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THE DIFFUSE GAMMA RAY BACKGROUND, LIGHT ELEMENT ABUNDANCES, AND SIGNATURES OF EARLY MASSIVE STAR FORMATION *

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Abstract

Spallation synthesis of the observed Population II beryllium and boron requires a cosmic ray flux in the early galaxy that, in an almost model-independent way, implies a potentially observable signature of redshifted π^0-decay photons in the extragalactic diffuse gamma ray background.

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I. *INTRODUCTION*

Beryllium and boron are generally considered to be produced by spallation of galactic cosmic rays on interstellar CNO (Reeves, Fowler and Hoyle 1970; Meneguzzi, Audouze and Reeves 1971; Mitler 1972; Walker, Mathews and Viola 1985). Detection of Be in several halo stars (Ryan et al. 1990, 1992; Gilmore, Edvardsson and Nissen 1991), and a recent detection of B (Duncan, Lambert and Lemke 1992), can be interpreted as evidence for cosmic ray spallation in the early galaxy. This has led to predictions of the spallation contribution (predominantly via $\alpha + \alpha \to p +^7 Li$) to the population II Li abundance (Steigman and Walker 1992), a lower bound on the B/Be ratio in population II stars (Walker et al. 1992), and constraints on the protogalactic cosmic ray flux (Fields, Schramm and Truran 1992).

In this letter, we draw attention to a potentially observable flux of diffuse extragalactic gamma rays produced by inelastic cosmic ray interactions ($p + p \to \pi^0 \to 2\gamma$)

that is inevitably a byproduct of spallation-synthesized Be. In particular, we constrain the epoch of cosmic ray-induced population II light element nucleosynthesis to be at redshift $z > 0.5$, and predict a spectral feature in the diffuse extragalactic gamma ray background with amplitude $\Delta i_\gamma / i_\gamma > 0.1$ above 10 MeV if the Be is synthesized at $z < 10$. We also discuss the possibility that the cosmic ray flux responsible for population II Be and B synthesis may be associated with a precursor, hypothesized, population III.

II. *DIFFUSE EXTRAGALACTIC GAMMA RAY SIGNATURE OF BERYLLIUM SYNTHESIS*

The total spallation production of ^{9}Be for solar composition of the interstellar medium (Cameron 1982) and demodulated cosmic ray spectrum of the form (Gloeckler and Jokipii 1967)

$$\phi_i(E) = \alpha_i (E + E_0)^{-\alpha};\ E_0 = m_0 c^2;\ \alpha = 2.6;\ \phi_p = 12.5 \phi_{GJ}\ \mathrm{cm}^{-3}\mathrm{s}^{-1}\mathrm{GeV}^{-1}\mathrm{nucleon}^{-1},$$

was found by Walker et al. (1985) to be $Be/H = 1.5 \times 10^{-10} \phi_{GJ} \Delta t_{10}$ where Δt_{10}, in units of 10^{10}yr, is the adopted duration of the spallation exposure to the (assumed uniform) cosmic ray flux with $\phi_{GJ} = 1$. This is equal to the solar photospheric determination of the Be abundance (Meyer 1979, Austin 1981) although only amounting to between $\frac{1}{3}$ and $\frac{1}{2}$ of the meteoritic abundance determinations (Cameron 1982; Anders and Ebihara 1982). We remark however that Simpson (1983) advocates a galactic cosmic ray flux, corrected for solar modulation effects, that is about a factor of 2 more intense ($\phi_p = 27.7\ \mathrm{cm}^{-3}\mathrm{s}^{-1}\mathrm{GeV}^{-1}\mathrm{nucleon}^{-1}; \alpha = 2.75$). We parametrize uncertainty in the cosmic ray flux by allowing ϕ_{GJ} to vary: $\phi_{GJ} = 2.2$ for Simpson's preferred flux near 1 GeV. Since the Be yield scales with the spallation cross-section-weighted abundances of C, N and O (note that these cross-sections are asymptotically 6,5 and 4 mb for p on C, N, O respectively: Read and Viola 1984; also (C,N,O)/H $= (4.2, 0.9, 6.9) \times 10^{-4}$). Since at $[Fe/H] \leq -1$, we have (Wheeler, Sneden, and Truran 1989) $[O/Fe] \approx 0.5, [C/Fe] \approx [N/Fe] \approx 0$, we can approximately scale Be/H with Fe/H for metal-poor halo stars. Scaling with O/H would be preferable, but the O/H abundances are uncertain in the low mass population II stars where Be has been observed. Hence we write, relative to the mean density of baryons in the universe, $n_H = 10^{-7}\ (\Omega_b h_{50}^2 / 0.05)\ \mathrm{cm}^{-3}$,

$$\frac{n_{Be}}{n_H} = 4.2 \times 10^{-11} \Delta t\ \phi_{GJ}\ 10^{[Fe/H]}, \tag{1}$$

where the normalization is taken from Steigman and Walker (1992),

$$\Delta t = g\ h_{50}^{-1}(1+z)^{-3/2}\ 1.3 \times 10^{10}\ \mathrm{yr},$$

z is the redshift at which the spallation was initiated, and

$$g = \frac{3}{2}\ H_0(1+z)^{3/2} \int_0^z \phi_{GJ}\ c\ dt$$

incorporates any evolution in the cosmic ray flux: $g = 1$ for a uniform flux.

The spallation production of Be is accompanied by secondary π^o-production that results in gamma rays. These are detectable as a contribution to the diffuse extragalactic background radiation. For a specified population II Be abundance generated by spallation, we may compute the corresponding number of γ-rays per baryon. This result will be independent of the time-evolution of the spallation process, although the $\gamma-$ray energy, as opposed to number, distribution is redshift-dependent. The cosmic ray-induced $\gamma-$ray emissivity per H atom has been evaluated by Dermer (1985), and may be fit by

$$f\ (> \varepsilon_\gamma) = 1.3 \times 10^{-25}\ f_\gamma\ \phi_{GJ}\ \text{photons s}^{-1}(\text{H atom})^{-1},$$

where we have included (pp), (αp), (pα) and ($\alpha\alpha$) processes, and introduced

$$f_\gamma = (1 + c_\alpha\ \varepsilon_{100}^{\alpha})^{-1};\ \varepsilon_{100} = \varepsilon_\gamma/100\text{MeV}.$$

Scaling to the previously adopted solar neighborhood cosmic ray flux, we obtain $c_\alpha \approx 0.18$, $\alpha \approx 2.6$, $\phi_{GJ} \approx 1$. In principle, the early cosmic ray flux could have a different spectrum from the current flux. In fact, flatter spectra minimize the B/Be and Li/Be ratios produced by spallation (Walker *et al.* 1992) and marginally provide a better fit to the observed B/Be ratio of about 10. The sensitivity of the Li/ Be ratio may eventually be able to constrain the early galaxy cosmic ray spectrum; for the present, we adopt $2.0 \lesssim \alpha \lesssim 2.6$. At sufficiently high energy ($\epsilon_\gamma \gg 300$ MeV), the differential $\gamma-$ray emissivity has the same spectral index as the cosmic ray spectrum, and has a negligible contribution at energies $\ll \frac{1}{2}m_{\pi 0} = 70MeV$.

The diffuse extragalactic $\gamma-$ray background that is generated simultaneously with Be spallation synthesis therefore extends down to energy $70(1+z)^{-1}$ MeV, and may be expressed in the form

$$\frac{n_\gamma}{n_H}(> \epsilon_\gamma) = 5.3 \times 10^{-8} f_\gamma\ \Delta t\ \phi_{GJ}. \tag{2}$$

Eliminating the time-dependence and cosmic ray flux normalization between equations (1) and (2) yields the prediction

$$\frac{n_\gamma}{n_H}(>\epsilon_\gamma) = 1.3 \times 10^3 \ \frac{n_{Be}}{n_H} \ 10^{-[Fe/H]} f_\gamma. \tag{3}$$

We adopt a normalization appropriate to the metal-poor halo star HD 140283 for which

$$(\log Be/H, [Fe/H]) = (-13.25, -2.7) \text{ or } (-12.8, -2.6)$$

from Ryan et al. (1991) and Gilmore et al. (1991), respectively, to finally obtain

$$\frac{n_\gamma}{n_H}(>\epsilon_\gamma) = 5.4 \times 10^{-8} \ f_\gamma. \tag{4}$$

The extragalactic component of the diffuse γ-ray background above 35 MeV from the SAS-2 telescope has (Thompson and Fichtel 1982) intensity $5.5(\pm 1.3) \times 10^{-5}$ photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ and power-law differential photon spectral index $2.35(+0.4-0.3)$. This enables us to write the observed flux as

$$\frac{n_\gamma}{n_H}(>\epsilon_\gamma) = 5.4 \times 10^{-8} \varepsilon_{100}^{-1.35} \ (0.05/\Omega_b \ h_{50}^2). \tag{5}$$

The uncertainty in the gamma ray spectral index allows consistency with the expected range of α used in f_γ. Improved data on the gamma ray spectrum as well as constraints on Li/Be and B/Be ratios will eventually provide a test of our proposal. We conclude that spallation-associated gamma rays can actually produce more than fifty percent of the extragalactic diffuse gamma ray background between ~100 MeV and 300 MeV independently of the epoch at which the spallation occurred. Of course, the age of the relevant population II stars implies that $z \gtrsim 0.5$. The preceding result is independent of redshift because the predicted spectral dependence ($\propto \epsilon_\gamma^{-\alpha}$) of the differential photon spectrum is indistinguishable from that of the background actually observed. In fact, if the spallation occurs at high redshift, there is also a feature in the diffuse gamma ray spectrum that extends down to the threshold, $\sim 70(1+z)^{-1}$MeV. The cut-off in the predicted flux below the π^0 decay threshold and the increase in n_γ/n_H observed below $\sim$ 100 MeV suggests that a potentially detectable spectral feature is present whose amplitude depends on the adopted redshift z of spallation. Specifically, we find that

$$\frac{\Delta i_\gamma}{i_\gamma} \approx 0.6(1+z)^{-1.35} \times (\Omega_b h_{50}^2/0.05)$$

at $\varepsilon_\gamma \approx 70(1+z)^{-1}$ MeV. We conclude that if $z \lesssim 10$, a potentially detectable spectral feature is observable that amounts to $\frac{\Delta i_\gamma}{i_\gamma} \gtrsim 0.1$.

III. *INDICATORS OF EARLY MASSIVE STAR FORMATION*

Cosmic ray production is usually associated with supernova injection and acceleration in supernova remnants. The inferred early cosmic ray flux that we have suggested may be directly constrainable via its secondary π^0 production incurred in interactions with interstellar hydrogen should therefore be proportional (in the integral of flux and duration) to the metallicity of the early galaxy. Naively, this might be expected to result in a quadratic relation between Be/H and Fe/H, since Be production depends on the product of metallicity with cosmic ray flux, the latter itself being presumably proportional to metallicity. In fact, there are indications (Ryan et al. 1992) that this is not the case, these latter authors seeking to explain the nearly linear observed dependence of Be/H on Fe/H via an effectively lower nucleosynthetic yield for Population II (Hartwick 1976). The connection between supernovae (and hence nucleosynthetic yield) and cosmic ray fluxes is also dependent on the cosmic ray confinement time, and any inference is therefore model-dependent. However, we note that an alternative solution to the possible weak dependence of cosmic ray flux on metallicity in the early galaxy is possible if the cosmic rays responsible for population II Be are of pregalactic or protogalactic origin, associated with the hypothesized population III that may or may not be responsible for halo dark matter, and is postulated to have preceded population II formation (e.g. Truran and Cameron 1971; Silk 1991). In this case, the early cosmic ray flux is independent of the population II star formation rate and abundances; hence a linear dependence of Be/H on Fe/H is predicted.

To lend support to this latter possibility, we comment on another possible indicator of an early pre-population II, massive star population. The abundances of the very heavy neutron capture elements undergo a change relative to Fe below [Fe/H]<-2, where r-process synthesis appears to dominate (Wheeler et al. 1989). This contrasts with the α-nuclei excess, observed to set in for [Fe/H]<-1 and interpreted as a signature of massive population II ($\sim 20 - 30 M_{\odot}$) stars (Type II supernovae). The difference suggests that the first r-process events are not the same events as the early Type II supernovae that produced the $\alpha-$nuclei, but perhaps are the consequence of a prior generation of short-lived massive objects.

Finally, we remark that the contrasting, present-day rarity of the r-process events suggests on the basis of yields that their rate today is only a small fraction of the Type II supernova rate ($\sim 1(50\ \mathrm{yr})^{-1}$ per $10^{10} L_{\odot}$ galaxy). If the rate is also sufficiently rare for population II objects, one would expect to find inhomogeneities in the r-process abundances of different extreme metal-poor halo stars. It is of interest to note that gamma ray bursts, which occur at a rate of $\sim$ 800/yr, are thought by some to be related to catastrophic neutron star events, such as collisions, at cosmological distances, for which we consequently infer a mean rate of $\sim 10^{-6}/yr/10^{10}L_{\odot}$ galaxy. If we speculatively identify these events as r-process sites, the implied rate of $1/10^{4}$ normal supernovae falls at the lowest extreme of previous estimates of r-process yields (*e.g.*, Eichler *et al.* 1989). With one event for every $\sim 10^{6}M_{\odot}$ of gas that eventually forms stars, appropriate for a $10^{11}M_{\odot}$ galaxy, the inferred scale of r-process inhomogeneity is likely to be on globular cluster mass scales.

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