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Beryllium and Boron Constraints on an Early Galactic Bright Phase*

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Abstract

The recent observations of Be and B in metal-deficient halo dwarfs are used to constrain the early galactic "bright phase" of rapid massive star formation. Assuming that this Be and B arises from cosmic ray spallation in the early galaxy, limits are placed on the intensity of the early (Population II) cosmic ray flux relative to the present (Population I) flux. A simple estimate of bounds on the flux ratio is $1 \lesssim \Phi_{PopII}/\Phi_{PopI} \lesssim 40$. This upper bound would restrict galaxies like our own from producing neutrino fluxes that would be detectable in any currently proposed detectors. It is found that the relative enhancement of the early flux varies inversely with the relative time of enhancement. It is noted that associated gamma ray production via $pp \rightarrow \pi^0 pp$ may be a significant contribution to the gamma ray background above 100 MeV.

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1. Introduction

A common feature of many models of galatic evolution is the prolific formation of rapidly evolving high mass stars in the early Galaxy (c. f. Cameron & Truran 1971). The detailed mechanism, timescale, and luminosity for this "bright phase" vary from model to model. However, such high massive star activity is generally thought to be accompanied by a correspondingly high cosmic ray production rate, a high supernova rate, rapid heavy element nucleosynthesis, a high γ-ray flux, and a high neutrino flux.

The prime evidence of the bright phase considered to date has been its γ-ray, neutrino, and cosmic ray products. This direct evidence is in principle accessible at high redshift ($z \sim 1$), at which one observes young galaxies presumably undergoing a bright phase, but in practice such distant objects are difficult to observe. Recently, however, it has become apparent that we have an alternative, indirect method available by which we may learn about the bright phase. This approach examines the bright phase not in the early photometric or neutrino activity in other galaxies, but through surviving fingerprints of the early cosmic ray activity in our own.

Though there is not yet consensus regarding the source and acceleration mechanism of cosmic rays, it likely that their origin is related to supernovae. Thus a knowlege of the cosmic ray flux at a particular era may give insight into the supernova rate for that same era. However, the relationship between the cosmic ray flux and the supernova rate is a model-dependent one, requiring assumptions about cosmic ray acceleration efficiency and confinement. Without a detailed account of these processes, we can only make the qualitative statement that we would expect the cosmic ray flux and the supernova rate to in some sense follow each other. Thus it seems reasonable that the degree of enhancement of the early cosmic ray flux might hint at the degree of enhancement of the supernova rate.

One important piece of evidence which the cosmic ray flux has provided is the abundances of the light (L-) elements: lithium, beryllium, boron (Fowler, Reeves, & Silk 1970; Meneguzzi, Audouze, & Reeves 1971, hereafter MAR; Walker, Mathews, & Viola 1984;

Steigman & Walker 1991; Walker et. al. 1992, hereafter WSSOF). These elements have loosely bound nuclei which are destroyed in stars at relatively low temperatures, and so are expected to have their origin elsewhere. Cosmic rays provide a plausible mechanism for this synthesis, in that spallation of cosmic ray protons and alpha particles onto the interstellar medium (containing helium and heavier nuclei) naturally leads to L-element formation. Detailed calculations support this model, reproducing (with the exception of ^{7}Li) the present day L-element abundances fairly well. (The bulk of the Pop I Li is presumed to be produced in AGB stars (Brown & Clayton 1992)).

Most work to date on the spallogenic origin of the L-elements has assumed the cosmic ray flux to have had a constant intensity and spectrum over the galactic history. The focus has often been on explaining L-abundances via cosmic ray processes, rather than on assuming a cosmic ray origin for the abundances and then deducing changes in the the present flux. If we take the latter stance of assuming cosmic ray production of the L-elements, then we may view the success of the analyses so far as an indication that the time-averaged cosmic ray flux has been close to the present day value for most of the galactic lifetime, through the production of the Pop I stars whose L-abundances have been sucessfully explained. As these disk stars are the younger ones in the Galaxy, however, and have formed out of an ISM which has been enriched for much of the age of the Galaxy, their L-abundances tell us only about relatively recent cosmic rays.

However, observers have recently been able to detect Be (Rebolo et. al. 1990; Ryan et. al. 1990) and B (Duncan, Lambert, & Lemke 1992) in several Pop II stars, including a very metal-poor ($Fe/Fe_{\odot} = 10^{-2.6}$) Pop II star, HD140283, where both Be and B were detected (Gilmore, Edvardsson, & Nissen 1991; Ryan et. al. 1992; Duncan et. al. 1992) This dwarf star is presumably very old, and so its L-abundances arose from spallation in the early ISM from which the star condensed. Consequently, information about the early cosmic ray flux is encoded in these abundances. The Pop II Be abundances appear in Figure 1, plotted against metallicity [Fe/H].

In this paper we determine how this early flux compared to the flux observed today, and how this constrains the bright phase.

2. Beryllium and Boron Abundances

Recently investigators have searched for Be in a number of low-metallicity stars. Rebolo et. al. looked for Be in dwarfs with [Fe/H] ranging from -1.0 to -2.2. They reported detection in some instances, and were able to establish upper bounds on the Be abundance in other cases. Ryan et. al. (1990) examined very metal poor dwarfs whose metallicities ranged from -2.2 down to -2.8, the latter being the value they claimed for HD140283. They failed to detect Be in any of these sites, and set upper bounds on the abundances of each. The most stringent such bound was for HD140283, with $\log Be/H < -13.2$.

Interest in HD140283 has remained high, as Gilmore et. al. (1991) reported a successful measurement of its Be abundance, $\log Be/H = -12.8 \pm 0.3$ (note that this value exceeds the Ryan limit). The Ryan et. al. (1992) subsequently examined this star again and also detected Be, but at a level of $\log Be/H = -13.25 \pm 0.4$, just below their previous upper bound.

Another L-element recently seen in HD140283 is boron, whose abundance sets important constraints on models for the production of these elements. Due to the small splitting in levels between isotopes, the observed abundances measure total B, i.e. B/H = ^{10}B/H + ^{11}B/H. Duncan et. al. report $\log B/H = -12.1 \pm 0.1$. WSSOF have shown that the B/Be ratio for this star is consistent with values one might expect from cosmic ray spallation processes and emphasize that the tracking of Be with Fe argued for a Galactic rather than a cosmological source. The only currently known Galactic source is cosmic ray spallation. We shall explore more implications of such early cosmic ray spallation further in this paper.

3. The Origin of Be and B: Cosmic Rays Versus Cosmology

The significance of the recent measurements in HD14028 arises from the star's low metal content. Determinations of its iron abundance have varied, with recent authors quoting [Fe/H] in a range from -2.6 to -2.8 (cf. Ryan et. al. 1990, Gilmore et. al. 1991, and Ryan et. al. 1992). The significant point here is that the star has very little metal enrichment. Consequently one expects it to have been formed early in the history of the Galaxy. Indeed, one expects the chemical content of HD140283 to be a fingerprint of the ISM at the time of of its formation.

Given the comparatively pristine nature of the youthful ISM from which HD140283 formed, its Be and B abundances are provocative. There is nucleosynthetic information not only in the separate Be and B abundances but also in their ratio. While some preliminary discussion (*NY Times* Jan. 1992) tried to connect the Be and B to a cosmological source, WSSOF showed that such an interpretation is not warrented by the present data. In particular, WSSOF have noted that, unlike the Li abundance in Pop II stars, the Be/H (and B/H) appears to strongly correlate with metallicity (see Figure 1) and thus must be made together with the heavy elements rather than be primordial. Furthermore, it should be noted that even inhomogeneous Big Bang Nucleosynthesis models which fit the $A \leq 7$ abundances (Kurki-Suonio et. al. 1990) do not appear to yield as high Be/H as that observed (Terasawa & Sato 1991; Thomas et. al. 1992).

It thus appears that, in order to understand Be and B abundances in Pop II stars, we must turn to the traditional model of L-element formation, that of cosmic ray spallation. This model recognizes that cosmic ray protons, alphas, and heavy nuclei interact with material in the ISM; in particular, there are inelastic collisions between cosmic ray nuclei and ambient nuclei in the ISM. These collisions have the L-elements as possible products (Reeves, Fowler, & Hoyle 1970).

In this model, the rate at which cosmic rays produce an L-element with number density

L is given by the rate equation

$$\frac{dL}{dt} = \sum_{ij} N_j \langle \Phi_i \sigma_{ij}^L \rangle \qquad [1]$$

where

$$\langle \Phi_i \sigma_{ij}^L \rangle = \int_{E_{th}}^{\infty} dE\ \phi_i(E)\, \sigma_{ij}^L(E) S_L(E) \qquad [2]$$

Here ϕ_i is the flux spectrum of the cosmic ray isotopic component i, integrated over kinetic energy per nucleon E above the threshold energy E_{th}. The flux spectrum is normalized to yield the total flux $\Phi_i = \int dE\, \phi_i$. We put σ_{ij}^L as the cross section for the reaction $i + j \longrightarrow L + \ldots$. The sum runs over cosmic ray components i and ISM target nuclei j, the latter having number densities N_j. The integral is bounded by the spallation threshold E_{th}. The dimensionless factor $S_L(E)$ gives the probability for an L-element, created in a collision having energy E, to remain trapped in the Galaxy and become part of the ISM. For cosmic ray protons and alpha nuclei on heavy ISM elements, $S_L(E) \approx 1$ for energies below about 100 MeV. For heavy cosmic ray nuclei on interstellar H, $S_l(E) \approx e^{-R_L(E)/\Lambda}$, where $R_L(E)$ is the ionization range of nucleus L and Λ is a constant, found to be $\Lambda \approx 6\,\mathrm{g/cm^2}$ (MAR).

Since both Be and B arise through the same mechanism, one can constrain models of cosmic ray spectra by demanding that a given spectrum reproduce the two abundances in the observed proportion. WSSOF have thoroughly examined the issue of the B/Be measurement in HD140283. They also find that a cosmic ray model, within errors, fits the observed ratio. They note that the cosmic ray spectrum at the time of that star's formation affects the B/Be ratio. In particular an $(E + m_p)^{-2.6}$ spectrum, as observed today, yields $B/Be \sim 12$ to 15, whereas a flatter spectrum can yield B/Be as low as 7.5. No spallation model seems to be able to yield B/Be below 7.5. Recent GRO/EGRET observations of γ-ray spectra as flat as E^{-2} show that spectra do vary. The present observations of B/Be are sufficiently uncertain that they do not yet severely constrain the spectra. Future observations may be of sufficient quality to discriminate between $(E + m_p)^{-2.6}$ and flatter

spectra, or even rule out the spallation model, if they find B/Be significantly below 7.5.

As current data is completely consistent with a cosmic ray mechanism for the production of Be and B, albeit possibly with a different spectrum, we will henceforth assume the correctness of this model.

4. Early Abundance Trends

A proper interpretation of the observed trends in the abundances of beryllium and boron, relative to oxygen and other heavy elements, in metal deficient stars demands a knowledge of the abundances of the heavy elements themselves. Indeed, it is these heavy elements that provide the targets for the spallation reactions that yield the lithium, beryllium, and boron isotopes of interest. A review of elemental abundance patterns as a function of metallicity has recently been provided by Wheeler, Sneden, & Truran (1989). The significant finding emphasized in this review concerns the ratios of the abundances of oxygen, and of the intermediate mass alpha-particle nuclei–magnesium, silicon, sulfur, and calcium–to that of iron. In particular, the abundances of these elements are found to be enriched relative to iron, viz: [O/Fe] $\sim$ 0.5 and [(Mg,Si,S,Ca,Ti)/Fe] $\sim$ 0.5, for metal deficient halo field stars of iron abundance [Fe/H] $<$ -1.0. The trends in the abundance of oxygen in halo population stars are shown in Figure 2. Similar abundance patterns are also known to be exhibited by stars associated with the halo population of globular clusters (Brown, Burkert, & Truran 1991). In contrast to the trends for oxygen, the abundances of both carbon and nitrogen would appear to be approximately solar, relative to iron (Laird 1985; Wheeler et. al. 1989).

These trends in oxygen and the intermediate mass elements in halo population stars are generally understood as due to the fact that they are products of the evolution of massive stars ($M > 10M_{\odot}$), of short lifetimes ($\tau < 10^8$ years) to Type II supernovae. It seems quite reasonable that the oldest stars in our Galaxy should reflect these signatures of massive star nucleosynthesis. The question posed by the presence of beryllium in these extremely

metal deficient stars is slightly more complicated. As we have argued, we believe it to be more likely that these light elements were formed in the 'conventional' manner, via the interactions of cosmic rays with interstellar matter. This is most consistent with the general trend in Be/O with metallicity Fe/H illustrated in Figure 1. The main contributions to beryllium and boron production, in this context, arise from interactions involving protons and alpha particles on carbon, nitrogen, and oxygen nuclei. Our discussion, above, makes clear that the interactions involving oxygen and, perhaps, the more abundant alpha-particle nuclei neon, magnesium, and silicon, should be the most important, since N and C follow Fe and should therefore be reduced by a factor ~ 3.

The observed trend in the ratio Be/O with the abundance of O, the prime nucleus from which the beryllium is formed, is shown in Figure 3. In our opinion, the most significant feature of this relationship is the fact that the ratio Be/O remains constant over a range of increase of two orders of magnitude in the O/H ratio. We interpret this as strong evidence for the cosmic ray model, in which O serves as the seed. To maintain the relatively high level of production of Be, relative to O, at very early times in the context of the cosmic ray production model requires a higher flux of cosmic ray primaries due to the shorter lived phase of cosmic ray exposure. These issues will now be elaborated in our subsequent discussions.

5. Ages of Pop II Dwarfs

To obtain a quantitative estimate of the early cosmic ray flux we will need to know the range of possible ages for the Pop II halo stars whose abundances we will use to deduce this flux. The bounds on this age t_{II} depends very much on the galactic evolution model one adopts. Very different pictures develop from two models of current interest: a one-zone model of collapse and early evolution, and a merger or thick disk model.

In the one-zone model, a roughly sperical gas distribution undergoes a fairly rapid ($\sim 10^8 - 10^9$yr $\sim t_{disk}/10$) collapse accompanied by a high rate of star formation (c. f.

Tinsley 1980). The disk then forms, and star formation gradually settles into its current rate. Thus, the central mechanism in this model is the dynamics of the collapse of a single protogalaxy.

Conversely, the merger model posits that an essential feature of galaxy formation is the interaction among many colliding progenitor gas clouds (Mathews & Schramm 1992). Collisions among these clouds drives star formation, and delays the formation of the disk until after the last collision, giving an age difference between halo and disk stars of $\Delta t = t_{halo} - t_{disk} \sim 2$ to 5 Gyr. A similar delay can also occur if an initial collapse forms a thick disk which cools slowly to form the present thin disk (Burkert, Truran, & Hensler 1991).

The differences in these pictures of galactic evolution are bourne out in the very distincive predictions they make for the Pop II halo age t_{II}. The lower bound comes from one-zone evolution models in which the disk forms quickly. In such schemes, the limiting timescale for producing the O abundance observed in Pop II halo stars is just the lifetime of the first massive ($M > 10M_{\odot}$) stars which become supernovae after no less than 5×10^7 yr. The upper bound on t_{II} comes from the merger model, in which the halo collapse is delayed until after the last merger. This predicts a timescale up to $\sim 5 \times 10^9$ yr for the formation of Pop II stars. The more interesting limit, as we will discover, is provided by the sorter timescale and correspondingly more intense phase of supernova activity and cosmic ray production.

In summary, we have

$$5 \times 10^7 \text{yr} < t_{II} < 5 \times 10^9 \text{yr} \qquad [3]$$

6. Beryllium, Boron, and the Bright Phase

In the calculations that follow, we will for definiteness focus on the cosmic ray production of Be; at the end we will quote analogous results for B. From the rate equation [1],

we find that at time t, we have

$$\frac{Be}{O}(t) = \frac{\sum_{ij} \int_0^t dt' \, N_j(t') \, \langle \Phi_i(t') \sigma_{ij}^{Be} \rangle}{O(t)} \qquad [4]$$

To begin with, we will assume simple power law spectral dependences for early (Pop II) as well as late (Pop I) cosmic rays, but will allow for different spectral indices γ_n. Also, for analytical convienience we will put $S_L(E) = 1$ which means physically that we will assume that the L-nuclei produced will not end up with Galactic escape velocities. Consequently, in this zeroth order approximation we will consider only the proton and alpha particle fluxes incident on ISM nuclei. The inverse process does of course occur, but it will not affect our results at our crude level of accuracy. The assumptions of our zeroth order model are thus:

1) We assume that the cosmic rays have at all times a power law spectrum in total energy per nucleon,

$$\phi_i(E) = a_i(E + m_p)^{-\gamma} \qquad [5]$$

where $i = p, \alpha$ denotes the cosmic ray nuclear species. We allow that the overall normalization a_i (and hence the total flux) can vary with epoch, as can the spectral index γ. Furthermore, we assume that cosmic ray isotopic distribution is in the same proportion as the ISM distribution for a given era. Hence we have defined a cosmic ray isotopic factor $y_i = N_i/H$ and we write the spectrum

$$\phi_i = y_i \phi_p \qquad [6]$$

To crudely approximate the time dependence of the flux we adopt a two-component model, in which the spectral index and normalization have different values for an early (Population II) epoch and for the present (Population I) epoch. we thus have

$$\phi_i(t; E) = \begin{cases} y_i \, a_{II} \, (E + m_p)^{-\gamma_{II}}, & 0 < t < t_{II} \\ y_i \, a_I \, (E + m_p)^{-\gamma_I}, & t_{II} < t < t_I \end{cases} \qquad [7]$$

where a_t is normalized to give the total flux Φ_t at each epoch.

2) The total flux Φ_t is summed above a minimum energy E_i different for protons and alphas. We find the scale for the low-energy cutoffs E_i for our flux spectrum calculation by considering the relevant observables. The only cosmic rays that can influence our calculations are those which are able to produce the spallation reactions we consider. Thus the lowest energy cosmic rays which we consider will be those just above the lowest reaction threshold of importance here. This minimum threshold for proton flux E_{th}^{min} is that for $p + N \longrightarrow Be + \ldots$, which gives

$$E_p = E_{th}^{min} = 17.5\,\mathrm{MeV} \qquad [8]$$

taking all E_{th} from a table of atomic masses. The threshold for alpha particle flux comes from the reaction $\alpha + Fe \longrightarrow L + \ldots$ and gives

$$E_\alpha = E_{th}^{min} = 19.4\,\mathrm{MeV} \qquad [9]$$

a slightly higher limit. It will turn out, however, that the differences between these thresholds are unimportant, as they are both far below the proton mass m_p which sets the scale here, and thus the correction for different thresholds will be of order $E_{th}/m_p \sim$ a few percent.

3) As mentioned above, we assume 100% efficiency in stopping the products of proton and alpha spallations in that we put $S_L(E) = 1$.

4) For the cross sections we will put

$$\sigma(E) = \beta\,\sigma_a \qquad [10]$$

where $\beta \leq 4$ is an enhancement factor allowing for variation of the cross section $\sigma(E)$ above the high-energy asymptotic cross section σ_a. Though this approximation is somewhat crude, it is a reasonable one, given that many of the spallation cross sections we use are unmeasured over all of their energy ranges, but those which have been measured do not appear to vary above σ_a beyond a factor of at most ~ 4.

5) For the Pop I abundance ratios of ISM targets (N_j/O) we take the Cameron (1982) solar abundances as representative. For Pop II we recognize that early on, C and N were not yet made, while O and α-nuclei above it (Ne, Mg, Na, Si, Fe) were made in type-II supernovae (see Fig. 2). Thus we take these abundances to be in the same ratio as they are today, and exclude C and N.

With our assumptions, the integral over energies of eq. [2] takes a form

$$\begin{aligned}\langle \Phi_i \sigma \rangle &= \beta\, y_i\, \Phi_p(t)\, \sigma_a \left(\frac{E_i + m_p}{E_{th} + m_p} \right)^{\gamma - 1} \\ &\approx \beta\, y_i\, \Phi_p(t)\, \sigma_a\end{aligned} \qquad [11]$$

To proceed, we have, within our approximations,

$$\frac{(Be/O)_{II}}{(Be/O)_I} = \frac{t_{II}}{t_I} \frac{\Phi_{II}}{\Phi_I} \frac{\sum_{ij} y_i (N_j/O)_{II}\, \sigma_{ij}}{\sum_{ij} y_i (N_j/O)_I\, \sigma_{ij}} \qquad [12]$$

Solving for flux, we have

$$\frac{\Phi_{II}}{\Phi_I} = \frac{t_I}{t_{II}} \frac{\sum_{ij} y_i (N_j/O)_I\, \sigma_{ij}}{\sum_{ij} y_i (N_j/O)_{II}\, \sigma_{ij}} \frac{(Be/O)_{II}}{(Be/O)_I} \qquad [13]$$

With this data, we additionally set the flux spectra today to be $\gamma_I = 2.6$, and that for the early Galaxy to be the steepest possible power law, $\gamma_{II} = 2 + \epsilon$. We are aware that demodulation of the measured local cosmic ray flux leaves an uncertainty in the impiled galactic flux today of a factor ~ 2 for Φ_I and that γ_I can be as steep as 2.75 (Simpson 1983). However, such uncertainties are within the bounds we will derive. With the above spectral indices we then have

$$\frac{\sum_{ij} y_i (N_j/O)_I\, \sigma_{ij}}{\sum_{ij} y_i (N_j/O)_{II} \sigma_{ij}} = 1.7 \qquad [14]$$

which gives

$$\frac{\Phi_{II}}{\Phi_I} = 1.7 \frac{t_I}{t_{II}} \frac{(Be/O)_{II}}{(Be/O)_I} \qquad [15]$$

This states that the ratio of early, enhanced, flux to the present flux is inversely proportional to the duration of enhancement.

The most metal-poor and hence the oldest star for which we have information on undisturbed Be content is HD140283. (A limit from Ryan et. al. (1990) on an even more metal-poor star, HD47147, is complicated by the possibility that it is probably a horizontal branch star, in which case its Be would have been destroyed.) Using Be/O ratio from HD140283, we get information about the earliest flux our model can examine. Taking the mean of the two measurements, we have

$$\frac{(Be/O)_{HD140283}}{(Be/O)_I} = 0.24$$

which gives a flux ratio

$$\frac{\Phi_{II}}{\Phi_I} = 0.4\frac{t_I}{t_{II}} \qquad [16]$$

where t_{II} now refers to the age of the Galaxy when HD140283 was formed.

Assuming our limits on Pop II dwarf ages (eq. [3]) as well that the age of disk of the Galaxy is $t_{disk} = t_I \sim 10 \times 10^9$ yr, we have for our estimate of the range of the cosmic ray flux

$$0.8 \lesssim \frac{\Phi_{II}}{\Phi_I} \lesssim 80 \qquad [17]$$

where the lower limit comes from the merger model and the upper limit from the one-zone model of galactic evolution.

The calculation of the flux limits from boron abundances is quite similar. In this case, the minimum proton flux is quite low and comes from the reaction $p +^{14} N \longrightarrow^{11} C + \ldots$, with the carbon subsequently decaying to ^{11}B. The threshold here is thus

$$E_p = 3.1\,\mathrm{MeV} \qquad [18]$$

The alpha threshold comes from $\alpha +^{14} N \longrightarrow^{10} B + \ldots$ and gives

$$E_\alpha = 14.9\,\mathrm{MeV} \qquad [19]$$

Assuming the same ISM evolution and cosmic ray flux spectra as in the case of the beryllium calculation, we find the analog of eq. [15] to be

$$\frac{\Phi_{II}}{\Phi_I} = 2.2\frac{t_I}{t_{II}}\frac{(B/O)_{II}}{(B/O)_I} \qquad [20]$$

Taking $(B/O)_{II}/(B/O)_I = (B/O)_{HD140283}/(B/O)_I = 0.25$, we deduce bounds on the cosmic ray flux to be

$$1.1 \lesssim \frac{\Phi_{II}}{\Phi_I} \lesssim 110 \qquad [21]$$

and so taking the concordant range requires

$$1.1 \lesssim \frac{\Phi_{II}}{\Phi_I} \lesssim 80 \qquad [22]$$

Since we expect the cosmic ray flux to be tied to the supernova rate, this result suggests that stellar activity in the young Milky Way was no livelier than the order of 80 times more than it is today, corrected for the ratio of cosmic ray confinement times in the Galaxy then versus the present cofinement time of $\sim 10^7$ yr. Indeed, the long timescales for the merger model may even imply that the cosmic ray flux and hence star formation may have been roughly constant over the Galaxy's history. In other words, the "bright phase" may not have been significantly brighter than the present phase.

How sensitive is this constraint to the assumptions of the calculation? One important feature was the use of a power law flux spectrum, which has the advantage of being at least functionally similar to that we observe today. If we were to pick an even harder early flux spectrum, one that entirely eliminates any low-energy component and so has all spallation cross sections in the asymptotic range, this gives

$$\langle \Phi\sigma \rangle = \Phi_{II}\sigma_a \qquad [23]$$

This is equivalent to a very flat power law spectrum except that the pure high-energy flux misses the higher values of σ at the lower energies and so lacks the factor of β used to correct for this enhancement. Thus the final limits all increase by a factor of β, which at most seems to be about a factor of 4.

7. Gamma Ray Background

Silk & Schramm (1992) have noted that there is a direct connection between the proton flux required for the spallation discussed here and the gamma ray flux. Through

π^0 production via the reaction $p + p \longrightarrow \pi^0 + p + p$ the photons from the π^0 decay would contribute to the γ-ray background. The number of γ's produced via π^0 production relative to Be via spallation off of CNO nuclei can be calculated as follows. The average cosmic ray proton inducing pion production through the *pp* reaction can be estimated to have an energy of 3.3 GeV (Stecker 1975). Furthermore, 85% of such pions are produced in the range 1–10 GeV. The cross section for this reaction at these energies is around

$$\sigma(p + p \longrightarrow \pi^0 + p + p) \sim 30\,\mathrm{mb} \qquad [24]$$

where, for comparison, a typical Be-producing cross section at such energies is

$$\sigma(p + O \longrightarrow Be + \ldots) \sim 5\,\mathrm{mb} \qquad [25]$$

Additionally, each π^0 produces two γ's. Thus the *pp* contribution to the γ number density n_γ is

$$n_\gamma = (\frac{Be}{H})\,\frac{2\,\sigma_{\pi_0}}{\sigma_{Be}}\,(\frac{H}{CNO})\,n_H \qquad [26]$$

Assuming $\Omega_b \sim 0.05$ and a Hubble constant $H_0 \approx 50$ km/sec/Mpc yields $n_H \sim 10^{-7}\mathrm{cm}^{-3}$. Then for HD140283 we have

$$n_\gamma \simeq 1.8 \times 10^{-14}\mathrm{cm}^{-3} \qquad [27]$$

This can be compared to the observed density of γ's with energies $\lesssim$ 100 MeV, which is $\lesssim 4 \times 10^{-15}\mathrm{cm}^{-3}$ (Fichtel, Simpson, & Thompson 1978).

If the source of the observed γ-ray background is at redshift z and the integral γ-ray flux scales as $E^{-1.3}$ then the density of γ's from that source is $\lesssim 4 \times 10^{-15}\mathrm{cm}^{-3}/(1+z)^{1.3}$. This implies that $1 + z \gtrsim 3.2$ for our source. Silk & Schramm (1992) explore the γ-ray constraint in more detail, but the basic point is that the bulk of the high-energy gamma ray background may be assoicated with Be and B production.

We may use this redshift limit to constrain the Pop II ages. If we further consider an $\Omega = 1$ cosmological model we know that

$$t_{II} \leq \frac{t_u}{(1+z)^{3/2}} \qquad [28]$$

where t_u is the age of the universe $\sim$ 13 Gyr. For the above limit $1+z \gtrsim 3.2$, the age-redshift relation requires $t_{II} \lesssim 2.3$ Gyr. This estimate, while crude, has the interesting implication of pushing the acceptable values for t_{II} below the longest estimates of the merger model. This limits $\Phi_{II}/\Phi_I \lesssim 40$ and yields our bright phase range to

$$1.1 \lesssim \Phi_{II}/\Phi_I \lesssim 40 \qquad [29]$$

With improved treatment of the cosmic ray contributions to gamma ray flux, as well as with improved Be measurements for low metallicity objects, this limit should improve.

Silk & Schramm (1992) additionally note that if the cosmic rays were produced predominantly at a single z then there would be a peak in the γ-ray background spectrum at $E_\gamma \sim m_{\pi^0}/2(1+z)$. The observation of such a peak would argue for a sharp onset to the cosmic ray production process. At present the only peak reported is at $E_\gamma \sim 1$ MeV. If this peak were due to cosmic ray π^0 production, the source would be at $z \sim 50$, with $t_{II} \lesssim 4 \times 10^7$ yr, just at the limit of type-II supernova timescales.

Note that this upper limit on cosmic ray flux also sets a bound on the early neutrino fluxes for galaxies like our own. In low- to medium-energy cosmic ray processes (below the photopion threshold at $\sim 10^{19}$ eV) neutrinos arise primarily from the reaction $p + p \longrightarrow \pi^+ + p + n$. The cross section for this reaction is comparable to that for the above neutral pion production, but each charged pion yields three neutrinos (a ν_μ from the π^+ decay and a ν_e and ν_μ from the muon decay) with enegies a fraction of the collision energy. Thus we expect the neutrino produciton to be roughly comparable to that for γ-rays, implying a neutrino flux at the earth of

$$\Phi_\nu \sim 5 \times 10^{-4}\,\mathrm{neutrinos/cm^2/sec/ster} \qquad [30]$$

For comparison, the proposed Super-Kamiokande detector is only sensitive to diffuse neutrino fluxes above $\Phi_\nu \sim 100\,\mathrm{neutrinos/cm^2/sec/ster}$ (Totsuka 1987). The early cosmic ray-induced neutrino flux thus appears to be far below the sensitivities of present or anticipated detectors.

8. Other Models and Data for the Bright Phase

Our result constraining the bright phase from above agrees well with another piece of information about early galactic chemical evolution. Meyer & Schramm (1986) and Reeves & Johns (1976) have shown in a detailed examination of cosmochronometers that nucleosynthetic activity in the Galaxy has been roughly constant over the galaxy's history; they find that the average nucleosynthesis rate was at most a factor of two higher in the early galaxy (see also the recent review by Cowan, Thielmann, & Truran 1991). Taking this result in conjuction with our present result constrains any bright phase to be only modestly bright if it lasts a long time, or to be short lived if it is very bright. This result is quantified in eq. [16], in which the flux ratio is inversely proportional to the duration of the enhancement. Thus we can rule out an intense and long-lived burst of stellar actvity in the galactic youth.

Models for the bright phase have often quantified the evolution of cosmic ray flux by invoking a quantity activity of η, the number of particles injected as cosmic rays per unit time. Typically, researchers have put (Berezinsky & Smirnov 1975; Berezinsky 1978; Berezinsky & Ginzburg 1980; Hill & Schramm 1985; Hill, Schramm, & Walker 1986; Berezinsky & Grigor'eva 1991)

$$\eta \sim (1+z)^m \qquad [31]$$

where z is the redshift and the index m has been set $\gtrsim 4$ in many models. These models have been used to estimate possible detectable neutrino fluxes from early galactic evolution via $pp \rightarrow \pi^0 pp$ followed by π^0 decay. From Hill & Schramm (1985) we see that only models with $m \gtrsim 4$ produce a flux of neutrinos that would be observable with proposed large neutrino detectors such as DUMAND. However, Berezinsky & Grigor'eva (1988) have already noted that to fit the observed dip in the ultrahigh-energy cosmic ray spectrum seems to constrain $m < 4$.

We may deduce limits on the value of the activity index m through a comparison with our flux limits derived here. We will assume that the activity η is proportional to the

cosmic ray flux at a given redshift. We then can put

$$\frac{\Phi_{II}}{\Phi_I} = \frac{\eta_{II}}{\eta_I} = (\frac{t_{II}}{t_u})^{-2m/3} \qquad [32]$$

and so we have

$$m = \frac{3}{2}\frac{\log \Phi_{II}/\Phi_I}{\log t_u/t_{II}} = -0.4 - 0.2 \quad \text{for the merger model} \qquad [33]$$

$$= 1.2 - 1.3 \quad \text{for the one} - \text{zone model}$$

These values are significantly lower than those assumed in some of the literature.

9. Conclusions

We have shown that if the Pop II Be and B have a spallogenic origin we are able in the context of a zeroth order model to make a prediction for the relative fluxes of early and modern cosmic rays, finding $\Phi_{PopII}/\Phi_{PopI} < 40$. This implies a possible constraint on the relative size of early stellar activity. However quantitative connections to stellar activity require knowledge of the relative cosmic ray confinement times at early epochs, as well as cosmic ray acceleration efficiencies, and so are very model dependent. Nonetheless, it is interesting to compare our results with the average nucleosynthesis rate which is not found to vary, on average, over the galactic history by more than a factor of two. Thus, early activity is either only modestly enhanced above todays if lasting for a long time, or only lasting a short time if significantly enhanced over today. This might provide a useful constraint on cosmic ray acceleration and confinement models. In no case is the flux produced sufficient to predict observable neutrinos from the early phase of galaxies like our own. We note that early cosmic ray fluxes can affect the ionization of the galactic and intergalactic gas (c. f. Ozernoi & Chermordik 1976). Following Silk & Schramm (1992) we also note that the gamma ray flux arising from $pp \rightarrow \pi^0 pp$ reactions may be a dominant component of the observed gamma ray background.

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References

Andersen, J., Edvardsson, B., Gustafsson, B., and Nissen, P. E. 1986 in The Impact of Very High S/N Spectroscopy on Stellar Physics IAU Symp. No. 132, ed. G. Cayrelde, Strobel, & M. Spite, 441

Barbury, B., 1988 A&A 191, 121

Bessel, M.S., & Norris, J. 1987 A&A 8, 99

Berezinsky, V.S. 1979 Proceedings of the 1978 DUMAND Summer Workshop, ed. A. Roberts v.2, 155

Berezinsky, V.S., & Ginzburg, V.L. 1981 Proceedings of the 1980 DUMAND Symposium, ed. V.J. Stenger, v. 2, 181

Berezinsky, V.S., & Grigor'eva, S.I. 1988 A&A 199, 1

Berezinsky, V.S., & Smirnov, A.Y. 1975 Ap. Sp. Sci. 32, 461

Brown, J.H., Burkert, A., & Truran, J.W. 1991 ApJ 376, 115

Brown, L., & Clayton, D. 1992 Clemson Univ. preprint, submitted to ApJ

Burkert, A., Truran, J.W., & Hensler, G. 1992, ApJ, in press

Boyd, R., & Kajino, T. 1990 ApJ 359, 267

Cowan, J.J., Thielemann, F.-K., & Truran, J.W. 1991 Ann. Rev. Astr. Ap. 29, 447

Duncan, D., Lambert, D., & Lemke, D. 1992 ApJ submitted

Cameron, A.G.W., & Truran, J.W., 1971, Ap Space Sci 14, 179

Fowler, W.A., Reeves, H., & Silk, J. 1970 ApJ 162, 49

Gilmore, G., Edvardsson, B., Nissen, P.E. 1991 ApJ 378, 17

Gratton, R.G., & Ortolani, S. 1986 A&A 169, 201

Hill, C.T., & Schramm, D.N. 1985 Phys. Rev. D 31, 564

Hill, C.T., Schramm, D.N., & Walker, T.P., 1986 Phys. Rev. D 34, 1622

Kawano, L.H., Fowler, W.A., Kavanagh, R.W., & Malaney, R. 1991, ApJ 372, 1

Kurki-Suonio, H., Matzner, P.A., Olive, K.A., & Schramm, D.N. 1990 ApJ 353, 406

Laird, J.B. 1985 ApJ 289, 556

Magain, P. 1985 A&A 146, 95

Malaney, R.A., & Fowler, W.A. 1988 ApJ 333, 14

Mathews, G.J., & Schramm, D.N., 1992 ApJ submitted

Meneguzzi, M., Audouze, J., & Reeves, H. 1971 A&A 15, 37

Meyer, B., & Schramm, D.N., 1986 ApJ 311, 406

Ozernoi, L.M., & Chernomordik, V.V. 1976 Sov. Astr. 20, 260

Rebolo, R., Molaro, P., Abia, C., & Beckman, J.E. 1989 A&A 193, 193

Reeves, H., Fowler, W.A., & Hoyle, F. 1970 Nature 2226, 727

Reeves, H., & Johns, O. 1976 ApJ 206, 958

Ryan, S.G., Bessel, M.S., Sutherland, R.S., & Norris, J.E. 1990 ApJ Lett 348, L57

Ryan, S.G., Norris, J.E., Bessel, M.S., & Deliyannis, C.P. 1992 ApJ 388, in press

Silk, J., & Schramm, D.N., 1992 Univ. of Calif. preprint

Simpson, J.A. 1983 Ann. Rev. Nucl. Part. Sci. 33, 323

Stecker, F.W., in The Origin of Cosmic Rays, ed. J.L. Osborne and A.W. Wolfendale (Boston:D. Reidel), 1975

Steigman, G., & Walker, T.P. 1991 ApJ submitted

Terasawa, N., & Sato, K. 1989 Prog. Theor. Phys. Lett. 81, 254

Tinsley, B., 1980 Fundam. Cosmic Phys. 5, 287

Totsuka, Y. in Seventh Workshop on Grand Unification 1987, ed. J. Arafune

Walker, T.P., Mathews, G.J., & Viola, V.E. 1985 ApJ 299, 745

Walker, Stiegman, Schramm, Olive, & Fields 1992 ApJ submitted

Wheeler, J.C., Sneden, C., & Truran, J.W. 1991 ApJ 376, 115

Figure Captions

Figure 1. A plot of beryllium abundance versus metallicity for metal poor Pop II stars. Note that Be traces Fe with slope near 1.

Figure 2. A plot of the oxygen-to-iron ratio for Pop I ([Fe/H] > 1) and Pop II ([Fe/H] < 1) stars, adapted from Wheeler, Sneden, & Truran (1991). In the Pop II range the oxygen is uniformly enhanced realtive to iron.

Figure 3. The beryllim abundances of Figure 1, with the oxygen evolution factored out (done by subtracting [O/H]), plotted against oxygen abundance. That the data points lie roughly on a flat line indicates that Be traces O well, with a slope of 1.

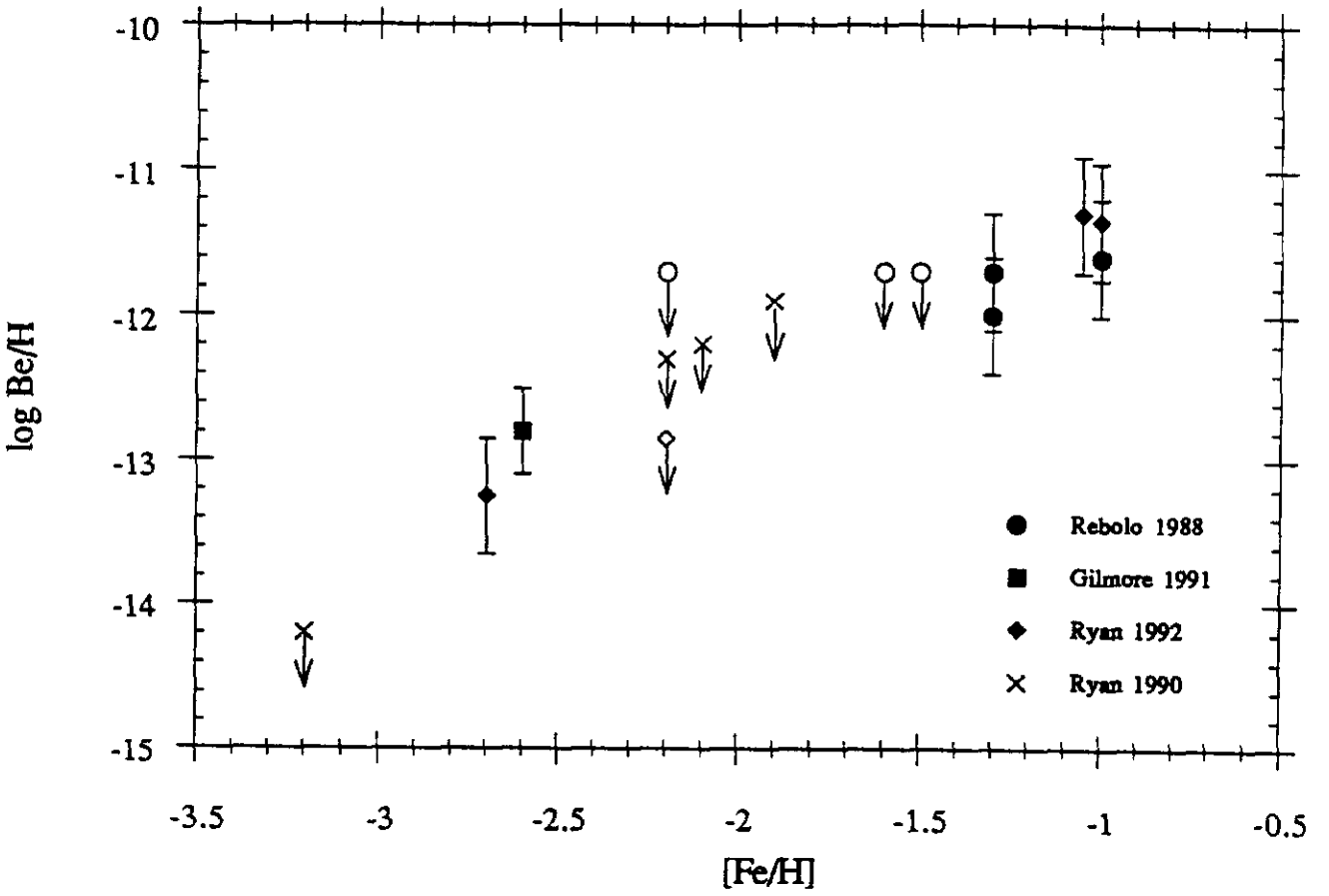

-10
-11
-12
-13
-14
-15
log Be/H
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
[Fe/H]
Rebolo 1988
Gilmore 1991
Ryan 1992
Ryan 1990

FIGURE 1

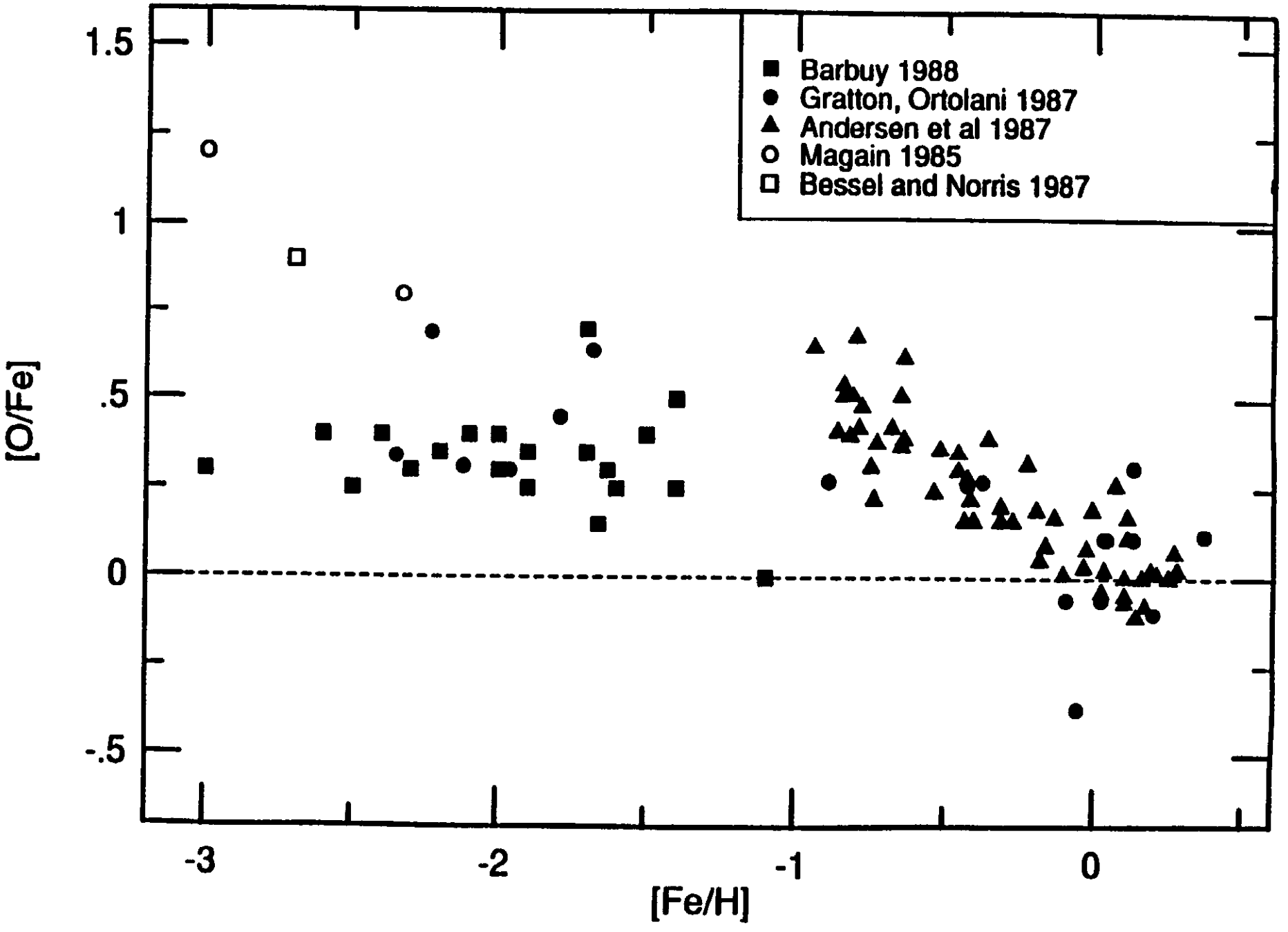
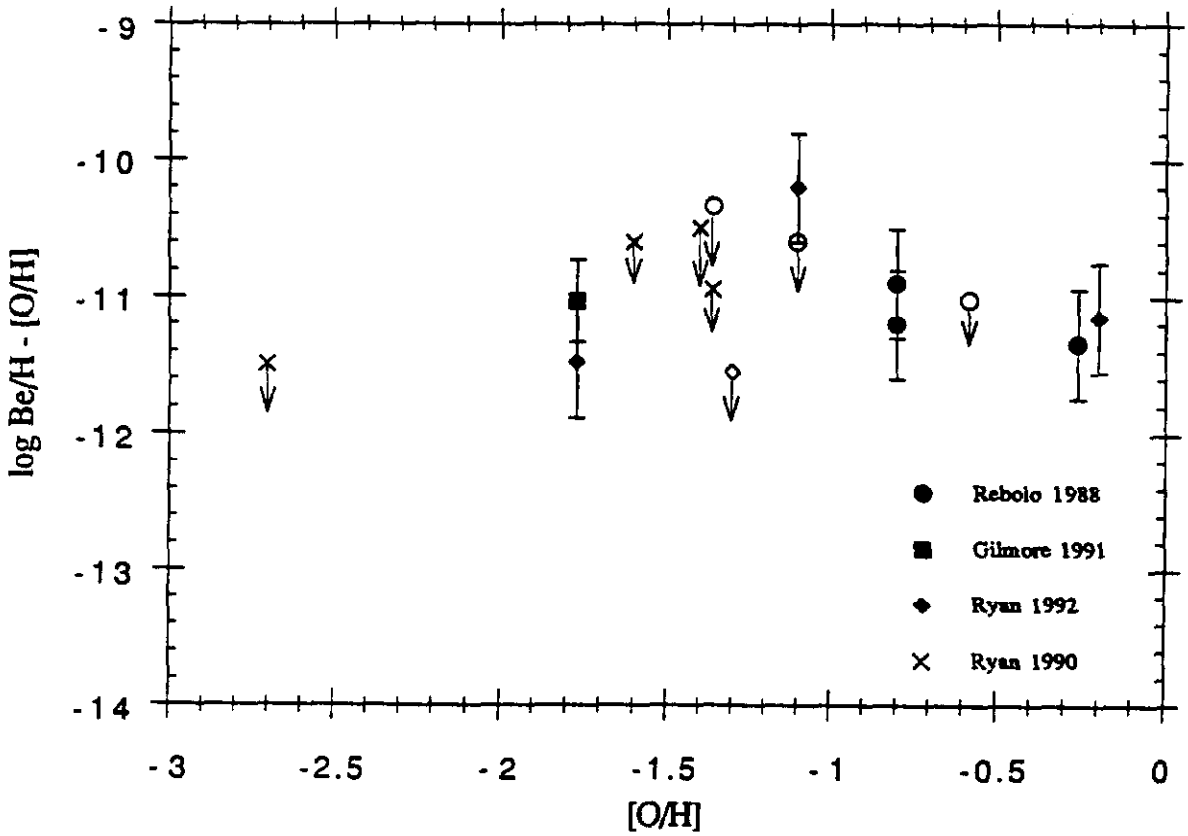

Barbuy 1988
Gratton, Ortolani 1987
Andersen et al 1987
Magain 1985
Bessel and Norris 1987
1.5
1
.5
0
-.5
[O/Fe]
-3
-2
-1
0
[Fe/H]

FIGURE 2

FIGURE 3


-9
-10
-11
-12
-13
-14
log Be/H - [O/H]
-3
-2.5
-2
-1.5
-1
-0.5
0
[O/H]
Rebolo 1988
Gilmore 1991
Ryan 1992
Ryan 1990