The Source of Cosmic Rays: 1. Be/Fe Evolution & Cosmic Ray Composition

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Abstract

Be abundance observations in old halo stars formed in the early Galaxy have opened a new channel in cosmic-ray origin studies. The essentially constant ratio of Be-to-Fe abundance as a function of the Fe abundance of the stars strongly suggests that the bulk of the cosmic rays metals are accelerated out of fresh supernova ejecta.

1 Introduction:

That cosmic-ray spallation is important to the origin of the light elements Li, Be and B (LiBeB) has been known for almost three decades (Reeves, Fowler, & Hoyle 1970). But only recently was it realized that the light element themselves, in particular Be detected in old halo stars formed in the early Galaxy, can provide new information on cosmic-ray origin, specifically on the source of the particles that are accelerated to become cosmic rays (Ramaty, Kozlovsky, & Lingenfelter 1998)

Although supernova shocks are generally accepted to be the dominant accelerator of the cosmic rays (at least up to $\sim 10^5$ GeV), the source of the particles that are accelerated is still highly debatable. The first suggestions that cosmic rays are accelerated in supernova remnants (e.g. Ginzburg & Syrovatskii 1961; Shapiro 1962) implicitly assumed that the cosmic-ray source is dominated by fresh nucleosynthetic material. With the subsequent developments in shock acceleration theory, it was realized that the most likely site for cosmic-ray acceleration is the hot, low density interstellar medium (see Axford 1981), where the cosmic ray source enrichments relative to the solar abundances could have resulted from the atomic mass-to-charge dependence of the acceleration (Eichler 1979). As this selection effect provided poor fits to the data (see Cassé 1983), alternatives appeared more promising, the acceleration of grain erosion products in the average ISM (interstellar medium), based on the anti-correlation of the enrichments with volatility (Epstein 1980), and the acceleration in the ISM of cosmic rays preaccelerated in stellar coronae, based on the correlation of the enrichments with first ionization potential (FIP, Cassé & Goret 1978; Meyer 1985). In both these models the cosmic-ray injection source is matter of solar composition modified by either volatility or FIP.

These ideas, prevalent in the 1980's, led to a LiBeB evolutionary model (hereafter CRI) in which the cosmic-ray source composition at all epochs of Galactic evolution was assumed to be similar to that of the average ISM at that epoch (Vangioni-Flam et al. 1990). The excess of the observed Be abundances in low metallicity stars over the predictions of this CRI model was first discussed by Pagel (1991), the focus of the discussion being on whether or not the excess was due to contributions from Big Bang nucleosynthesis. The Big Bang contribution to Be production is now known to be insignificant in comparison with the available Be data at even the lowest metallicities. However, the Be data have major implications on cosmic-ray origin stemming from the fact that Be production by cosmic rays accelerated out of the average ISM in the early Galaxy severely underpredicts the observed abundances in the old halo stars because the ISM at that epoch was very poor in C and O, the main progenitors of Be. As a consequence, and motivated by reports of nuclear gamma ray lines from the Orion star formation region, the CRI model was modified (Cassé, Lehoucq, & Vangioni-Flam 1995) by superimposing onto the cosmic rays accelerated out of the average ISM a metal enriched low energy component. As these gamma ray data have been retracted, we do not consider this model here.

Another attempt to restore the viability of cosmic-ray acceleration out of the average ISM in the early Galaxy is that of Fields & Olive (1999) who have based their argument on the recent observations (Israelian, Garcia Lopez, & Rebolo 1998) of increased O abundances in old halo stars. But we have shown (Ramaty & Lingenfelter 1999, hereafter RL99) that for realistic assumptions on core collapse supernova Fe and O yields and ejecta kinetic energies, cosmic rays accelerated out of the average ISM still underproduce the Be abundance, the enhanced O abundance notwithstanding.

We thus return to our previous suggestion, elaborated in a series of papers (Ramaty et al. 1998; Lingenfelter, Ramaty, & Kozlovsky 1998; Higdon, Lingenfelter, & Ramaty 1998), that the Be evolution can be best understood in a model (hereafter CRS) in which the cosmic-ray metals are accelerated out of fresh supernova ejecta. In the present paper we confirm this result using an expanded version of the evolutionary code developed previously (RL99).

2 O and Fe Evolution

We consider a one-zone model. Following the prescriptions of Kobayashi et al. (1988), we accumulate ISM mass, $d\mathrm{M}_{\mathrm{ISM}}(t)/dt = (10^{11}\mathrm{M}_{\odot}/\tau^2)te^{-t/\tau}$, and form stars, $\Psi = \alpha \mathrm{M}_{\mathrm{ISM}}$, with $\tau = 5$ Gyr and $\alpha = 0.37$ Gyr^{-1}. We employ the Salpeter IMF over the range 0.1 – 100 $\mathrm{M}_{\odot}$. Core collapse supernovae from $>10\mathrm{M}_{\odot}$ progenitors produce Fe and O with yields (RL99) based on values given by the Shigeyama & Tsujimoto (1998)/Tsujimoto & Shigeyama (1998) and Woosley & Weaver (1995) (hereafter the TS and WW95 yields). For [Fe/H]≡log(Fe/H)-log(Fe/H)$_{\odot} > -1$ we augment these Fe productions with contributions from thermonuclear supernovae (Type Ia), again using the prescription of Kobayashi et al. (1998). We include the delayed deposition of Fe into the ISM, which, as we have shown (RL99), is needed to account for the increased O abundance at low metallicities. We find good agreement with the observed O/Fe abundance ratio data (Israelian et al. 1998) over the entire range $-3 < [\mathrm{Fe/H}] < 0$.

3 Be Production and Evolution

The Be yield per supernova depends on several factors: the composition of both the accelerated particles and the ambient medium, the energy spectrum of the accelerated particles, the energy per supernova imparted to the accelerated particles, and the interaction model for the accelerated particles, characterized by a path length for escape from the Galaxy, $\mathrm{X}_{\mathrm{esc}}$. For the CRS model at all past epochs the accelerated particle composition is identical to the current epoch cosmic-ray source composition. This is most likely achieved by cosmic-ray acceleration of ejecta enriched matter in the interiors of superbubbles (Higdon et al. 1998). For the CRI model the composition of the accelerated particles depends on [Fe/H], being derived from the ISM composition at the same [Fe/H] by applying the enhancement factors that modify the current epoch ISM to yield the current epoch cosmic-ray source, within the Ellison, Drury, & Meyer (1997) shock acceleration theory. The ambient medium composition is solar, scaled with $10^{[\mathrm{Fe/H}]}$, except that for O the scaling is given by $\mathrm{O/H} = (\mathrm{O/H})_{\odot}10^{0.6[\mathrm{Fe/H}]}$, which provides a good fit to the data on the dependence of the O abundance on [Fe/H] (Israelian et al. 1998). The accelerated particle source energy spectra are given by an expression appropriate for shock acceleration, $q(E) \propto (p^{-2.2}/\beta)$, where $p, c\beta$ and E are particle momen-

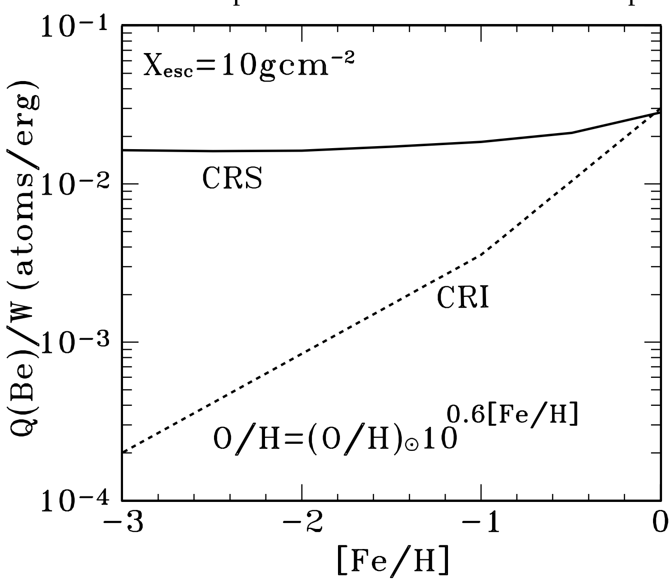

Figure 1: Number of Be atoms produced per unit cosmic-ray energy for the CRS and CRI models; for $\mathrm{X}_{\mathrm{esc}} \to \infty$ (closed Galaxy) Q/W increases by about a factor of 2; for the CRI model, Q/W depends on the ISM composition for which we use the indicated O/H dependence based on the Israelian et al. (1998) data.

tum/nucleon, velocity and energy/nucleon, respectively. We derive Q(Be)/W, the total number of Be nuclei produced by an accelerated particle distribution normalized to unit cosmic-ray energy, for a given source energy spectrum and composition, and interacting in an ambient medium of given composition. Q(Be)/W is shown in Figure 1 as a function of the [Fe/H] of the ambient medium, for the CRS and CRI models. For the CRS model, it is essentially constant for [Fe/H]< -1, increasing slowly thereafter, but by no more than a factor of 2. For the CRI model, Q(Be)/W is a strong function of [Fe/H], increasing from a value at [Fe/H]= -3 that is almost 2 orders of magnitude smaller than the corresponding Q/W for the CRS model. This Q/W differs from that given in RL99 for [Fe/H]> -1, because here we assumed that the CRI cosmic-ray source composition becomes gradually metal enriched so that at [Fe/H]=0 it is identical to that of the current epoch cosmic rays.

The number of Be atoms produced per supernova at a given epoch is then (Q(Be)/W) W_{cr}, where W_{cr} is the energy imparted to cosmic rays per supernova. We assume the same W_{cr} for the core collapse and thermonuclear supernovae. Since for the CRI model, the accelerated particles originate from the average ISM, the Be yield per supernova is the same for the two supernova types. For the CRS model, we assume that about 50% of the thermonuclear supernovae occur in the superbubbles, so we allow only half of these supernovae to contribute to Be production. But we note that the thermonuclear supernovae do not contribute at all for [Fe/H]< -1, and even at higher metallicities their contributions are quite marginal.

The calculated Be evolution is shown in Figure 2 together with recent data (Garcia Lopez 1999). The value at [Fe/H]=0 is the solar Be abundance. We show results for both the CRS and CRI models and for the two assumed sets of nucleosynthetic Fe yields from core collapse supernovae (TS and WW95) augmented with the contributions of the thermonuclear supernovae. We assumed a mixing time of 30 Myr for Fe (RL99) and we also delayed the Be deposition because of the finite propagation and interaction time of the accelerated particles in an ambient medium of average density 0.3 cm^{-3}. For the CRS model we varied W_{cr} to obtain a good fit to the data. The resultant $W_{cr} = 10^{50}$ erg/supernova is in excellent agreement with the energy per supernova obtained from current epoch cosmic-ray data and supernova statistics (Lingenfelter et al. 1998). This provides strong support for the validity of the CRS model. The same W_{cr} for the CRI model leads to a Be abundances which underpredicts the data by more than two orders of magnitude at the lowest [Fe/H], thereby demonstrating the energetic inconsistency of this model.

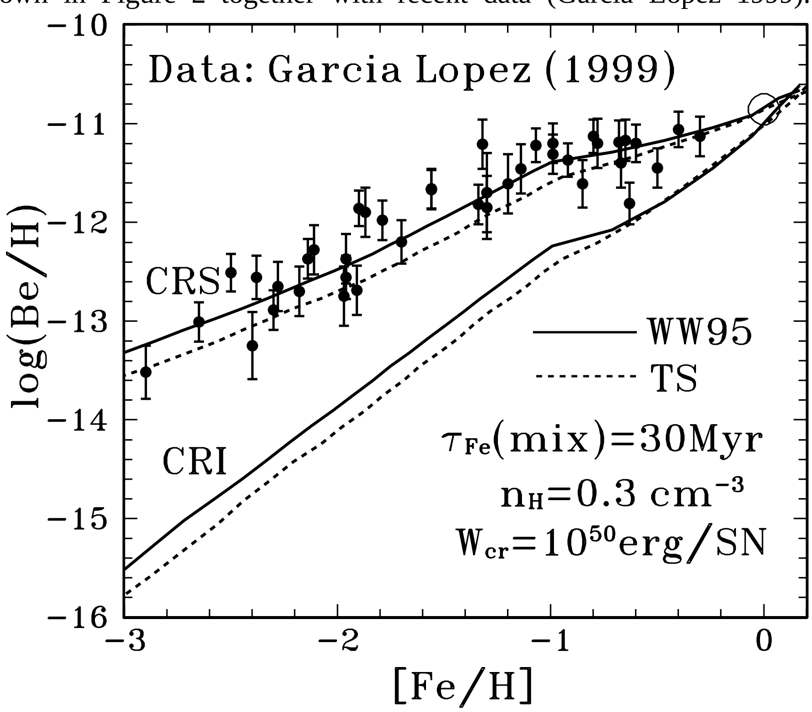

Figure 2: Be evolution for the CRS and CRI models.

We have evaluated the energy in cosmic rays per supernova that would be required to account for the observed Be evolution if the cosmic rays were accelerated out of the average ISM. This is shown by the CRI curve in Figure 3, where we have extended the calculation down to [Fe/H]=-3.3 because the Be abundance at [Fe/H]~ -3 (Figure 2) is sensitive to the production in the range -3.3 to -3.

Also shown in Figure 3 is the constant energy of 10^{50} erg/supernova that is required for the CRS model.

When compared with the ejecta kinetic energies of 1 to 3×10^{51} erg (Woosley & Weaver 1995), this CRS value requires a very reasonable acceleration efficiency of only 3 to 10%. On the other hand, the CRI model would require (at the lowest metallicity still sensitive to the data, [Fe/H]$=-3.3$) an acceleration efficiency $>300\%$, which is clearly untenable. Our conclusion differs from that of Fields & Olive (1999) who found that the required energy in the CRI model (for their best case) only exceeds the current epoch value by a factor of 5. The discrepancies between their and our findings are probably caused by differences in the employed Fe ejected masses, particularly those relevant at the lowest metallicities (see RL99 for details), and by the fact that Fields & Olive (1999) have not extended their energy estimates below [Fe/H]$=-3$. But since we have employed the best available ejected masses, we believe that the energetics of Be production indeed render untenable the acceleration of the bulk of the cosmic rays out of the average ISM.

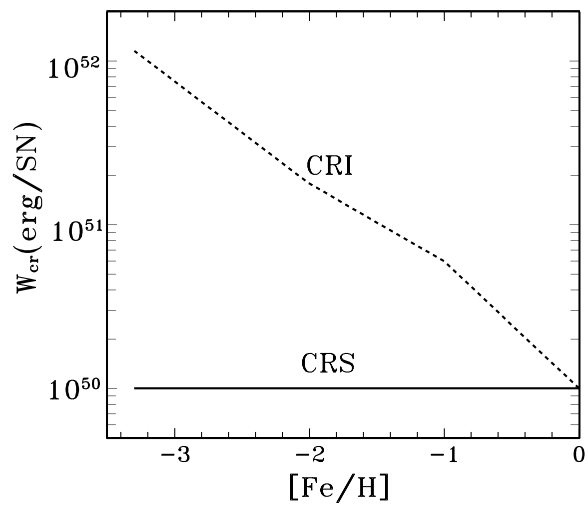

Figure 3: Energy in cosmic rays per supernova required to reproduce the observed Be evolution.

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