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THE SUPERBUBBLE ORIGIN OF ^{22}Ne IN COSMIC RAYS

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ABSTRACT

We investigate a superbubble origin for the well-known anomalous ^{22}Ne/^{20}Ne ratio found (Binns and coworkers) for the sources of cosmic rays, which is 5 times the solar wind value. We calculate self-consistently the neon isotopes synthesized by massive stars residing in cores of superbubbles. Our model yields, based on the recent nucleosynthetic calculations, depend on two parameters: the limiting mass for Type II supernovae (SNe II) above which single massive stars lose their hydrogen envelopes and explode as Type Ib and Ic supernovae (SNe Ibc), and the cutoff mass above which stellar collapse creates black holes without supernova explosions. We then model the mean ^{22}Ne/^{20}Ne ratio in superbubble cores, resulting from the dispersal of this newly synthesized neon ejected in the metal-rich winds and supernova explosions together with the debris of older interstellar medium within the superbubbles. We characterize this dispersal in terms of the mean superbubble metallicity, $Z_{\rm sb}$, the elemental mass fraction heavier than helium. Finally, we determine the expected ^{22}Ne/^{20}Ne ratio in the local cosmic rays, based on observations of the relative fractions of supernovae occurring in superbubbles and other phases of the interstellar medium. Considering all of the uncertainties, we find that the cosmic-ray source abundance ratio of ^{22}Ne/^{20}Ne can be easily understood as the result of cosmic rays accelerated primarily out of superbubble cores with a mean metallicity $Z_{\rm sb}$ between 2.3 and 3.1 $Z_\odot$. This metallicity, which corresponds to a mean wind and ejecta mass fraction of between 13% and 23%, is quite consistent with values of the mean superbubble core metallicity inferred from other observations and provides additional evidence for a superbubble origin of the bulk of the cosmic rays.

Subject headings: cosmic rays — Galaxy: evolution — nuclear reactions, nucleosynthesis, abundances — stars: Wolf-Rayet — supernovae: general

1. INTRODUCTION

The ^{22}Ne/^{20}Ne ratio has been observed (e.g., Garcia-Munoz, Simpson, & Wefel 1979; Wiedenbeck & Greiner 1981; Mewaldt et al. 1980; Lukasiak et al. 1994; Du Vernois et al. 1996; Binns et al. 2001) to be much greater in the Galactic cosmic rays than in the solar system. The most accurate (Binns et al. 2001) cosmic-ray neon isotopic measurements have been obtained by the Cosmic Ray Isotope Spectrometer (CRIS) instrument aboard the *Advanced Composition Explorer* (*ACE*) spacecraft. The analysis (Binns et al. 2001) of *ACE*/CRIS data found a ^{22}Ne/^{20}Ne source abundance ratio of 0.366 ± 0.015; this ratio is 5.0 ± 0.2 greater than 0.073, the value found (Anders & Grevesse 1989) in the solar wind.

Casse & Paul (1982) suggested that the cosmic-ray ^{22}Ne anomaly was produced by the wind injection and acceleration of a separate component of cosmic rays during the WC phase of massive Wolf-Rayet (W-R) stars. An alternative W-R origin for the cosmic-ray neon isotopic anomaly was suggested by Maeder & Meynet (1993) and further explored by Soutoul & Legrain (2000), assuming that the local cosmic rays were accelerated out of the diffuse interstellar medium (ISM) in the distant, higher Z inner galaxy. However, Meynet et al. (2001) have recently shown that both of these models face serious difficulties in trying to account for the measured cosmic-ray ^{22}Ne source abundance.

Here we show that the ^{22}Ne abundance in the cosmic rays is not anomalous but is a natural consequence of the superbubble origin of cosmic rays (Higdon, Lingenfelter, & Ramaty 1998), in which the bulk of Galactic cosmic rays are accelerated by supernova shocks in the high-metallicity, W-R wind and supernova ejecta enriched, interiors of superbubbles. In fact, we suggest that the measured value of the cosmic-ray ^{22}Ne/^{20}Ne ratio provides additional evidence for such an origin. Such superbubbles are created (e.g., Mac Low & McCray 1988) by correlated core-collapse (SN II and SN Ibc) supernovae, whose stellar progenitors were born in Galactic OB associations. The stellar winds of the most massive, most short-lived stars, which evolve into W-R stars, initiate the formation of superbubbles and, consequently, would enrich the interiors of the superbubbles with their metal-rich wind ejecta. The expansion of these superbubbles is further powered by the subsequent supernova explosions of the less massive stars in these OB associations, and they are further enriched by the high-metallicity ejecta of these supernovae. Since the majority of Galactic supernovae occur in these superbubbles, we suggested (Higdon et al. 1998) that the bulk of the Galactic cosmic rays are also accelerated by the supernova shocks in the interiors of these superbubbles, where they are enriched not only in the metals synthesized in the supernovae, but also in ^{22}Ne from the W-R winds of the more massive supernova

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progenitors (Lingenfelter, Higdon, & Ramaty 2000). Here we calculate the latter enrichment in detail.

In § 2 we briefly review current models of W-R stars. In § 3 we review the calculations of the ^{22}Ne and ^{20}Ne yields in W-R winds and supernova ejecta. In § 4 we combine these contributions with interstellar material to calculate the mean ^{22}Ne and ^{20}Ne abundances in superbubbles. In § 5 we use the observations of the fraction of supernovae occurring outside of superbubbles to calculate the range of ^{22}Ne/^{20}Ne ratios expected in the local cosmic rays, and finally we compare that range with the measured value to determine the mean superbubble core metallicity.

2. WOLF-RAYET STARS

W-R stars are post–main-sequence massive stars that have lost their H-rich stellar envelopes by either intense stellar winds or Roche overflows to close companion stars (e.g., Maeder & Conti 1994). The WN subclass of W-R stars are helium stars whose surface abundances are dominated by the equilibrium products of CNO hydrogen burning; the surface abundances of the WC subclass of W-R stars result from helium burning (e.g., Maeder & Conti 1994). Models (e.g., Maeder 1991) predict the nucleosynthesis of significant abundances of ^{22}Ne during the WC phase of W-R stellar evolution; these predicted ^{22}Ne surface enhancements have been confirmed by observations with the *Infrared Space Observatory* (e.g., Willis et al. 1997; Dessart et al. 2000).

The threshold mass for the formation of W-R stars depends on stellar metallicity, angular rotation, and presence of a close stellar companion (Maeder & Meynet 2000). Both models (e.g., Maeder 1991; Maeder & Meynet 1993) and observations (Massey & Duffy 2001; Massey, Waterhouse, & DeGioia-Eastwood 2000; Massey, DeGioia-Eastwood, & Waterhouse 2001) show that the minimum mass limit $M_{\rm LIM}$ for single-star W-R formation is greater in low-Z interstellar media. Moreover, the relative number of WC/WN stars varies systematically with metallicity (e.g., Massey & Johnson 1998). Empirically, from analyses of turnoff masses of coeval stellar clusters, minimum W-R masses $M_{\rm LIM}$ of 18, 30, and 70 $M_\odot$ have been found for the local Milky Way (Massey et al. 2001), the LMC, and the SMC (Massey et al. 2000), respectively. Moreover, in the low-metallicity LMC, Massey et al. (2000) observed W-R stars in stellar clusters with turnoff masses ranging from 30 to 100 $M_\odot$; they suggested that all LMC stars more massive than 30 $M_\odot$ become W-R stars. Furthermore, in the LMC they found that WC stars are located in clusters with turnoff masses $\leq$45 $M_\odot$, similar to masses derived for WN stars, and they concluded that WC stars come from the same mass range as the WN stars.

As a result of uncertainties in stellar mass-loss rates from the post–main-sequence massive stars, it is difficult to model the properties of W-R stars. For example, many investigations (e.g., Schaller et al. 1992; Woosley, Langer, & Weaver 1995) have employed the older empirical (Hamann, Schonberger, & Heber 1982) or modeled (Langer 1989) W-R mass loss rates. However, recent analyses (e.g., Hamann & Koesterke 1998; Nugis, Crowther, & Willis 1998) have demonstrated that clumping in W-R ejecta, an effect neglected in older derivations of mass loss, creates overestimates of the rates by a factor of $\sim$2–3. Although wind clumping modifies estimates of wind loss, it does not affect significantly the determinations of W-R luminosities, temperatures, and, most of all, surface compositions (Willis 1999). Moreover, Wellstein & Langer (1999) demonstrated that for main-sequence 40 and 60 $M_\odot$ stars, the mass-loss rate must be considerably lower before the He core mass is significantly increased; e.g., when the W-R mass-loss rate is decreased by a factor of $\sim$4, the final He core of a 60 $M_\odot$ star increased by $\sim$1.9.

Model calculations show that rapid stellar rotation decreases the minimum W-R mass. At $Z_\odot$ Maeder & Meynet (2000) suggested that the minimum W-R mass for single stars is 25 $M_\odot$ for an initial $v_{\rm rot} = 300$ km s^{-1}, but the minimum W-R mass is significantly greater, between 35 and 40 $M_\odot$ for nonrotating stars.

The fraction of W-R stars created by mass exchange in close binaries is a matter of debate. Maeder & Meynet (1993) estimated that the fraction of W-R stars created by binary mass exchange is low, only $\sim$5% at solar metallicities. However, in a detailed study of stellar evolution in massive close binaries, Podsiadlowski, Joss, & Hsu (1992) found that, as a result of binary mass exchange, 15%–30% of all massive stars greater than 8 $M_\odot$ become helium stars, i.e., W-R stars. Assuming a Salpeter (e.g., Massey 2002) initial mass function (IMF), the expected number of such binary low-mass He stars, 30% of all stars more massive than 8 $M_\odot$, is $\geq$1.5–3 times the number of all massive stars $\geq$40 $M_\odot$, a conservative (Maeder & Meynet 2000) estimate for the mass threshold for the single-star formation of W-R stars.

Thus, in the following calculations we explore a range of values from 15 to 35 $M_\odot$ for the limiting minimum initial stellar mass, $M_{\rm LIM}$, at which W-R stars can be formed.

3. WOLF-RAYET AND SUPERNOVA SOURCES OF ^{22}Ne and ^{20}Ne

In order to derive the neon isotope abundances in superbubbles and cosmic rays, we use the calculated neon yields, as a function of the initial stellar mass, not only in the W-R winds, which are the primary source of ^{22}Ne, but also in the ejecta of the associated core-collapse supernovae, which are the primary sources of ^{20}Ne. The latter include both SNe Ibc, which are thought (e.g., Woosley et al. 1995) to result from the subsequent core collapse of the helium stars left after the W-R wind phase, and SNe II, which result from core collapse of the less massive, 8 $M_\odot \leq M \leq M_{\rm LIM}$, single and long-period binary stars, which do not become W-R stars (e.g., Woosley & Weaver 1995).

3.1. *Neon Ejecta from Wolf-Rayet Stars*

The yields of ^{22}Ne and ^{20}Ne in the W-R winds of nonrotating massive stars[2] depend on both the initial mass of the star and its initial metallicity. There is significant (e.g., Edvardsson et al. 1993) variation in the metallicities of stars formed at any time in the Galactic disk, but the mean metallicity of the present-day ISM seems (Twarog 1980; Rana 1991; Timmes, Woosley, & Weaver 1995; Dwek 1998) to be 1.32 times the solar value of $Z_\odot = 0.02$, so that the present-day $Z_{\rm ISM} = 0.0264$.

[2] We employed here nucleosynthetic yields for nonrotating stars, since the published models for rotating stars span an insufficient range of initial stellar masses.

There are model calculations of the neon isotope yields for a wide range of initial masses and metallicities. However, they have not been carried out specifically for the present-day interstellar metallicity. Thus, we use two model calculations at bracketing values of metallicity and interpolate the yields for the present metallicity.

Here we determined the mass of neon ejected by W-R stars from the stellar models of Schaller et al. (1992) for $Z = 0.02$ and Schaerer et al. (1993) for $Z = 0.04$, for initial masses, M, ranging from 20 to 120 $M_\odot$, for their standard model of mass loss. Using linear interpolation and their tabulations of the surface mass fraction, $\Sigma_i(t)$, of isotope, i, and mass-loss rates, $\dot{M}(t)$, the total mass of isotope, i, in the wind ejecta, ${}_{wr}m_i$, is determined via an integration over the stellar lifetime, t_*, taken to be the end of carbon core burning,

$$ {}_{wr}m_i = \int_0^{t_*} \Sigma_i(t)\dot{M}(t)dt \ . \qquad (1)$$

The resulting isotopic neon yields in $M_\odot$, determined for the grid of massive stars from the model calculations at $Z = 0.020$ and 0.040, together with the linearly interpolated values for the present interstellar metallicity of $Z = 0.0264$, are listed in Table 1. Also listed are the total wind ejecta, as well as the mass ejected in metals, i.e., the sum of mass of all isotopes heavier than ^{4}He, which were determined in the same manner.

Because of the uncertain value of the minimum stellar mass necessary to create a W-R star in the local Galaxy, we calculate ^{22}Ne and ^{20}Ne production for the local W-R population as a function of the minimum initial stellar mass, $M_{\rm LIM}$, required to create a W-R star, but we assume that the most likely value of $M_{\rm LIM}$ is in the range of 25 ± 10 $M_\odot$. In § 4 we employ the yields from Table 1, together with a range of $M_{\rm LIM}$, to calculate neon yields in the wind ejecta of local W-R stars.

TABLE 1

Wind Ejecta Yields $M_\odot$ for Different Initial Masses and Metallicities

$M_{\rm initial}$	^{20}Ne	^{22}Ne	Ejecta	Metals
		$Z = 0.020$		
15	0.0020	0.00016	1.41	0.0257
20	0.00496	0.00040	3.48	0.0633
25	0.0135	0.00109	9.42	0.173
40	0.0455	0.138	31.9	5.22
60	0.0587	0.455	52.2	13.1
85	0.0912	0.678	76.0	23.8
120	0.181	1.69	112.0	42.6
		$Z = 0.0264$		
20	0.0074	0.00061	3.82	0.0958
25	0.020	0.00161	10.4	0.258
40	0.0613	0.219	32.6	5.37
60	0.0928	0.618	52.8	12.3
85	0.1353	0.881	76.9	20.8
120	0.2260	1.69	113.0	34.4
		$Z = 0.040$		
20	0.0127	0.00102	4.53	0.165
25	0.0339	0.00273	12.1	0.441
40	0.0950	0.393	34.0	5.70
60	0.166	0.967	54.0	10.4
85	0.230	1.32	78.8	14.3
120	0.323	1.68	114.0	16.8

3.2. *Neon Ejecta in SN II Explosions*

To model the supernova ejecta yields of ^{22}Ne and ^{20}Ne, we employed the yields calculated by Woosley & Weaver (1995; above 30 $M_\odot$ we used their B models) for SN II ejecta as a function of initial stellar mass at $Z_\odot$. We assume that these yields are essentially the same as those in young stars formed from the present ISM with a metallicity of 1.32 $Z_\odot$, since they are much less sensitive to metallicity than those in the W-R winds. These models neglected stellar mass loss. Timmes et al. (1995) suggested that single stars with main-sequence masses above 30–40 $M_\odot$ may enter the W-R stage. Similarly, Langer & Henkel (1995) found that their model results differed significantly from those of Woosley & Weaver (1995) for stars with main-sequence masses greater than 30 $M_\odot$, as a result of their inclusion of radiatively driven mass loss.

Since the identification of a core-collapse supernova as an SN II depends on the identification of hydrogen recombination lines, it is thought (e.g., Filippenko 1997) that massive stars that enter the W-R phase will collapse in SNe Ibc (no hydrogen line emission) rather than in SNe II. Thus, the mass parameter, $M_{\rm LIM}$, which identifies the smallest stellar mass that becomes a W-R star, is also the stellar mass limit that separates the stellar core-collapse supernovae types, SN II and SN Ibc. Therefore, we considered all stars, single and long-period binaries, as candidate SNe II with masses M such that $8\ M_\odot \le M \le M_{\rm LIM}$. We considered all stars with initial masses $M > M_{\rm LIM}$ as candidate SNe Ibc.

3.3. *Neon Ejecta in SN Ibc Explosions*

Assuming that the Milky Way can be classified as a late spiral galaxy (Hubble type Sbc–Sd), van den Bergh & McClure (1994) estimated that SNe Ibc contribute $\sim\frac{1}{4}$ to $\sim\frac{1}{2}$ of Galactic core-collapse supernovae. Using an automated supernova search, Muller et al. (1992) estimated that SNe Ibc contribute $\geq\frac{1}{2}$ of core-collapse supernovae in late spiral galaxies. However, from analyses of the Asiago and Crimean supernova searches, conducted over three decades, Cappellaro et al. (1993) found that SNe Ibc constitute a much smaller fraction, $\sim\frac{1}{8}$ of core-collapse supernovae in late spiral galaxies. Consequently, we choose a ratio of the number of SNe Ibc to the number of SNe II, $f_{\rm SN\,Ibc} = 0.25$.

We consider SN Ibc explosions of the helium stars from the W-R phase of massive, $M > M_{\rm LIM}$, stars that are either single or in wide binary systems and of less massive stars in close, interacting binaries.

3.3.1. *Single Stars and Long-Period Binaries*

Supernova explosions of the very rare, most massive (>60 $M_\odot$) stars have not been simulated in as much detail as more frequently occurring lower mass stars. Although Woosley et al. (1995) determined that an SN Ib could result from the explosion of a 4.25 $M_\odot$ helium star, created by efficient W-R mass loss from a single main-sequence star of 60 $M_\odot$, they suggested that even smaller masses would be preferred as the origin for the common SNe Ibc. However, Crowther (2002) estimated from observations of Galactic WC stars that the pre-supernova masses of these stars will be in the range of 7–14 $M_\odot$, which may collapse into black holes without forming SNe Ibc. We discuss lower mass limits for black hole formation, $M_{\rm BH}$, in § 3.4.

We consider the contribution of single massive stars, collapsing into SNe Ibc, to neon production in the following way. Above a chosen $M_{\rm LIM}$, we modeled the nucleosynthetic yields of single-star SNe Ibc in two stages. First, for $M > M_{\rm LIM}$, we assumed that W-R winds efficiently stripped the H-rich mantles of massive stars early in their evolution, revealing their naked stellar helium cores of mass $M_{\rm He}$; we employed the results of Arnett (1978) to relate the masses of the helium cores, $M_{\rm He}$, to the initial main-sequence masses, M. Second, we used the results of Woosley et al. (1995) to model the supernova yields of SNe Ibc as a function of the initial helium cores, $M_{\rm He}$. For the more massive main-sequence stars, $M > 40\ M_\odot$, whose resultant helium cores $M_{\rm He} > 20\ M_\odot$, the greatest helium stellar mass exploded by Woosley et al. (1995), we modeled the resultant explosions of all helium cores greater than 20 $M_\odot$ by results of the 20 $M_\odot$ helium core explosion. We made this choice in view of the fact that efficient mass-dependent W-R winds cause these massive helium stars, initially 4–20 $M_\odot$, to evolve (Woosley et al. 1995) to converge to final masses over a narrow mass range, 2.25–3.5 $M_\odot$.

We weighted ejecta yields, for this class of sources, over a Salpeter IMF, $dN/dM \propto M^{-2.35}$ (e.g., Massey 2002) for initial stellar masses in the range $M_{\rm LIM} \leq M \leq M_{\rm BH}$, the lower mass limit for black hole formation.

3.3.2. *Close Binaries*

The modeling of supernovae in interacting binaries is complex. For example, Tutukov, Yungelson, & Iben (1992) identified "about two dozen different kinds of supernovae" occurring in binaries. Here we will address solely the issue of the binary star contribution to SNe Ibc. Woosley & Eastman (1997) suggested that SNe Ibc occur most frequently in binaries, and Nomoto et al. (1997) proposed that common envelope evolution of massive binary stars can explain the origin of SNe Ib and SNe Ic in a unified approach. These two studies suggest that the common SNe Ib and SNe Ic result from explosions of small pre-supernova masses of $\sim$2–4 $M_\odot$. For example, Nomoto et al. (1997) showed that the light curves of SNIc 1994I could be modeled well by a 15 $M_\odot$ main-sequence primary, which looses its H-rich envelope via Roche overflow to a companion star before becoming a 4 $M_\odot$ He star, which in turn looses its He envelope by Roche overflow, creating a pre-supernova CO star of 2.1 $M_\odot$. Finally, Podsiadlowski et al. (1992) found that, as a result of binary mass exchange, 15%–30% of all massive stars greater than 8 $M_\odot$ become 2–6 $M_\odot$ helium stars, whose collapse can reproduce the expected frequency of SNe Ibc without the contribution of single more massive W-R stars, discussed previously.

We consider the contribution of binary massive stars, collapsing as SNe Ibc, to the neon production in the following way. In view of the studies of Shigeyama et al. (1990), Hachisu et al. (1991), and Nomoto et al. (1997), we assume that the helium star masses of the modeled binary SNe Ibc range from 3 to 6 $M_\odot$, which correspond (e.g., Arnett 1978) to main-sequence masses of 10–16 $M_\odot$. To represent the ejecta yields for these SNe Ibc, we again use the calculations of Woosley et al. (1995) for the supernova yields as a function of initial helium star masses.

3.4. *Stellar Collapse into Black Holes*

The collapse of a massive star into a black hole affects the injection of neon isotopes in superbubbles, since some or even all of the stellar envelope is accreted by the black hole. Core collapse of a massive star can form a black hole either directly without a corresponding supernova explosion or subsequent to a supernova explosion via ejecta fallback onto the surface of a newly formed neutron star (e.g., Colgate 1971; Woosley 1988; Fryer 1999). However, detailed calculations of black hole formation in stellar collapse depend not only on the main-sequence stellar mass (e.g., Fryer 1999) but also on additional parameters, such as stellar rotation (e.g., Heger, Langer, & Woosley 2000), metallicity-dependent stellar wind mass loss (e.g., Langer 1989), and the assumed convection model (e.g., Wellstein & Langer 1999), as well as the presence of a close stellar companion.

Estimates of the minimum main-sequence mass threshold, $M_{\rm BH}$, for directly creating a black hole via core collapse of a single star without producing a supernova have ranged from as low as $\sim$20 $M_\odot$ (Maeder 1992) to $\sim$30 $M_\odot$ (Brown & Bethe 1994), without considering wind losses, and $\sim$40 $M_\odot$ (Fryer 1999; Wellstein & Langer 1999), considering wind losses. Estimates of the minimum mass for black hole formation via fallback after a supernova explosion are slightly lower, from $\sim$18 (Brown & Bethe 1994) to $\sim$25 $M_\odot$ (Fryer 1999), but since such fallback is expected to involve only the inner portion of the supernova ejecta, these limits are likely not relevant for the neon isotopes.

Black hole formation in interacting stellar systems is thought (e.g., Lewin, van Paradijs, & van den Heuvel 1995) to create the Galactic soft X-ray sources, powered by accretion from low-mass companion stars onto low-mass black holes. In order to reproduce the observed number of such sources, Portegies Zwart, Verbunt, & Ergma (1997) found that the bulk of binary systems with primary main-sequence masses $\geq$20 $M_\odot$ must collapse to black holes. In addition, Brown, Lee, & Bethe (1999) suggest that black holes can form in binaries with such primary masses, provided that the primary's hydrogen envelope is removed late via common envelope evolution after He core burning.

We will explore the effect of black hole formation on the massive-star production of neon isotopes by assuming a single parameter, $M_{\rm BH}$, as the cutoff mass between core collapse as a supernova (either SN II or SN Ibc) and core collapse into a black hole without a supernova explosion. In the following calculations, we shall assume that the most likely value of the minimum mass for black hole formation, $M_{\rm BH}$, lies in the range of $40 \pm 15\ M_\odot$.

4. ^{22}Ne AND ^{20}Ne ABUNDANCES IN SUPERBUBBLES

We calculate the ^{22}Ne and ^{20}Ne abundances in the cores of superbubbles by first determining the neon isotope abundances in the combined W-R winds and supernova ejecta and then determining the dilution of these abundances by the mixing with old interstellar gas and dust in the superbubbles.

4.1. *Neon Isotopes in Wolf-Rayet Winds and Supernova Ejecta*

We calculate neon production in superbubbles by massive stars from the combined contributions of W-R stars, SNe II, and SNe Ibc. We calculate neon production over a wide range of values of both M_{LIM} and M_{BH}. For W-R stars we consider the initial mass range, $M_{LIM} \leq M \leq 120\ M_\odot$. For SNe II and single-star SNe Ibc we include contributions from $8\ M_\odot \leq M \leq M_{LIM}$ and $M_{LIM} \leq M \leq M_{BH}$, respectively, assuming that $M_{BH} > M_{LIM}$. If $M_{BH} < M_{LIM}$, the contribution of single-star SNe Ibc is zero and the SN II range becomes $8\ M_\odot \leq M \leq M_{BH}$. For these three classes of sources we weight the neon production over the Salpeter IMF (e.g., Massey 2002), $dN/dM \propto M^{-2.35}$. Thus, the relative contribution of each source is calculated consistently. We include the contribution of SNe Ibc from binaries employing a different approach. As discussed previously, we assume an SN Ibc/SN II number ratio, $f_{\rm SN\,Ibc} = 0.25$. Only if the number of single-star SNe Ibc is less than 0.25 of the number of SNe II, both weighted over a Salpeter IMF, do we include a contribution of SNe Ibc from binaries. To calculate the contribution of neon yields from binary SNe Ibc, we determine neon yields from Woosley et al. (1995) for helium stars corresponding to main-sequence primary masses over the range of $10\ M_\odot \leq M \leq 16\ M_\odot$, as discussed in § 3.3; these SN Ibc ejecta yields are weighted over the Salpeter IMF and normalized to the difference between $f_{\rm SN\,Ibc}$ and the contribution of single-star SNe Ibc.

Thus, the dimensionless, differential combined yield or mass fraction $d\mu_{\rm Ne}(M)/dM$ of each Ne isotope ejected by winds and supernovae into a superbubble, as a function of the initial stellar mass, is simply the sum, weighted over the IMF,

$$\frac{d\mu_{\rm Ne}(M)}{dM} = \frac{dN}{dM(M)[{}_{wr}m_{\rm Ne}(M) + {}_{\rm SN\,Ibc}m_{\rm Ne}(M) + {}_{\rm SN\,II}m_{\rm Ne}(M)]}\ , \tag{2}$$

where the IMF, dN/dM in units of $M_\odot^{-1}$, is normalized to unity at $M = 8\ M_\odot$. This function is shown for both ^{22}Ne and ^{20}Ne in Figure 1, for $f_{\rm SN\,Ibc} = 0.25$, and for representative values of $M_{LIM} = 25\ M_\odot$ and $M_{BH} = 40\ M_\odot$. Here we see that the relative contribution of SNe Ibc from both single and binary stars is minor, so that the overall ratio of ^{22}Ne/^{20}Ne is not strongly dependent on the choice of M_{BH}. Thus, the major uncertainty in the neon isotope ratio comes from the choice of M_{LIM}. Since Woosley & Weaver (1995) have calculated neon yields only for supernovae of stars with initial masses of 11 $M_\odot$ and above, we assume that the neon isotope mass fractions for stars between 8 and 11 $M_\odot$ simply decrease linearly from the calculated value at 11 $M_\odot$ to the ISM value at 8 $M_\odot$. This is not a large variation because the ISM value is roughly $\frac{2}{3}$ of the 11 $M_\odot$ value for both ^{22}Ne and ^{20}Ne.

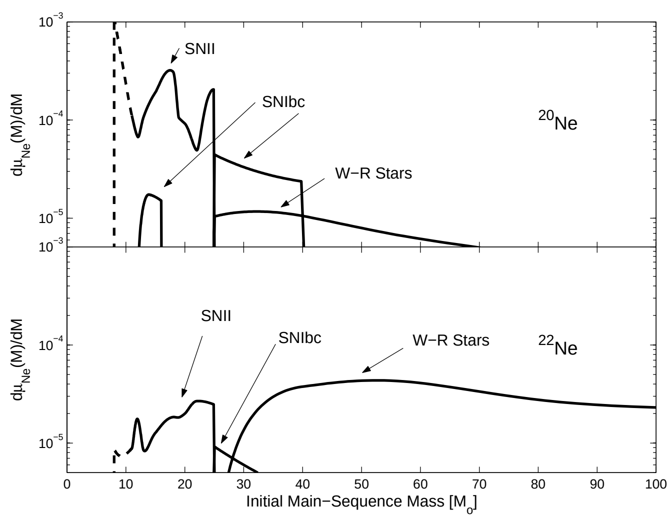

FIG. 1.—Masses of ^{20}Ne and ^{22}Ne ejected per star into a superbubble from SN II and SN Ibc explosions and W-R winds weighted by the Salpeter IMF, as a function of main-sequence star mass M, for representative values of the lower limiting stellar masses for the onset of W-R winds, $M_{LIM} = 25\ M_\odot$, and the formation of black holes, $M_{BH} = 40\ M_\odot$.

Since the lifetimes (Schaller et al. 1992) of the these stars $t_*(M)$ range from 3 Myr ($M = 120\ M_\odot$) to 37 Myr ($M = 8\ M_\odot$), the ^{22}Ne/^{20}Ne ratio in the accumulated W-R wind and supernova ejecta in a superbubble changes significantly over the age of a superbubble, t. Thus, we calculate the accumulated masses of the neon isotopes in the wind and ejecta in a superbubble as a function of age: for 3 Myr $< t < t_*(M_{LIM})$,

$$\mu_{\rm Ne}(t) = \int_3^t {}_{wr}m_{\rm Ne}(t')\left(\frac{dN}{dt'}\right)dt' + \int_{t_*(M_{BH})}^t {}_{\rm SN\,Ibc}m_{\rm Ne}(t')\left(\frac{dN}{dt'}\right)dt'\ , \tag{3}$$

and for $t_*(M_{LIM}) < t < t_*(8\ M_\odot)$,

$$\begin{aligned}\mu_{\rm Ne}(t) = &\int_3^{t_*(M_{LIM})} {}_{wr}m_{\rm Ne}(t')\left(\frac{dN}{dt'}\right)dt' \\ &+ \int_{t_*(M_{BH})}^{t_*(M_{LIM})} {}_{\rm SN\,Ibc}m_{\rm Ne}(t')\left(\frac{dN}{dt'}\right)dt' \\ &+ \int_{t_*(M_{LIM})}^{t} {}_{\rm SN\,II}m_{\rm Ne}(t')\left(\frac{dN}{dt'}\right)dt' \\ &+ f_{\rm binary}\int_{\min[t,t_*(16\ M_\odot)]}^{\min[t,t_*(10\ M_\odot)]} {}_{\rm SN\,Ibc}m_{\rm Ne}(t')\left(\frac{dN}{dt'}\right)dt'\ ,\end{aligned} \tag{4}$$

where the $m_{\rm Ne}(t)$ are the different age-dependent neon isotope yields for W-R stars, SNe Ibc, and SNe II; $f_{\rm binary}$ is the possible weighting of the binary star portion of the SNe Ibc, as discussed above; and dN/dt is the age-dependent supernova rate derived below.

The age-dependent supernova birth rate is derived from the stellar ages (i.e., the end of core carbon burning) tabulated by Schaller et al. (1992), as a function of main-sequence mass for the range $7\ M_\odot \leq M \leq 120\ M_\odot$ and the assumed IMF. We approximated these ages using a quartic least-squares fit, $t_*(M)$, in $\ln M$:

$$\ln t_*(M) = C_5 + C_4 \ln M + C_3(\ln M)^2 + C_2(\ln M)^3 + C_1(\ln M)^4\ , \tag{5}$$

where $C_{1-5} = [0.0119914, -0.218395, 1.69502, -6.6851, 11.9115]$. This least-squares fit is compared with the tabulated values from Schaller et al. (1992) in the top panel of Figure 2. We determined the superbubble supernova rate, dN/dt, for a single generation of star formation, simply from the Salpeter IMF (e.g., Massey 2002), $dN/dM \propto M^{-2.35}$, for the supernova progenitors, and the derivative, dt_*/dM, of $t_*(M)$, the stellar age-to-mass

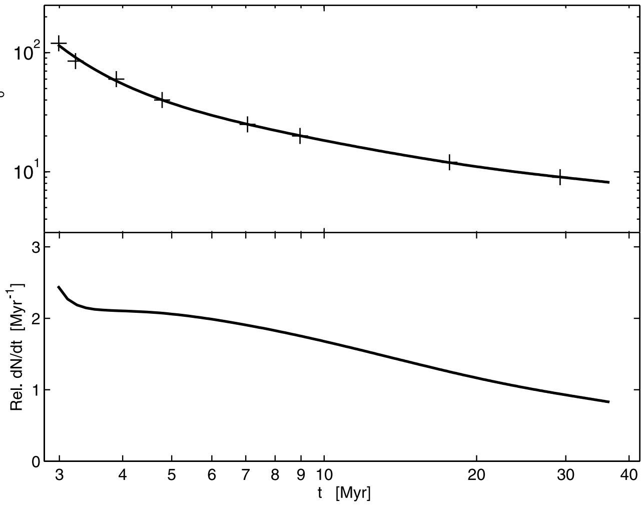

FIG. 2.—*Top:* Stellar ages (to the end of core carbon burning) as a function of initial stellar mass from Schaller et al. (1992; *crosses*), compared with the quartic fit in ln M (*solid curve*), given in eq. (5). *Bottom:* Relative supernova birthrate, $dN/dt = (dN/dM)(dM/dt)$, as a function of time after star formation, or equivalently superbubble age.

relation, equation (5),

$$\frac{dN}{dt} = \left(\frac{dN}{dM}\right)\left(\frac{dM}{dt_*}\right) . \tag{6}$$

This relative supernova rate, dN/dt, is shown in the bottom panel of Figure 2, as a function of time after star formation, or equivalently the superbubble age. As can be seen, the supernova rate, dN/dt, varies by less than a factor of 2 over a factor of 10 in age. The lack of strong time dependence in the supernova rate has been remarked on previously (e.g., Mac Low & McCray 1988). Since the timescale of cosmic-ray acceleration by the supernova shocks is short ($\sim$0.1 Myr; e.g., Higdon, Lingenfelter, & Ramaty 1999) compared to the time-dependent supernova rate, the time-dependent cosmic-ray acceleration rate is proportional to the supernova rate.

Using equations (3) and (4), we calculate the accumulated masses of the ^{22}Ne and ^{20}Ne in the W-R winds and supernova ejecta within a superbubble as a function of superbubble age. Calculating the resulting ^{22}Ne/^{20}Ne ratio in the accumulated winds and ejecta versus superbubble age for a representative range of $M_{\rm LIM}$ from 15 to 35 $M_\odot$ and $M_{\rm BH}$ of 40 $M_\odot$, we find that during the first few Myr, while the ^{22}Ne-rich W-R winds are the dominant neon source, the ^{22}Ne/^{20}Ne is nearly 7, or almost 100 times the solar wind value, but averaged over the duration of supernova activity the ratio drops to between about 0.8 and 1.8, which is still roughly 10–20 times solar.

Since the local cosmic rays are accelerated by many supernovae (Higdon & Lingenfelter 2003) in a number of superbubbles of varying ages, we would expect that the mean, relative ^{22}Ne and ^{20}Ne abundances sampled by the cosmic rays accelerated in an ensemble of superbubbles should approach the limiting case of the time-averaged, supernova-weighted values in a single superbubble. Thus, we calculate the mean ^{22}Ne and ^{20}Ne abundances from the age-dependent accumulated neon masses, $\mu_{\rm Ne}(t)$, given in equations (3) and (4), weighted by the age dependence of the cosmic-ray acceleration, which is proportional to the supernova birthrate in a superbubble, (dN/dt), and averaged over the duration of supernova activity in a superbubble, $t_*(M_{\rm BH})$ to $t_*(8\ M_\odot)$,

$$\langle \mu_{\rm Ne} \rangle = \int_{t_*(M_{\rm BH})}^{t_*(8\ M_\odot)} \mu_{\rm Ne}(t') \left(\frac{dN}{dt'}\right) dt' . \tag{7}$$

Using the resulting mean masses of ^{22}Ne and ^{20}Ne from equation (7) and a similar determination of the mean mass of the total ejecta, $\langle \mu_{\rm ej} \rangle$, we determine the mean mass fractions, $(f_{\rm Ne})_{\rm ej}$, of ^{22}Ne and ^{20}Ne in the accumulated SN II and SN Ibc ejecta and W-R winds, averaged over the duration of core-collapse supernova explosions in a superbubble, and hence of cosmic-ray acceleration,

$$(f_{\rm Ne})_{\rm ej} = \frac{\langle \mu_{\rm Ne} \rangle}{\langle \mu_{\rm ej} \rangle} . \tag{8}$$

We explore the variation in the ^{22}Ne and ^{20}Ne $(f_{\rm Ne})_{\rm ej}$, as a result of the uncertainties in the lower limiting masses for the onset of W-R winds, $M_{\rm LIM}$, and the formation of black holes, $M_{\rm BH}$, by calculating the neon isotope mass fractions for a wide range of values of $M_{\rm LIM}$ from 15 to 40 $M_\odot$ and $M_{\rm BH}$ from 20 to 60 $M_\odot$. Contours of the resulting mean ^{22}Ne and ^{20}Ne mass fractions in superbubble cores are shown in Figure 3, as a function of the assumed values of $M_{\rm LIM}$ and $M_{\rm BH}$. The irregular structure in the ^{20}Ne contours reflects irregularities in the SN II yields calculated by Woosley & Weaver (1995). We also note that although there are differences between the pre-supernova masses calculated by Woosley et al. (1995) for their SN Ibc models and those calculated by Schaller et al. (1992) and Schaerer et al. (1993) for W-R winds, these differences have a negligible effect on mean neon mass fractions.

Overall we see that despite rather large uncertainties in $M_{\rm LIM}$ and $M_{\rm BH}$, the assumed range of $M_{\rm LIM}$ of $25 \pm 10\ M_\odot$ and $M_{\rm BH}$ of $40 \pm 15\ M_\odot$ gives only a narrow maximum

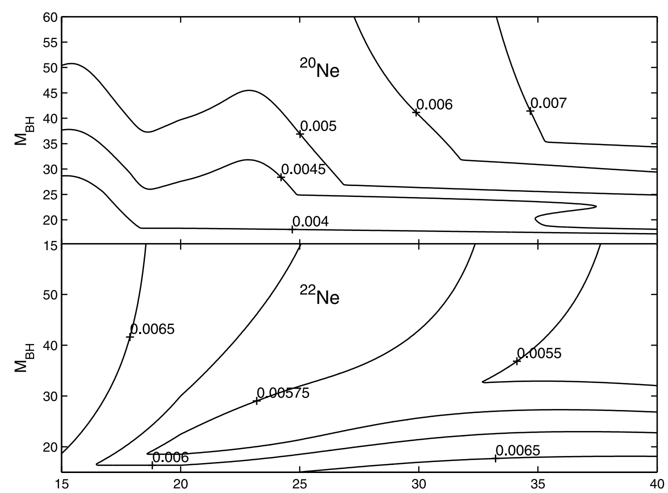

FIG. 3.—Mean ^{22}Ne and ^{20}Ne mass fractions in the combined SN II and SN Ibc ejecta and W-R winds, averaged over the time span of core-collapse supernova explosions in a superbubble for a wide range of values of the lower limiting masses for the onset of W-R winds, $M_{\rm LIM}$, and the formation of black holes, $M_{\rm BH}$. We see that for an assumed range of $M_{\rm LIM}$ of 25 ± 10 $M_\odot$ and $M_{\rm BH}$ of $40 \pm 15\ M_\odot$ the full range of the mean ^{22}Ne and ^{20}Ne mass fractions is 0.0063 ± 0.0008 and 0.0056 ± 0.018, respectively.

range of variation over the full range of roughly $\pm 10\%$ in the mean $^{22}\mathrm{Ne}_{\mathrm{ej}}$ mass fraction of 0.0063 ± 0.0008, dominated by the W-R wind yields. The corresponding range for $^{20}\mathrm{Ne}_{\mathrm{ej}}$ mass fraction 0.0056 ± 0.0018, on the other hand, has a much larger variation of roughly $\pm 40\%$ because it is dominated by the mean SN II yields, which are strongly dependent on M_{LIM}. As we show below, however, the large uncertainties in the ejecta $^{20}\mathrm{Ne}$ mass fraction do not significantly affect the overall $^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$ ratio in either the superbubble cores or the cosmic rays, since these ratios are basically determined only by the $^{20}\mathrm{Ne}$ in the older ISM and the $^{22}\mathrm{Ne}$ in the ejecta. Thus, these ratios are quite robust and depend only weakly on the uncertainties in the limiting masses for W-R and black hole commencement.

In our model (Higdon et al. 1998) of a superbubble origin for the bulk of the Galactic cosmic rays, supernova shocks accelerate cosmic rays out from the hot, tenuous superbubble medium, which includes the highly metal-enriched stellar winds and supernova ejecta dispersed and mixed with older interstellar debris of much lower metallicity from clumps of overrun molecular clouds, at early times (<4 Myr), produced by photoevaporating clouds created by the intense UV flux of young massive stars (McKee, van Buren, & Lazareff 1984), and at later times, from mass stripping (Arthur & Henney 1996) of swept-up diffuse clouds. In the most detailed study available of supernova-driven mixing and dispersal of interstellar inhomogeneities, de Avillez & Mac Low (2002) found that (1) the mixing times initially decrease with an increasing supernova rate but saturate at high supernova rates, (2) the mixing times have a weak dependence on spatial scales, and (3) the mixing times were long, of the order of tens of Myr or more.

However, de Avillez & Mac Low (2002) investigated the supernova-driven dispersal of preexisting inhomogeneities. What is relevant here is supernova-driven dispersal (and not necessarily mixing) of inhomogeneities, created by the supernovae themselves and their stellar precursors. The spatial dispersion of the OB stars in an association, the scale size of the W-R winds, and the reach of the supernova shocks are all roughly of the same size, of the order of 100 pc, so that the winds and ejecta are continually dispersed by interacting supernova shocks. The initial stellar velocities $\leq 5\ \mathrm{km\ s^{-1}}$ (e.g., Blaauw 1991) of the massive stars, created in a gravitationally unbound parent OB association, lead to a random dispersion of $\leq 10^2$ pc in the locations of most of the subsequent W-R winds and core-collapse supernovae in superbubble interiors. These winds also intermingle, expanding out to $\leq 10^2$ pc (e.g., Koo & McKee 1992). Finally, the core-collapse supernova remnants and their shocks also expand out to radii of the order of $\sim 10^2$ pc (e.g., Higdon et al. 1999) in the hot, low-density superbubble interiors of $\sim 10^{-3}\ \mathrm{H\ cm^{-3}}$, so that they further overlap with both the winds and other supernova remnants to continuously disperse the wind and ejecta in the cores of the superbubbles. These cores are much smaller than the ~ 700 pc size of large superbubbles (e.g., Higdon et al. 1998).

Thus, most of the core-collapse supernovae and their supernova shocks are contained within the cores of the superbubbles, so most of the cosmic rays should also be accelerated by their shocks in the high-metallicity medium of these metal-enriched cores. However, the processes by which wind and supernova ejecta are dispersed in superbubble cores await detailed numerical simulations. Consequently, in the remainder of this study we will treat the simplest measure of this complex dispersal process, the ratio of the mass of wind and ejecta containing the freshly synthesized elements to the mass of old interstellar debris as a parameter to be determined by model comparisons to observations.

4.2. *Mass and Metallicity of Wolf-Rayet Winds and Supernova Ejecta*

We also need to calculate the mean mass and metallicity of the combined W-R winds and supernova ejecta, which, as we show below, are important factors in determining the $^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$ ratios in the superbubble cores and the cosmic rays resulting from dilution by older ISM. The amount of this dilution can be characterized most easily by either the ejecta mass fraction or the metallicity of the mix. Thus, we carry out integrations not only of the total ejecta mass, as mentioned above, but also of the total mass of metals (atomic mass greater than 4) ejected in the winds and supernovae. Using the calculated masses for W-R stars (Schaller et al. 1992; Schaerer et al. 1993; interpolated for the present ISM metallicity), SNe II (Woosley & Weaver 1995), and SNe Ibc (Woosley et al. 1995), we do integrations for the same range of M_{LIM} and M_{BH}. The resulting range of variation in the mean total ejecta mass is shown in the top panel of Figure 4, and that for the mean ejecta metallicity, determined by the ratio of the metal and ejecta masses, is shown in the bottom panel of Figure 4. We see that over the assumed range of M_{LIM} of $25 \pm 10\ M_\odot$ and M_{BH} of $40 \pm 15\ M_\odot$ the total ejecta mass per supernova varies by roughly $\pm 20\%$, with a mean value of $11 \pm 2\ M_\odot$. The range of uncertainty in the mean ejecta mass results from the uncertainty in the onset of formation of black holes that consume potential supernova ejecta. The mean ejecta metallicity varies by roughly the same percentage for the same reason, with a mean value of 0.18 ± 0.02, or 9 ± 1 times solar.

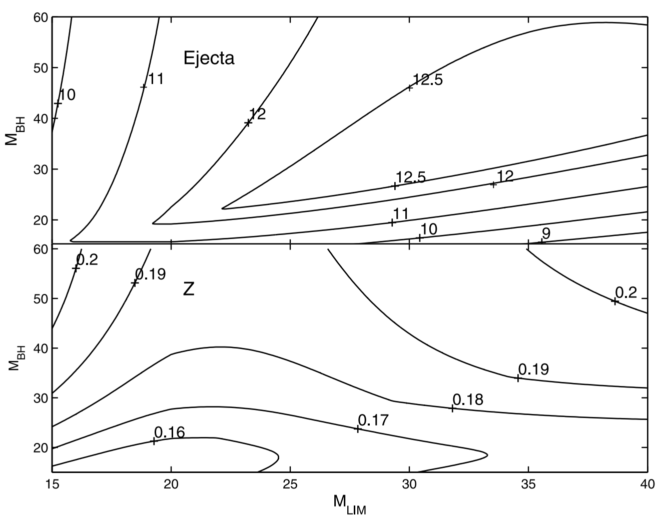

FIG. 4.—Mean ejecta mass and metallicity in the combined SN II and SN Ibc ejecta and W-R winds, averaged over the time span of core-collapse supernova explosions in a superbubble for a wide range of values of the lower limiting masses for the onset of W-R winds, M_{LIM}, and the formation of black holes, M_{BH}. We see that for an assumed range of M_{LIM} of $25 \pm 10\ M_\odot$ and M_{BH} of $40 \pm 15\ M_\odot$ the full range of the mean ejecta mass per supernova is $11 \pm 2\ M_\odot$, and the mean ejecta metallicity is 0.18 ± 0.03, or 9 ± 1 times solar.

4.3. *Neon Isotopes in the Present Interstellar Medium*

Since the ^{22}Ne and ^{20}Ne in the winds and ejecta are diluted by the neon isotopes in the gas evaporated from molecular clouds and the swept-up ISM surrounding the superbubble, we would also like to know the neon isotope ratio in the present ISM. We would expect modest evolution of the neon isotopes in the ISM since the formation of the solar system. But since the relative overabundance of ^{22}Ne in the cosmic rays is so large, namely 5 times the solar wind value, we do not expect that the difference between the neon isotope ratios in the present ISM and in the solar wind is significant by comparison. Thus, in the following calculations, we simply assume that the ^{22}Ne/^{20}Ne ratio in the present ISM is the same as the solar wind value of 0.073 (e.g., Anders & Grevesse 1989). We also assume that the mass fractions of the neon isotopes in the present ISM are 1.32 times the solar values, being proportional to the overall ISM metallicity.

4.4. *Neon Isotopes in Superbubbles*

From the mean neon abundances calculated for the accumulated W-R winds and supernova ejecta and those assumed for the current ISM, we calculate the ^{22}Ne/^{20}Ne abundance ratio expected in the hot, tenuous medium in the superbubbles, as a function of their mean metallicity resulting from dispersal with older interstellar debris. Here we assume for simplicity that the diluting mass of the old ISM in a supernova-active, superbubble core is proportional to the accumulated mass of the W-R winds and supernova ejecta as a function of time, so there is a single mean mass fraction of W-R wind and supernova ejecta, $f_{\rm ej}$, relative to the accumulated mass of gas and dust in the superbubble core independent of time. This also leads to a single mean superbubble core metallicity, $Z_{\rm sb}$, that can be compared with other studies. This mean superbubble core metallicity is thus a simple mix of the mean metallicities of the old ISM and the fresh W-R winds and supernova ejecta, i.e.,

$$Z_{\rm sb} = Z_{\rm ISM}\left(1 - f_{\rm ej}\right) + f_{\rm ej} Z_{\rm ej} \; , \qquad (9)$$

where $Z_{\rm sb}$ is expressed relative to solar metallicity, the mean metallicity of the present ISM, $Z_{\rm ISM}$, is roughly 1.32 times solar, as discussed above, and the mean metallicity, $Z_{\rm ej}$, of the combined W-R wind and supernova ejecta is 9 ± 1 times solar, averaged over the Salpeter IMF for wind and ejecta with the range of limiting masses for W-R wind commencement and black hole formation considered above (Fig. 4, *bottom panel*). These values give $Z_{\rm sb} = 1.3 + (7.7 \pm 1.0) f_{\rm ej}$.

Similarly, the cosmic rays accelerated in the superbubble would also be drawn from a simple mix of the two components, so that the mean mass fraction of each neon isotope in the superbubble core, $(f_{\rm Ne})_{\rm sb}$, relative to the accumulated mass of gas and dust in the superbubble core, is the mix of the mean neon isotope mass fractions in the wind ejecta and ISM components, weighted by the relative mass fractions of the two components, i.e.,

$$(f_{\rm Ne})_{\rm sb} = (f_{\rm Ne})_{\rm ISM} + f_{\rm ej}\left[(f_{\rm Ne})_{\rm ej} - (f_{\rm Ne})_{\rm ISM}\right] \; , \qquad (10)$$

or, written in terms of the mean superbubble core metallicity,

$$(f_{\rm Ne})_{\rm sb} = (f_{\rm Ne})_{\rm ISM} + \left[(f_{\rm Ne})_{\rm ej} - (f_{\rm Ne})_{\rm ISM}\right]\left[\frac{(Z_{\rm sb} - Z_{\rm ISM})}{(Z_{\rm ej} - Z_{\rm ISM})}\right] . \qquad (11)$$

Therefore, the mean (^{22}Ne/^{20}Ne) isotope ratio in the superbubble cores is

$$\left(\frac{^{22}\rm Ne}{^{20}\rm Ne}\right)_{\rm sb} = \frac{20}{22}\,\frac{(f_{^{22}\rm Ne})_{\rm sb}}{(f_{^{20}\rm Ne})_{\rm sb}} \; . \qquad (12)$$

Thus, taking the interstellar and wind ejecta metallicities of 1.32 and 9 ± 1 times solar, together with the mean neon isotope mass fractions in the present ISM of $(f_{^{20}\rm Ne})_{\rm ISM} = 2.13 \times 10^{-3}$ and $(f_{^{22}\rm Ne})_{\rm ISM} = 1.72 \times 10^{-4}$ from Anders & Grevesse (1989) solar values scaled by the present metallicity, and the mean, supernova rate–weighted, wind ejecta mass fractions $(f_{^{20}\rm Ne})_{\rm ej} = (5.6 \pm 1.8) \times 10^{-3}$ and $(f_{^{22}\rm Ne})_{\rm ej} = (6.3 \pm 0.8) \times 10^{-3}$, determined from the range of mean Ne and ejecta masses, calculated above, we have a time-averaged mean neon isotope ratio in the supernova-active cores of superbubbles,

$$\left(\frac{^{22}\rm Ne}{^{20}\rm Ne}\right)_{\rm sb} = \frac{(5.5 \pm 0.7) f_{\rm ej} + 0.16}{(3.5 \pm 1.8) f_{\rm ej} + 2.1} \; . \qquad (13)$$

As can be seen from these equations, the (^{22}Ne/^{20}Ne)$_{\rm sb}$ ratio in supernova-active superbubble cores is basically determined by the wind and ejecta abundance of ^{22}Ne and the older ISM abundance of ^{20}Ne because the wind and ejecta abundance of ^{20}Ne and the older ISM abundance of ^{22}Ne are small by comparison.

5. ^{22}Ne AND ^{20}Ne ABUNDANCES IN THE COSMIC RAYS

Using observations of the fraction of Galactic supernovae that are core-collapse supernovae and the fraction of those that occur in the superbubble phase of the ISM, together with the filling factor of that medium, we can now calculate the expected abundance ratios of the neon isotopes in the local cosmic rays. We would not expect any significant isotopic fractionation in the neon isotopes between the source ratio and the accelerated cosmic-ray ratio from either the first ionization potential or the volatility injection mechanisms.

Observations of supernovae show (e.g., van den Bergh & McClure 1994) that core-collapse (SNe II and SNe Ibc) supernovae of relatively young (<35 Myr) massive O and B stars make up the major fraction $f_{\rm cc} = 85\% \pm 5\%$ of the supernovae in our Galaxy, and the remainder are thermonuclear explosions (SNe Ia) of much older white dwarfs accreting from binary companions. Van Dyk, Hamuy, & Filippenko (1996) found that a major fraction, ~70%, of the core-collapse supernovae in late-type galaxies were located within the boundaries of giant H II regions, as traced by Hα emission. In Higdon et al. (1998) we suggested that this fraction is actually a lower limit on the fraction of associated supernovae, since their Hα threshold would resolve only ~76% of H II regions in late galaxies, when the H II luminosity distributions of Kennicutt, Edgar, & Hodge (1989) were employed. Moreover, all but three of the H II regions resolved by van Dyk et al. (1996) were more luminous than the present-day Orion Nebula, whose previous generations of massive stars created (e.g., Heiles 2000) the Eridanus superbubble. Since only a few (≤ 5) correlated supernova explosions are needed (Tenorio-Tagle 1996) to create an expanding superbubble, we suggest that the great bulk, $f_{ccsb} \sim 90\% \pm 10\%$, of core-collapse supernovae occur in superbubbles.

The filling factor of the superbubble, hot phase of the ISM is dependent on Galactic location. Based on H I surveys of the northern sky, Heiles (1980) estimated that the filling factor of superbubbles is between 10% and 20%, and McKee (1993) investigated the effects of correlated supernovae and suggested that the Galactic average superbubble filling factor is a modest 10%. Locally ($\sim$1 kpc), however, Heiles (2000) has found that superbubbles are so numerous that they interact with each other, filling such a large volume that the local ISM is, in fact, superbubble dominated.[3] The concentration of superbubbles in the local ($\leq$1 kpc) ISM can affect significantly the source of cosmic rays. In a Monte Carlo simulation of cosmic-ray propagation, we (Higdon & Lingenfelter 2003) found that more than 70% of the cosmic rays measured at Earth were accelerated by supernovae within 1 kpc of Earth, if the cosmic-ray scattering mean free path is $\leq$0.3 pc. Such a scattering mean path reproduces well (Higdon & Lingenfelter 2003) measurements of the cosmic-ray secondary to primary ratios (Yanasak et al. 2001). Depending on the relative contribution of local ($\leq$1 kpc) correlated supernovae, the volume filling factor of hot tenuous plasmas in superbubble interiors is $f_{hsb} = 40\% \pm 30\%$.

Moreover, even with a large uncertainty in the local filling factor of the superbubble, hot phase of the ISM, $f_{hsb} \sim 40\% \pm 30\%$, a significant fraction of local ($\leq$1 kpc) thermonuclear supernovae can also occur within the superbubbles just by chance. Thus, with a core-collapse supernova fraction of $f_{cc} = 85\% \pm 5\%$, we see that the major fraction, $f_{cc} f_{ccsb} + f_{hsb}(1 - f_{cc}) = 83\% \pm 11\%$, of all Galactic supernovae occur in the superbubble, hot phase of the ISM, and only about $17\% \pm 11\%$ occur in the rest of the ISM. Moreover, since the shock acceleration efficiency is expected (e.g., Axford 1981) to be much higher in the low-density superbubbles, where energy losses are much lower than in the average ISM, $(dE/dt)_{sb} < 10^{-2}(dE/dt)_{ISM}$, an even larger fraction of the cosmic rays should be accelerated by supernova shocks in the superbubbles.

For a conservative estimate, however, we will assume that the cosmic-ray shock acceleration efficiencies are equal in the superbubbles and the average ISM and calculate the cosmic-ray neon isotope abundances for the mix of source abundances weighted by the relative supernova rates. Thus, the mean abundance ratios of the neon isotopes in the local cosmic rays result from the mix of acceleration sites and supernova types. With core-collapse (SNe II/Ibc) supernovae making up a fraction f_{cc} of the supernovae in the Galaxy and a fraction f_{ccsb} of these occurring in superbubbles, which have a local filling factor f_{hsb}, the mean neon isotope fractions in the local cosmic rays should be

$$(f_{Ne})_{cr} = (f_{Ne})_{ISM} + \left[(f_{Ne})_{ccsb} - (f_{Ne})_{ISM}\right] \times \left[f_{cc} f_{ccsb} + (1 - f_{cc}) f_{hsb}\right] , \quad (14)$$

or

$$(f_{Ne})_{cr} = (f_{Ne})_{ISM} + f_{ej}\left[(f_{Ne})_{ej} - (f_{Ne})_{ISM}\right] \times \left[f_{cc} f_{ccsb} + (1 - f_{cc}) f_{hsb}\right] . \quad (15)$$

Again taking the interstellar and wind ejecta metallicities together with the mean neon isotope mass fractions in the present ISM and in the W-R wind and ejecta, as well as in the ISM of 0.073, we have a time-averaged mean neon isotope ratio in the local cosmic rays of

$$\left(\frac{^{22}\mathrm{Ne}}{^{20}\mathrm{Ne}}\right)_{cr} = \frac{(4.6 \pm 0.9) f_{ej} + 0.16}{(2.9 \pm 1.5) f_{ej} + 2.1} . \quad (16)$$

Thus, we see from this relationship that the cosmic-ray source abundance ratio of $(^{22}\mathrm{Ne}/^{20}\mathrm{Ne})_{cr} = 0.366 \pm 0.015$, determined (Binns et al. 2001) from the *ACE*/CRIS measurements, can be easily understood as the result of cosmic rays accelerated primarily out of superbubbles with a mean wind and ejecta mass fraction, $f_{ej} = 18\% \pm 5\%$, which corresponds to a mean superbubble metallicity, $Z_{sb} = 2.7 \pm 0.4$ times solar.

This metallicity is quite consistent with the value of the mean superbubble core metallicity found from Li, Be, and B abundances in old halo stars in our Galaxy. In particular, the mean metallicity of superbubble cores has been determined from modelling of the extensive measurements of Li, Be, and B abundances in early stars, which show that these elements have roughly constant (within about $\pm 30\%$) abundances relative to O and Fe in stars whose O/H and Fe/H ratios range from about 10^{-3} to 1 times the solar ratios (e.g., Ramaty et al. 1997; Alibes, Labay, & Canal 2002). This implies that, if these elements are produced primarily by cosmic-ray spallation, as has long been thought since Reeves, Fowler, & Hoyle (1970), then the cosmic rays must be accelerated out of gas and dust with a mean metallicity of 2, or more, times solar, so that the cosmic-ray metallicity does not change by more than about a factor of 2 over the age of the Galaxy. Recent analyses (Alibes et al. 2002) show that the LiBeB evolution can be fitted with cosmic rays accelerated from superbubble cores having mean supernova ejecta mass fractions, f_{ej}, between 12% and 41%, with a best-fit value of 25%. These mass fractions correspond to a mean Galactic superbubble core metallicity of 3.3 ± 1.2 times solar, assuming a current interstellar metallicity of 1.3 times solar and a mean ejecta metallicity of 9 ± 1 times solar.

There is a significant gradient between the inner cores, enriched by W-R winds and supernova ejecta, and the outer regions of the superbubbles, dominated by swept-up interstellar gas. There is a suggestion of such a gradient in the low-energy "anomalous cosmic rays" thought to be neutral gas from the local ISM that has penetrated into the heliosphere where it was ionized and accelerated (Fisk, Kozlovsky, & Ramaty 1974). The measured $^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$ ratio in these anomalous cosmic rays is only 0.08 ± 0.03 (Leske et al. 1996; Binns et al. 2000), or 1.1 ± 0.4 times the solar system ratio, compared to the local Galactic cosmic-ray $^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$ ratio of 5 times the solar system ratio (Binns et al. 2001). Although the Sun is currently in a superbubble

[3] Heiles (2000) suggests that the local superbubble filling factor was underestimated in the past, because prior H I analyses did not include the fourth Galactic quadrant, which is dominated by local superbubbles, and the occurrence of superbubbles is correlated, where superbubble shocks trigger new generations of massive star formation.

complex (Heiles 2000), this difference between the neon ratios is not surprising, however, since the Sun is not in a supernova-active core. Consequently, we should not necessarily expect the local neutral gas to be highly enriched, even if it is swept up, compressed, and cooled from the local hot plasma. Still, we cannot be certain that the local plasma is not enriched because the neutral gas sampled by the anomalous cosmic rays may simply be in an older interstellar cloud overrun by the expanding local superbubble.

6. SUMMARY

The abundances of the neon isotopes in the cosmic rays can provide critical constraints on the major sites of their acceleration. Using recent calculations of the W-R winds and supernova yields, we have determined the neon isotope abundances averaged over the lifetime of cosmic-ray accelerating supernova explosions in superbubbles. We have then calculated the ^{22}Ne/^{20}Ne abundances expected in the hot, tenuous cores of superbubbles, as a function of their mean metallicity resulting from dilution with the surrounding ISM. Finally, using observations of the relative fractions of Galactic supernovae that occur in superbubbles and other phases of the ISM, we calculate the expected neon isotope abundances in cosmic rays accelerated by all of the Galactic supernovae. We find that the cosmic-ray source abundance ratio of $(^{22}\mathrm{Ne}/^{20}\mathrm{Ne})_{\mathrm{cr}} = 0.366 \pm 0.015$, determined (Binns et al. 2001) from the *ACE*/CRIS measurements, can be easily understood as the result of cosmic rays accelerated primarily out of supernova-active superbubble cores with a mean metallicity $Z_{\mathrm{sb}} = 2.7 \pm 0.4$ times solar, or a mean wind and ejecta mass fraction of $18\% \pm 5\%$. This value is quite robust, since it allows for large uncertainties in the filling factor of the superbubble, hot phase of the local ISM, $f_{\mathrm{hsb}} \sim 40\% \pm 30\%$, and in the lower limiting masses for the onset of W-R winds, $M_{\mathrm{LIM}} \sim 25 \pm 10\ M_{\odot}$, and the formation of black holes, $M_{\mathrm{BH}} \sim 40 \pm 15\ M_{\odot}$. The mean metallicity implied by the cosmic-ray ^{22}Ne/^{20}Ne ratio is also quite consistent with values of the mean superbubble metallicity determined from other observations. Thus, it provides strong, additional evidence for a superbubble origin of the bulk of the cosmic rays.

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