The Source of Cosmic Rays: 3. Supernova Grain Composition

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Abstract

We show that the expected composition of cosmic rays accelerated from the erosion products of fast supernova grains in the hot interstellar medium (HISM) of ejecta enriched superbubbles, where the bulk ($\sim$85%) of Galactic supernovae occur, is consistent with the currently available cosmic ray data. In particular, we show that if the cosmic ray metals come from the sputtering of fast refractory grains that condense in expanding supernova ejecta and populate the superbubbles, then: (i) the abundances of the refractory cosmic ray metals, including C and O, are consistent with the required cosmic ray source abundances; (ii) the problematic cosmic ray C-to-O ratio is explained by refractory oxide and graphite grain abundances; (iii) the scattering of ambient gas by the fast grains can account for the relative abundance of cosmic ray volatiles; (iv) the mean time delay for cosmic ray acceleration is consistent with the ACE measurements; and (v) the resulting cosmic ray metallicity is consistent with the Galactic evolution of the Be abundance. In addition, we point out that acceleration in the HISM is energetically much more favorable than acceleration in the denser phases of the interstellar medium because the bulk of the supernovae occur in the HISM where the shocks suffer much lower radiative losses than those of supernovae in the denser average interstellar medium.

1 Introduction:

Although supernova shocks are generally thought to be the source of the energy in cosmic rays, the source of the particles that are accelerated is still debated. Compared to the composition of the solar photosphere, the cosmic ray source abundances are enriched in the highly refractory elements (principally Mg, Al, Si, Ca, Fe and Ni) relative to the highly volatiles (H, He, N, Ne, and Ar). It was suggested (Meyer, Drury, & Ellison 1997; Ellison, Drury, & Meyer 1997) that this enrichment results from the preferential acceleration of the erosion products of refractory interstellar grains in the average, well mixed interstellar medium (ISM), while the less dramatic mass dependent abundances of the highly volatiles arise from mass/charge (A/Q) dependent acceleration, and the C and O are mostly accelerated out of the winds of Wolf Rayet stars. As we have shown (Ramaty & Lingenfelter 1999 and references therein), however, such acceleration is not consistent with the Galactic evolution of the Be/Fe abundance ratio.

Thus, we proposed (Lingenfelter, Ramaty, & Kozlovsky 1998; Higdon, Lingenfelter, & Ramaty 1998) that the cosmic ray refractory metals (including C and O) are accelerated out of the erosion products of supernova grains in ejecta enriched superbubbles. We showed that such grain acceleration resolved the abundance based arguments (Meyer et al. 1997) against supernova ejecta and that cosmic ray acceleration by successive supernova shocks in the ejecta-enriched interiors of superbubbles answered the constraints of cosmic ray ^{59}Ni and ^{59}Co abundance measurements (Binns et al. 1999; Mewaldt et al. 1999 OG 1.1.13) requiring a $\sim 10^5$ yr delay before acceleration. These superbubbles form the hot, tenuous phase of the interstellar medium (HISM) which has been long thought to be the most efficient site for acceleration (e.g. Axford 1981).

Nonetheless, Meyer & Ellison (1999) reiterated the abundance-based arguments, and Ellison & Meyer (1999) argue that the A/Q dependence of their model will not work in the HISM and therefore requires that the acceleration must therefore take place exclusively in the cooler, denser phases of the interstellar medium. But, since only $\sim$ 15% of the supernovae occur in such phases (Higdon et al. 1998, Higdon, Lingenfelter, & Ramaty 1999 OG 3.1.04), cosmic ray acceleration only in these phases would require unreasonably large ($>$70%) conversion efficiencies of supernova energy into cosmic rays, while the remnants there rapidly dissipate their energy by radiation losses (McCray & Snow 1979). On the other hand, the acceleration of the bulk of the cosmic rays in the superbubble HISM where most (∼85%) of the supernovae occur, as we have shown, requires only a very modest acceleration efficiency of ∼ 10%. The very large fraction of supernovae occurring in the superbubble HISM results not only from the concentration of the core collapse supernovae (Type II and Ib) from OB associations but also from the chance occurrence of roughly half of the thermonuclear (Type Ia) supernovae because of the large (∼50% e.g. Yorke 1986) filling factor of the HISM. Furthermore, acceleration in the tenuous HISM is most efficient, because the energy losses of both the cosmic rays and the supernova shocks are minimized (Higdon et al. 1999 OG 3.1.04). In addition, acceleration predominantly in the supernova metal-enriched, superbubbles can easily account (Ramaty & Lingenfelter 1999; Ramaty et al. 1999 OG 3.1.03) for the Galactic Be evolution.

Here we show that the averaged supernova grain dominated injection abundances expected for cosmic ray acceleration in superbubbles are consistent with those required of the cosmic ray source. In addition, we propose an alternative injection mechanism for the mass dependent abundances of the highly volatile elements, namely the preferential injection of gas scattered by high velocity grain atoms, whose scattering cross sections depend on the mass of the gas atoms. This mechanism quite naturally gives the observed ratio of cosmic ray refractory to volatile elements.

2 Expected Abundances of Refractory Cosmic Rays:

The enrichment of the cosmic ray refractory elements in the ISM injection model of Meyer et al. (1997) is due to the preferential acceleration of suprathermal ions sputtered off refractory grains which have themselves been accelerated to velocities of a few 10^3 km s^{-1} by supernova blast waves. But since refractory grains are formed as condensates at comparable velocities in the expanding supernova ejecta (e.g. Kozasa, Hasegawa & Nomoto 1991), we suggested (Lingenfelter et al. 1998; Higdon et al. 1998) that the sputtering of high velocity supernova grains in superbubbles can be the cosmic ray refractory injection source, which also can account for the Galactic Be observations.

The measured (Naya et al. 1996) broad width (5.4±1.4 keV) of the Galactic 1.809 MeV line from the decay of long-lived (1.0x10^6 yr mean life) ^{26}Al, most likely produced in Type II supernovae also suggests that refractory grains, containing most of the live Galactic ^{26}Al, are still moving at velocities of ∼450 km s^{-1} some 10^6 yrs after their formation, and that the bulk of the grains are in low density superbubbles because the grains would have been stopped much earlier in the much denser average ISM. Only a very small fraction (∼10^{-4}) of the grains formed in a typical supernova need be accelerated to account for the average injection of cosmic ray metals.

The similarity of the cosmic ray source and solar abundance ratios of refractory elements, has been used (Meyer et al. 1997; Meyer & Ellison 1999) as an argument against the supernova ejecta origin. But this argument ignores the fact that supernovae are thought to be the primary source of these elements (e.g. Timmes et al. 1995). As we have shown (Lingenfelter et al. 1998) in detail, within the current calculational uncertainties, the weighted abundances from all supernovae grains (SNGrains Table 1) are in good agreement with both cosmic ray source and solar system abundances. Supernova grains can also explain the origin of the cosmic ray C and O abundance ratios which have long been a puzzle, since the cosmic ray source C/Fe and O/Fe are much lower than both the solar values and those in ISM grains in the cooler phases of the ISM. For supernova grain injection, however, the cosmic ray O/Fe is determined only by the fraction of the O that is bound in refractories (primarily $MgSiO_3$, Fe_3O_4, Al_2O_3, CaO and NiO) and the cosmic ray C/Fe is mainly determined by the supernova value, while most of the C in the ISM comes from stellar winds.

Here, we show that average grain abundances in superbubbles (SBGrains), and the supernova weighted Galactic average refractory grain injection abundances (CRInject) are also quite consistent with the required cosmic ray source (CRSource) within the current calculational uncertainties. The expected superbubble grains assume a range of mixes of supernova and ISM grains from the maximum supernova grain fraction of ∼90% from the magnetic superbubble model of Tomisaka (1992), to the minimum of ∼50% from the Be/Fe evolution that allows (Ramaty & Lingenfelter 1999, Ramaty et al. 1999 OG 3.1.03) no more than a ∼50% reduction in the cosmic ray source metallicity as the ISM metallicity approaches zero. The present Galactic average cosmic ray source from grain injection (CRInject) is the weighted (Higdon et al. 1998; 1999 OG 3.1.04) product of the relative supernova rates in the superbubble (∼85%) and cooler ISM (∼15%) and the ratio of the masses of swept up, or processed, grains in the two phases, which ranges from ∼ 5:1 to 2:1 for supernovae in superbubbles versus those in the cooler ISM, for the above grain fractions in superbubbles. Thus with ∼ 85% of supernovae occurring in the superbubble hot phase, we would expect about the same fraction of the cosmic ray H and He to be accelerated there, while, because of the higher supernova grain dominated metallicity of the superbubbles, between 92% and 97% of the cosmic ray metals should be accelerated there.

Table 1: Cosmic Ray Injection Abundance Ratios by Number (%)

	ISMGrains	ISMCores	SNGrains	SBGrains	CRInject	CRSource	Solar
C/Fe	690	430	210–510	375–610	380–590	422±14	1122±139
O/Fe	1400	400	320–520	460–690	455–665	522±11	2344±414
Mg/Fe	115	110	50–150	90–190	90–185	103±3	120±4
Al/Fe	10	10	5–16	8–20	8–20	7.7±1.5	9.8±0.3
Si/Fe	105	65	110–170	105–185	100–175	99±2	115±4
Ca/Fe	6	6	4–8	5–9	5–9	6.0±0.9	7.1±0.2
Ni/Fe	6	6	6–14	6–9	6–9	5.6±0.2	5.6±0.2

ISMGrains and ISMCores – HST interstellar depletion determined abundances from Savage & Sembach (1997), except for C and O that are not measured for the ISMCores; we assume that O is limited to bound refractories, as discussed for SNGrains just below, and C is scaled from ISMGrains in the same ratio as measured Si. *SNGrains* – Range of mixed SN ejecta yields (Nomoto et al. 1997; Woosley et al. 1995; Woosley & Weaver 1995), weighted (Lingenfelter et al. 1998) with relative SNII:SNIb:SNIa rates of 67-75%:13-15%:20-10%, except for O; for the SNII and SNIb contributions, refractory O is assumed to be bound in $MgSiO_3$, Fe_3O_4, Al_2O_3, CaO and NiO, and for (the very small) SNIa contribution, all the produced O is assumed bound to Fe. *SBGrains* – Modified SNGrains for 85% of SNII and SNIb and 50% of SNIa in superbubbles (Higdon et al. 1998; Yorke 1986) plus ISM refractory grain ISMCores for a mean superbubble metallicity range of 2–5 times that of ISM, as discussed in the text. *CRInject* – Galactic supernova averaged grain abundances for cosmic ray injection, taking a mix of SBGrain abundances for supernova acceleration in superbubbles and ISMCore grain abundances (without any supernova enrichment) for supernova acceleration outside the superbubbles, weighted by the relative swept-up metal masses and supernova rates (Higdon et al. 1999, OG 3.1.04). *CRSource* – elemental abundances from Engelmann et al. (1990). *Solar* system elemental abundances from Grevesse, Noels & Sauval (1996).

The supernova-ejecta and stellar-wind enriched superbubble mix can also account for cosmic ray abundances of the heavier elements. Although s-elements are not synthesized in supernova explosions, as we have discussed (Lingenfelter et al. 1998) in detail, their presence in the cosmic rays does not contradict acceleration out of supernova ejecta enriched matter in superbubbles, as argued by Meyer & Ellison (1999), because s-elements are present in supernova ejecta along with the other much more abundant products of pre-supernova burning, as well as in the progenitor winds. In addition, because the large filling factor of the superbubble HISM (∼50%, e.g. Yorke 1986), the superbubbles are also enriched by roughly 50% of the winds blown off of less massive stars.

3 Expected Abundances of Volatile Cosmic Rays:

In addition to the sputtering of refractory ions, the interactions of the high velocity, supernova grains can also provide a simultaneous, self consistent cosmic ray injection source of H, He and other volatiles. Cesarsky & Bibring (1981) suggested that high velocity grains may temporarily pick up by implantation volatile atoms from the gas through which they pass, and their subsequent sputtering could provide a source of less enriched suprathermal volatiles. We suggest a much more direct injection process for the volatiles. Since direct collisions of fast grains with ambient gas atoms and ions are thought to be the primary means of grain momentum loss (e.g. Ellison et al. 1997 §2.3), we would expect that the supernova grains should simply scatter ambient H, He and other volatile atoms to the same suprathermal injection velocities as the grains and their sputtered refractory products. Such a process would, in fact, directly account for the measured cosmic ray abundance ratio by number of the refractory (including C and "bound" O) to volatile elements, i.e. (C,O,Mg,Al,Si,Fe,etc)/(H,He,etc) = 0.010 (Engelmann et al. 1990), since Ellison et al. (1997 §2.4) assume that roughly 0.5%-1% of grain collisions with ambient gas atoms, predominantly scattering volatile atoms, result in the sputtering of a refractory atom from the grain surface, all of which come off with essentially the same injection velocity. Moreover, because the scattering cross sections of atoms increase with their mass, such scattering should also lead to a mass-dependent enrichment of heavier volatiles with respect to H, as is observed in the cosmic rays (e.g. Meyer et al. 1997), and which can not (Ellison & Meyer 1999) be accounted for by a mass/charge (A/Z) dependent acceleration bias in the hot ISM.

The composition of the grain-scattered suprathermal volatiles can be further enriched by the fact that most of the supernova shocks will be interacting with grains and gas in the supernova-ejecta and progenitor-wind enriched superbubbles. Since the ^{22}Ne/^{20}Ne ratio in the Wolf Rayet winds of massive, supernova progenitors may exceed the solar system value by more than two orders of magnitude (Maeder & Meynet 1993), grain-scattering of such wind enriched matter could account for the high ^{22}Ne/^{20}Ne observed (Mewaldt, Leske & Cummings 1996) in the cosmic rays. The existence of such a Wolf Rayet signature in the cosmic rays also provides further evidence for the acceleration of cosmic rays in the superbubble hot phase where the bulk of the massive Wolf Rayet, supernova progenitors are also confined.

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