SPALLOGENIC LIGHT ELEMENTS AND COSMIC RAY ORIGIN

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Abstract.

We discuss the new information that the light elements, particularly Be, have brought to cosmic-ray studies, specifically to the issue of the origin of the seed material of the cosmic rays. The primary nature of the Be evolution strongly suggests that supernova ejecta are the sources of this material. We discuss the superbubble models that emerged as the most likely site for the acceleration of supernova ejecta, and we review the arguments that support the model in which the present epoch cosmic rays have the same origin as those that produce the light elements throughout the evolutionary history of the Galaxy. These arguments include the facts that the bulk of the Galactic supernovae are confined within the interiors of superbubbles, where their ejecta could dominate the metallicity, and that high velocity grains, which condense out of the cooling and expanding ejecta, serve as the injection source for shock acceleration, via sputtering of grain material and scattering of volatile gas atoms. We also review the evolutionary calculations that show that a secondary origin for the evolution of Be as a function of the O abundance is energetically untenable, and unnecessary if cosmic-ray transport is properly taken into account.

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1. Introduction

That cosmic-ray driven nucleosynthesis is important to the origin of the light elements Li, Be and B (LiBeB) has been known for three decades (Reeves, Fowler, and Hoyle, 1970). But only recently was it realized that the light elements themselves, in particular Be, could provide new information on cosmic-ray origin, specifically on the source of the particles that are accelerated to become cosmic rays (Ramaty, Kozlovsky, and 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 debatable. The first suggestions that cosmic rays are accelerated in supernova remnants (e.g. Ginzburg and 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 efficient site for cosmic-ray acceleration is the hot, low density interstellar medium (see Axford, 1981). Several cosmic-ray injection sources were proposed to explain the large differences between cosmic-ray and solar abundances, including the acceleration in the ISM (interstellar medium) of cosmic rays preaccelerated in stellar coronae, based on the correlation of the enrichments with first ionization potential (FIP, Cassé and Goret, 1978), and the acceleration of grain erosion products in the average ISM, based on the anti-correlation of the enrichments with volatility (Epstein, 1980; Cesarsky and Bibring, 1981). Recent analyses (Meyer, Drury, and Ellison, 1997; Ellison, Drury and Meyer, 1997) favor a volatility, rather than FIP biased acceleration out of the average ISM, augmented by the mass-to-charge dependent acceleration of volatiles.

These ideas, prevalent in the 1980's, led to a LiBeB evolutionary model (hereafter the Cosmic Ray ISM, CRI model) 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). In this model the LiBeB production is a secondary process because it depends on the ISM abundances of C and O, elements that are produced by primary nucleosynthetic processes. The excess of the observed Be abundances in low metallicity stars over the predictions of this secondary model was first discussed by Pagel (1991). The CRI model was eventually modified by superposing onto the cosmic rays accelerated out of the average ISM a metal enriched low energy component whose composition was taken independent of the ISM abundances, thus leading to primary LiBeB evolution (Cassé, Lehoucq, and Vangioni-Flam, 1995; Vangioni-Flam et al., 1996; Ramaty, Kozlovsky, and Lingenfelter, 1996; Vangioni-Flam, Cassé, and Ramaty, 1997). A strong motivation for postulating these low energy cosmic rays (LECRs) was the report of the detection of C and O nuclear gamma-ray lines from the Orion star formation region (Bloemen et al., 1994). These gamma rays required that the cosmic rays be predominantly of low energy (maximum energies not exceeding about 100 MeV/nucleon) and highly enriched in C and O relative to protons and α particles (e.g. Ramaty, 1996). It was suggested that such enriched LECRs might be accelerated out of metal-rich winds of massive stars and supernova ejecta (Bykov and Bloemen, 1994; Ramaty *et al.,* 1996; Parizot, Cassé, and Vangioni-Flam, 1997) by an ensemble of shocks in superbubbles (Bykov and Fleishman, 1992; Parizot *et al.,* 1997). In the resultant hybrid model, the primary component is dominant until essentially solar metallicity (see figure 2 or 3 in Vangioni-Flam *et al.,* 1997). The Orion gamma-ray data, however, have been retracted (Bloemen et al., 1999). Nonetheless, as the possible existence of the postulated LECRs remains, new gamma-ray line data are needed to determine the role of the LECRs in light element production (see Ramaty *et al.,* 1996; Vangioni-Flam and Cassé, 2000).

The possible increase of [O/Fe] with decreasing [Fe/H] at low metallicities (Israelian, Garcia Lopez, and Rebolo, 1998; Boesgaard *et al.,* 1999a; Mishenina *et al.,* 2000), even though still somewhat controversial (Fulbright and Kraft, 1999; Westin *et al.,* 2000), led to the claim that a secondary origin for Be (i.e. the CRI model) is possible at all metallicities (Fields and Olive, 1999). Subsequently, Fields *et al.* (1999) found that if the Be evolution is considered as a function of [O/H], a transition is possible from primary to secondary behavior at [O/H] between about -2 and -1. Likewise, Boesgaard *et al.* (1999b) showed that the slope of [Be/H] vs. [O/H], over the entire range up to solar metallicity, is 1.45±0.04, which seems to indicate a behavior intermediate between primary and secondary. But as we have shown (Ramaty, Lingenfelter, and Kozlovsky, 2000b), and also review in the present paper, if delays due to the transport of the cosmic rays are taken into account, a purely primary behavior is consistent with these data at all metallicities. Furthermore, if the energy imparted to cosmic rays per supernova is normalized to reasonable values, the contribution of the CRI cosmic rays (i.e. a secondary component) cannot be dominant for almost the entire range of metallicities up to solar (Ramaty et al., 2000a,b). In the present paper we review this result as well. Hereafter, as is commonly done in the literature, chemical symbols in square brackets denote logarithms of abundance ratios by number normalized to solar abundances.

Superbubbles have emerged as the mostly likely site for the acceleration of cosmic rays leading to primary LiBeB behavior. Higdon, Lingenfelter, and Ramaty (1998) and Lingenfelter, Higdon, and Ramaty (2000) showed that the metallicity of these superbubbles, throughout the evolutionary history of the Galaxy including the current epoch, is dominated by supernova ejecta. The superbubble/hot phase (hereafter SB/HISM) of the ISM can thus provide a cosmic-ray source which leads to primary LiBeB evolution. In this evolutionary model (hereafter the cosmic-ray superbubble model, CRS, Ramaty *et al.,* 2000a), the cosmic-ray source composition is taken constant, independent of metallicity, the same as the composition of the current epoch cosmic rays. Since, as discussed below, the acceleration is of grain erosion and scattering products by successive supernova shocks on time scales of at least 10^5 years (Lingenfelter *et al.,* 2000), the model is consistent with the delay between nucleosynthesis and acceleration implied by the ^{59}Co and ^{59}Ni observations (Wiedenbeck *et al.,* 1999). The ^{59}Co/^{59}Ni test was originally suggested by Cassé and Soutoul (1975).

Another superbubble acceleration model has been proposed by Parizot and Drury (1999;2000) and Parizot (2000). This model differs from that developed by Higdon *et al.* (1998) and Lingenfelter *et al.* (2000). In the Parizot/Drury model the particles that are accelerated in the superbubble are not the cosmic rays, but a new hypothetical component, accelerated to energies as high as 500 MeV/nucleon. How this component co-exists with the cosmic rays which must also be accelerated in the SB/HISM is not clear. Moreover, the new component is different from the LECRs mentioned previously, that were introduced to explain the linear evolution of the Be abundance. Those LECRs were assumed to be accelerated to energies on the order of tens of MeV/nucleon, since their existence was motivated by the Orion gamma-ray reports (now retracted) which required relatively low energy particles. Thus it will be very difficult to confirm by gamma-ray line observations the existence of the accelerated particles of the Parizot/Drury model, since the ratio of gamma-ray line emission to Be production is a decreasing function of accelerated particle energy (Ramaty *et al.,* 1997), rendering the new, hypothetical component much less efficient in producing gamma-ray line emission than the original LECR component.

In the Parizot and Drury (2000) and Parizot (2000) model, the superbubble metallicity in the early Galaxy is dominated by supernova ejecta, but later on the composition becomes that of the average ISM. The evolutionary transition from primary to secondary, implied by such a change in the origin of the metals that become the sources of the accelerated particles, is inconsistent with the [Be/H] vs. [Fe/H] data (e.g. Boesgaard *et al.,* 1999b), but not with [Be/H] vs. [O/H], for which a transition was claimed by Fields *et al.* (1999). But as we have already mentioned, and will review in the present paper, a secondary behavior of [Be/H] vs. either [Fe/H] or [O/H] is inconsistent with reasonable cosmic-ray energetics per supernova. Furthermore, as we have also mentioned, and will review in the present paper, the slope of 1.45 ± 0.04 of [Be/H] vs. [O/H] measured by Boesgaard *et al.* (1999b), is consistent with a primary behavior if the delay in the deposition of the Be due to the transport of the cosmic rays is taken into account (Ramaty *et al.,* 2000b). In addition, as demonstrated by Lingenfelter *et al.* (2000), the metallicity of the superbubbles could be dominated by supernova ejecta during the entire evolutionary history of the Galaxy.

2. Superbubbles and the Origin of the Current Epoch Cosmic Rays

Core-collapse (Type II and Ib/c) supernovae are highly correlated in space and time, thus creating in the ISM giant cavities, or superbubbles, rather than many smaller isolated bubbles (e.g Mac Low and McCray, 1988; Tomisaka, 1992). These hot, large and low density bubbles are, in fact, the hot phase of the ISM (SB/HISM) where shock acceleration of cosmic rays is expected (e.g. Axford, 1981; Bykov and Fleishman, 1992) to be most effective because the energy losses of the accelerated particles are minimized and the supernova shocks do not suffer major radiative losses, as they would in a denser medium.

From the comparison of the total mass of the SB/HISM and the mass of supernova ejecta produced during the mean life of an average superbubble, it was shown that supernova ejecta appear to be able to provide sufficient metals to dominate the metallicity of the SB/HISM at all epochs of Galactic evolution (Lingenfelter *et al.,* 2000). Observational evidence of such supernova ejecta enriched superbubble metallicity may be found in the X-ray emission from the interiors of giant HII regions in the LMC, thought to be superbubbles powered by supernovae. The observed X-ray luminosities of these bubbles, which should scale directly with metallicity, are an order of magnitude higher than would be expected (Chu and Mac Low, 1990) if they had a typical LMC metallicity of only 1/3 solar. Thus, the X-ray observations do in fact suggest an average metallicity of roughly 3 times solar in these superbubbles. Such metallicities are larger than that calculated from the simple analytic superbubble model of Mac Low and McCray (1988), which assumes conductive heating and evaporation of swept-up ISM as the primary source of superbubble gas and predicts an averaged metallicity of only $\sim$1.1 times solar. But as discussed by Lingenfelter *et al.* (2000), this model of superbubble expansion in an infinite non-magnetic medium, greatly underestimates the superbubble metallicity, because it underestimates the number of supernovae needed to power the expansion against the added magnetic pressure and the loss of superbubble pressure from "blowout" into the halo. The model also overestimates the input of evaporated swept-up ISM gas because of the reduced conductive heating across the magnetic field from the hot superbubble gas into the warm swept up shell. This heating provides the energy for the evaporation of the swept up gas.

A large fraction of the C, O and refractory metals in the ejecta may be in graphite and oxide grains, since in the core-collapse supernova 1987A roughly 0.2 $M_\odot$ of this material condensed as high velocity ($\sim$ 2500 km/s) grains within 2 years after the explosion, and as much as 1 $M_\odot$ could be expected to condense before the ejecta is reheated and slowed by the reverse shock (see references in Lingenfelter *et al.,* 2000). The best evidence that these grains will survive in the SB/HISM and maintain their high velocities is provided by observations (Naya *et al.,* 1996) of the broad width (5.4$\pm$1.4 keV) of the Galactic 1.809 MeV line from the decay of long-lived (1.0x10^6 yr mean life) ^{26}Al. These observations clearly suggests that refractory grains, containing most of the live Galactic ^{26}Al, are still moving at velocities of $\sim$450 km s^{-1} some 10^6 yrs after their formation, and that the bulk of the grains are in the SB/HISM because the grains would have been stopped much earlier in the much denser average ISM. The grains are also not expected to move rectilinearly because of their charge, and thus are prevented from escaping from the Galactic disk on time scales less than a million years.

The similarity of the cosmic-ray source and solar abundance ratios of refractory elements, mainly Mg, Al, Si, Ca relative to Fe, is an often used argument against cosmic-ray acceleration out of supernova ejecta (e.g. Meyer *et al.,* 1997). The argument is based on the fact that Mg and Si, and other refractory elements, are primarily produced in core-collapse supernovae (SNII/Ibc), while only about half of the Fe is made in them and the other half is made in thermonuclear SNIa. Yet abundance ratios such as Mg/Fe and Si/Fe are very nearly the same for the cosmic-ray source and the solar system. However, as we have emphasized above, the large SB/HISM filling factor (e.g. Yorke, 1986) ensures that much of the Fe from thermonuclear supernovae also contributes to the high velocity grain population in the SB/HISM. This was quantitatively demonstrated in both Lingenfelter and Ramaty (1999) and Lingenfelter *et al.* (2000). Most recently, Vangioni-Flam and Cassé (2000) have remarked that the fact that Si/Fe in ISM grain cores (Savage and Sembach 1996) is much lower than in the cosmic-ray source (Engelmann *et al.,* 1990) could be an argument against cosmic rays originating from supernova grains in the SB/HISM. But this is in fact an argument against the ISM grain scenario

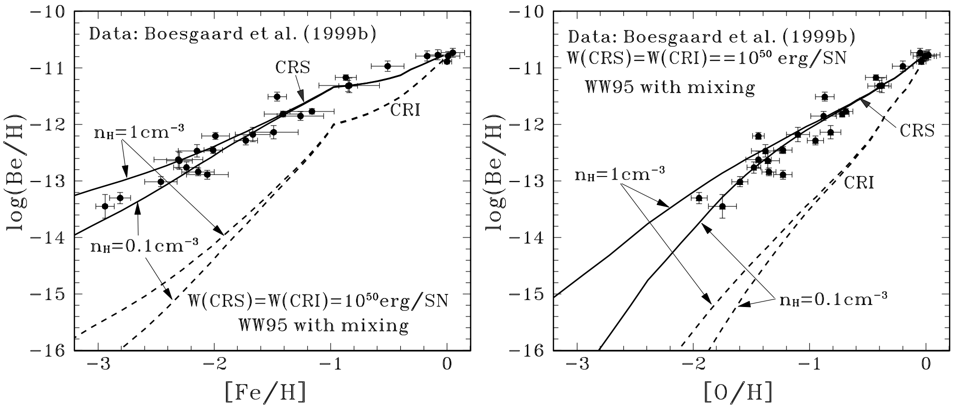

Figure 1. Be abundance evolution for the CRS and CRI models, vs. [Fe/H] (*left panel*) and [O/H] (*right panel*). n_H is the density of ambient hydrogen which influences the propagation of the cosmic rays and determines the delay between supernova explosion and the deposition of the synthesized Be. The yields of Fe and O for core collapse supernovae are from Woosley and Weaver (1995). The contribution of thermonuclear supernovae to Fe production is included (Ramaty *et al.* 2000a). The deposition of Fe is delayed due to its incorporation into high velocity grains.

of Meyer *et al.* (1997), since the Savage and Sembach (1996) data is directly applicable to these old grains, but not to the much younger supernova grains in the SB/HISM.

The sputtering of ions off the high velocity grains in the SB/HISM is most likely the injection source for the cosmic-ray refractory metals. The high initial velocities of these ions should be responsible for the enrichment of refractories vs. volatiles in the cosmic rays, similar to the model of Ellison *et al.* (1997), except that the high velocities in that model result from shock acceleration of average ISM grains, whereas here the grains are freshly formed in supernova explosions. While the enrichment of the cosmic refractories relative to the volatiles is thus due to the preferential acceleration of the suprathermal ions sputtered off high velocity grains, the mass-dependent enrichment of heavier volatiles with respect to H (Meyer *et al.,* 1997) is interpreted in the Ellison *et al.* (1997) model as a mass-to-charge dependence of shock acceleration, which requires warm partially ionized gas. The occurrence of most supernovae in the SB/HISM and cosmic-ray acceleration in that hot phase argues against such acceleration of the volatiles.

Alternatively, we have proposed (Lingenfelter and Ramaty, 1999) that the mass-dependent enrichment of the volatiles could result from the scattering of the ambient gas ions in direct collisions with fast grains that must accompany the sputtering of the grains. That scattering by, and sputtering of high velocity grains could account for the measured abundance ratio by number $\simeq$100 of the volatile cosmic rays to the refractory cosmic-ray metals (including C and O) (Engelmann *et al.,* 1990), can be verified using laboratory measurements and computer simulations of reflection of fast ions from solids and the accompanying sputtering of the solid material (e.g. Eckstein 1991). For instance, the sputtering yield of a H projectile of a few keV (the typical energy of a superbubble proton in the frame of a fast moving grain) impinging on a Ni target is about 10^{-2} (Biersak, 1987), while for the same target and projectile, the reflection coefficient in the keV range is between 0.5 and 1 (Eckstein and Biersak, 1985), yielding a ratio of 50 to 100 between scattering and sputtering. We note in addition that Coulomb repulsion between the positively charged grains (Draine and Salpeter, 1979) and the fully stripped volatile ions in the superbubble will increase the ratio relative to the laboratory value for which the target material is neutral. This effect, could also provide a self consistent explanation for the mass dependent enrichment of the volatiles (Meyer *et al.,* 1997) because of the increased Coulomb repulsion of the heavier volatile ions.

3. LiBeB Evolution

In this section we briefly review the LiBeB evolutionary calculations described in detail in Ramaty *et al.* (2000a,b). The delayed deposition of the refractory Fe (but not of the mostly volatile O), due to the incorporation of the Fe into high velocity grains, can account for the possible rise of [O/Fe] with decreasing [Fe/O]. As a test of this model we made a prediction (Ramaty *et al.,* 2000b) for the α elements. Specifically, that volatile S should behave as O, i.e. that S/Fe should rise, while the abundances of refractory Mg, Si, Ca and Ti relative to Fe should not. This prediction was recently confirmed (Takeda *et al.,* 2000).

For the LiBeB evolution we consider two models, CRS (cosmic rays superbubble) and CRI (cosmic rays ISM). In the CRS model the cosmic rays at all epochs are accelerated out of supernova ejecta in superbubbles with their source composition independent of metallicity and equal to that of the current epoch cosmic rays. The grain scattering injection mentioned in the previous section would probably ensure such a constancy. In the CRI model the cosmic-ray source composition is that of evolving ISM, with modifications as expected from shock acceleration (see Ramaty *et al.,* 2000b). In both models a fixed amount of energy per supernova is imparted to the cosmic rays in the calculations.

The resultant Be evolution is shown in Figure 1. With an energy of 10^{50} erg per supernova imparted to the cosmic rays the CRS curves provide good fits to the measured Be abundances, both as a function of [Fe/H] and [O/H]. The fact that this value is in very good agreement with current epoch cosmic-ray energetics provides strong support for the validity of the CRS model. On the other hand, the CRI model, similarly normalized, severely underpredicts the data, independent of whether the Be evolution is considered as a function of [Fe/H] or [O/H].

Considering the slopes of the data and of the calculated curves, we note that even though the overall slope of log(Be/H) vs. [Fe/H] is practically unity, while that of log(Be/H) vs. [O/H] is significantly steeper (0.96 ± 0.04 and 1.45 ± 0.04, respectively, Boesgaard et al. 1999b), the CRS model provides a good fit to these evolutionary trends, particularly if n_H is near 0.1. Such a value is reasonable for a spherical halo of radius 10 kpc containing $10^{10} M_\odot$. The calculated log(Be/H) vs. [Fe/H] is flatter than log(Be/H) vs. [O/H] because the delayed deposition of the synthesized Be, caused by the low n_H, is compensated by the delayed Fe deposition, due to the incorporation of Fe in high velocity dust, but not compensated by the lack of significant delay for O. We thus see that primary evolution of Be vs. both [Fe/H] and [O/H], predicted by the CRS model, is possible if the delays due to cosmic-ray transport and Fe incorporation into high velocity grains are properly taken into account. Thus the steeper evolution of the Be abundance vs. [O/H] should not be simply interpreted as secondary evolution (Fields *et al.,* 1999), because such evolution, predicted by the CRI model, is energetically untenable and also unnecessary since primary evolution, with delays taken into account, can fit the data.

In addition to the CRS and CRI models, in Ramaty *et al.,* (2000b) a hybrid model was also considered to account for the Be by a possible primary LECR component superposed onto the CRI cosmic rays. This component, normalized to 1.5×10^{50} ergs per supernova, would dominate the Be evolution almost up to solar metallicity, as was found earlier by Vangioni-Flam *et al.* (1997). In all three models, CRS, CRI and CRI+LECR, the B isotopic ratio in meteorites requires the addition of neutrino produced ^{11}B in core collapse supernovae. Also, all three models fail to account for the ^{6}Li abundances measured below [Fe/H]=-2. For details on the B and Li evolutions see Ramaty *et al.,* (2000b) and references therein. It was pointed out by Jedamzik (2000) that ^{6}Li could be produced after the epoch of big bang nucleosynthesis by fast ^{3}He and ^{3}H interacting with ^{4}He, where these fast projectiles result from the breakup of ^{4}He by photons resulting from the decay of relic particles.

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