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COSMIC RAYS, DUST, AND THE MIXING OF SUPERNOVA EJECTA INTO THE INTERSTELLAR MEDIUM IN SUPERBUBBLES

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ABSTRACT

Most of the galactic core-collapse supernovae occur in OB associations that produce superbubbles, and thus, the bulk of the cosmic rays are accelerated in the cores of such superbubbles by the shock waves from these supernovae. Here we show that the initial mixing of the freshly synthesized elements from such supernovae with the gas and dust in the interstellar medium also occurs in the cores of these superbubbles, and that the unique composition of the galactic cosmic rays can be produced there by suprathermal ion injection from interactions of this mix of dust, gas, and supernova shocks. We further show that the basic features of the cosmic-ray composition provide a unique measure of the mixing ratio of the fresh supernova ejecta and the old interstellar medium in this initial phase of interstellar mixing.

Subject headings: cosmic rays — dust, extinction — ISM: abundances — ISM: bubbles — stars: Wolf-Rayet — supernovae: general

1. INTRODUCTION

The composition of galactic cosmic rays differs very significantly from that of the local interstellar medium, inferred from solar system material. These differences provide crucial insights into the initial mixing of freshly synthesized elements into the interstellar medium, and they offer direct measures of the metallicity of the supernova-active cores of superbubbles. Here we consider the processes and environments that are thought to determine these differences and show quantitatively how they combine to produce the peculiar, but potentially universal, composition of the cosmic rays.

There are three basic differences between the cosmic-ray source composition, as deduced from the *HEAO-3* measurements (Engelmann et al. 1990), and the protosolar composition. (1) The refractory element abundances relative to H are all enriched by a roughly constant factor of roughly 20 compared to protosolar values. (2) The corresponding volatile element abundances have a mass-dependent enrichment for those heavier than He ($A > 4$) that reaches a factor of as much as 10 for the heaviest volatiles. (3) Carbon and oxygen do not fit into either scheme and are enriched by intermediate factors of 9 and 5. These enrichments are all shown in Figure 1.

The roughly constant enrichment of the refractory elements is thought to result from suprathermal injection by the sputtering of ions off of fast refractory grains through collisions with the ambient gas (Cesarsky & Bibring 1981; Ellison et al. 1997). The strong correlation of cosmic-ray enrichment with elemental condensation temperature, defining the continuum between "refractory" and "volatile" elements, has been shown by Meyer et al. (1997). Even though the sputtering cross sections are mass dependent (e.g., Sigmund 1981), the total sputtering yield is still expected to simply reflect the grain composition, because the fast, shock-accelerated grains are completely destroyed by repeated sputtering, making supernova shock interactions the principal process of grain destruction (e.g., Draine & McKee 1993). A similar correlation also exists between the cosmic-ray enrichment and the first ionization potential of the elements, which is inversely correlated with the condensation temperature. But as we discuss below, the vast majority (~90%) of the cosmic rays heavier than He are accelerated by supernovae occurring in the hot (~10^6 K), dust-rich, fully ionized gas in the cores of superbubbles (e.g., Higdon et al. 1998; Higdon & Lingenfelter 2005), where the ionization potential has no apparent significance.

As we have suggested (Lingenfelter et al. 2000), the mass-dependent enrichment of volatile elements can also result from suprathermal injection of the volatiles in the hot ambient gas scattered by fast refractory grains, and, as we show below, the mass dependence of the scattering cross section is quite consistent with that of the cosmic-ray enrichment. Here the mass dependence of the cross section is preserved because only a very small fraction of the ambient gas is scattered by the fast grains, and they preferentially scatter the heavier elements.

Finally, as we have shown (Lingenfelter et al. 1998, 2000), the intermediate enrichment of carbon and oxygen can also result from suprathermal injection by sputtering of C and O ions from graphite and oxides in the fast refractory grains, with a small additional contribution from scattering of volatile C and O in the hot interstellar gas. Here we also show quantitatively that the cosmic-ray C/Fe and O/Fe ratios provide additional measures of the mixing of the fresh supernova and Wolf-Rayet (WR) wind ejecta with the old interstellar medium in superbubble cores.

In the following, we first briefly review the evidence that superbubbles are the shock acceleration sites of the bulk of the cosmic rays. Next, we discuss the selective injection of ions into such accelerating shocks by the sputtering and scattering of suprathermal ions off of shock-accelerated refractory grains in the supernova-active cores of the superbubbles. Then we use the cosmic-ray source abundance ratios of all of the refractory elements, determined by Engelmann et al. (1990), as well as those conspicuously anomalous elements C and O, to calculate new independent measures of the mixing fraction of the fresh supernova ejecta and WR winds in the old interstellar gas and dust in the superbubble cores. We show that these new measures together with those previously

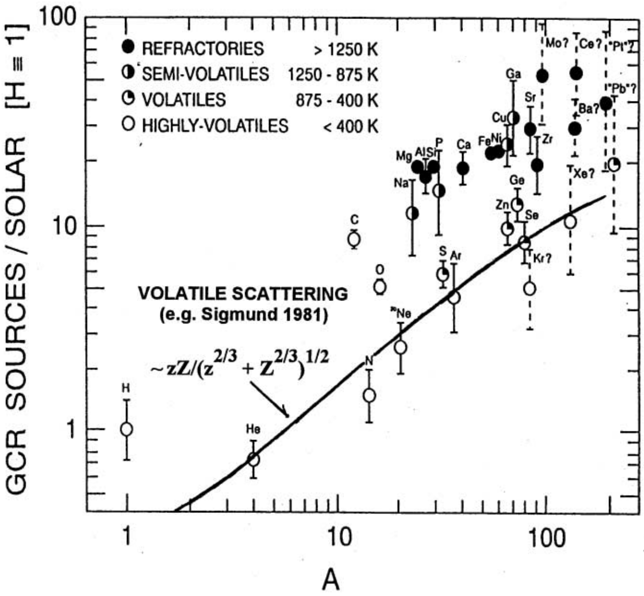

FIG. 1.—Cosmic-ray source abundance enrichment relative to solar abundances as a function of mass (modified from Meyer et al. 1997). Also shown for comparison with the volatiles is the cross section for the scattering of gas ions by fast grains at a constant velocity, proportional to $zZ/(z^{2/3} + Z^{2/3})^{1/2}$, where z and Z are the nuclear charges of the grain and gas nuclei (e.g., Sigmund 1981), normalized to He for masses $A \geq 4$, which all have essentially the same charge-to-mass ratio, $Z \sim A/2$.

determined from other cosmic-ray-related abundances, including cosmic-ray spallation produced Li, Be, and B, in old halo stars, all suggest a roughly constant mixing ratio in superbubbles throughout the age of the Galaxy.

2. OB ASSOCIATIONS AND SUPERBUBBLE ORIGIN OF COSMIC RAYS

In order to quantitatively understand the composition of cosmic rays we need to consider the environment in which they are accelerated. The galactic cosmic rays are thought to result primarily from the preferential acceleration of suprathermal ions by shock waves from supernovae (e.g., Axford 1981). Core-collapse supernovae (SN II and SN Ib/c) from massive ($M > 8\ M_\odot$) O and B stars account for ~85% of all galactic supernovae (e.g., van den Bergh & McClure 1994), and together with WR winds they produce nearly all of the elements $A > 4$, although about one-half of the Fe is produced by thermonuclear explosions (SN Ia), which make up the remaining 15% of galactic supernovae (e.g., Timmes et al. 1995). Most (80%–90%) of the SN II and SN Ib/c occur in OB associations, and they form superbubbles, which thus contain ~70%–75% of all galactic supernovae (Higdon & Lingenfelter 2005).

Thus, roughly ~70%–75% of the H and He are accelerated in superbubbles, and ~25%–30% or less come from the warm interstellar medium, where shock acceleration is less efficient (e.g., Axford 1981). The superbubble contribution to heavier, $A > 4$, cosmic rays, however, is much larger because, as we discuss in detail below, the superbubble metallicity $Z_{\rm sb}$ is ~2.5 times that of the average interstellar medium $Z_{\rm ISM}$. Thus, with superbubbles containing a fraction $F_{\rm SN} \sim 70\%–75\%$ of the supernovae, the fraction of heavier ($A > 4$) cosmic rays accelerated in superbubbles is $F_{\rm SN}(Z_{\rm sb}/Z_{\rm ISM})/[F_{\rm SN}(Z_{\rm sb}/Z_{\rm ISM}) + F_{\rm SN} + 1] \sim 85\%–88\%$ (Higdon & Lingenfelter 2005).

Essentially all of the cosmic-ray acceleration in superbubbles is concentrated in their cores, which are enriched by the ejecta of all of their supernovae and WR winds. Giant molecular clouds can form OB associations with radii <10 pc, which can produce anywhere from several to 10,000 core-collapse supernovae. These core-collapse supernova progenitors live anywhere from ~3 to ~35 Myr, depending on their mass, before they explode (e.g., Schaller et al. 1992). Since these stars have a mean dispersion velocity of <4 km s^{-1}, or <4 pc Myr^{-1} (e.g., Blaauw 1991), their subsequent supernovae all occur within a radius $r \sim 150$ pc. These supernovae, together with the radiatively driven WR winds from their progenitors, collectively create the hot, tenuous ~10^{-3} H cm^{-3} superbubbles, where the supernova shocks reach radii of ~100 pc (e.g., Higdon et al. 1999). Thus, the shocks from each of the supernovae successively sweep through all of the ejecta of previous supernovae and accelerate cosmic rays out of the enriched mix of fresh SN-WR ejecta and old interstellar medium (ISM) in the supernova-active cores of superbubbles.

3. REFRACTORY GRAINS AND COSMIC-RAY INJECTION

The most abundant of the freshly nucleosynthesized elements in the supernova ejecta form refractory oxides: MgO, Al_2O_3, SiO_2, CaO, Fe_3O_4, etc. As the expanding ejecta adiabatically cools, these oxides condense into refractory grains within a couple of years after the explosion, as was dramatically shown in SN 1987A, when the optical luminosity of the ejecta dropped by almost a factor of 10 to emerge in the submillimeter band as thermal emission from newly formed dust (e.g., Kozasa et al. 1991). In the supernova-active cores of superbubbles, these fresh supernova grains mix with old interstellar grains, which are depleted relative to Fe by as much as half in some elements, such as Si, which remains primarily as Fe_2SiO_4 (e.g., Spitzer & Fitzpatrick 1993; Savage & Sembach 1996; Jenkins 2004).

Subsequent supernova shocks accelerate some of these weakly charged grains to velocities well above the ~10^6 K thermal velocities of ~$100\ A^{-1/2}$ km s^{-1} of gas atoms of mass A (Epstein 1980; Ellison et al. 1997). The collisions of these accelerated grains with the ambient gas sputter refractory elements off of the grains as suprathermal ions at grain velocities. That sputtering preferentially injects these refractory ions into the same shock for acceleration to cosmic-ray energies (Cesarsky & Bibring 1981; Meyer et al. 1997).

In these same interactions of accelerated refractory grains with the ambient gas, ambient H, He, and heavier volatiles are also scattered by the fast grains to the same velocity. The scattering cross section at a constant grain velocity is $\sim zZ/(z^{2/3} + Z^{2/3})^{1/2}$, where z and Z are the nuclear charges of the grain and gas nuclei (e.g., Sigmund 1981). That scattering also injects the volatile elements into the same shock for acceleration to cosmic-ray energies (Lingenfelter et al. 2000). As can be seen in Figure 1, this charge dependence of the scattering cross section is quite similar to the observed mass-dependent enrichment of the volatile elements in the cosmic rays heavier than H, all of which have essentially the same mass-to-charge ratio, $A/Z \sim 2$. This clearly suggests that such scattering may account for the mass-dependent volatile enrichment, but obviously much more detailed calculations are needed.

Although most of the O in the ISM is in the gas phase, from which some is injected by fast grain scattering, the fraction of O bound in refractory oxides in the grains is also injected by sputtering and appears to be the major source for cosmic rays. The cosmic-ray source O/Fe ratio is 5.2 ± 0.3 (Engelmann et al. 1990), and the bulk of this can be accounted for simply from the chemistry of the grains and the relative cosmic-ray abundances of the major refractory elements (Lingenfelter et al. 1998). These elements have cosmic-ray source abundance ratios of Si : Mg : Fe : Al : Ca of 0.99 : 1.03 : 1.00 : 0.08 : 0.06 (Engelmann et al. 1990), so if they all were sputtered from their refractory oxides, principally SiO_2, MgO, Fe_3O_4, Al_2O_3, and CaO, in grains, they should be accompanied by sputtered O with an O/Fe = 4.5. This would account for ~87% of the measured cosmic-ray source abundance ratio, leaving the small remainder to grain-scattered O from the surrounding gas. As we show in detail below, the relative abundances of these refractory elements in the cosmic rays can be produced by a mix of fresh SN-WR ejecta with a refractory oxide grain O/Fe ratio of ~8 and old ISM grains, primarily Fe_2SiO_4, with an O/Fe ratio of ~3.

Unlike nearly all of the other elements, most of the C in the Galaxy appears to come from the winds of asymptotic giant branch stars rather than supernovae (e.g., Timmes et al. 1995; Gavilan et al. 2005). The bulk of the C in the ISM is also in gas as CO (e.g., Savage & Sembach 1996), and some of it is injected by fast grain scattering, but it cannot be strongly enriched in this way. However, nearly all of the freshly synthesized C in supernova ejecta condenses into the refractory grains as graphite, since the intense radiation in supernovae prevents significant CO formation in the ejecta (Clayton et al. 2001; Lingenfelter et al. 1998). Thus, this C is injected by sputtering, and, as we show in detail below, the cosmic-ray source C/Fe ratio of 4.2 ± 0.3 (Engelmann et al. 1990) can simply reflect the C/Fe ratio in the superbubble core mix, dominated by the SN-WR ejecta ratio.

4. SUPERBUBBLE CORE MIXING AND COSMIC-RAY SOURCE ABUNDANCES

The cosmic-ray source abundances thus depend on the average mixing ratio of the fresh SN-WR ejecta and the old ISM in the supernova-active cores of superbubbles, where most of the cosmic rays are accelerated. From the measured cosmic-ray abundance ratios, therefore, we can make independent measures of the mixing ratio.

In general, the cosmic-ray source abundance ratios $R_{\rm cr} = N_x/N_y$ of any two elements, or isotopes, of atomic mass X and Y, resulting from the mix of fresh SN-WR ejecta and old ISM with total mass fractions, $F_{\rm ej}$ and $(1 - F_{\rm ej})$, is given by the ratio of mass fraction

$$(X/Y)R_{\rm cr} = \frac{[{}_x f_{\rm ISM} + F_{\rm ej}({}_x f_{\rm ej} - {}_x f_{\rm ISM})]}{[{}_y f_{\rm ISM} + F_{\rm ej}({}_y f_{\rm ej} - {}_y f_{\rm ISM})]},$$

where ${}_x f_{\rm ej}$, ${}_x f_{\rm ISM}$, ${}_y f_{\rm ej}$, and ${}_y f_{\rm ISM}$ are the mass fractions of X and Y in refractory grains in the fresh SN-WR ejecta and the old ISM. Thus, the implied average SN-WR ejecta mass fraction of the mix from which all of the cosmic rays are drawn is

$${}_{\rm cr}F_{\rm ej} = \frac{[{}_y f_{\rm ISM}(X/Y)R_{\rm cr} - {}_x f_{\rm ISM}]}{[({}_x f_{\rm ej} - {}_x f_{\rm ISM}) - ({}_y f_{\rm ej} - {}_y f_{\rm ISM})(X/Y)R_{\rm cr}]}.$$

Then, since a fraction $F_{\rm sb}$ of all galactic supernovae occur in superbubbles, while the rest occur in the old ISM, the corresponding average SN-WR ejecta mass fraction in the supernova-active cores of superbubbles, ${}_{\rm sb}F_{\rm ej} = {}_{\rm cr}F_{\rm ej}/F_{\rm sb}$.

Thus, the resulting average metallicity of the superbubble cores is

$$Z_{\rm sb} = {}_{\rm sb}F_{\rm ej}Z_{\rm ej} + (1 - {}_{\rm sb}F_{\rm ej})Z_{\rm ISM},$$

where the metallicity of the present ISM, $Z_{\rm ISM}$ (e.g., Timmes et al. 1995), is about 1.32 times $Z_\odot$, the protosolar value. This metallicity is dominated by O and has recently been redetermined by Lodders (2003) to be 0.0149, only 75% of the previously accepted value of Anders & Grevesse (1989). Thus, the present $Z_{\rm ISM} = 1.32 \times 0.0149 = 0.0197$, which coincidentally happens to equal almost exactly the previously accepted solar value of 0.020, which has been widely used in the nucleosynthesis calculations. The mean initial mass function (IMF)–averaged metallicity of the core-collapse SN and WR wind ejecta, $Z_{\rm ej}$, is about 10 ± 1 times the protosolar value (e.g., Higdon & Lingenfelter 2003a; Kobayashi et al. 2006). This value, which is also dominated by O, seems to be rather robust for a wide range of supernova yields (e.g., Woosley & Weaver 1995; Limongi & Chieffi 2003; Nomoto et al. 2006) and WR wind yields (e.g., Schaller et al. 1992; S. Goriely 2006, private communication). Thus, $Z_{\rm sb} = 1.3 + (8.7 \pm 1.0)_{\rm sb}F_{\rm ej}$ in units of the new protosolar value.

The individual interstellar mass fractions, ${}_x f_{\rm ISM}$, are taken from the redeterminations by Lodders (2003), and the mass fractions in refractory grains are determined from the gas-phase abundance depletions in warm clouds (e.g., Savage & Sembach 1996; Jenkins 2004). The corresponding core-collapse supernova and WR wind ejecta mass fractions, ${}_x f_{\rm ej}$, are Salpeter IMF-averaged sums of calculated contributions from SN II (8–25 $M_\odot$), SN Ibc (25–49 $M_\odot$), and WR winds (25–120 $M_\odot$), divided by the IMF-averaged total ejecta and wind mass, equal to ~18 $M_\odot$ per star of initial mass between 8 and 120 $M_\odot$ (e.g., Higdon & Lingenfelter 2003a). Here we take the SN II yields from Woosley & Weaver (1995) up to 15 $M_\odot$ and Rauscher et al. (2002) from 15 to 25 $M_\odot$ for the stars that are not thought to have lost most of their H envelope in winds. For the WR stars above about 25 $M_\odot$, which are thought to blow off most of their mass, we take the yields calculated by Schaller et al. (1992) up to 40 $M_\odot$, and their more recent values above that (S. Goriely 2006, private communication). For the added contribution of SN Ibc, which are thought to result from core collapse of the residual He cores of WR stars with masses up to about 40 $M_\odot$, we have taken the yields of Woosley et al. (1995), assuming that more massive stars end in black holes.

Although there is still significant uncertainty in the yields of many less abundant elements and isotopes, the yields of the most abundant elements, which we consider here, seem to be quite robust. Similar values have been calculated by other groups (e.g., Limongi & Chieffi 2003; Nomoto et al. 2006), and all have found good agreement with galactic chemical evolution (e.g., Timmes et al. 1995; Kobayashi et al. 2006). Because the major refractory elements are all produced primarily in SN II, their ratios do not vary greatly with supernova progenitor mass, and their ratios in the accumulating ejecta in the superbubble cores also do not vary much from their IMF-weighted average of yields from all the supernovae in a superbubble. However, the mean life of local cosmic rays of ~20 Myr (e.g., Higdon & Lingenfelter 2003b) is significantly less than the ~40 Myr supernova-active lifetime of a superbubble (e.g., Higdon & Lingenfelter 2005). Thus, we calculate the mass fractions in the superbubble mix as a function of its age. Nonetheless, it is unlikely that a single superbubble is the source of all the local cosmic rays, and the average mass fractions over the lifetime of a superbubble would still seem to be a reasonable value for local cosmic rays from an ensemble of superbubbles.

To determine the average abundance ratios expected in the cosmic rays as a function of superbubble age, we calculate the accumulating ejecta abundances as a function of time over the supernova-active lifetime of a superbubble and weight the time-dependent contribution to the cosmic ray abundances by the supernova rate as a function of time in the superbubble, assuming a constant supernova kinetic energy and a constant fraction of it going into cosmic rays. The time-dependent supernova rate is determined from the presupernova lifetimes as a function of mass calculated by Schaller et al. (1992). We have described this procedure in detail in our previous calculations (Higdon & Lingenfelter 2003a) of the expected $^{22}Ne/^{20}Ne$ isotope ratio in superbubble-accelerated cosmic rays. In that case the $^{22}Ne/^{20}Ne$ ratio varies greatly with progenitor mass and thus with time, since the bulk of the ^{22}Ne is produced early in the life of the superbubble by the WR winds of stars above 25 $M_{\odot}$, while the bulk of the ^{20}Ne is produced late by SN II from progenitors below 25 $M_{\odot}$.

The best-determined of the cosmic-ray source abundances of the refractory elements is the Si/Fe ratio. It gives the most sensitive measure of the mix of fresh supernova ejecta grains and old ISM grains in superbubble cores, and we show that the source abundances of all the other refractory elements determined by Engelmann et al. (1990), Mg, Al, Ca, Co, and Ni, are also quite consistent with the same mix. The interstellar Si/Fe ratio also gives an equally sensitive measure of the mix of core-collapse and thermonuclear supernova yields in the ISM. The protosolar ISM average Si/Fe of 1.19 (Lodders 2003) can be produced by a roughly 1:1 accumulated mix of Fe from thermonuclear (SN Ia) supernovae with Si/Fe ~ 0.40 (e.g., Travaglio et al. 2004; Kobayashi et al. 2006), and from core-collapse (SN II and SN Ibc) supernovae with an IMF-averaged yield of Si/Fe ~ 2.1 from SN-WR ejecta, calculated for the core-collapse supernova and WR wind models discussed above. This mixing ratio is the same as that inferred from measurements of the evolution of the Si/Fe ratio versus Fe/H in old stars (e.g., Timmes et al. 1995; Kobayashi et al. 2006).

The cosmic-ray source abundance ratio of Si/Fe of 0.99 ± 0.06 (Engelmann et al. 1990) can likewise be produced by a mix of fresh supernova grains and old ISM grains. From the same supernova and WR wind calculations, the IMF-averaged SN-WR ejecta ratio Si/Fe ~ 2.1 with mass fractions, ${}_{\rm Si}f_{\rm ej}$ and ${}_{\rm Fe}f_{\rm ej}$, of 4.2×10^{-3} and 4.1×10^{-3}, respectively, essentially all of which is likely to be in grains (e.g., Kozasa et al. 1991). The old ISM refractory grains, on the other hand, contain about 90% of the Fe and only 46% of the Si (e.g., Savage & Sembach 1996; Jenkins 2004), mostly as Fe_2SiO_4 (Spitzer & Fitzpatrick 1993), with a ratio Si/Fe ~ 0.6 from grain mass fractions, ${}_{\rm Si}f_{\rm ISM}$ and ${}_{\rm Fe}f_{\rm ISM}$, of 0.50×10^{-3} and 1.6×10^{-3}, respectively, assuming that the present ISM mass fractions are increased by the metallicity factor of 1.32 (e.g., Timmes et al. 1995) compared to the protosolar values of Lodders (2003). From the mixing equation above, the cosmic-ray source Si/Fe ratio, $R_{\rm cr}$ of 0.99 and these mass fractions imply cosmic-ray acceleration out of a mix of old ISM grains and fresh SN grains with an average SN-WR ejecta mass fraction ${}_{\rm cr}F_{\rm ej}$ of about 12% $\pm$ 4%, allowing a $\sim$20% uncertainty in the calculated yields. With a fraction $F_{\rm SN} = 70\%$–75% of all supernovae occurring in superbubbles and the remainder in the ISM, the average SN-WR ejecta mass fraction in the supernova-active cores of superbubbles ${}_{\rm sb}F_{\rm ej}$ is about 17% $\pm$ 5%, which corresponds to a superbubble core metallicity $Z_{\rm sb} \sim 2.8 \pm 0.5$ times protosolar.

Very similar values are also implied from the cosmic-ray source abundance ratios of all of the other refractory elements, Mg, Al, Ca, Co, and Ni, that were studied by Engelmann et al. (1990). They also have comparable gas-phase depletion in the ISM (e.g., Savage & Sembach 1996; Jenkins 2004), which suggest that the old ISM grains contain about 49% of the Mg and Al, and about 90% of the Ca, Co, and Ni. Using these ISM grain fractions together with the SN ejecta and WR wind yields from the above models, we find that the SN-WR ejecta mass fraction of 17% $\pm$ 5% in superbubbles inferred from the Si/Fe ratio, also gives cosmic-ray source abundances for all of these elements that are quite consistent with those determined by Engelmann et al. (1990), as can be seen in Table 1.

TABLE 1
Refractory Element Abundances: Superbubble versus Cosmic-Ray Sources

Element	SB Source (${}_{\rm sb}F_{\rm ej} \sim 17 \pm 5$)	CR Source (Engelmann et al.)
Mg	92 ± 18	103.8 ± 2.6
Al	7.6 ± 2.2	7.8 ± 1.5
Si	100 ± 17	100.0 ± 1.3
Ca	7.8 ± 2.3	6.0 ± 0.9
Fe	101 ± 20	100.8 ± 1.9
Co	0.3 ± 0.1	0.19 ± 0.06
Ni	6.1 ± 1.8	5.68 ± 0.22

Independently, the cosmic-ray source abundances of the two conspicuously anomalous volatile-refractory elements C and O can also be produced primarily by sputtering from a mix of fresh SN-WR grains with old ISM grains from the interstellar medium, and these also provide independent estimates of the mixing ratio in superbubble cores.

The cosmic-ray C source abundance ratio, C/Fe, is 4.2 ± 0.3 (Engelmann et al. 1990), compared to the protosolar value of 8.45 (Lodders 2003). Although 90% of the interstellar Fe mass fraction discussed above is in grains (e.g., Savage & Sembach 1996; Jenkins 2004), nearly all of the interstellar C mass fraction ${}_{\rm C}f_{\rm ISM}$ of 2.5×10^{-3} is in CO, and other gases and only a negligible fraction are thought to be in refractory graphite grains (e.g., Savage & Sembach 1996; Lodders 2003). From the same models considered above, the IMF-averaged SN ejecta mass fraction of C is 1.0×10^{-2}, and that of the WR winds is 1.2×10^{-2}. As noted above, the bulk of the C in the SN ejecta is expected to condense as graphite, because the intense radiation in supernovae prevents significant CO formation (Clayton et al. 2001), but the fraction of C in the WR wind that condenses as graphite in their weaker radiation field is not known, so we leave it as a variable, $g_{\rm wr}$. Thus, we assume that the graphite mass fraction in the combined IMF-averaged SN-WR ejecta ${}_{\rm C}f_{\rm ej}$ is $1.0 \times 10^{-2}(1 + 1.2g_{\rm wr})$. Again from the mixing equation, the cosmic-ray source C/Fe ratio, $R_{\rm cr}$ of 4.2, and these mass fractions imply an average SN-WR ejecta mass fraction ${}_{\rm cr}F_{\rm ej}$ of about $21/(1 + 1.7g_{\rm wr})$%. With a superbubble fraction of supernovae, $F_{\rm SN} = 70\%$–75%, the average SN-WR ejecta mass fraction in their supernova-active cores, ${}_{\rm sb}F_{\rm ej}$, is about $29/(1 + 1.7g_{\rm wr})$%, or somewhere between about 11% and 29% depending on the graphite grain fraction of C in WR winds.

The cosmic-ray O source abundance ratio, O/Fe is 5.2 ± 0.3 (Engelmann et al. 1990), of which, as noted above, refractory oxide could account for $\sim$87%, or O/Fe of $\sim$4.5, compared to the protosolar value of 16.8 (Lodders 2003). Although most of the interstellar O mass fraction of 6.6×10^{-3} is in gas, about 16% can be in old refractory grains, primarily Fe_2SiO_4 (Spitzer & Fitzpatrick 1993) and various other mineral combinations of the principal refractory oxides, SiO_2, MgO, Fe_3O_4, Al_2O_3, and CaO. This follows from multiplying the protosolar abundances of these refractories, Si : Mg : Fe : Al : Ca of 1.19 : 1.22 : 1.00 : 0.15 : 0.08 (Lodders 2003) by their corresponding grain fractions of 0.46 : 0.49 : 0.90 : $\sim$0.5 : 0.9 determined from Galactic disk depletion factors (e.g., Savage & Sembach 1996; Jenkins 2004), and their O/X ratios of 2 : 1 : 1.3 : 1.5 : 1, which gives a combined O/Fe ratio of 3.0, or a mass ratio of 0.86. Scaling that to the present Fe mass fraction in old ISM grains of 1.6×10^{-3}, gives an O mass fraction, ${}_{\rm O}f_{\rm ISM}$ of 1.4×10^{-3} in refractory grains. The grain O mass fraction in the SN-WR ejecta is also determined by the principal

TABLE 2

Cosmic-Ray Measures of Superbubble Core Mixing and Metallicity

Measurement	Duration (Myr)	Distance (kpc)	Ejecta Mass Percent in CR Source	Ejecta Mass Percent in SB Cores	SB Core $Z \times$ Solar	References
			Old Halo Stars			
Be/Fe	$\sim 10^4$	~ 10	25 ± 14	29 ± 15	3.3 ± 1.6	1
			Cosmic Rays			
Si/Fe	~ 20	~ 1	12 ± 4	17 ± 5	2.8 ± 0.4	2
C/Fe	~ 20	~ 1	8–21	11–29	2.3–3.8	2
O/Fe	~ 20	~ 1	18 ± 6	24 ± 8	3.4 ± 0.9	2
22Ne/20Ne	~ 20	~ 1	13 ± 4	18 ± 5	2.9 ± 0.4	3
ThU/Pt-group	~ 1	~ 0.3	20 ± 8	27 ± 11	3.6 ± 0.8	4

References.—(1) Alibes et al. 2002; (2) this paper; (3) Higdon & Lingenfelter 2003a (but see text); (4) Lingenfelter et al. 2003.

refractory oxides in the fresh condensates. The same models used above give an IMF-averaged SN-WR ejecta abundance ratios for Si : Mg : Fe : Al : Ca of 2.1 : 1.5 : 1.0 : 0.1 : 0.1. These give a combined O/Fe ~ 7.3, and, scaling from the SN-WR ejecta Fe, an ejecta O mass fraction in refractory grains, ${}_{\rm O}f_{\rm ej} = 4.1 \times 10^{-3}(7.3)(16/56) = 8.6 \times 10^{-3}$. These mass fractions and the cosmic-ray O/Fe source abundance ratio thus imply a cosmic-ray averaged SN-WR ejecta mass fraction ${}_{\rm cr}F_{\rm ej}$ of about 18% ± 6%, and a corresponding superbubble core SN-WR ejecta mass fraction ${}_{\rm sb}F_{\rm ej}$ of about 24% ± 8%.

As can be seen from Table 2, these values are all quite similar to the superbubble core mixing ratios that have previously been inferred from other cosmic-ray abundance measurements of the ^{22}Ne/^{20}Ne and ThU/Pt-group. The cosmic-ray-determined ratios mostly sample a local volume of ~ 1 kpc over the last ~ 20 Myr, the characteristic propagation distance and lifetime of most local cosmic rays, except the ultraheavy Th, U, and the Pt-group, which have breakup lifetimes of only ~ 1 Myr and probably come from within ~ 0.3 kpc (e.g., Higdon & Lingenfelter 2003b). A much more wide-ranging measure, however, has been made from the old halo star abundances of the rare light elements, Li, Be, and B, which are thought to be produced primarily by the cosmic-ray breakup of C and O (e.g., Reeves et al. 1970; Ramaty et al. 1997). These LiBeB abundances in old halo stars give a mean measure of the SN-WR ejecta mixing fraction in superbubble cores averaged over much, ~ 10 kpc, of the Galaxy, and over most, ~ 10 Gyr, of its age.

The most sensitive of these measurements are those of the Be/Fe ratio as a function of stellar metallicity, as represented by Fe/H (e.g., Alibes et al. 2002). These measurements showed that the Be/Fe ratio was surprisingly constant throughout the early history of the Galaxy, rather than increasing with the rising Fe/H metallicity of the ISM, which increased from about 0.001 to 0.1 over the age span of the measurements, as would have been expected if the cosmic-ray C and O, from which the Be was produced, had been accelerated out of the ISM. This constancy clearly showed that the cosmic-ray C and O had to come from sites of relatively constant metallicity (Ramaty et al. 1997). These sites have since been shown to be the superbubbles (Higdon et al. 1998; Higdon & Lingenfelter 2005). The most recent analysis of all the Be/Fe measurements up to the present epoch show (Alibes et al. 2002) that the cosmic rays must have been accelerated in a mix with an average SN-WR ejecta fraction of 25% ± 14% throughout the age of the Galaxy. This corresponds to a mean SN-WR ejecta fraction of 29% ± 14% in the cores of superbubbles, since at times when Fe/H was <0.1, the SN Ia were not yet significant and roughly 85% of all supernovae occurred in superbubbles. That gives a superbubble core metallicity of ~ 2.9 times the protosolar value in the early Galaxy, when the ISM metallicity was <0.1 and a present value of ~ 3.8 times protosolar with an ISM value of 1.32 and 70%–75% of all supernovae occurring in superbubbles.

The current measurements of Th and U in the cosmic rays (Donnelly et al. 1999; Weaver & Westphal 2002) suggest a cosmic-ray injection source abundance ratio of (actinide)/(Pt-group) of $\sim 0.028 \pm 0.008$, compared to a value of $\sim 0.014 \pm 0.002$ expected in the present ISM. The cosmic-ray ratio would imply an average SN-WR ejecta fraction of 27% ± 11% in superbubble cores and a core metallicity $Z_{\rm sb} \sim 3.6 \pm 0.8$ times protosolar (Lingenfelter et al. 2003).

Previous analysis (Higdon & Lingenfelter 2003a) of the anomalous cosmic-ray ^{22}Ne/^{20}Ne (Binns et al. 2001, 2006) implied a SN-WR ejecta mass fraction that is also quite similar to these values. The cosmic-ray ratio of 0.39 is 5.3 ± 0.3 (Binns et al. 2005) times the protosolar ratio of 0.073. Using the WR wind yield calculations of Schaller et al. (1992), which are the dominant ^{22}Ne source, mixed with the core-collapse supernova yields (e.g., Woosley & Weaver 1995; Woosley et al. 1995), which are the dominant ^{20}Ne source, Higdon & Lingenfelter (2003a) showed that the resulting SN-WR ejecta had a ^{22}Ne/^{20}Ne ratio of 1.0 ± 0.35, or ~ 14 times the protosolar value. Since nearly all the WR stars and core-collapse supernovae occur in superbubbles, the cosmic-ray ratio implies that in superbubble cores the time-averaged mean SN-WR ejecta mass fraction is 18% ± 5%, which give it an average metallicity $Z_{\rm sb} \sim 2.9 \pm 0.4$ times protosolar. Recently revised calculations of the WR winds (Hirschi 2004; S. Goriely 2006, private communication), however, give ^{22}Ne yields that are much lower than the previous values of Schaller et al. (1992), and new detailed calculations of the expected cosmic-ray isotope ratio as a function of superbubble age now seem called for, instead of the overall average value, but we will not attempt that here.

Another large difference in the cosmic-ray source abundances is the ^{58}Fe/^{56}Fe ratio, which is 1.7 ± 0.3 times the protosolar value (Binns et al. 2006). But unfortunately it cannot yet be used as a measure of the mixing, because the nucleosynthetic yields of the neutron capture isotope, ^{58}Fe, have not yet been consistently determined for either core-collapse or thermonuclear supernovae. As we saw with the Si/Fe ratio, the protosolar value of the ^{58}Fe/^{56}Fe ratio should be essentially a 1:1 mix of Fe from SN Ia and SN-WR ejecta. But recent independent calculations of even the "standard" W7 model for SN Ia give very different values of the ^{58}Fe/^{56}Fe ratio, ranging from 0.08 (Travaglio et al. 2004) to 0.50 (Kobayashi et al. 2006) times the protosolar value for this neutron capture product, even though all of the thermonuclear burning yields are quite similar. There are similarly large variations in the core-collapse supernova yields, so we must also await more consistent determinations of the ^{58}Fe yield.

5. CONCLUSION

Thus, we see that all the major distinctive features of the galactic cosmic-ray source composition, which clearly set them apart from that of the local interstellar medium (ISM), can result from preferential enrichment primarily by suprathermal ions sputtered off of fast refractory grains in the supernova ejecta and Wolf-Rayet wind–enriched mix of gas and dust in the supernova-active cores of superbubbles, where most (70%–75%) galactic supernova occur.

Perhaps most important, we see that the distinctive features of the cosmic-ray source composition offer new insights into the first stage of the long process of elemental mixing of freshly synthesized material into the ISM. Moreover, they provide quantitative measures of the mixing ratio of the fresh supernova ejecta and the old ISM in the primal cores of superbubbles. Finally, as we see in Table 2 with or without the Ne ratio, these initial SN-WR ejecta mixing fractions in these superbubbles appear to be essentially constant throughout most of the Galaxy and most of its history.

The cause of the apparent constancy of the ejecta mixing ratio in the superbubble cores is not yet clear, but its seemingly ubiquitous nature suggests that it arises from a very robust and potential fundamental process.

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REFERENCES

Alibes, A., Labay, J., & Canal, R. 2002, ApJ, 571, 326
Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Axford, W. I. 1981, Proc. 17th Int. Cosmic-Ray Conf. (Paris), 155
Binns, W. R., et al. 2001, in AIP Conf. Proc. 598, Solar and Galactic Composition, ed. R. F. Wimmer-Schweingruber (Melville: AIP), 257
———. 2005, ApJ, 634, 351
———. 2006, NewA Rev., 50, 516
Blaauw, A. 1991, in The Physics of Star Formation and Early Stellar Evolution, ed. C. J. Lada & N. D. Kylafis (Dordrecht: Kluwer), 125
Cesarsky, C. J., & Bibring, J.-P. 1981, in IAU Symp. 94, Origin of Cosmic Rays, ed. G. Setti et al. (Dordrecht: Reidel), 361
Clayton, D. D., Deneault, E. A., & Meyer, B. S. 2001, ApJ, 562, 480
Donnelly, J., Thompson, A., O'Sullivan, D., Keane, A., Drury, L., & Wenzel, K. 1999, Proc. 26th Int. Cosmic-Ray Conf. (Salt Lake City), 109
Draine, B. T., & McKee, C. F. 1993, ARA&A, 31, 373
Ellison, D. C., Drury, L., & Meyer, J.-P. 1997, ApJ, 487, 197
Engelmann, J. J., Ferrando, P., Soutoul, A., Goret, P., & Juliusson, E. 1990, A&A, 233, 96
Epstein, R. I. 1980, MNRAS, 193, 723
Gavilan, M., Buell, J. F., & Molla, M. 2005, A&A, 432, 861
Higdon, J. C., & Lingenfelter, R. E. 2003a, ApJ, 590, 822
———. 2003b, ApJ, 582, 330
———. 2005, ApJ, 628, 738
Higdon, J. C., Lingenfelter, R. E., & Ramaty, R. 1998, ApJ, 509, L33
———. 1999, Proc. 26th Int. Cosmic-Ray Conf. (Salt Lake City), 144
Hirschi, R. 2004, Ph.D. thesis, Univ. de Genève
Jenkins, E. B. 2004, in Origin and Evolution of the Elements, ed. A. McWilliams & M. Rauch (Cambridge: Cambridge Univ. Press), 336
Kobayashi, C., Umeda, H., Nomoto, K., Tominaga, N., & Ohkubo, T. 2006, ApJ, 653, 1145
Kozasa, T., Hasegawa, H., & Nomoto, K. 1991, A&A, 249, 474
Limongi, M., & Chieffi, A. 2003, ApJ, 592, 404
Lingenfelter, R. E., Higdon, J. C., Kratz, K.-L., & Pfeiffer, B. 2003, ApJ, 591, 228
Lingenfelter, R. E., Higdon, J. C., & Ramaty, R. 2000, in AIP Conf. Proc. 528, Acceleration and Transport of Energetic Particles Observed in the Heliosphere, ed. R. Mewalt et al. (Melville: AIP), 375
Lingenfelter, R. E., Ramaty, R., & Kozlovsky, B. 1998, ApJ, 500, L153
Lodders, K. 2003, ApJ, 591, 1220
Meyer, J-P., Drury, L., & Ellison, D. C. 1997, ApJ, 487, 182
Nomoto, K., Tominaga, N., Umeda, H., Kobayashi, C., & Maeda, K. 2006, Nucl. Phys. A, 777, 424
Ramaty, R., Kozlovsky, B., Lingenfelter, R. E., & Reeves, H. 1997, ApJ, 488, 730
Rauscher, T., Heger, A., Hoffman, R. D., & Woosley, S. E. 2002, ApJ, 576, 323
Reeves, H., Fowler, W. A., & Hoyle, F. 1970, Nature, 226, 727
Savage, B. D., & Sembach, K. R. 1996, ARA&A, 34, 279
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Sigmund, P. 1981, in Sputtering by Particle Bombardment I, ed. R. Behrisch (New York: Springer), 9
Spitzer, L., & Fitzpatrick, E. L. 1993, ApJ, 409, 299
Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1995, ApJS, 98, 617
Travaglio, C., Hillebrandt, W., Reinecke, M., & Thielemann, F.-K. 2004, A&A, 425, 1029
van den Bergh, S., & McClure, R. D. 1994, ApJ, 425, 205
Weaver, B. A., & Westphal, A. J. 2002, ApJ, 569, 493
Woosley, S. E., Langer, N., & Weaver, T. A. 1995, ApJ, 448, 315
Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181