Early Galactic Li, Be and B: Implications on Cosmic Ray Origin

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ABSTRACT

Be abundances of old, low metallicity halo stars have major implications on cosmic-ray origin, requiring acceleration out of fresh supernova ejecta. The observed, essentially constant Be/Fe fixes the Be production per SNII, allowing the determination of the energy supplied to cosmic rays per SNII. The results rule out acceleration out of the metal-poor ISM, and favor Be production at all epochs of Galactic evolution by cosmic rays having the same spectrum and source composition as those at the current epoch. Individual supernova acceleration of its own nucleosynthetic products and the collective acceleration by SN shocks of ejecta-enriched matter in the interiors of superbubbles have been proposed for such origin. The supernova acceleration efficiency is about 2% for the refractory metals and 10% for all the cosmic rays.

1. Introduction

It has been known for almost three decades that cosmic-ray interactions in the interstellar medium (hereafter ISM) have an important role in producing the Galactic inventories of the light elements Li, Be and B, hereafter LiBeB (Reeves, Fowler & Hoyle 1970; for reviews see also Reeves 1994 and Ramaty, Kozlovsky & Lingenfelter 1998a). However, not all the LiBeB isotopes are cosmic-ray produced. About 10% of the $^7$Li inventory results from nucleosynthesis in the Big Bang (e.g. Spite & Spite 1993), and nucleosynthesis in a variety of Galactic objects, including core collapse supernovae (SNIIs, Woosley & Weaver 1995), novae (Hernanz et al. 1996) and giant stars (Plez, Smith & Lambert 1993; Wallerstein & Morrell 1994), can produce a large fraction of the remaining 90%. Core collapse supernovae also contribute to $^{11}$B production via $^{12}$C spallation by neutrinos during the explosion (Woosley et al. 1990; Woosley & Weaver 1995). But essentially all of the $^6$Li, Be and $^{10}$B, and about 50% of the $^{11}$B are cosmic-ray produced.

Starting about a decade ago, observations with ground based telescopes led to Be abundance determinations in old, low metallicity halo stars (see Vangioni-Flam et al. 1998 for a recent
Fig. 1.— Li and Be abundances for stars of various ages as a function of their Fe abundance. Data compilation by M. Lemoine for Li and Vangioni-Flam et al. (1998) for Be.

compilation of the data). These stars, with Fe-to-H abundance ratios as low as $10^{-3}$ of the solar value, were born in the early Galaxy and still preserve fossil records of conditions that existed in that epoch of Galactic evolution. Thus, as the Be is entirely cosmic-ray produced, the early Galactic data extend the time scale of cosmic-ray research from the $10^7$ year mean age of the current epoch cosmic rays to the more than 10 billion year age of the Galaxy. In particular, the fact that the average early Galactic ISM, unlike the ISM of the current epoch, was almost totally devoid of metals (C and heavier atoms), provides new clues on the nature of the source material out of which cosmic rays are accelerated. As we shall see, the early Galactic Be data strongly suggests that the cosmic rays are accelerated out of fresh supernova ejecta rather than the average ISM, because if they had been accelerated out of the ISM, the Be in the early Galaxy would have been highly underproduced. To allow the direct acceleration of supernova ejecta before they mix into the average ISM, two related cosmic-ray origin scenarios were developed recently. The first considers the individual supernova shock acceleration of its own nucleosynthetic products (Lingenfelter, Ramaty & Kozlovsky 1998), while the second addresses the collective acceleration by successive SN shocks of ejecta-enriched matter in the interiors of superbubbles (Higdon, Lingenfelter & Ramaty 1998). Freshly formed dust grains in supernovae play a central role in both models, as we shall see.
2. LiBeB Origin

Li and Be abundances for various stars as a function of their metallicity are shown in Fig. 1. The metallicity of a star is defined in terms of its Fe abundance, \([\text{Fe}/\text{H}]\equiv \log(\text{Fe}/\text{H}) - \log((\text{Fe}/\text{H})_{\odot})\), where \(\text{Fe}/\text{H}\) is the Fe abundance by number relative to H and \((\text{Fe}/\text{H})_{\odot}\) is the solar system value. \([\text{Fe}/\text{H}]\) increases with time, reflecting the accumulating production of supernova nucleosynthesis, and thus provides a convenient, but nonlinear, representation of elapsed time since the formation of the Galaxy. Studies of Galactic chemical evolution (e.g. Ramaty, Lingenfelter & Kozlovsky 1998b; see also Pagel 1997 and references therein) have provided information on the age-metallicity relation. The halo phase of our Galaxy, for which \([\text{Fe}/\text{H}] < \sim -1\), corresponds to a period of \(\sim 10^9\) years preceding the formation of the Galactic disk. LiBeB observations of the early Galaxy (e.g. Molaro et al. 1997; Hobbs & Thorburn 1997; Duncan et al. 1997; Garcia Lopez et al. 1998) are very challenging because their spectral lines are weak and they are usually blended with interfering lines from other more abundant elements. The observations and their interpretation therefore require large telescopes and very efficient, high resolution detectors. While the Li and Be lines can be observed from the ground, the B lines require observations from space (with the Hubble Space Telescope, see Duncan et al. 1997).

The flat portion of the Li evolution (Fig. 1), usually referred to as the Spite plateau (Spite & Spite 1993), is generally believed (see Reeves 1994) to represent the \(^7\)Li abundance resulting from nucleosynthesis in the Big Bang. The subsequent increase in Li/H is due to nucleosynthesis in the various Galactic objects mentioned in the Introduction. Unlike Li/H, Be/H increases with increasing \([\text{Fe}/\text{H}]\) at all metallicities, implying a Galactic origin for Be even at the lowest metallicities where \(\log(\text{Be}/\text{H}) \sim -13\). Indeed, the maximum contribution of Big Bang nucleosynthesis is insignificant, \(\log(\text{Be}/\text{H})_{\text{BBNS}} \sim -15\) (Orito et al. 1997).

The implications of the Be data for cosmic-ray origin become more obvious (Ramaty et al. 1998a) when \(\log(\text{Be}/\text{Fe})\), rather than \(\log(\text{Be}/\text{H})\) is considered (Fig. 2). Here the horizontal line provides (Vangioni-Flam et al. 1998) the best fit to the data for \([\text{Fe}/\text{H}] < -1\). Fe production in this epoch (Timmes, Woosley & Weaver 1995) is dominated by SNIIIs, which result from massive (>10\(M_\odot\)), short lived (\(\sim 30\) Myr) stellar progenitors with an IMF (initial mass function) averaged Fe yield per SNII of \(~0.1M_\odot\), essentially independent of metallicity (Woosley & Weaver 1995). The decrease of Be/Fe for \([\text{Fe}/\text{H}] \gtrsim -1\) most likely results from the additional Fe production in Type Ia supernovae (Timmes et al. 1995). These come from more slowly evolving white dwarf systems and are less frequent than the SNIIIs, but because they do not produce neutron star remnants, they eject much more Fe per supernova and thus account for about half of the present Fe production.

The essentially constant observed Be-to-Fe abundance ratio for \([\text{Fe}/\text{H}] \lesssim -1\), coupled with the fact that Fe in this epoch is produced only by SNIIIs with a yield independent of \([\text{Fe}/\text{H}]\), requires an essentially constant Be production per SNII,

\[
Q_{\text{Be}} \simeq 0.1 \times 1.45 \times 10^{-6} \times (9/56) = 2.3 \times 10^{-8}M_\odot ,
\]  

(1)
Fig. 2.— Observed Be-Fe abundance ratio as a function of [Fe/H]; data compilation Vangioni-Flam et al. (1998). The best fit, for [Fe/H] $\lesssim -1$, implies that $2.3 \times 10^{-8} M_\odot$ of Be are produced per average SNII. The decrease at higher [Fe/H] is due to contributions of Type Ia supernovae which make Fe but very little Be.

independent of [Fe/H]. This is in conflict with cosmic-ray acceleration out of the ISM because in that case the composition of the cosmic rays (particularly C/H and O/H) would evolve in proportion to that of the ISM and $Q_{\text{Be}}$ would increase with [Fe/H], contrary to the requirements of the data.

Independent evidence against cosmic ray acceleration purely out of the ISM is provided by energetics. The energy in cosmic rays per SNII, $W_{\text{SNII}}$, needed to produce the required amount of Be depends on the composition of both the ISM and the cosmic rays, on the energy spectrum of the cosmic rays, and on the cosmic-ray escape length from the Galaxy, $X_{\text{esc}}$ measured in g cm$^{-2}$ (Ramaty, Kozlovsky, Lingenfelter & Reeves 1997). In Fig. 3 (from Ramaty et al. 1998b) we show $W_{\text{SNII}}$ as a function of [Fe/H] for two values of $X_{\text{esc}}$, and for two Galactic cosmic-ray origin models: a proposed CRS model for which the cosmic rays at all [Fe/H] have the same source composition and spectrum as the current epoch cosmic rays, and the ISM model for which the cosmic rays are accelerated out of a metallicity dependent interstellar medium with an energy spectrum that is also identical to that of the current epoch cosmic rays. The ambient ISM composition for both models is solar, scaled with $10^{[\text{Fe/H}]}$, except that O/H is allowed to increase by a factor of 3 for [Fe/H] $< -1$ to allow for the well known increase of O/H at low metallicities relative to its solar value (see Pagel 1997). To take into account recent shock acceleration results (Ellison, Drury & Meyer 1997), the cosmic-ray C/H and O/H relative to the corresponding metallicity dependent ISM values are also increased by factors of 1.5 and 2. We see that the ISM model requires that $W_{\text{SN}}$, the cosmic-ray energy per SNII, not only be metallicity dependent, which is unlikely, but
also untenably large, exceeding the total available ejecta kinetic energy ($\sim 1.5 \times 10^{51}$ erg, Woosley & Weaver 1995) when $[\text{Fe}/\text{H}] < -2$. This reinforces the previous conclusion that cosmic rays accelerated out of the average, metal poor ISM cannot be responsible for the Be production in the early Galaxy.

For the CRS model, on the other hand, $W_{\text{SNII}}$ is essentially constant (Fig. 3), equal to the very reasonable value of $\sim 10^{50}$ erg/SNII, practically the same as the energy supplied per supernova to the current epoch cosmic rays (Lingenfelter 1992). That these two energies are consistent, led to a different cosmic-ray paradigm, direct acceleration out of fresh supernova ejecta, at least for the refractory metals (Ramaty et al. 1998a; Lingenfelter, Ramaty & Kozlovsky 1998; Higdon, Lingenfelter & Ramaty 1998). The constancy of Be/Fe is a straightforward consequence of such a model and clearly such a cosmic-ray origin provides the simplest explanation for the origin of Be throughout the entire evolutionary history of our Galaxy. Moreover, as we shall see (§3), acceleration of fresh ejecta, rather than average ISM material, is to be expected since the hot phase of the interstellar medium, where shock acceleration is most efficient (Axford 1981), is probably highly enriched in fresh gas and dust from the same supernovae whose shocks accelerate the cosmic rays (Higdon et al. 1998). There is also another, more complex scenario for Be production by a possible, separate low energy cosmic-ray (LECR) component, also accelerated from fresh nucleosynthetic matter (Cassé, Lehoucq & Vangioni-Flam 1995; Ramaty, Kozlovsky & Lingenfelter 1996.) Such LECRs might allow the acceleration of the standard Galactic cosmic rays out of the ISM at all epochs of Galactic evolution, including the current one, but the nuclear gamma-ray lines that would provide the only evidence for their existence have not yet been seen. We consider these issues in §3, but before that we briefly discuss the B and $^6\text{Li}$ data.

Observations (Duncan et al. 1997; Garcia Lopez 1998) with the Hubble Space Telescope of the B abundance show (Fig. 4) that the B-to-Be abundance ratio is also essentially independent of $[\text{Fe}/\text{H}]$, implying a common origin for these two elements. It has often been pointed out (e.g. Reeves 1994) that there is a problem with a pure cosmic-ray origin for B in that its isotopic ratio, $^{11}\text{B}/^{10}\text{B}=4.05\pm0.2$ measured in meteorites (Chaussidon & Robert 1995) and $^{11}\text{B}/^{10}\text{B}=3.4\pm0.7$ in the interstellar medium (Lambert et al. 1998), exceeds the calculated ratio (2 to 2.5) for production by the Galactic cosmic rays (Ramaty et al. 1997). However, significant $^{11}\text{B}$ production is also expected from $^{12}\text{C}$ spallation by neutrinos in SNIIs (Woosley et al. 1990). In fact, if $\sim 30\%$ of the $^{11}\text{B}$ is from neutrinos the observed $^{11}\text{B}/^{10}\text{B}$ can be explained, and since both the neutrino and cosmic-ray induced spallation processes are related to such supernovae, the constancy of the B-to-Be ratio is assured. The neutrinos mostly make $^{11}\text{B}$ and not $^{10}\text{B}$ because their temperature is not high enough for interactions above the higher threshold energy for $^{10}\text{B}$ production. The required additional $^{11}\text{B}$ production per SNII (Ramaty et al. 1997), about $(2-7)\times10^{-7} \text{M}_\odot$, is consistent with the supernova calculations (Woosley & Weaver 1995).

The CRS model predicts (Ramaty et al. 1997) an abundance ratio $^{6}\text{Li}/\text{Be}=5\pm0.5$, essentially independent of $[\text{Fe}/\text{H}]$ and consistent with the meteoritic value of 5.8 (Anders & Grevesse 1989). But at low metallicities ($[\text{Fe}/\text{H}]\simeq-2.3$), values of $^{6}\text{Li}/\text{Be}$ as high as 60 are reported (Smith, Lambert
Fig. 3.— Energy in cosmic rays per SNII required to produce $2.3 \times 10^{-8} \text{M}_\odot$ of Be. The cosmic ray source composition is metallicity independent for the CRS model and metallicity scaled for the ISM model. $X_{\text{esc}} \simeq 10 \text{ g cm}^{-2}$ is the approximate current epoch cosmic-ray escape length; in the early Galaxy it could have been different, depending on the density and magnetic structure of the early Galactic halo. When $X_{\text{esc}} \to \infty$, the cosmic rays are trapped in the halo until they are either stopped by Coulomb collisions or destroyed by nuclear reactions; this choice of escape length yields the lowest $W_{\text{SN}}$ for the given Be production.

& Nissen 1998) which, even though still subject to large uncertainties, appear inconsistent with CRS production alone and would imply an additional source which dominated $^6\text{Li}$ production at early times. Since significant $^6\text{Li}$ can be produced by the $\alpha$-$\alpha$ reaction $^4\text{He}(\alpha, \text{pn})^6\text{Li}$ whose cross section is very large below about 100 MeV/nucleon, $^6\text{Li}/\text{Be}$ is strongly dependent on both the cosmic-ray composition (He/CNO) and energy spectrum, suggesting two possible additional sources. LECRs might account for these early Galactic $^6\text{Li}$ data, but if $^6\text{Li}/\text{Be}$ were to remain constant as a function of $[\text{Fe/H}]$, as would be the case if the LECR component were also responsible for producing the Be at all metallicities, then $^6\text{Li}/\text{Be}$ would be inconsistent with the meteoritic value (at $[\text{Fe/H}]=0$), and the total cosmic-ray produced Li abundance (which includes $^7\text{Li}$ with $^7\text{Li}/^6\text{Li}=1.5$) would significantly exceed the Li/H data around $[\text{Fe/H}] \simeq -1$ (see Fig. 1). Alternatively, there could have been significant $^6\text{Li}$ production via the $\alpha$-$\alpha$ reaction by possible pre-Galactic cosmic rays consisting almost entirely of primordial protons and $\alpha$ particles that would produce no Be. Further studies of this very exciting possibility, however, must await...
3. Cosmic-Ray Origin

Motivated by the need to accelerate the cosmic rays out of fresh supernova ejecta, two related CRS scenarios were developed. The first considers the individual supernova shock acceleration of its own nucleosynthetic products (Lingenfelter et al. 1998), while the second addresses the collective acceleration by successive SN shocks of ejecta-enriched matter in the interiors of superbubbles (Higdon et al. 1998). In the individual supernova model, freshly formed high velocity grains in the slowing ejecta reach the forward supernova shock which then accelerates the grain erosion products. The superbubble model emphasizes the fact that the bulk of the SNIIs occur in the cores of supernova generated superbubbles where the ambient matter is likely to be dominated by fresh supernova ejecta. In both scenarios, grain erosion products play a central role. They provide an explanation for the observed cosmic-ray enrichment of the highly refractory Mg, Al, Si, Ca, Fe and Ni relative to the highly volatile H, He, N, Ne, Ar, an idea developed in detail previously for the ISM model (Meyer, Drury & Ellison 1997). In both the individual supernova and superbubble scenarios, the accelerated C and O originate from grains, O from oxides (MgSiO$_3$, Fe$_3$O$_4$,Al$_2$O$_3$,CaO) and C mainly from graphite. As shown previously (Lingenfelter et al. 1998) such an origin for the C and O can explain the problematic C-to-O ratio in the cosmic rays which

![Graph showing log(B/Be) vs. [Fe/H]](image)

Fig. 4.— Observations of the B-to-Be ratio as a function of $[\text{Fe/H}]$. The fact that this ratio does not vary much with metallicity implies a common origin for these two elements. SNII accelerated cosmic rays produce both B and Be and additional B comes from C spallation by neutrinos in SNIIs.

improvements in the reliability of the early Galactic $^6\text{Li}$ measurements, which are very difficult. The contribution of Big Bang nucleosynthesis to Galactic $^6\text{Li}$ again is very small (Nollett, Lemoine & Schramm 1997).
exceeds the corresponding solar ratio by about a factor of 2.

The similarity of the cosmic-ray source and solar abundance ratios of refractory elements, mainly Mg, Al, Si, Ca, relative to Fe, has been mentioned (Meyer et al. 1997) as an argument against the supernova ejecta origin for the cosmic rays. That this is not the case was demonstrated by Lingenfelter et al. (1998), the principal reason being that the combined contributions from SNIIs and Type Ia supernovae are responsible for both the cosmic-ray source and solar abundances of these refractories.

The presence of s-elements in the cosmic rays has also been used as an argument against cosmic-ray acceleration out of supernova ejecta (e.g. Meyer et al. 1997), since such elements are not synthesized in the supernova explosions. However, this does not contradict acceleration out of the ejecta because s-elements are present in supernova ejecta along with the other much more abundant products of pre-supernova burning. The s-process elements are made in the cores of stars and can be ejected both in supernova explosions and in strong stellar winds (e.g. Arnould & Takahashi 1993). In fact, the observations of SN1987A (e.g. Mazzali, Lucy & Butler 1992 and references therein) show very significant overabundances of the prominent s-process products, Sr and Ba, relative to Fe by perhaps as much as an order of magnitude compared to solar values. Only a fraction of such supernova ejecta could account for the much more modest Sr and Ba overabundances of about 1.5, required for cosmic-ray source ratios (e.g. Binns et al. 1989). Moreover, the enrichment of r-process nuclei in the cosmic rays, especially the strong Pt peak (Waddington 1996), provides direct support for a supernova ejecta origin. The r-process elements are thought to be made just above the newly formed neutron star (e.g. Cardall & Fuller 1997) in core collapse supernovae. Thus, both r- and s-process elements are blown off in the supernova ejecta along with the products of explosive burning and other products of earlier burning, and all the refractories condense in the ejecta.

Finally, electron-capture decay nuclei, such as $^{59}$Ni (decaying into $^{59}$Co with mean life of $1.1\times10^5$ yrs), can give a measure of the time between nucleosynthesis and acceleration, since such decay is suppressed once the nuclei are accelerated and fully ionized. Preliminary ACE data on the $^{59}$Ni-$^{59}$Co ratio (Wiedenbeck et al. 1998) show that $^{59}$Ni has decayed, suggesting delayed acceleration. This result favors the superbubble model for which the mean time between successive supernova explosions, $\sim 3\times10^5$ yr, ensures that each supernova shock will on average accelerate ejecta accumulated from many previous supernovae on time scales clearly exceeding the $^{59}$Ni mean life.

4. Nuclear Gamma-Ray Line Emission

The possible existence of a distinct low energy component of cosmic rays which could not be observed in the inner solar system because of solar modulation, is a topic of major interest for cosmic-ray research. Evidence for a strong enough LECR component that could produce
significant amounts of LiBeB could only come from nuclear gamma-ray line data (e.g. Ramaty, Kozlovsky & Lingenfelter 1979). Indeed, as mentioned above, following the reported (Bloemen et al. 1994) detection with COMPTEL/CGRO of C and O gamma-ray lines from the Orion star formation region, Cassé et al. (1995) suggested that the LECRs postulated to exist in the Orion region might be responsible for the Be (and B) production in the early Galaxy. The motivation for this idea was the indication (based on the reported spectrum of the line emission) that the LECRs in Orion are enriched in C and O relative to protons and α particles (see Ramaty 1996 for review and Ramaty, Kozlovsky & Lingenfelter 1996 for extensive calculations of LiBeB production by LECRs). It was proposed (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 (>60M⊙) which explode within the bubble around the star formation region due to their very short lifetimes. These arguments led to the suggestion (Vangioni-Flam et al. 1996; Vangioni-Flam, Cassé & Ramaty 1997) that the composition of the LECRs could be independent of Galactic metallicity, thus allowing them to reproduce the constancy of Be/Fe in the early Galaxy. The problem with this model is its energetic inefficiency, mostly because it relies on >60M⊙ SNII progenitors which are much less numerous, but not significantly more energetic than the progenitors of all the SNIIs (>10M⊙) which accelerate the cosmic rays in the CRS model. Moreover, the Orion gamma-ray line data have recently been withdrawn by the COMPTEL team (private communication, V. Schönhfelder, 1998). The planned high resolution observations of the Galaxy-wide nuclear gamma-ray line emission by the INTEGRAL mission should better define the possible contribution of LECRs to Galactic Be production.

5. Conclusions

We have seen how recent atomic spectroscopy observations of light element abundances in old halo stars have brought exciting new insights to the question of the origin of the cosmic rays, a problem that so far has been investigated mainly by in situ cosmic-ray observations. The cosmic rays in the early Galaxy, or at least their C and O, must have been accelerated from freshly nucleosynthesized matter rather than from the then extremely metal poor interstellar medium. This strongly suggests that the present epoch cosmic rays are also accelerated from fresh material, unlike in most current models. We have outlined two recently proposed scenarios for cosmic-ray acceleration from supernova ejecta that could account for such an origin.

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