LIBEB ENERGETICS AND COSMIC RAY ORIGIN

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Abstract.
Three different models have been proposed for LiBeB production by cosmic rays: the CRI model in which the cosmic rays are accelerated out of an ISM of solar composition scaled with metallicity; the CRS model in which cosmic rays with composition similar to that of the current epoch cosmic rays are accelerated out of fresh supernova ejecta; and the LECR model in which a distinct low energy component coexists with the postulated cosmic rays of the CRI model. These models are usually distinguished by their predictions concerning the evolution of the Be and B abundances. Here we emphasize the energetics which favor the CRS model. This model is also favored by observations showing that the bulk (80 to 90%) of all supernovae occur in hot, low density superbubbles, where supernova shocks can accelerate the cosmic rays from supernova ejecta enriched matter.

1. Introduction and Overview
In a series of papers (Ramaty et al. 1997; Ramaty, Kozlovsky & Lingenfelter 1998a; Lingenfelter, Ramaty & Kozlovsky 1998b; Higdon, Lingenfelter & Ramaty 1998; Ramaty, Lingenfelter & Kozlovsky 1998b) we developed a LiBeB (Li, Be, B) and cosmic-ray origin paradigm (CRS) in which at all epochs of Galactic evolution the cosmic rays are accelerated out of fresh supernova ejecta, and all of the Be and part of the B are produced by interactions of such cosmic rays with the ambient interstellar medium (ISM). This model differs from the CRI paradigm which posits that the current epoch cosmic rays are accelerated out an ambient medium of solar composi-
tion (suggested to be the ISM, Meyer, Drury & Ellison 1997), and that at all past epochs the composition of the source particles of the cosmic rays was that of the average ISM at that epoch. Hybrid models of LiBeB origin were also suggested (Cassé, Lehoucq & Vangioni-Flam 1995; Vangioni-Flam et al. 1996; Ramaty, Kozlovsky & Lingenfelter 1996). In these models (LECR) a Galaxy-wide separate low energy cosmic-ray component, also accelerated out of fresh nucleosynthetic matter, coexists with the CRI cosmic rays and dominates the Be and B production, particularly in the early Galaxy.

The excess of the observed Be abundances in low metallicity stars over the CRI predictions was discussed by Pagel (1991), and as additional Be data accumulated (see Vangioni-Flam et al. 1998), it became clear that the dependence of log(Be/H) on [Fe/H] is essentially linear, not quadratic as predicted by this model. On the other hand, both the CRS and LECR models predict a linear evolution, consistent with the observations, although Fields & Olive (1998) recently suggested that the CRI model should still be considered as viable, based on their re-analysis of the data including O in low metallicity stars (Israelian, Garcia Lopez, & Rebolo 1998).

We showed previously (see references above) that the energy $W_{SN}$ in cosmic rays per supernova required to produce the observed Be abundance is a powerful diagnostic of the models. This can be seen by considering log(Be/Fe) as a function of [Fe/H] in Figure 1a (Ramaty et al. 1998a; Vangioni-Flam et al. 1998), where for [Fe/H] < −1 the data are consistent with a constant, log(Be/Fe) = −5.84 ± 0.05. Since Fe production in this epoch is dominated by core collapse supernovae (SNII), the constancy of Be/Fe strongly suggests that Be production is also due to SNIIIs, which is eminently reasonable since supernova shocks are the most likely accelerators of the cosmic rays (e.g. Axford 1981). The decrease of Be/Fe for [Fe/H] > −1 probably results from the additional Fe production in Type Ia supernovae (e.g. Matteucci & Greggio 1986). The essentially constant Be/Fe, together with information on the average Fe yield per SNII, allows the determination of the Be yield per SNII which, coupled with calculations of LiBeB production by cosmic rays (Ramaty et al. 1997), leads to the energy in cosmic rays per SNII for the various models. We have shown that for the CRS model $W_{SN} \approx 10^{50}$erg, a value which is quite consistent with that required to produce the current epoch cosmic rays, based on direct cosmic ray measurements and supernova statistics. We have also shown that the LECR model is energetically less favored, and that the CRI model faces very severe problems of energetics (Ramaty et al. 1998b).

The three models (CRI, CRS, LECR) imply different current epoch cosmic-ray origin scenarios. While the CRI scenario posits acceleration from the ambient ISM (Ellison, Drury & Meyer 1997), the CRS model implies that the cosmic rays are accelerated out of fresh supernova ejecta. We have
Figure 1. Panel (a): observed Be-Fe abundance ratio as a function of [Fe/H]; data compilation by Vangioni-Flam et al. (1998). Panel (b): number of Be atoms produced per erg of cosmic-ray source kinetic energy; the ambient medium is neutral and the cosmic-ray escape length from the Galaxy is 10 g cm$^{-2}$. If no cosmic-ray escape is allowed (closed Galaxy), Q(Be)/W would increase by a factor of $\approx 2$, except for the LECR model for which most of the accelerated particles stop in 10 g cm$^{-2}$. The CRI curve for $\alpha = 0.6$ takes into account the less rapid decrease of O/H at low [Fe/H] (Israelian et al. 1998).

shown (Lingenfelter et al. 1998) that the standard arguments against such a cosmic-ray origin (Webber 1997; Meyer et al. 1998) can be answered, and that the most likely scenario involves the collective acceleration by successive supernova shocks of ejecta-enriched matter in the interiors of superbubbles (Higdon et al. 1998). This scenario is based on observations (summarized by Higdon et al. 1998) showing that most of the Type II and Ibc supernova progenitors (O and B stars) are produced in giant OB associations, that the subsequent supernova explosions produce giant superbubbles that make up the hot, low density phase filling roughly half of the ISM, and that the bulk (80 to 90%) of all supernovae occur in these superbubbles enabling their shocks to mostly accelerate fresh ejecta matter. These results, by themselves and quite apart from the LiBeB origin arguments, favor the CRS over the CRI scenario for cosmic ray origin. Independent arguments that the cosmic rays are accelerated from supernova ejecta were given by Erlykin & Wolfendale (1997).

The LECR scenario was motivated by the reported (Bloemen et al. 1994) detection with COMPTEL/CGRO of C and O nuclear gamma-ray lines from Orion. These gamma rays were attributed to a low energy cosmic-ray component highly enriched in C and O relative to protons and $\alpha$ par-
particles (see Ramaty 1996 for review and Ramaty et al. 1996 for extensive calculations of LiBeB production by LECRs). It was suggested (Bykov 1995; Ramaty et al. 1996; Parizot, Cassé, & Vangioni-Flam 1997) that such enriched LECRs might be accelerated out of metal-rich winds of massive stars and the ejecta of supernovae from massive star progenitors which explode within the bubble around the star formation region due to their very short lifetimes. But since the validity of these Orion observations has been questioned by the COMPTEL team (private communication, V. Schönfelder, 1998), the determination of the role of LECRs in LiBeB origin must await future nuclear gamma-ray line observations.

2. The Energetics of Be Production

We calculate the energy in cosmic rays, $W$, needed to produce a given number of Be atoms, $Q(\text{Be})$ (Ramaty et al. 1997). The calculation assumes a cosmic-ray source generating accelerated particles with given composition and energy spectrum, which then propagate and interact in an ambient medium of given composition. The transport of the particles is characterized by a target thickness, $X$, measured in g cm$^{-2}$. Results are shown in Figure 1b for a neutral ambient medium and $X = 10$ g cm$^{-2}$, the approximate Galactic target thickness for the current epoch cosmic rays. The accelerated particle source energy spectra are taken proportional to $(p^{-2.2}/\beta)e^{-E/E_0}$, where $p$, $c\beta$ and $E$ are particle momentum, velocity and energy/nucleon, respectively; except for the LECR case, $E_0$ is ultrarelativistic. For both the CRS and LECR cases, the accelerated particle composition is independent of [Fe/H] and the same as that of the current epoch cosmic rays, except that there are no protons and $\alpha$-particles for the latter. The ambient medium composition is solar scaled with Fe/H, except that for the CRI case we also consider a slower decrease of the O abundance, O/H=$(\text{O/H})_\odot10^{0.6[\text{Fe/H}]}$, which fits the recent Israeli et al. (1998) data. Such a modification of the ambient medium abundances has only a negligible effect on the calculations for the CRS and LECR models. The accelerated particle composition for the CRI case varies with [Fe/H], being equal to the ambient medium abundances increased by factors consistent with ISM shock acceleration theory (Ellison et al. 1997). For both the CRS and LECR cases $Q(\text{Be})/W$ is essentially constant. On the other hand, for the CRI case $Q(\text{Be})/W$ decreases with decreasing [Fe/H], becoming very low at low [Fe/H] in spite of the increase by as much as an order of magnitude due to the incorporation of the enhanced ISM O abundance.

The required energy per SNII is given by

$$W_{\text{SN}} = Q_{\text{SN}}(\text{Be})/(Q(\text{Be})/W),$$

(1)
**Figure 2.** IMF averaged Fe mass ejected mostly as $^{56}\text{Ni}$ per SNII for progenitor masses in the range $M_{\text{low}}$ to 40 $M_\odot$. Curves A, B and C, corresponding to different final ejecta kinetic energies, are based on the calculations of Woosley & Weaver (1995) for metallicity $10^{-4}$. The TS98 curve employs the results of Tsujimoto & Shigeyama (1998).

Independent of the details of the employed Galactic chemical evolution model, thus, for any given cosmic-ray scenario, the main uncertainty is due to $Q_{\text{SN}}(\text{Be})$, the Be yield per SNII. As Figure 1a indicates that the Be and Fe yields should be well correlated, we take $Q_{\text{SN}}(\text{Be}) = (\text{Be}/\text{Fe})Q_{\text{SN}}(\text{Fe})$, where $Q_{\text{SN}}(\text{Fe})$ is the number of Fe nuclei ejected per SNII. The problem then is the determination of this number.

Using the calculations of Woosley & Weaver (1995, WW95), we calculate the ejected Fe mass (mostly from $^{56}\text{Ni}$) per SNII averaged over the Salpeter IMF for progenitor masses $M_{\text{low}}<M<40 M_\odot$. The results are shown by curves A, B and C in Figure 2. These correspond to the WW95 cases A, B and C which give different $^{56}\text{Ni}$ yields for progenitor masses above 30 $M_\odot$, due to different assumed final ejecta kinetic energies, typically 1.2, 2 and $2.5\times10^{51}$ ergs for cases A, B and C, respectively. Also shown in Figure 2 (the TS98 curve) is a similar average based on the results of Tsujimoto & Shigeyama (1998). We see that the ejected mass averaged over the entire 10 to 40 $M_\odot$ range is about 0.1 $M_\odot$ for all four cases. Taking into account the main sequence lifetimes of the SNII progenitors in this mass range, such an average would be appropriate for evolutionary scenarios in which [Fe/H] reaches $10^{-3}$ in 10 Myrs or more. Since this is quite reasonable (e.g. Ramaty et al. 1998b), we shall use 0.1 $M_\odot$ in our subsequent estimates. However we note that if [Fe/H]=$10^{-3}$ is reached in just a few Myrs, only SNIIs from progenitors more massive than about 25 $M_\odot$ can contribute, allowing ejected Fe masses lower than 0.1 $M_\odot$, but only for case A.
Combining the average ejected Fe mass of 0.1 $M_\odot$ with the constant Be/Fe (Figure 1), we obtain the required Be yield per SNII, $3 \times 10^{48}$ atoms. As the recent analysis of Fields & Olive (1998) indicates somewhat lower Be/Fe values at the lowest [Fe/H], we assign a downward uncertainty to this value of about a factor of 3. Using $Q_{\text{SN}}(\text{Be}) \simeq 3 \times 10^{48}$ in Equation (1), we obtain $W_{\text{SN}}(\text{CRS}) \simeq 1.5 \times 10^{50}$ erg, which as already mentioned is in excellent agreement with the current epoch value. On the other hand, using the $\alpha=0.6$ curve in Figure 1b at [Fe/H] = $10^{-3}$, we obtain $W_{\text{SN}}(\text{CRI}) \simeq 1.5 \times 10^{52}$ erg, a highly excessive value, even if it were possible to reduce it by the above mentioned factor of 3. For the LECR model of Vangioni-Flam et al. (1996), in which only the $>60 M_\odot$ progenitors contribute, we obtain $W_{\text{SN}}(\text{LECR}) \simeq 8 \times 10^{50}$ erg. This energy, however, is just that residing in the metals. If protons and $\alpha$ particles accompany the metals with abundances equal to those of the current epoch cosmic rays, $W_{\text{SN}}(\text{LECR}) \simeq 5 \times 10^{51}$ erg for this model. But this energetic efficiency can be improved by relaxing the $>60 M_\odot$ progenitor constraint, and by allowing $E_0$ (defined above) to exceed 30 MeV/nucleon but still be nonrelativistic. Observations of Galaxy-wide nuclear gamma-ray lines are needed to determine the contribution of the LECR component to LiBeB production.

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