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THE PRODUCTION OF BERYLLIUM IN THE EARLY GALAXY

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ABSTRACT

The formation of beryllium in the early Galaxy is discussed. It is shown that if spallation occurs predominantly in regions rich in heavy elements, i.e., close to supernovae, the linear relation recently obtained by Gilmore et al. (1992) between beryllium and oxygen abundances for Population II stars may be reproduced. Estimates of relevant timescales for mixing show that the decisive factor, the ratio of the timescale of cosmic-ray diffusion out of the locally enriched regions to the decay time of cosmic rays in the Galaxy as a whole, admits this scenario. Although energetically possible, it requires, however, very high local cosmic-ray fluxes ($\geq 10^5$ cm^{-2} s^{-1}), which predicts γ-ray fluxes above those observed from supernova remnants and the Galaxy. We therefore consider other models, such as those given by Duncan et al. (1992) or Prantzos et al. (1993), more probable.

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

1. INTRODUCTION

The discovery by Gilmore, Edwardsson, & Nissen (1991) of beryllium in the very metal-poor dwarf HD 140283 ([Fe/H] ~ -2.7) led to considerable discussion of the possibility that this beryllium was created in the very early Universe as a result of inhomogeneities in the big bang (see, e.g., Pagel 1991). The beryllium abundance measured for HD 140283 by Gilmore et al. (1991, 1992) and by Ryan et al. (1992) is about two orders of magnitude above the predictions from models for production of light elements by spallation of CNO elements by cosmic rays in the early Galaxy (Vangioni-Flam et al. 1990). Later, boron has been, somewhat tentatively, identified in HD 140283 by Duncan, Lambert, & Lemke (1992) and in two other Population II dwarfs. These authors find boron/beryllium ratios consistent with those expected from spallation, although the uncertainties are considerable and non-LTE effects modify their result (Kiselman 1993). In a recent study Gilmore et al. (1992) have found that the beryllium abundance in Population II dwarfs varies linearly with the oxygen abundance, indicating a behavior of beryllium as that of a "primary element," rather than the quadratic behavior which, according to simple single-models with instantaneous mixing of oxygen and cosmic rays in the interstellar medium, is expected for "secondary elements." This linear variation of the beryllium abundance with oxygen obviously suggests a production of beryllium in proportion to the production of oxygen in the early Galaxy. The boron observations in three stars by Duncan et al. (1992) also suggest a linear relation between the boron abundance and the metallicity. The linear relations for beryllium and possibly for boron versus oxygen could be explained in a model in which spallation took place in the immediate neighborhood of supernovae, where the abundance of target nuclei for spallation is high. Here, we shall discuss, using very schematic models of the early Galaxy, whether this is a viable explanation for the linear relation found by Gilmore et al. (1992).

2. ANALYSIS

2.1. *Single-Zone Models*

Models have been constructed for the chemical evolution of the Galaxy in which the heavy elements and cosmic rays produced in supernovae are instantaneously mixed out into the whole Galaxy (e.g., Vangioni-Flam et al. 1990). The spallation then takes place in this well-mixed medium. Vangioni-Flam et al. (1990) find a roughly quadratic dependence of the beryllium abundance on the oxygen abundance in the early Galaxy. In order to investigate whether this is an inevitable characteristic of the single-zone models, we have studied the beryllium production in simple parameterized models.

Consider a region, of volume v, which has a time-dependent total number of oxygen nuclei, $n_{\rm O}(t)$, of beryllium nuclei, $n_{\rm Be}(t)$, and of cosmic-ray particles $n_{\rm CR}(t)$. The region has a star formation rate (proportional to the supernova rate), $r(t)$. The production rate of oxygen nuclei is $\alpha_{\rm O}\, r(t)$ and of cosmic-ray particles $\alpha_{\rm CR}\, r(t)$. We neglect the initial heavy-element abundances in the region, i.e., we adopt the initial conditions $n_{\rm O}(0) = n_{\rm Be}(0) = n_{\rm CR}(0) = 0$. There is a loss rate of oxygen, beryllium, and cosmic-rays from the region of $\lambda_{\rm O}\, n_{\rm O}(t)$, $\lambda_{\rm Be}\, n_{\rm Be}(t)$, and $\lambda_{\rm CR}\, n_{\rm CR}(t)$, respectively.

We then have the following equations:

$$\frac{dn_{\rm O}(t)}{dt} = \alpha_{\rm O}\, r(t) - \lambda_{\rm O}\, n_{\rm O}(t)\ , \tag{1}$$

$$\frac{dn_{\rm CR}(t)}{dt} = \alpha_{\rm CR}\, r(t) - \lambda_{\rm CR}\, n_{\rm CR}(t)\ . \tag{2}$$

Beryllium is assumed to be essentially produced by cosmic rays hitting the oxygen nuclei. The production rate is proportional to $\bar{\sigma}$ [cm^3 s^{-1}], which is the weighted mean of the product of relative particle velocity times cross section. We have

$$\frac{dn_{\rm Be}(t)}{dt} = \frac{\bar{\sigma}}{v}\, n_{\rm O}(t) n_{\rm CR}(t) - \lambda_{\rm Be}\, n_{\rm Be}(t)\ . \tag{3}$$

The solution to this system of equations is

$$n_{\rm O}(t) = \alpha_{\rm O} \int_0^t e^{-\lambda_{\rm O}(t-s)} r(s) ds\ , \tag{4}$$

$$n_{\rm CR}(t) = \alpha_{\rm CR} \int_0^t e^{-\lambda_{\rm CR}(t-s)} r(s) ds\ , \tag{5}$$

$$n_{\rm Be}(t) = \frac{\bar{\sigma}}{v}\,\alpha_{\rm O}\,\alpha_{\rm CR}\,e^{-\lambda_{\rm Be}t}\int_0^t e^{(\lambda_{\rm Be}-\lambda_{\rm CR}-\lambda_{\rm O})s}\,ds \times \int_0^s e^{\lambda_{\rm O}x}r(x)dx \int_0^s e^{\lambda_{\rm CR}x}r(x)dx\,. \quad (6)$$

We now parameterize the star formation rate:

$$r(t) = \theta\mathcal{N}e^{-\theta t}\,,$$
$$\mathcal{N} = \int_0^\infty r(t)dt\,, \quad (7)$$

$\mathcal{N}$ being the total accumulated number of supernovae in the region.

We have, numerically, calculated the behavior of the solutions, assuming different relations between the star formation decay rate, θ, and the diffusion parameters, $\lambda_{\rm CR}$, $\lambda_{\rm Be} \approx \lambda_{\rm O}$. From our calculations we draw the conclusions that, in this model, at early times beryllium cannot be produced in proportion to the oxygen abundance for any choice of relation between the parameters. This is because the spallation production term in equation (3) contains the product of the oxygen abundance and the cosmic-ray density, both being related to the number of supernovae, while the oxygen abundance is linearly dependent on the accumulated number of supernoae. The steep slope in $n_{\rm Be}/n_{\rm O}$, as obtained in more detailed models, e.g., Vangioni-Flam et al. (1990), is also due to this ($n_{\rm Be}$ and $n_{\rm O}$ denoting the total number of each kind formed in the whole Galaxy). At later times astration of beryllium and decay of cosmic rays lower the curves in more detailed models. We also find $n_{\rm Be}(t) \propto n_{\rm O}(t)$ at later times in some single-zone models. This reflects a state in which the supernova rate is so low that there is hardly any new production of oxygen and beryllium so that the abundance ratio $n_{\rm Be}/n_{\rm O}$ stays constant. The observational result of Gilmore et al. (1992) cannot be explained by this property of singlezone models since that would imply that the overall metallicity in the Galaxy should decrease with time.

2.2. *Double-Zone Models*

We now consider an idealized proton-Galaxy of volume V, containing a number of regions where star formation and supernovae occur, each region of volume v. Each region is described in the same manner as in the single-zone model. The rate of formation of such enriched regions is $R(t)$. For the Galaxy as a whole, we have loss terms similar to those in the single-zone model, $\Lambda_{\rm O}N_{\rm O}(t)$, $\Lambda_{\rm Be}N_{\rm Be}(t)$, and $\Lambda_{\rm CR}N_{\rm CR}(t)$, with $N_{\rm O}(t)$ denoting the total number of oxygen nuclei, $N_{\rm Be}(t)$ the number of beryllium nuclei, and $N_{\rm CR}(t)$ the number of cosmic rays in the interstellar medium.

In this model spallation occurs in regions locally enriched in target nuclei by supernovae, and we assume that the cosmic rays are also created in enriched regions, in winds from massive early-type stars or supernovae. For our two-phase model Galaxy, we have the following differential equations:

$$\frac{dN_{\rm O}(t)}{dt} = \int_0^t R(t-x)\lambda_{\rm O}\,n_{\rm O}(x)dx - \Lambda_{\rm O}N_{\rm O}(t)\,, \quad (8)$$

$$\frac{dN_{\rm CR}(t)}{dt} = \int_0^t R(t-x)\lambda_{\rm CR}\,n_{\rm CR}(x)dx - \Lambda_{\rm CR}N_{\rm CR}(t)\,. \quad (9)$$

Beryllium in the overall interstellar medium has two sources; leakage from the enriched regions and spallation in the medium itself. Thus we may write

$$\frac{dN_{\rm Be}(t)}{dt} = \int_0^t R(t-x)\lambda_{\rm Be}\,n_{\rm Be}(x)dx + \frac{\bar{\sigma}}{V}N_{\rm O}(t)N_{\rm CR}(t) - \Lambda_{\rm Be}N_{\rm Be}(t)\,. \quad (10)$$

Strictly speaking, the volume appearing in the denominator of the second term on the right-hand side should be the volume of the interstellar medium phase, which, however, can be assumed to be close to that of the whole Galaxy. We adopt the following initial conditions: $N_{\rm O}(0) = 0$, $N_{\rm CR}(0) = 0$, and $N_{\rm Be}(0) = 0$. One may write the solution for $N_{\rm Be}(t)$ in the explicit form

$$N_{\rm Be}(t) = \int_0^t e^{-\Lambda_{\rm Be}(t-s)}Y(s)ds\,, \quad (11)$$

where $Y(s)$ is a known function.

For the present discussion we are interested in limiting cases rather than a specific model which is sensitive to parameter choices. We thus consider the behavior at early times and neglect the losses of oxygen and beryllium nuclei from the Galaxy as a whole (i.e., setting $\Lambda_{\rm O} = \Lambda_{\rm Be} = 0$). The characteristic loss rate of cosmic rays due to absorption in the interstellar matter or diffusion losses out of the Galaxy is smaller than the local cosmic-ray diffusion rate, i.e., $\Lambda_{\rm CR} < \lambda_{\rm CR}$. The timescale for the decay of cosmic rays in the volume of the whole early Galaxy is not known. For the present Galaxy $\Lambda_{\rm CR}^{-1}$ may be estimated from the abundances of radioactive cosmic-ray nuclei from which values around $(1\text{–}2) \times 10^7$ yr are found (Bloemen 1987). The recent discovery of a 1–4 μG magnetic field in a galaxy at $z = 0.395$ toward PKS 1229−021 (Kronberg, Perry, & Zukowski 1992) suggests that substantial field may have existed in the early Galaxy. Lacking any certain knowledge about this, and about other early conditions in the Galaxy, we adopt $\Lambda_{\rm CR}^{-1} \sim 10^7$ yr. It is reasonable to assume that the characteristic time for fresh oxygen to be mixed into the interstellar medium is shorter than 10^7 yr. We assume that $\Lambda_{\rm CR} < \lambda_{\rm O}$ also for the early Galaxy.

We also parameterize the rate of formation of enriched regions by

$$R(t) = \mathcal{R}\Theta e^{-\Theta t}\,. \quad (12)$$

The characteristic time (Θ^{-1}) for the decay of global star formation in contemporary Galaxy models is on the order of 10^9 yr. Assuming $\Lambda_{\rm CR} \gg \Theta$ also in the early Galaxy we obtain for $t < \Theta^{-1}$:

$$\frac{N_{\rm Be}(t)}{N_{\rm O}(t)} = \bar{\sigma}\alpha_{\rm CR}\mathcal{N}\left[\frac{1}{v(\lambda_{\rm Be}+\lambda_{\rm CR})} + \frac{\mathcal{R}\Theta t}{2V\Lambda_{\rm CR}}\right]. \quad (13)$$

Since, in this approximation,

$$N_{\rm O}(t) = \alpha_{\rm O}\mathcal{N}\mathcal{R}\Theta t\,, \quad (14)$$

we find

$$N_{\rm Be}(t) = \bar{\sigma}\alpha_{\rm CR}\left[\frac{\mathcal{N}N_{\rm O}(t)}{v(\lambda_{\rm Be}+\lambda_{\rm CR})} + \frac{N_{\rm O}^2(t)}{2V\Lambda_{\rm CR}\alpha_{\rm O}}\right]. \quad (15)$$

The first term in the right-hand side of equation (15) is a (diffusion-corrected) spallation term which is linearly proportional to the oxygen abundance. The second, which has a quadratic dependence on oxygen, reflects spallation production in the interstellar medium after the cosmic rays have diffused from the enriched regions. From equation (13) we find that the beryllium abundance scales linearly with the oxygen abundance as long as

$$t \ll t_{\rm crit} \equiv \frac{2V\Lambda_{\rm CR}}{v\mathscr{R}\Theta(\lambda_{\rm Be}+\lambda_{\rm CR})} . \quad (16)$$

Obviously, long local diffusion times ($\lambda_{\rm Be}$ and $\lambda_{\rm CR}$ being small), long-lasting star formation (Θ being small) and/or rapidly decaying global cosmic rays ($\Lambda_{\rm CR}$ being large), tend to favor a linear dependence for a longer time. Note, however, that this conclusion is valid only as long as $\lambda_{\rm Be} > \Lambda_{\rm CR}$.

It is reasonable to assume that the diffusion time for the cosmic rays out of the enriched region is much shorter than the diffusion time for the heavy nuclei, so that $\lambda_{\rm CR} \gg \lambda_{\rm Be}$. From equation (16) we then have

$$t_{\rm crit} = \frac{2V\Lambda_{\rm CR}}{v\mathscr{R}\Theta\lambda_{\rm CR}} . \quad (17)$$

Note that the linear relation between $N_{\rm Be}(t)$ and $N_{\rm O}(t)$ in our model depends critically on the assumption that the enriched regions are relatively short-lived, so that they dissolve or spallation stops for other reasons before formation of the next generation of stars takes place in them. A gradual build-up of target nuclei and beryllium within an enriched region with several generations of star formation will lead to stars in each region with a range of abundances displaying a quadratic relation between $N_{\rm Be}(t)$ and $N_{\rm O}(t)$. Also, a different number of supernovae in different regions will produce variations in the beryllium abundance scaling with the square of the oxygen abundance (cf. the production $\mathscr{N} N_{\rm O}(t)$ in the first term in the right-hand side of equation (15), remembering that $n_{\rm O} \propto \mathscr{N}$). Thus, the observed linearity suggests that such differences are eliminated by global mixing of the gas before star formation proceeds. This latter condition means either that enriched regions are fairly similar (i.e., with $\mathscr{N}$ constant and, e.g., $= 1$) or that mixing in the interstellar matter of the early Galaxy is very efficient.

2.3. *Energy and Flux Requirements and Characteristic Times*

We now estimate the energy, E, needed to produce the observed ratio of beryllium to oxygen. If the cosmic-ray flux is ϕ, then

$$E = \frac{\phi E_{\rm part}}{u_{\rm part}} v , \quad (18)$$

where $E_{\rm part}$ is the energy carried by one of the spallating protons, $u_{\rm part}$ is the particle velocity, and v is the volume in which the spallation takes place. The amount of beryllium produced in each enriched region is roughly

$$n_{\rm Be} \approx \sigma\phi\tau n_{\rm O} , \quad (19)$$

where σ is the cross section for spallation and τ is the time during which the spallation occurs, the so-called irradiation time. We then have from equation (18)

$$E = \frac{n_{\rm Be}}{n_{\rm O}} \frac{E_{\rm part}}{u_{\rm part}\sigma\tau} v . \quad (20)$$

Using this, we can eliminate v in equation (17) and obtain

$$t_{\rm crit} = \frac{n_{\rm Be}}{n_{\rm O}} \cdot \frac{E_{\rm part}2V\Lambda_{\rm CR}}{u_{\rm part}\sigma\tau E\mathscr{R}\Theta\lambda_{\rm CR}} . \quad (21)$$

By setting the irradiation time and the lifetime of the cosmic rays in the volume equal, i.e., $\lambda_{\rm CR} \sim \tau^{-1}$, we arrive at

$$t_{\rm crit} = \frac{n_{\rm Be}}{n_{\rm O}} \cdot \frac{E_{\rm part}2V\Lambda_{\rm CR}}{Eu_{\rm part}\sigma\mathscr{R}\Theta} . \quad (22)$$

The number of supernovae necessary to raise the oxygen abundance in the Galaxy to 1% of its present value is about 4.5×10^8, a value which we adopt for $\mathscr{R}$. This is an upper limit since it assumes only one supernova in each region. The volume of the early Galaxy is approximated by a sphere of radius 10 kpc. The observed $n_{\rm Be}/n_{\rm O}$ ratio is 10^{-7}, and we take σ, the cross section for beryllium production by 100 MeV protons, 10^{-26} cm^2, and a corresponding value of $u_{\rm part}$.

The energy that is available for cosmic-ray acceleration from each supernova is on the order of $\approx 10^{50}$ ergs, at the most. From equation (22) we then find

$$t_{\rm crit} \geq 2 \times 10^9 \text{ yr} . \quad (23)$$

The linear relation between the oxygen and beryllium abundances observed by Gilmore et al. (1992) suggests that $t_{\rm crit}$ is greater than 10^9 yr, which means that our estimate is consistent with observations and that the cosmic-ray energy required for this local spallation mechanism to work in the early Galaxy is not unreasonable. There are, however, two possible problems with this scenario: one regarding the B/Be ratio and the other concerning the cosmic-ray fluxes needed.

The observed abundances of the light isotopes, and in particular that of $N_{\rm B}/N_{\rm Be} \sim 10$ for the Population II dwarf HD 140283 (Duncan et al. 1992), are reasonably well reproduced by models of spallation in the interstellar medium (cf., e.g., Prantzos, Vasse, & Vangioni-Flam 1992). Would these also be reproduced by spallation by cosmic rays with a spectrum characteristic of the immediate neighborhood of the acceleration region? The answer is dependent on the particular model of the spallation region and the cosmic-ray accelerator, We note that the observed B/Be ratio in HD 140283, when properly corrected for non-LTE effects of B I ($N_{\rm B}/N_{\rm Be} > 10$ and probably $\sim$50–80; Kiselman 1993), seems to be significantly greater than that which would be produced by presently observed cosmic-ray energy spectra. This suggests that the cosmic-ray spectra at low energies were considerably steeper at the spallation than that observed and assumed to characterize the interstellar medium (cf. the calculations of spallation yields by Meneguzzi & Reeves 1975 and Walker, Mathews, & Viola 1985).

The second problem is hard to explain away: in our scenario the cosmic-ray flux may be excessive. equation (19) gives directly

$$\tau = \frac{4.7 \times 10^{22}}{\phi} \text{ s} , \quad (24)$$

and we see that in order for the spallation to occur during the lifetime of a supernova ($\lesssim 10^6$ yr) the flux must be quite high, at least $\gtrsim 10^5$ particles s^{-1} cm^{-2}. Thus, unless it is possible to acquire such a high flux in the remnant, either quite early (when the flux has to be even considerably greater, according to eq. [24]) or later in the so-called Sedov phase (see below), it seems unlikely that the linear relation between oxygen and beryllium could be due to spallation in the supernova remnants.

In the generally adopted picture of the evolution of supernova remnants (see, e.g., Woltjer 1972), the gas expands freely and adiabatically until deceleration starts due to swept-up matter. In the first phase, no cosmic-ray acceleration is, generally, assumed to take place, while in the second, the Sedov phase which begins after typically 10^3 yr, Fermi acceleration of cosmic rays may occur. The problem is, however, whether cosmic-ray fluxes of the magnitude required are really produced in this phase. These would namely lead to considerable gamma-ray fluxes from the remnants, due to proton-proton collisions and subsequent π^0 decay. Using the direct connection noted by Silk & Schramm (1992) (see also Fields, Schramm, & Truran 1993) between the cosmic-ray flux required for spallation and the gamma-ray flux, we easily find the following expression for the gamma-ray luminosity from a supernova remnant:

$$L_\gamma \sim \frac{n_{\rm Be}}{n_{\rm O}} \frac{2\sigma_{\pi^0}}{\sigma_{\rm Be}} \frac{M_{\rm SNR}}{m_{\rm H}} \frac{E_\gamma}{t_{\rm SNR}} , \tag{25}$$

where σ_{π^0} and $\sigma_{\rm Be}$ are cross sections for π^0 production and Be production, respectively, $M_{\rm SNR}$ is the mass of the remnant gas (including swept-up gas) where spallation occurs, E_γ is the characteristic photon energy, and $t_{\rm SNR}$ is the age of the supernova remnant. We find $L_\gamma > 10^{36}$ ergs s^{-1} which is higher than the typical point source intensity ($\sim 10^{35}$ ergs s^{-1}) observed by the *COS B* experiment (Bignami, Caraveo, & Maraschi 1978) and significantly higher than existing upper limits for present Galactic supernova remnants. Also, the expected Galactic gamma-ray background gets significantly higher than the observed one if the high cosmic-ray fluxes prevail in the remnants longer than about 10^3 yr.

It is also questionable whether the correlation required by our mechanism between oxygen-enriched gas and cosmic rays can prevail through the Sedov phase, in view of the sweeping up of oxygen-poor gas and the leakage of cosmic rays from the remnant. These difficulties may point toward SN spallation at early stages, which, however, would require still greater fluxes according to equation (24).

A possible scenario for early spallation might involve acceleration by a pulsar inside the supernova remnant. The reaction between the accelerated particles and the ejecta could lead to spallation (Hardinger et al. 1991) and the production of high-energy γ-rays. A problem, however, is that the energy flux available from the pulsar is probably not much greater than 10^{40} ergs s^{-1} (see, e.g., Ruderman 1972 and Reynolds & Chevalier 1984). Thus, a highly efficient mechanism will be needed in this particular model, and we find that it has to operate for at least some hundred years in order to supply enough cosmic rays, which is again in conflict with the gamma-ray estimates given above. Although there is evidence for early acceleration of electrons in SN 1987A, with an initial burst and later synchrotron radiation turned on (due to acceleration at the shock front formed at the swept-up red giant wind), there is no evidence that protons are similarly accelerated (Sarkar 1993). Morfill & Drury (1981) found, by discussing the gamma-ray fluxes that would be expected from supernovae in dense molecular clouds, an upper limit of prompt cosmic-ray production of 10^{48} ergs. Thus, the dominating flux of cosmic rays in the Galaxy (about 10^{50} ergs per supernova) must be supplied differently.

In conclusion we find that the production of the observed beryllium in supernova remnants through locally accelerated cosmic rays does not seem very probable. The ad hoc hypothesis that low initial metallicity supernovae accelerate much greater cosmic-ray fluxes would diminish the gamma-ray difficulties with the two-zone model, but this might, in fact, not be needed since the higher flux in itself would make the $N_{\rm Be}$-$N_{\rm O}$ relation less steep (cf. Fields et al. 1993). If the basic idea of the two-zone model is to be retained, one has to postulate spurious and very effective cosmic-ray acceleration processes, of presently unknown origin, to occur in the enriched regions.

3. CONCLUSIONS

We have found that a spatial correlation between the production of heavy elements and of cosmic rays in the early Galaxy could possibly be an explanation for the linear relation found by Gilmore et al. (1992) between the beryllium and the oxygen abundances. This is illustrated in Figure 1. A necessary condition for this explanation to work would be, however, that the cosmic rays, at very high fluxes, are produced when the correlation between the densities of target nuclei and of cosmic rays is great enough. This seems not to be the case, in view of the low limits set by observed gamma-ray fluxes, although the energy needed is available.

Disregarding exotic or unknown processes (cf., e.g., Boyd & Fencl 1991 and Pagel 1991), a more promising alternative explanation for the observed linear relation between abundances of beryllium and oxygen would be that the principal channel of synthesis involves cosmic-ray CNO nuclei, colliding with interstellar protons, as was suggested by Duncan et al. (1992). As for our model, this channel probably needs supernovae, and not early-type stars, to be directly involved in the acceleration of the cosmic-ray particles, since in this case a high CNO fraction in the rays is required. However, at least the current cosmic rays seem to consist mainly of ordinary stellar matter, modified by acceleration and propagation effects (cf. Montmerle 1988 and references quoted therein) and not particularly enriched supernova matter. Another alternative was recently suggested by Prantzos et al. (1993), based on a new scenario for the propagation of cosmic rays in the early Galaxy. Here, the cosmic rays are supposed to be very efficiently confined in the halo phase and to have considerably flatter spectrum at low energies than presently observed. Prantzos et al. (1993) find a good agreement with observed abundances of lithium, beryllium, and boron (however, uncorrected for non-LTE effects; see above) for their two-phase model for the galactic chemical evolution in spite of the "secondary" behavior of beryllium and boron in the halo and the disk phase of their model, respectively. With this model, beryllium and boron abundances for stars with [Fe/H] ~ -3.5 are predicted to be considerably lower than for our scenario, or that of Duncan et al. (1992), which should display "primary" behavior for beryllium and boron also for very low metallicities (cf. Malaney & Butler 1993). Pagel (1993) recently explored the possibility of solving the beryllium problem by using inhomogeneous halo models with metal-enhanced winds. He found that the cosmic-ray boost, characteristic of the Prantzos et al. (1993) halo model, could be significantly reduced, but no linear relation was obtained. A somewhat related scenario, in which the basic idea of the two-zone model could work, would be if supernova activity—in particular of those supernovae that efficiently enrich the interstellar medium and do not lose most of their winds from the early Galaxy—as well as the cosmic-ray acceleration which predominantly occured in the central part of the system during the halo formation phase (we note in passing that Maeder & Meynet 1993 argue that the cosmic rays still mainly originate from the inner

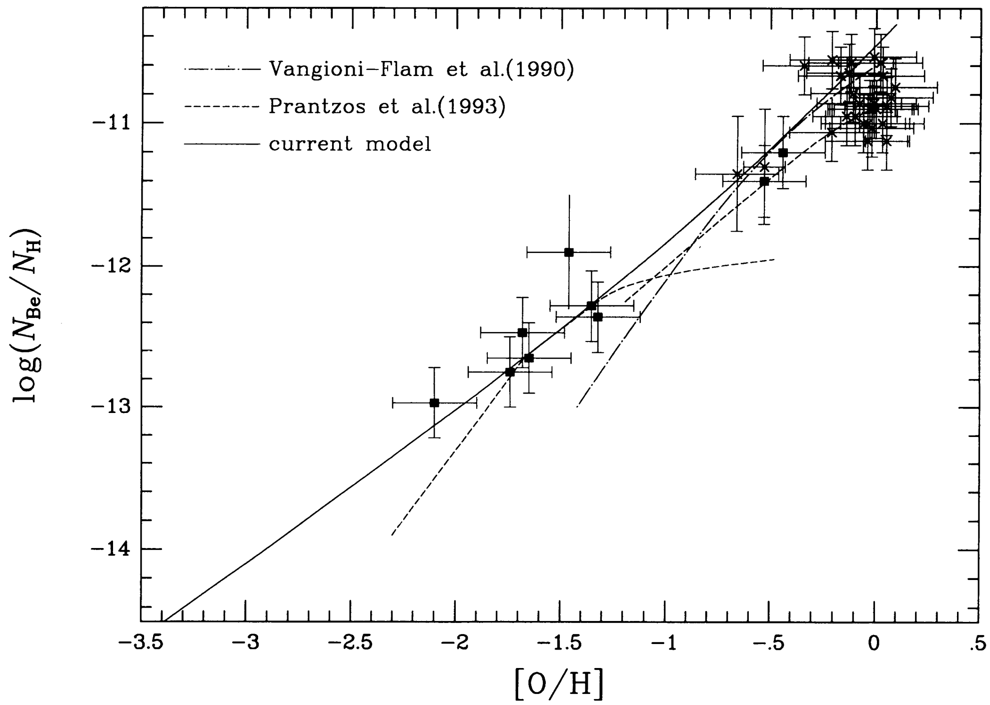

FIG. 1.—Different models compared with observations of beryllium and oxygen abundances in halo dwarfs. Models are Vangioni-Flam et al. (1990), an example of a one-zone model; Prantzos et al. (1993), a model where the confinement time for cosmic rays is much larger in the early Galaxy than now; our model, normalized in order to contain as many observed halo stars as possible. Note that our model does not fit the Sun, but rather overproduces beryllium at solar oxygen abundance. This is expected since astration is not taken into account. The model curves from Vangioni-Flam et al. (1990) and Prantzos et al. (1993) have been transformed from beryllium vs. iron to beryllium vs. oxygen with the help of oxygen and iron abundances from Nissen et al. (1993) (halo stars) and Edvardsson et al. (1993) (disk stars). Observational data are from Gilmore et al. (1992).

Galaxy). If this oxygen- and beryllium-rich gas were efficiently and systematically mixed with infalling metal-poor gas before new generations of halo stars were formed from it again, a linear $N_{\rm Be}$-$N_{\rm O}$ relation would result. Another possible explanation for the abundances is that the cosmic-ray flux in the early Galaxy was tuned such that it decreased roughly inversely to the oxygen abundances (Fields et al. 1993). In this case, a mechanism to flatten the cosmic-ray spectrum also seems needed, in order to avoid the overproduction of lithium by α-α reactions (cf. Steigman & Walker 1992).

It still remains to clarify which, if any of these different explanations is the most relevant.

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