The Source of Cosmic Rays: 2. Superbubble Composition

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Abstract

We show that the bulk of the Galactic supernovae, their expanding remnants, together with their metal-rich grain and gas ejecta, and their cosmic ray accelerating shocks, are all confined within the interiors of hot, low-density superbubbles, generated by the multiple, correlated supernova explosions of massive stars formed from giant OB associations. These bubbles provide a cosmic ray injection source of essentially constant metallicity throughout the age of the Galaxy, as required by the observed galactic Be/Fe evolution. The acceleration of cosmic rays in these bubbles by the shocks of multiple supernovae occurring every few times 10^5 yr is also consistent with recent ACE observations of ^{59}Ni.

1 Introduction

The source of energy for cosmic ray acceleration appears to be shock waves driven by the expansion energy of supernova ejecta (e.g. Axford, 1981). The power required to maintain the Galactic cosmic rays is about 10^{41} erg s^{-1} (e.g. Lingenfelter 1992). The Galactic supernova rate is about 3 supernovae per century (van den Bergh & McClure 1994), most of which (80 to 90%) are core-collapse (Type II and Ib/c) supernovae of relatively young ($<$ few 10^7 yrs) massive O and B stars; the remainder are Type Ia thermonuclear explosions of much older accreting white dwarfs. Thus, the average cosmic ray energy needed per supernova is about 10^{50} ergs, which requires an acceleration efficiency of about 10% from the blast wave shocks of the supernovae, since supernovae all seem to have similar ejecta kinetic energies of about 10^{51} ergs (e.g. Woosley & Weaver 1995; Nomoto et al. 1997).

The source of the particles that are accelerated and the site of their acceleration, however, are still debated. But if the energy comes from supernova shocks, the site and source of the particles clearly must be in the material through which the shocks pass. New clues to the origin of the particles also come from recent measurements of Be abundances in old halo stars that show (Ramaty, Kozlovsky & Lingenfelter 1998; Ramaty, Lingenfelter, & Kozlovsky 1999 OG 3.1.03) that the ratio of cosmic ray spallation-produced Be relative to core-collapse supernova-produced Fe has remained roughly constant throughout the evolution of the Galaxy. This Be/Fe constancy requires that the cosmic rays be accelerated out of supernova-synthesized matter whose metallicity has not yet been significantly diluted by mixing with the interstellar medium (ISM), and not from the well-mixed ISM as has been recently assumed (e.g. Meyer et al. 1997; Ellison et al. 1997).

Here we show that this is, in fact, the environment through which most supernova shocks propagate. As we have discussed in Higdon, Lingenfelter & Ramaty (1998), a variety of observations show that the bulk of the core-collapse supernova progenitors are formed in OB associations from giant molecular clouds and that the combined winds and supernova ejecta of these stars form hot, low density superbubbles, that reach dimensions of several hundred pc and last for tens of Myr, and during this time the bulk of the supernova ejecta and the supernova shocks which accelerate the cosmic rays are all are confined within these superbubbles.

Core-collapse (Type II and Ib/c) supernovae are highly correlated in space and time (e.g. McCray & Snow 1979). Such supernovae thus create giant cavities, or superbubbles, in the ISM rather than many smaller, isolated bubbles (e.g. Mac Low & McCray 1988; Tomisaka 1992). This is expected because: (i) the massive O and B star supernova progenitors ($>$8 $M_\odot$; e.g. Woosley & Weaver 1995; Nomoto et al. 1997) are not distributed uniformly in interstellar space, but tend to form clusters, since the majority of these massive stars are born in the most massive ($> 10^5$ $M_\odot$) molecular clouds in gravitationally unbound OB associations while less massive clouds will be destroyed by the intense UV irradiation with the birth of their first O star (McKee & Williams 1997); and (ii) these O and B stars are short-lived and slow moving with main sequence lifetimes of $\sim$ 35 to 3 Myr and dispersion velocities of only $\sim$4 km s^{-1} (Blaauw, 1991), so they do not travel too far ($\sim$120 pc in 30 Myr) from their birthplaces before they expire in supernova explosions. Consequently, the combined effects of successive supernova explosions create superbubbles, which form the hot ($\sim$10^6 K), tenuous ($\sim$10^{-3} cm^{-3}) phase of the ISM with a Galactic averaged filling factor of $\sim$ 50% (e.g. Yorke 1986; Spitzer 1990).

An analysis of the surface brightness distribution of the remnants of historical supernovae in our Galaxy has shown (Higdon & Lingenfelter 1980) that 85% $\pm$ 10%, of the observed Galactic supernovae occurred in the superbubble hot phase of the ISM. This is quite consistent with more extensive observations of supernovae in other late type galaxies. As discussed in detail in Higdon et al. (1998), the observations of van Dyk et al. (1996) show that the great majority, $\sim$ 90% $\pm$ 10%, of the core-collapse supernovae in late type galaxies also occur within superbubbles. Because of the large filling factor of the superbubble, hot-phase of the ISM, roughly half of the Type Ia should also occur within the superbubbles just by chance. Thus, since core-collapse supernovae account of 80 to 90% of all supernovae in our Galaxy and the Type Ia's make up the remainder, the great bulk ($\sim$85%) of all supernovae occur in the superbubble hot phase of the ISM, and the bulk of the cosmic rays accelerated by their shocks are also produced there.

2 Composition of Superbubbles

The evolution of supernova-driven superbubbles has been modeled by Mac Low & McCray (1988), assuming expansion into a homogeneous nonmagnetic ISM, and they find that a superbubble would be expected to reach a nominal radius of $\sim$ 700 pc in a lifetime of $\sim$ 50 Myr. More recently Tomisaka (1992) has carried out MHD calculations of superbubble expansion which include the asymmetric pressure effects of the swept up Galactic magnetic field, and finds that along the direction of the bulk field superbubbles should reach dimensions comparable to the radius expected in the nonmagnetic case, but in directions transverse to the field their dimensions should be constrained to roughly half that radius, in a typical Galactic field of $\sim$ 3 μG.

For both the nonmagnetic and magnetic models, we calculated (Higdon et al. 1998) the expected density and composition distribution of the matter within the superbubbles and found that in both models supernova ejecta should dominate the superbubble metallicity (i.e. the mass fraction of elements heavier than He). A major factor in this dominance is the fact that the supernova ejecta and wind metallicity is $\sim$ 10 times the typical ISM value, since the IMF averaged supernova metallicity in core-collapse supernovae (e.g. Woosley & Weaver 1995) is $\sim$ 0.2, compared to the solar value of 0.019. Because of this high metallicity, we find that in the magnetic bubble model the supernova ejecta should account for 40% of the total mass of material within the bubble and with a metallicity of 10 times solar the ejecta would provide nearly 90% of the metals in the bubble interior, assuming solar metallicity in the evaporates, giving an average bubble metallicity $\sim$ 5 times solar. Even in the nonmagnetic superbubble model the supernova ejecta and precursor winds would be the dominant source of metallicity within a core of more than half the superbubble radius, or $\sim$ 400 pc core, where the bulk of the core-collapse supernova occur. Moreover, in the early Galaxy where the ISM metallicity is $<$ 0.1 of solar, the supernova ejecta and winds would be the dominant source of metallicity out to more than 95% of the superbubble radius.

A large fraction of the C, O and refractory metals in this ejecta may be in graphite and oxide grains, since in the core-collapse supernova 1987A roughly 0.2 M$_\odot$ of this material condensed out of the cooling, expanding ejecta as high velocity ($\sim$ 2500 km s^{-1}) grains within 2 years after the explosion (Kozasa, Hasegawa & Nomoto 1991) and as much as 1 M$_\odot$ could be expected (Dwek 1988) to condense before the ejecta is reheated and slowed by the reverse shock and the grains with a much smaller charge to mass ratio begin to move separately from the ejecta plasma. In fact, Dwek (1988) suggests that supernova ejecta are the major source of refractory grains in the Galaxy and that their subsequent interactions with supernova shocks are the major cause of their destruction.

Thus, supernova ejecta and winds can be expected to dominate the metallicity and grains within the superbubbles, where the bulk of supernova shock waves are dissipated and the bulk of cosmic rays should be accelerated. These supernova grains should therefore be the major injection source required for the cosmic ray metals, because of their high initial velocity (Lingenfelter et al. 1998) and possible subsequent acceleration (Ellison et al. 1997). Moreover, because the metallicity of the supernova ejecta is essentially independent of progenitor metallicity (Woosley & Weaver 1995), these superbubbles can provide the essentially constant source of cosmic ray metals required by Be observations. Therefore, we would expect that throughout the age of the Galaxy, the bulk of the core-collapse supernovae occur in the high metallicity cores of superbubbles, and the blast wave shocks of their remnants accelerate the bulk of the Galactic cosmic rays out of the enriched gas and grains in these bubbles.

Since the mean time between successive supernovae in these superbubbles is on the order of $\sim 3{\times}10^5$ yr (Mac Low & McCray 1988), the acceleration of cosmic ray metals from the accumulated grains of many supernovae is also consistent with ACE observations (Binns et al. 1999; Wiedenbeck et al. 1999 OG 1.1.01), suggesting the decay of the bulk of the ^{59}Ni with a $1.1{\times}10^5$ yr mean life in the cosmic ray source material prior to acceleration.

3 Cosmic Ray Acceleration in Superbubbles

These hot, low density superbubbles are the hot phase of the ISM, where shock acceleration of cosmic rays is expected (Axford, 1981) to be "most effective", because the energy losses of the accelerated particles are greatly reduced and the supernova shocks do not suffer major radiative losses (Mac Low & McCray 1988), as they would in a denser medium. As can be seen in Fig. 1, for a supernova ejecta energy of 10^{51} erg, radiative losses rapidly dissipate the energy beyond a radius $R_r \sim 20n^{-0.42}$ pc (McCray & Snow 1979), limiting the effective acceleration radius to ~20 pc for supernovae in the mean ($n \sim 1$ cm^{-3}) density ISM assumed by Ellison et al. (1997), while for supernovae in the low density superbubbles with $n < 4 \times 10^{-3}$ cm^{-3} radiative losses would not become important until after the expansion velocity becomes subsonic at a radius of 200 pc, so the shock energy is not diminished by radiative losses. Thus, at full shock energy, supernovae in the low density superbubbles expand to $\sim 10^3$ times the volume of those in the average ISM. Therefore supernova shocks in low density, metal enriched superbubbles process a comparable mass of gas ($\sim 10^3$ M$_\odot$) and an order of magnitude more metals ($\sim 10^2$ M$_\odot$) than those in the average ISM, contrary to Ellison & Meyer's (1999) estimate.

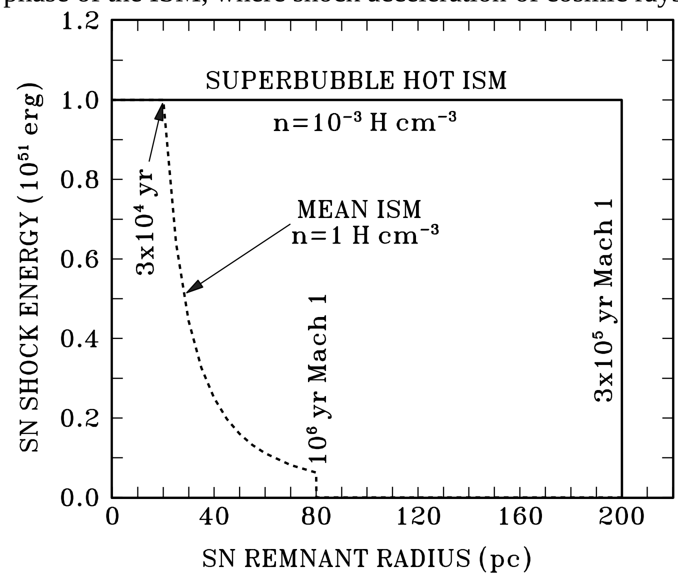

Figure 1: The rapid radiative loss of supernova remnant energy in the average ISM compared to the undiminished shock energy of nonradiative remnants in the superbubble hot phase.

Despite the observed concentration of supernovae in the superbubble hot phase and the much higher acceleration efficiency expected there, some (e.g. Meyer 1985) argued against cosmic ray acceleration in the hot phase because a first-ionization-potential (FIP) injection bias required warm partially ionized gas, not the fully ionized gas of the hot phase. Even now assuming a volatility bias with fast refractory grain sputtered injection, Ellison & Meyer (1999) still argue against cosmic ray acceleration in the hot phase because their mass/charge (A/Q) dependent acceleration model for the volatile elements also requires partially ionized, not fully ionized gas. There are, however, other possible mass dependent injection processes, such as direct collisions with fast grain atoms, as we discuss in Lingenfelter & Ramaty (OG 3.1.05).

Clearly, if cosmic rays were not efficiently accelerated in the superbubble hot phase, where roughly 85% or more of the supernovae occur, the acceleration efficiency of the remaining 15% or less occurring in the warm phase, would have to be more than 70%, which is unreasonably large. Nonetheless, the injection model dependent arguments of Meyer (1985) and Ellison & Meyer (1999) against hot phase acceleration also ignore the extensive observational evidence (e.g. Cox & Reynolds 1987; Spitzer 1990) that supernovae occurring and expanding in the hot, low density ISM simply sweep up the older supernova ejecta enriched hot phase material, and eventually it radiatively cools into the thin shells of warm, partially ionized gas and dust seen in Hα around old remnants, although their filling factor is small. So, even though the bulk of the supernovae occur in the superbubble hot phase, their cosmic ray accelerating shocks will also encounter these partially ionized warm shells. Thus the swept-up ejecta-enriched supernova gas, grains, occasional shells and progenitor winds in the superbubbles all provide injection sources of cosmic ray nuclei, from fast refractory grain sputtering, and direct scattering of volatiles by fast grains, as well as some A/Q dependent volatile acceleration.

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