steigman & Walker 1992; Walker et al. 1993; Duncan et al. 1992; Prantzos, Casse, & Vangioni-Flam 1993; Fields, Schramm, & Truran 1993). Furthermore, if a beryllium or boron plateau were ever discovered, it could be an important indication of some primordial production which would have a significant impact on models for primordial nucleosynthesis.

In this regard, the present study introduces a cautionary note. We demonstrate here that the same flattening of light-element abundances with metallicity could be achieved via the accretion of interstellar material during repeated passages of halo stars through the disk. We propose that observations of both beryllium and boron abundances at lower metallicity ($[Z] < -3$) could serve to confirm or deny this hypothesis. We construct an analytic model that is consistent with the observed metallicity distribution in the halo and all present observations of light-element abundances. This model also accounts for the observed flattening of the observed (Be/O) ratio at high metallicity and the decrease in (Be/O) at low metallicity. The effects of interstellar accretion in this model are then derived and shown to be potentially significant for light elements.

2. INTERSTELLAR ACCRETION ON HALO STARS

The possibility that halo stars could accumulate a small amount of metal-enriched material in their outer convective regions through encounters with interstellar clouds in the Galactic plane has been a speculation for some time (Talbot & Newman 1977; Wesemael 1979; Yoshii 1981; Iben 1983). Such a scenario has been proposed as a means to account for the paucity of stars at low metallicity. Indeed, there is even some evidence for accretion to have occurred in local white dwarfs. Aannestad & Sion (1985) analyzed the spatial and velocity distributions of 17 cool metal-line white dwarfs. They found evidence that these white dwarfs were associated with known local regions of interstellar gas, and over half appear to have passed through regions of enhanced density within the past 10^6 yr. Accretion during these encounters would account for the presence of trace metals on their surface. A subsequent study (Aannestad et al. 1993) of the spatial correlation between gas and stars for 15 metal-poor white dwarfs, however, has concluded that only a few of the stars could have recently accreted or presently be accreting from local clouds. Nevertheless, accretion is now widely regarded as the solution to the white

---

[1] Institute of Astronomy, University of Tokyo, Mitaka, Tokyo 181, Japan.

[2] University of California, Lawrence Livermore National Laboratory; University of Notre Dame, Department of Physics; and National Astronomical Observatory, Tokyo. Postal address: University of Notre Dame, Department of Physics, Notre Dame, IN 46556.

[3] Division of Theoretical Astrophysics, National Astronomical Observatory, Mitaka, Tokyo 181, Japan.

dwarf metal-line puzzle, that is, a way to explain the presence of metals which should rapidly sink below the atmospheres of white dwarfs. Indeed, Kenyon et al. (1988) and Sion, Aannestad, & Kenyon (1988) have found calcium absorption features in the trace atmospheric hydrogen of DBA and DB white dwarfs. They infer a calcium-to-hydrogen abundance that is close to cosmic abundances, as would be expected if the calcium and hydrogen were accreted from the interstellar medium. Although such data are not definitive, they are at least suggestive.

In this context it is of interest to consider how the accretion of metal-enriched material might affect the correlations among different elements. In particular, the enrichment history of such cosmic-ray–produced elements as beryllium and boron could be quite different than that for primary products of stellar nucleosynthesis such as oxygen and iron. The same could hold true for any secondary element produced only from preexisting seed material, such as heavy *s*-process nuclei.

2.1. *The Accretion Model*

The accretion rate onto a star of mass M as it passes through an interstellar gas cloud with a velocity $v_{\rm rel}$ relative to the unperturbed parts of the cloud can be approximated (Bondi 1952):

$$\dot{M} \approx 2\pi(GM)^2 \rho_c (v_{\rm rel}^2 + c_s^2)^{-3/2} , \tag{1}$$

where ρ_c is the average unperturbed cloud density and $c_s = \gamma P_c/\rho_c$ is the unperturbed sound speed in the cloud (where P_c is the cloud pressure and γ is the adiabatic index). The second factor in parentheses in equation (1) is an *Ansatz* that allows one to interpolate between the two well-defined extremes of a temperature- (or pressure-) limited rate of accretion ($v_{\rm rel} \ll c_s$) and an accretion rate determined by the motion of the star relative to the cloud ($v_{\rm rel} \gg c_s$). Substituting appropriate numerical factors, the accretion rate can be written as

$$\dot{M} \approx 3 \times 10^{-15} \left(\frac{M}{M_\odot}\right)^2 \left(\frac{n_{\rm H}}{10^3\ {\rm cm}^{-3}}\right) \times \left(\frac{c_{\rm eff}}{100\ {\rm km\ s}^{-1}}\right)^{-3} M_\odot\ {\rm yr}^{-1} , \tag{2}$$

where $n_{\rm H}$ is the average hydrogen number density in dense clouds and $c_{\rm eff} = (v_{\rm rel}^2 + c_s^2)^{1/2}$ is an effective sound velocity (Bondi 1952).

The average accretion rate $\dot{M}_a$ is obtained by multiplying equations (1) or (2) by the fraction of time that stars spend within the clouds. This fraction can be estimated from the ratio of the time Δt during which the stars are passing through clouds to the mean time t_e between encounters with clouds:

$$\dot{M}_a = \frac{\Delta t}{t_e} \dot{M} . \tag{3}$$

The transit time through the clouds can just be estimated from the ratio of cloud radius to the relative velocity. Averaging over the impact parameter for an encounter with a spherical cloud gives

$$\Delta t = \frac{4R_c}{3v_{\rm rel}} , \tag{4}$$

where R_c is the average cloud radius, $R_c \sim 10$ pc.

The time between encounters is given simply by the average number density of clouds n_c and their average geometric cross section:

$$t_e = \frac{1}{\pi R_c^2 v_{\rm rel} n_c} . \tag{5}$$

For a star with an orbit within the plane, the number density is just that within the Galactic disk $n_c^{\rm disk} \sim 10^{-5}$ pc^{-3} (McKee & Ostriker 1977; Talbot & Newman 1977). For stars with an orbit which oscillates significantly above and below the Galactic plane, the average number density must be decreased by a factor of the ratio of the time spent in the plane to the oscillation period. Also, stars that pass through the plane have a higher relative velocity, which decreases the accretion rate in equation (2). We thus consider the above estimate to be an upper limit:

$$\frac{\Delta t}{t_e} \le \frac{4\pi R_c^3 n_c}{3} \sim 0.04 \left(\frac{R_c}{10\ {\rm pc}}\right)^3 \left(\frac{n_c}{10^{-5}\ {\rm pc}^{-3}}\right) . \tag{6}$$

Taking $c_{\rm eff} \sim 100$ km s^{-1}, the typical average accretion rate is probably $\lesssim 10^{-16}\ M_\odot$ yr^{-1}. Taking the age of halo stars to be $\sim 10^{10}$ yr, the total accreted mass is $M_a \lesssim 10^{-6}\ M_\odot$.

This accreted matter, although minuscule, can affect the elemental abundances in the surface convective zones for these stars. The accretion we are concerned with occurs during the main sequence (i.e., pre– and post–main-sequence accretion are irrelevant). During the main sequence, the mass of the convective envelope has some dependence on stellar mass, metallicity, and age (Yoshii 1981; Pinsonneault, Deliyannis, & Demarque 1992). Typical values for models without rotation range from $M_c \sim 10^{-4}$ for $M \sim 0.9\ M_\odot$ and $Z \lesssim 10^{-3}$ up to $M_c \sim 4 \times 10^{-2}$ for $M \sim 0.7\ M_\odot$ and $Z \approx 10^{-2}$. Models with rotation can permit significant light-element destruction. However, this destruction is constrained by the recent observation of ^{6}Li on a halo star (Smith, Lambert, & Nissen 1992). Furthermore, to the degree that depletion occurs (Pinsonneault et al. 1992), it is largely independent of metallicity. This implies that it can be compensated in galactic evolution calculations described below by an overall rescaling of the yields.

For the present illustration we therefore take a 0.8 $M_\odot$ dwarf with fixed $M_c \approx 4 \times 10^{-3}$ as a representative case. In a sense, this is the most pessimistic scenario. The model calculations (e.g., Pinsonneault et al. 1992) suggest that the convective shell mass actually decreases in time. For a fixed accretion rate, this will have the effect of increasing the mass fraction observed at present of the higher metallicity matter in the convective shell relative to that for a fixed convective shell mass. However, for simplicity we neglect that effect here.

Accordingly, for our sample calculation, accreted matter accounts for ~0.01% or more of the present convective shell mass. For such small outer convective regions even this slight accretion can make a significant difference in the surface metallicity.

Let us consider a closed surface convective region with no exchange of material with the inner radiative core and no mass loss. The metallicity is then affected only by the accretion of new material (Yoshii 1981):

$$\frac{d(M_c Z_c)}{dt} = Z_g \dot{M} , \tag{7}$$

where Z_c is the metallicity of the convective surface and Z_g is the metallicity of the accreting gas.

Equation (7) can be solved for the metallicity in the convective surface as a function of the total accreted mass M_a at the present time T for a star that was born at time t:

$$Z_c(T, t) = \frac{Z_g(t)M_c + \langle Z_g \rangle_d M_a}{M_c + M_a} . \tag{8}$$

The quantity $\langle Z_g \rangle_d$ denotes the time-averaged metallicity of accreting gas between t and T. The subscript d has been added to emphasize that this accretion occurs during encounters with molecular clouds in the disk.

If one considers the ratio of two species, for example, (Be/O), then equation (8) simplifies even further to

$$\left(\frac{\mathrm{Be}}{\mathrm{O}}\right)_c = \frac{\mathrm{Be}(t)M_c + \langle \mathrm{Be} \rangle_d M_a}{\mathrm{O}(t)M_c + \langle \mathrm{O} \rangle_d M_a} . \tag{9}$$

To see what effects accretion might have on the light-element abundance correlations, one must consider the different nucleosynthetic origins for oxygen and beryllium (or boron).

2.2. *Galactic Chemical Evolution for the Halo and Disk*

It is commonly accepted that the simplest modification (Hartwick 1976) of the closed-box model with instantaneous recycling (Tinsley 1980), which allows for a reproduction of the metallicity distribution in the halo, is to allow for a galactic wind in the halo proportional to the rate of star formation,

$$\frac{dM_{\mathrm{tot}}}{dt} = -c\psi(t) , \tag{10}$$

where $\psi(t)$ is the mass of interstellar halo gas going into new star formation per unit time and c is a unitless constant of proportionality. Typically, $c \sim 6$ for the halo and $c \approx 0$ for the disk. The abundance of primary elements produced in massive stars (like oxygen) then simply scales with the star formation rate,

$$\frac{d(ZM_g)}{dt} = y\psi(t) - (1 - R + c)\psi(t)Z , \tag{11}$$

where M_g is the mass of the interstellar medium, y is the average fraction of the initial stellar mass that is ejected as newly produced material from a generation of stars, and R is the average fraction of the initial stellar mass that is returned to the interstellar medium. (Note that eq. [11] applies equally well to the halo or disk. The only difference is that $c = 0$ for the disk.)

By making a change of variable from time to gas fraction μ, the abundance of any primary element can then be written

$$Z = -p \ln(\mu) , \tag{12}$$

where $p = y/(1 - R + c)$ is an effective metallicity yield. For total metallicity, $p \sim 0.01$. For $R \sim 0.2$ the effective yield p for the halo is then about a factor of 5 lower than that for the disk. This explains the rapid decrease in the number of halo stars with increasing metallicity compared to the disk metallicity distribution (Hartwick 1976).

The abundance of light elements like beryllium and boron, however, cannot be described with a simple form like equation (12). These elements are thought to be largely produced by the interactions of cosmic rays with the interstellar medium that induce spallation reactions of heavier C, N, and O nuclei.

The equation analogous to equation (11) for the evolution of the mass fraction Z_L of a nuclide produced by cosmic-ray spallation on heavier species Z_j is then

$$\frac{d(Z_L M_g)}{dt} = M_g \sum_j Z_j \left(\frac{A_L}{A_j}\right) \langle \sigma_{j,L} \Phi \rangle - (1 + c)\psi(t)Z_L , \tag{13}$$

where (A_L/A_j) accounts for mass conservation, and

$$\langle \sigma_{j,L} \Phi \rangle = \sum_i \int \phi_i(E, t)\sigma_{ij}^L(E)S_L(E)dE , \tag{14}$$

where ϕ_i is the flux of impinging cosmic-ray projectiles, $\sigma_{ij}^L(E)$ is the cross section for cosmic-ray interactions with nuclei j, and $S_L(E)$ gives the fraction of light-element products that survive slow-down and incorporation into the interstellar medium (Walker, Mathews, & Viola 1985).

The factor $(1 + c)$ replaces the factor $(1 - R + c)$ in the loss term in equation (13) since, to an excellent approximation (Iben 1967; Boesgaard & Chesley 1976; Dearborn 1992), all of the initial light elements present in a star are destroyed before material is returned to the interstellar medium. This complicates the evolution equation slightly, as we shall see.

Note that a factor of Z enters into this expression either from the factor Z_j (for cosmic-ray protons and α-particles impinging on interstellar CNO) or from the relative cosmic-ray fluxes (for cosmic-ray CNO nuclei impinging on interstellar protons and α-particles). This latter point follows from the observation that, for the most part, the inferred present cosmic-ray source abundances are close to the present interstellar medium abundances.

We also note that the equilibrium cosmic-ray flux within a fixed volume is just proportional to the rate at which sources eject mass into cosmic rays. It is generally accepted that the cosmic-ray sources are in one way or another associated with supernovae, supernova progenitors, or supernova remnants. Hence, if we take the mass of produced cosmic rays to be proportional to the mass ejection rate from supernovae, we can write

$$\phi_i \propto \psi(t) . \tag{15}$$

This introduces a factor of $\psi(t)$ into the light-element source term for equation (13), as in the stellar source term of equation (11). However, the extra factor of M_g in the source term in equation (13) alters the analog of equation (12) for cosmic-ray nucleosynthesis to

$$Z_L = \alpha\left[\mu \ln(\mu) - \left(\frac{1}{1 - \gamma}\right)(\mu - \mu^\gamma)\right] + Z_L^0 \mu^\gamma , \tag{16}$$

where α is a normalization constant, Z_L^0 accounts for any primordial contribution (taken here to be the standard big bang abundances of Thomas et al. 1993), and γ is related to the returned fraction R and the outflow coefficient c:

$$\gamma = \frac{R}{1 - R + c} . \tag{17}$$

Combining equation (16) with equation (12) gives the explicit dependence of light-element abundances on metallicity:

$$Z_L = \alpha\left[-\left(\frac{Z}{p}\right)e^{-Z/p} - \left(\frac{1}{1 - \gamma}\right)(e^{-Z/p} - e^{-\gamma Z/p})\right] + Z_L^0 e^{-\gamma Z/p} . \tag{18}$$

Of course, one is not certain of the cosmic-ray activity and survival fraction in the past, which introduces additional parameters into the calculation (see Prantzos et al. 1993; Fields et al. 1993). However, we find that this simple halo model reproduces all of the observed trends in the data and is consistent with the halo metallicity distribution. It is thus adequate for the present schematic study.

Note that equation (18) does not simply scale as the square of metallicity, as one would expect from a true secondary element that is produced from preexisting heavy seed material in a star. That limit is achieved only as $Z \to 0$. Again, the different behavior is due to the extra factor of M_g from the cosmic-ray source term in equation (13). What happens instead is that, as the gas becomes depleted, the cosmic-ray source term diminishes more rapidly than would be expected for simple stellar secondary production. This means that Z_L flattens with Z at the highest metallicity relative to the $Z_L \propto Z^2$ behavior at low metallicity. For sufficiently high metallicity, the loss term dominates even over the production terms, and Z_L will eventually decrease with Z. As we shall see, with reasonable parameters for the halo, the analytic form in equation (18) is consistent with the data. For example, the flattening of the observed [Be/O] correlation for $[\mathrm{O/H}] > -2$ is a natural consequence and does not require that the cosmic-ray flux vary much faster than the supernova rate (Fields et al. 1993), or a time variation of the cosmic-ray escape length (Prantzos et al. 1993; Malaney & Butler 1993).

With the evolution of light-element abundances and metallicity as a function of time now specified, we can return to the question of the effect of accreting material on the observed light-element abundances. The remaining quantity desired to determine the abundances after accretion observed at present is the time-averaged disk metallicity and light-element abundance to insert into equations (8) and (9). From equation (11), the metallicity in the disk at time T relative to that for a star born at a time t is just

$$Z_g(T) = Z_g(t) + y \int_t^T \frac{\psi(t')}{M_g(t')}\, dt' . \qquad (19)$$

To compute the time average, we must assume a specific time dependence for the fractional rate, $\psi(t)/M_g(t)$, of interstellar gas going into new star formation. For the purposes of this schematic model, a star formation rate proportional to the gas mass M_g is reasonable, $\psi(t) = \nu M_g$. In this case, the fraction $\psi(t)/M_g(t) = \nu$ is a constant, and the metallicity grows linearly with time. The average metallicity encountered by a star born with initial metallicity Z is then just

$$\langle Z \rangle_d = \frac{\int_t^T Z_g(t')dt'}{T - t} = 0.5[Z_g(t) + Z_\odot] , \qquad (20)$$

where we have assumed a present average metallicity of solar for gas in the disk. The mean light-element abundance, $\langle Z_L \rangle_d$, encountered by halo stars as they transit the disk is given by an integration of equation (18). The exact analytic solution is

$$\langle Z_L \rangle_d = \frac{p}{Z_\odot - Z}\left[F\left(\frac{Z_\odot}{p}\right) - F\left(\frac{Z}{p}\right)\right] , \qquad (21)$$

where

$$F(x) = \alpha\left[(1 + x)e^{-x} + \left(\frac{1}{1 - \gamma}\right)\left(e^{-x} - \frac{1}{\gamma}\, e^{-\gamma x}\right)\right] - \frac{Z_L^0}{\gamma}\, e^{-\gamma x} . \qquad (22)$$

Here one can see that there is a considerable difference between the mean abundance of accreted light elements and the mean metallicity. The light elements grow at first more slowly than metallicity and then grow rapidly at higher metallicity. The mean light-element abundance at time T is thus not much affected by the evolution at early times and low metallicity. In the limit of low metallicity ($Z/p \ll 1$), equation (21) thus goes to a constant value. This constant dominates the numerator of equation (8) at low initial metallicity, so that the effect of accretion is to produce a constant apparent light-element abundance independently of the initial light-element abundance or metallicity. This flattening of the accreted light-element abundance versus metallicity mimics a contribution from the production of light elements in the big bang.

3. RESULTS

For the purposes of comparison with observations, we have compiled and selected beryllium and boron data from several sources. The Be data for metal-poor stars are taken from Rebolo et al. (1988), Ryan et al. (1990, 1992), Gilmore et al. (1992), and Boesgaard & King (1993). The Be data for metal-rich stars are from Boesgaard (1976). When the same star is observed by two different groups, the following selection criterion were used:

1. In the case of detection, the different values are shown by different symbols, for example, HD 140283 by Gilmore et al. (1992), Ryan et al. (1992), and Boesgaard & King (1993).
2. In the case of upper limits, only the lower of the two limits is shown, that is, HD 19445 by Rebolo et al. (1988) and Ryan et al. (1990), and HD 84937 by Gilmore et al. (1992) and Ryan et al. (1992). For these two stars, the Ryan et al. (1992) limits are lower and are shown.
3. The upper limit for HD 47147 in Ryan et al. (1990) is not shown because this is a red horizontal-branch star and beryllium could be greatly depleted.
4. The upper limit for HD 200654 in Gilmore et al. (1992) is shown. This is the most metal-poor star in our sample. Gilmore et al. (1992), however, deleted this from their sample, arguing that this is a subgiant with a cool effective temperature $T_{\mathrm{eff}} \sim 5090$ K and the beryllium could be depleted. They justify this argument by referring to the paper by Deliyannis & Pinsonneault (1990). However, this paper shows that, for the standard stellar models without rotation, Be depletion does not occur for stars with $T_{\mathrm{eff}} > 4900$ K. For stellar models with rotation, Be depletion does occur, but the depletion factor is less than 1.5 for such stars. Considering that the depletion factor for HD 200654 with $T_{\mathrm{eff}} \sim 5090$ K is almost unity in the standard stellar models or near unity even in the nonstandard rotation models, we conclude that there is no compelling reason to exclude this star from the sample.
5. Only six stars (HD 19445, HD 64090, HD 84937, HD 94028, HD 140283, and HD 194598) are selected from Boesgaard & King (1993). That is, we chose only those with $[\mathrm{O/H}] < 0.5$ in order to avoid confusion and $T_e > 5100$ K to minimize possible depletion on cooler stars, and we chose stars that are new detections.

The B data for three metal-poor stars are from Duncan et al. (1992). The recently reported (Edvardsson et al. 1994) B abundance for HD 140283 quotes two different abundances by using both LTE and non-LTE models for the stellar atmosphere: $\log(\mathrm{B/H}) = -12.20$ (LTE) and -11.66 (non-LTE). The LTE abundance is fully consistent with the Duncan et al.

(1992) points shown in Figure 5. As long as $[O/H] = -2.1$ is used for HD 140283, the non-LTE abundance of Edvardsson et al. is above the theoretical curve in our figures. However, if $[O/H] = -1.79$ (Boesgaard & King 1993) is used, the non-LTE abundance just fits on the curve. Until both B and O for this star are determined using the same non-LTE method, it is not possible to determine whether or not the B abundance for HD 140283 deviates from the theoretical prediction. Hence, we omit this point from the figures.

For stars with $[O/H] = 0.0$, the meteoritic Be and B abundances of Anders & Grevesse (1989) are often used in the literature. However, light-element abundances from meteorites are systematically larger than those from solar photosphere or metal-rich disk stars. Considering these systematics, we prefer to use the abundances adopted by Reeves & Meyer (1978). Their Figure 1 shows the systematics of measured light-element abundances in various media. Their adopted values are $\mathrm{Be/H} = 1.4 \times 10^{-11}$ and $\mathrm{B/H} = 2 \times 10^{-10}$. In particular, the Be abundance is consistent with the mean Be abundance for Boesgaard's metal-rich F and G dwarf stars that are used in our paper (see Table 3 of Boesgaard 1976). The present-day average Be and B abundances are tabulated in a more recent review (Arnould & Forestini 1989), but the adopted values are the same as those of Reeves & Meyer (1978).

The oxygen abundances for most of the sample stars are measured or estimated in Gilmore et al. (1992). When not available, we used a well-established empirical formula $[O/H] = [Fe/H] + 0.5$ for stars with $[Fe/H] < -1$.

In order to compare the data, the returned fraction was taken to be $R = 0.2$, and the halo mass ejection rate was set to $c = 6$, which fits the halo metallicity distribution. We take the average yield to be $y = 0.008$ (i.e., $p = 0.01$ for the disk). The remaining two parameters, α and ν, which describe the cosmic-ray normalization and the star formation rate, respectively, should be regarded as separate adjustable parameters for the disk and halo. The star formation parameter ν_{halo} was adjusted to give a metallicity of $[Z] = -0.5$ after 3×10^9 yr (Yoshii & Saio 1979; Dickens et al. 1991) for the halo phase. For the disk phase, ν_{disk} was adjusted to give $[Z] = 0.0$ after 10^{10} yr. The parameter α_{halo} was adjusted to give $\log(\mathrm{Be/H}) = -11.4$ [or $\log(\mathrm{B/H}) = -10.3$] at 3×10^9 yr. For the disk, α_{disk} was adjusted to give $\log(\mathrm{Be/H}) = -10.85$ [or $\log(\mathrm{B/H}) = -9.7$] (Reeves & Meyer 1978) at $T = 10^{10}$ yr.

Figure 1 shows a sample calculation of the expected values for (Be/H) as a function of [O/H], both for the case of no accretion (*lower curve*) and for the case in which accretion has occurred at a rate of $10^{-16}\ M_\odot\ \mathrm{yr}^{-1}$ (*upper curve*). Figure 2 shows the same calculation for an average accretion rate of $10^{-17}\ M_\odot\ \mathrm{yr}^{-1}$. These calculations are compared with the observed abundances as described above. The dotted lines connect initial and final abundances for stars that have experienced accretion. For both calculations the initial beryllium abundance was taken to be the big bang value 1.7×10^{-18} (Thomas et al. 1993). The different evolution history for stars in the halo and disk are also shown as separate lines for $[O/H] \gtrsim -1$. These figures clearly show the dramatic flattening of the abundance correlation at low metallicity ($[O/H] \lesssim -3$) for stars that have accreted disk material. Of course, in a real sample there should be a dispersion in the data due to differing accretion histories and convective envelope masses. Nevertheless, if this accretion picture is correct, then observed Be abundances at low metallicity ($\lesssim -3$) should fall between the upper and lower curves in Figure 1.

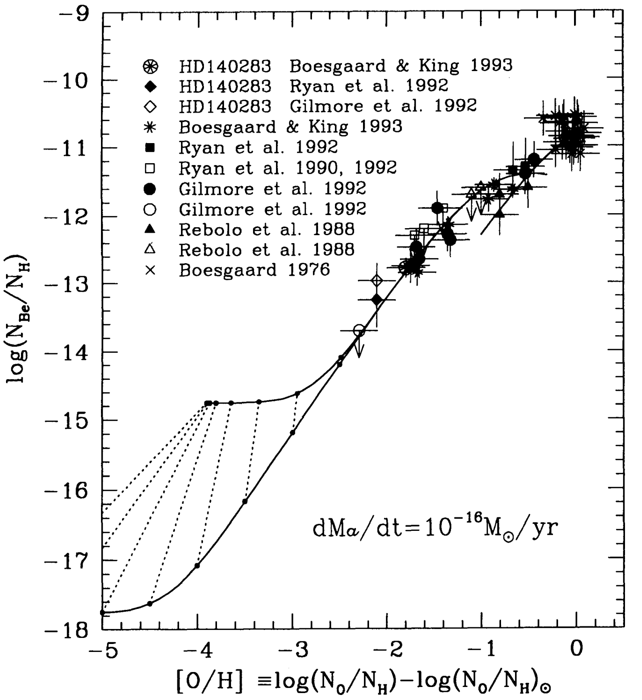

FIG. 1.— $\log (N_{\mathrm{Be}}/N_{\mathrm{H}})$ as a function of [O/H]. The data are from various sources as labeled according to the selection criteria described in the text. The solid lines show the expected beryllium abundance, both without accretion (*lower curve*) and with an average accretion rate of $10^{-16}\ M_\odot\ \mathrm{yr}^{-1}$ (*upper curve*). The calculations assume an initial standard big bang value of $\mathrm{Be/H} = 1.7 \times 10^{-18}$ (Thomas et al. 1993). The dotted lines connect initial and final abundances of beryllium and oxygen for stars born with different initial metallicity, which then accrete disk material.

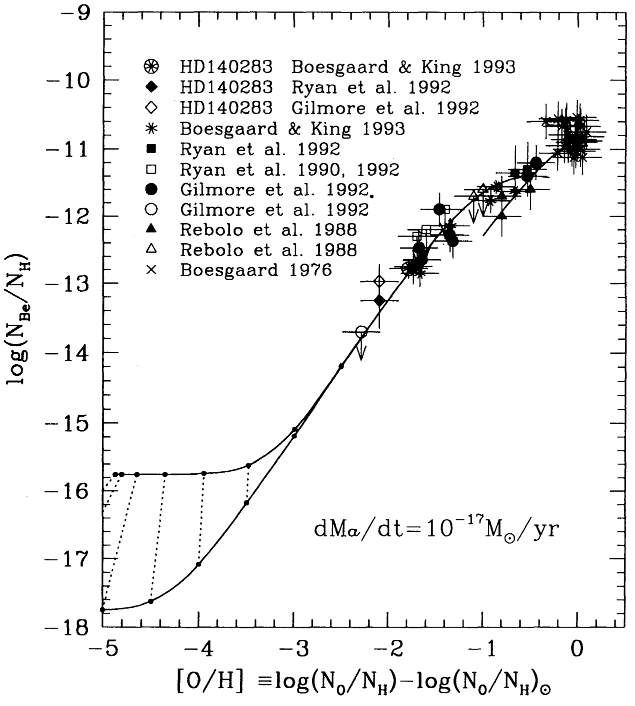

FIG. 2.—Same as Fig. 1, but with an accretion rate of $10^{-17}\ M_\odot\ \mathrm{yr}^{-1}$

1995ApJ...447..184Y

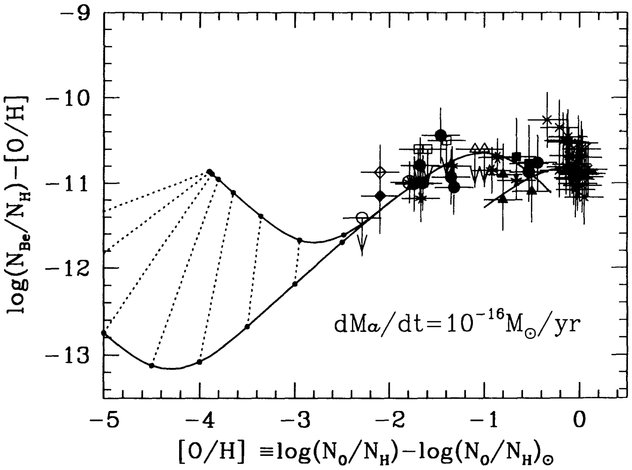

FIG. 3.—Values of $\log(N_{\rm Be}/N_{\rm H}) - [{\rm O/H}]$ as a function of [O/H] for an average accretion rate of $10^{-16}\ M_\odot\ {\rm yr}^{-1}$ (*upper curve*) and no accretion (*lower curve*).

Figures 3 and 4 show the same calculations and data plotted for the (Be/O) ratio. The dotted lines show the trajectory from initial to final abundances for stars born at different times and initial metallicity as in Figures 1 and 2. It is interesting to note that our upper limit to the accretion rate is just below the level at which the data would be sensitive to accretion. Our prediction is that measurements at lower metallicity should exhibit an increase in the Be/O ratio as a result of the fact that the apparent beryllium abundance remains fixed as the oxygen abundance decreases toward lower metallicity.

At present, the data place an upper limit on the average accretion rate of $\dot{M} \lesssim 10^{-16}\ M_\odot\ {\rm yr}^{-1}$. The extension of the observed beryllium abundances to yet lower metallicity would strengthen this limit.

Figures 5 and 6 show the same models applied to the boron observations. Here the standard big bang boron abundance was taken to be $B/H = 8.9 \times 10^{-18}$. Clearly, there is a need for more data at lower metallicity. Nevertheless, as in the beryllium curves, a flattening of the abundances is predicted for $[{\rm O/H}] \lesssim -3$ if accretion has occurred. An important point to note, however, is that even if there is a dispersion in the correlation between light-element abundances and oxygen, the stellar B/Be ratios should remain constant at the cosmic-ray production ratio independently of the accretion history. We return to this point below.

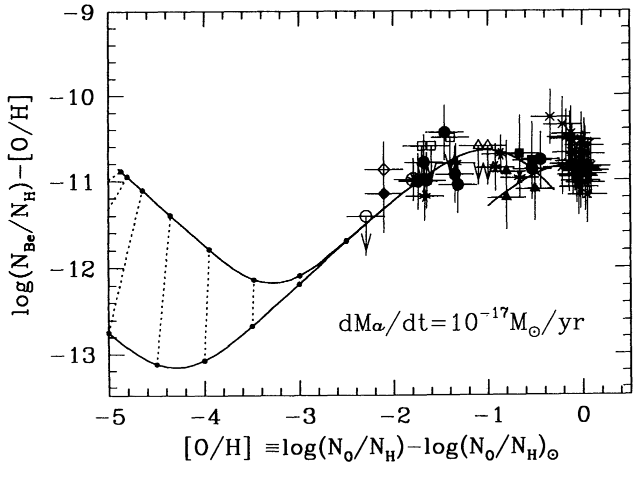

FIG. 4.—Values of $\log(N_{\rm Be}/N_{\rm H}) - [{\rm O/H}]$ as in Fig. 3, but with an accretion rate of $10^{-17}\ M_\odot\ {\rm yr}^{-1}$.

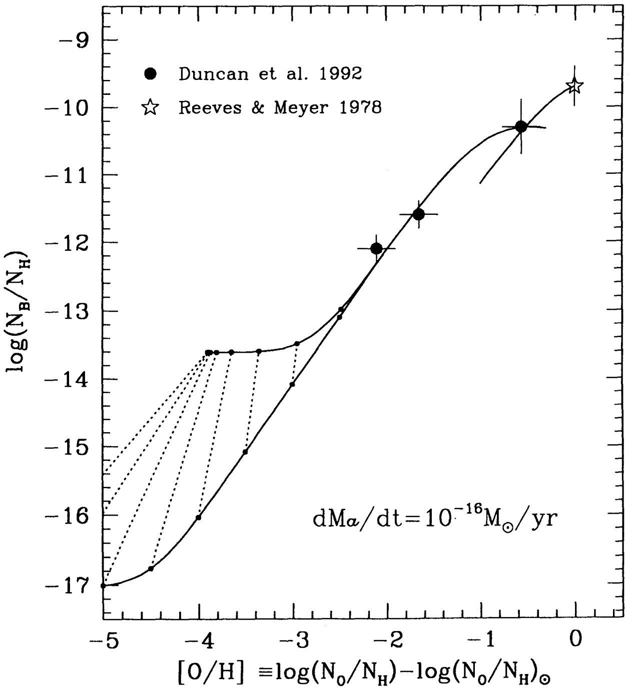

FIG. 5.—Values of $\log(N_{\rm B}/N_{\rm H})$ as a function of [O/H]. The solid lines show the expected boron abundance, both without accretion (*lower curve*) and with an average accretion rate of $10^{-16}\ M_\odot\ {\rm yr}^{-1}$ (*upper curve*).

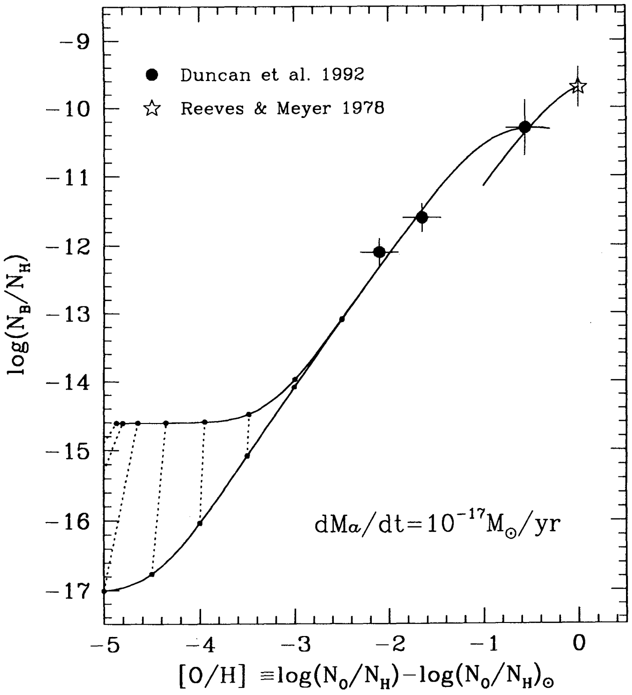

FIG. 6.—Values of $\log(N_{\rm B}/N_{\rm H})$ as in Fig. 5, but with an accretion rate of $10^{-17}\ M_\odot\ {\rm yr}^{-1}$.

4. CONCLUSIONS

We have considered the effects on observed surface light-element abundances from the accretion of metal-enriched interstellar matter onto metal-poor halo stars as they pass through dense molecular clouds in the disk. Based on reasonable estimates for the accretion rate, we have shown that a plateau in the light-element abundance correlation with metallicity may emerge that would mimic a primordial abundance signature. In particular, the correlation of Be and B abundances with [O/H] should increase and flatten for $[O/H] \lesssim -3$. Hence, the observation of such a flattening of light-element abundances may be an indicator of the interstellar accretion rate and not a signature of primordial inhomogeneities from the big bang.

We propose that it may be possible to distinguish between a primordial or accretion enrichment scenario by determining abundances of both beryllium and boron in the plateau region. This ratio is fixed for an individual star by the cosmic-ray production ratio, B/Be ~ 12–14, in the accretion model. This ratio is independent of the accretion rate and simply reflects the cosmic-ray spallation processes of the interstellar medium. For inhomogeneous big bang models, however, this ratio is strongly dependent on the baryon density in low- and high-density regions, as depicted in Figure 7. For low average baryon density, the value is less than unity. For higher baryon density, this ratio increases by many orders of magnitude. This rapid variation is due to the strong density dependence of the nuclear reactions that produce light elements in the big bang. Thus, the probability of a primordial B/Be ratio being coincidentally close to the cosmic-ray production ratio is small.

In view of this, we suggest that there is now more motivation than ever to search for a flattening of the beryllium and boron abundances at low metallicity. Of course, we recognize that extending the Be and B abundance determinations into the regime $[O/H] \lesssim -3$ (or $[Fe/H] \lesssim -3.5$) will be *very* difficult, perhaps impossible, because the accessible lines of Be II and B I may vanish below the limit of detectability. Nevertheless, if such observations could be made, they would serve not only as a means to distinguish between cosmic-ray and primordial nucleosynthesis, but also as a means to confirm and quantify the degree to which the accretion of molecular cloud material has occurred on the surface convective zones of halo stars.

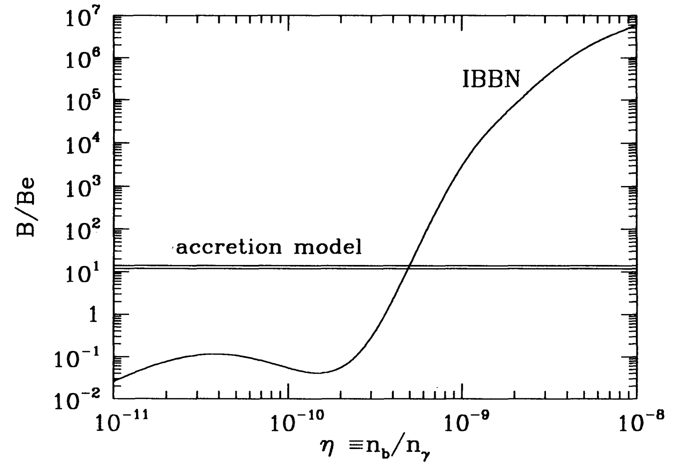

FIG. 7.—B/Be ratio as a function of local baryon-to-photon ratio η for a representative inhomogeneous big bang model calculation (with $R = 10^6$, $f_v^{1/3} = 0.25$, and $r = 50$ m at $T = 100$ MeV of Mathews, Kajino, & Orito 1994) in which the fluctuation scale is in excess of the neutron diffusion length. The value of this ratio expected from cosmic-ray nucleosynthesis as would occur in the accretion model discussed here is also shown.

One of us (G. J. M.) wishes to thank the National Astronomical Observatory of Japan for its support while much of this work was done. This work was also performed in part under the auspices of the US Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48 and Department of Energy Nuclear Theory grant number SF-ENG-48.

REFERENCES

Aannestad, P. A., Kenyon, S. J., Hammond, G. L., & Sion, E. M. 1993, AJ, 105, 1033
Aannestad, P. A., & Sion, E. M. 1985, AJ, 90, 1832
Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Arnould, M., & Forestini, M. 1989, in Nuclear Astrophysics, ed. M. Lozano, M. I. Gallardo, & J. M. Arias (Berlin: Springer), 48
Boesgaard, A. M. 1976, ApJ, 210, 466
Boesgaard, A. M., & Chesley, S. E. 1976, ApJ, 210, 475
Boesgaard, A. M., & King, J. R. 1993, AJ, 106, 2309
Bondi, H. 1952, MNRAS, 112, 195
Boyd, R. N., & Kajino, T. 1989, ApJ, 336, L55
Dearborn, D. S. 1992, Phys. Rep., 220, 367
Deliyannis, C., & Pinsonneault, M. 1990, ApJ, 365, L67
Dickens, R., Croke, B., Cannon, R., & Bell, R. 1991, Nature, 351, 212
Duncan, D., Lambert, D., & Lemke, D. 1992, ApJ, 400, 584
Edvardsson, B., et al. 1994, A&A, 290, 176
Fields, B. D., Schramm, D. N., & Truran, J. W. 1993, ApJ, 405, 559
Gilmore, G., Edvardsson, B., & Nissen, P. 1991, ApJ, 378, 17
Gilmore, G., Gustafsson, B., Edvardsson, B., & Nissen, P. 1992, Nature, 357, 379
Hartwick, F. D. A. 1976, ApJ, 209, 418
Iben, I. 1967, ApJ, 147, 624
Iben, I. 1983, Mem. Soc. Astron. Ital., 54, 321
Jedamzik, K., Fuller, G. M., & Mathews, G. J. 1994, ApJ, 423, 50
Kajino, T., & Boyd, R. N. 1990, ApJ, 359, 267
Kenyon, S. J., Shipman, H. L., Sion, E. M., & Aannestad, P. A. 1988, ApJ, 328, L90
Kurki-Suonio, H., Matzner, R. A., Olive, K. A., & Schramm, D. N. 1990, ApJ, 353, 406
Malaney, R. A., & Butler, M. N. 1993, ApJ, 407, L73
Malaney, R. A., & Fowler, W. A. 1989, ApJ, 345, L5
Mathews, G. J., Kajino, T., & Orito, M. 1994, ApJ, submitted
Mathews, G. J., Meyer, B. S., Alcock, C. R., & Fuller, G. M. 1990, ApJ, 358, 36
McKee, C. F., & Ostriker, J. P. 1977, ApJ, 218, 148
Pinsonneault, M. H., Deliyannis, C. P., & Demarque, P. 1992, ApJS, 78, 179
Prantzos, N., Casse, M., & Vangioni-Flam, E. 1993, ApJ, 403, 630
Rebolo, R., Molaro, P., Abia, C., & Beckman, J. 1988, A&A, 193, 93
Reeves, H., & Meyer, J. P. 1978, ApJ, 226, 613
Ryan, S. G., Bessel, M. S., Sutherland, R. S., & Norris, J. E. 1990, ApJ, 348, L57
Ryan, S. G., Norris, J. E., Bessel, M. S., & Deliyannis, C. P. 1992, ApJ, 388, 184
Sion, E. M., Aannestad, P. A., & Kenyon, S. J. 1988, ApJ, 330, L55
Smith, V. V., Lambert, D. L., & Nissen, P. E. 1992, ApJ, 408, 262
Steigman, G., & Walker, T. 1992, ApJ, 385, L13
Talbot, R. J., & Newman, M. J. 1977, ApJS, 34, 295
Terasawa, N., & Sato, K. 1990, ApJ, 362, L47
Thomas, D., Schramm, D. N., Olive, K. A., & Fields, B. D. 1993, ApJ, 406, 569
Thomas, D., et al. 1994, ApJ, 430, 291
Tinsley, B. M. 1980, Fund. Cosmic Phys., 5, 287
Wagoner, R. V. 1973, ApJ, 197, 343
Wagoner, R. V., Fowler, W. A., & Hoyle, F. 1967, ApJ, 148, 3
Walker, T. P., Mathews, G. J., & Viola, V. E. 1985, ApJ, 299, 745
Walker, T. P., Steigman, G., Schramm, D. N., Olive, K. A., & Fields, B. D. 1993, ApJ, 413, 562
Wesemael, F. 1979, A&A, 72, 104
Yoshii, Y. 1981, A&A, 97, 280
Yoshii, Y., & Saio, H. 1979, PASJ, 183, 339