Superbubbles, Wolf-Rayet stars, and the origin of galactic cosmic rays

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Abstract. The abundances of neon and several other isotopic ratios in the galactic cosmic rays (GCRs) have been measured using data from the Cosmic Ray Isotope Spectrometer (CRIS) aboard the Advanced Composition Explorer (ACE). We have derived the $^{22}Ne/^{20}Ne$ ratio at the cosmic-ray source using the measured ^{21}Ne, ^{19}F, and ^{17}O abundances as "tracers" of secondary isotope production. Using this approach, the $^{22}Ne/^{20}Ne$ abundance ratio obtained for the cosmic-ray source is 0.387 ± 0.007 (stat.) ± 0.022 (syst.). This corresponds to an enhancement by a factor of 5.3±0.3 over the $^{22}Ne/^{20}Ne$ ratio in the solar wind. We compare our data for neon and refractory isotope ratios, and data from other experiments, with recent results from two-component Wolf-Rayet (WR) models. The three largest deviations of GCR isotope ratios from solar-system ratios predicted by these models, $^{12}C/^{16}O$, $^{22}Ne/^{20}Ne$, and $^{58}Fe/^{56}Fe$, are present in the GCRs. In fact, all of the isotope ratios that we have measured are consistent with a GCR source consisting of about 80% material with solar-system composition and about 20% of WR material. Since WR stars are evolutionary products of O and B stars, and most OB stars exist in OB associations that form superbubbles, the good agreement of these data with WR models suggests that superbubbles are the likely source of at least a substantial fraction of GCRs.

Key words: Galactic cosmic rays—Galaxy: stars—Wolf-Rayet: general—Galaxy:abundances—Galaxy: ISM—ISM: abundances—ISM: Galactic Cosmic Rays

1. Introduction

A number of experiments have shown that the $^{22}Ne/^{20}Ne$ ratio at the GCR source is substantially greater than that in the solar wind (Maehl et al. 1975; Garcia-Munoz, Simpson, & Wefel 1979; Wiedenbeck & Greiner 1981; Mewaldt et al. 1980; Lukasiak et al. 1994; Webber et al. 1997; Connell & Simpson 1997; DuVernois et al. 1996). Several models have been proposed to explain the large $^{22}Ne/^{20}Ne$

ratio (Woosley and Weaver 1981, Reeves 1978, Olive and Schramm 1982, Cassé and Paul 1982, Prantzos et al. 1987, Maeder and Meynet 1993, Soutoul and Legrain 1999 & 2000, and Higdon and Lingenfelter 2003). The mechanism most widely accepted for producing the neon ratio excess was first introduced by Cassé and Paul (1982) and was studied in more detail by Prantzos et al. (1987). They suggested that the large ^{22}Ne/^{20}Ne ratio in GCRs could result from Wolf-Rayet (WR) star ejecta mixed with material of solar-system composition. The WC phase (Maeder and Meynet 1993) of WR stars is characterized by the enrichment of the wind from He-burning products, especially carbon and oxygen. Also, in the early part of the He-burning phase, ^{22}Ne is strongly enhanced as a result of ^{14}N destruction (e.g. Prantzos et al. 1986; Maeder and Meynet 1993) through the α-capture reactions $^{14}N(\alpha,\gamma)^{18}F(e^{+}\nu)^{18}O(\alpha,\gamma)^{22}Ne$. An excess of the elemental Ne/He ratio in the winds of WC stars has been confirmed observationally (Dessart et al. 2000), which is consistent with a large ^{22}Ne excess, and gives support to the idea of Cassé and Paul (1982). The high velocity winds that are characteristic of WR stars can inject the surface material into regions where standing shocks, formed by those winds and the winds of the hot, young, precursor OB stars interacting with the interstellar medium (ISM), can pre-accelerate the WR material.

Acceleration and confinement of cosmic rays in superbubbles was originally suggested by Kafatos et al. (1981). Streitmatter et al. (1985) showed that the observed energy spectra and anisotropy of cosmic rays were consistent with such a model. Recently they have shown that the first and second “knees” above $\sim 10^{15}$ and 10^{17} eV in the all-particle energy spectrum may be explained in the context of a superbubble model (Streitmatter & Jones, 2005). Higdon and Lingenfelter (2003) have argued that GCRs originate in superbubbles based on the ^{22}Ne/^{20}Ne excess in GCRs. This expands on their initial work, in which they point out that most core-collapse SNe and WR stars occur within superbubbles (Higdon et al. 1998). In their model, WR star ejecta and ejecta from core-collapse SNe occurring within superbubbles are mixed with ISM material of solar-system composition and accelerated by subsequent SN shocks within the superbubble to provide the bulk of the GCRs. The calculations of Schaller et al. (1992) and Woosley & Weaver (1995) are utilized to estimate the yields of ^{20}Ne and ^{22}Ne from WR stars and core-collapse SN. Higdon & Lingenfelter conclude that the elevated ^{22}Ne/^{20}Ne ratio is a natural consequence of the superbubble origin of GCRs since most WR stars exist in OB associations.

In this paper our measurements of the isotopic composition of neon and other heavier refractory isotopes, and measurements from other experiments, are compared with recent WR model calculations. These results are then considered in the context of a possible superbubble origin of GCRs (Higdon & Lingenfelter 2003).

2. Measurements

The CRIS instrument (Stone et al. 1998) consists of four stacks of silicon solid-state detectors to measure dE/dx and total energy (E_{tot}), and a scintillating-fiber hodoscope to measure trajectory. The dE/dx-E_{tot} method is used to determine particle charge and mass. The geometrical factor of the instrument is ~250 cm^{2}sr and the total vertical thickness of silicon for which particle mass can be determined is 4.2 cm. The precision with which angle is measured by the fiber hodoscope is ≤ 0.1°.

Figure 1a-g shows the CRIS neon data in 7 range bins and Figure 1h shows the sum of all events. These data were collected from 1997 December 5 through 1999 September 24 and are a selected, high-resolution data set. These events are selected to have trajectory angles ≤25° relative to the normal to the detector surfaces, and particles stopping within 750 μm of the single surface of each silicon wafer having a significant dead layer were excluded from this analysis. Nuclei that interacted in the instrument were identified and rejected by requiring no signal in the bottom silicon anticoincidence detector, requiring consistency in charge estimates obtained using different combinations of silicon detectors for events penetrating beyond the second detector in the silicon stack, and by rejecting particles with trajectories that exit through the side of a silicon stack. The average mass resolution for neon is 0.15 amu (rms) which is sufficiently good that there is only a slight overlap of the particle distributions for adjacent masses. In Figure 1, the total number of neon events is $\sim 4.6 \times 10^4$.

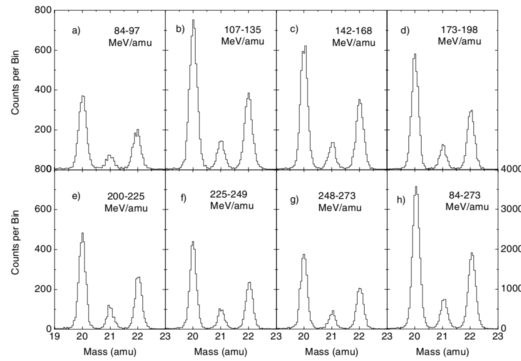

Figure 1. Histograms of neon isotopes by range (ranges 2 to 8 corresponding to panels a) to g), and the sum of all events is given in panel h).

The final corrected ratios are plotted in Figure 2 as a function of energy and are also compared with measurements made by other experiments. The uncertainties plotted for the individual detector ranges are statistical only. The GCR $^{22}Ne/^{20}Ne$ ratio that we obtain is nearly independent of energy with a small increase with energy. The measured ratios reported from those experiments (Wiedenbeck & Greiner 1981 [ISEE-3]; Webber et al. 1997 [Voyager]; Connell & Simpson 1997 [Ulysses]; DuVernois et al. 1996 [CRRES]) are plotted as open symbols and the agreement of our CRIS measurements with the other experiments is generally good. The mean levels of modulation for the Voyager and Ulysses measurements were similar to that of our CRIS measurement, although the Voyager data were taken over a wide range of modulation levels. Although ISEE-3 and CRRES measurements were at a different modulation, the effect of that difference is within the statistical uncertainty of their measurements. Therefore the ratios from these experiments have not been adjusted for differing solar modulation. The energy range corresponding to each of the experiments is shown as a horizontal bar at the bottom of Figure 2. The CRIS measurements have sufficient statistics to obtain, for the first time, energy spectra of the neon isotopes over this energy range.

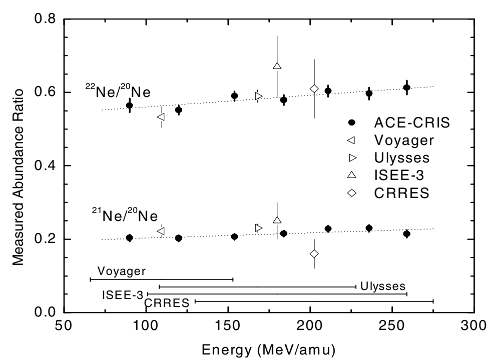

Figure 2. Our measurements of the isotope ratios $^{22}Ne/^{20}Ne$ and $^{21}Ne/^{20}Ne$ at the top of the CRIS instrument are plotted as a function of energy. The dotted lines are least squares fits to our data. Abundances measured by other experiments (see text for references) are plotted as open symbols. The energy intervals for their measurements are shown as horizontal bars at the bottom of the figure.

3. Source composition

To obtain the ^{22}Ne/^{20}Ne abundance ratio at the comic-ray source from the ratio observed, we used the "tracer method" of Stone and Wiedenbeck (1979), which uses observed abundances of isotopes that are almost entirely secondary to infer the secondary contribution to isotopes like ^{22}Ne, for which the observed fluxes are a mixture of primary and secondary nuclei. ^{21}Ne, ^{19}F, and ^{17}O are the "tracer" isotopes that we have used in this analysis. We have used cross-sections from accelerator measurements to estimate cross-sections for some of the most important reactions in the propagation. For all other reactions, the Silberberg et al. (1998) cross-sections, scaled to measured data when available, were used (Binns et al. 2005).

Combining the results derived using the three tracer isotopes in this analysis gives an overall ^{22}Ne/^{20}Ne ratio of 0.387 ± 0.007 (stat.) ± 0.022 (syst.). This corresponds to a ratio relative to the solar wind, which is 0.0730±0.0016 (Geiss, 1973), of $(^{22}\mathrm{Ne}/^{20}\mathrm{Ne})_{GCRS}/(^{22}\mathrm{Ne}/^{20}\mathrm{Ne})_{SW} = 5.3 \pm 0.3$. (See Binns et al. 2005 for more details on the source abundance estimates and error analysis.)

4. Discussion

Supernovae shocks are believed to be the accelerators of GCRs for energies <~10^{15} eV. Most of the core-collapse SNe in our galaxy (~90%) are believed to occur in OB associations that form superbubbles (Higdon et al. 1998; Higdon & Lingenfelter, 2003). Likewise, most WR stars are observed in OB associations and many of their O and B star constituents are expected to evolve into WR stars (Knödlseder et al. 2002; Maeder, 2000). Two dimensional modeling calculations have been performed for 35-$M_\odot$ OB stars in ISM from star formation through the WR phase (Van Marle, et al. 2005). These calculations show that winds of the hot, young, OB stars blow bubbles in the ISM with radius ~40 pc. This is followed by a burst of high velocity winds when the star enters the WR phase, and finally the star evolves into a core-collapse SN. The lifetime of these massive stars is short, typically a few million years, and the time spent in the WR phase is typically a few hundred thousand years (Meynet & Maeder 2003). It therefore seems almost certain that pre-supernova WR wind material will be swept up and accelerated either by the SN shock from the evolved WR star that ejected the material in the first place or by nearby SNe resulting from short-lived massive O and B stars. Approximately 10^{-4}-10^{-5} solar masses of material per year is ejected from individual WR stars in high velocity winds (Nugis and Lamers 2000). There are two primary successive phases of WR stars, the WN and WC phases (Maeder and Meynet 1993). Large quantities of He-burning material enriched in ^{22}Ne are expelled from the stars when they are in the WC phase, resulting in ^{22}Ne/^{20}Ne ratios in the wind material that are enhanced by about two orders of magnitude over solar-system abundances. CNO processed material is ejected in the WN phase with the resultant production of high ^{13}C/^{12}C and ^{14}N/^{16}O ratios, but no significant increase in the ^{22}Ne/^{20}Ne ratio (Prantzos et al. 1987; Maeder & Meynet 1993).

Higdon and Lingenfelter (2003) have calculated the mass of the neon isotopes synthesized and ejected in superbubbles by massive stars in their WR and core-collapse SN phases, and then modeled the mean ^{22}Ne/^{20}Ne ratio within the superbubble as a function of the mixing fraction with old ISM taken from Anders and Grevesse (1989) adjusted for the present-day ISM metallicity. They estimate that a mass fraction, f_{ej}=(18±5)%, of WR plus SN ejecta must be mixed with ISM material of solar-system composition in the superbubble core in order to obtain the ^{22}Ne/^{20}Ne ratio that we reported in a preliminary analysis of the CRIS results (Binns et al. 2001), which is very close to the final results reported here (f_{ej} is defined as the mass fraction of WR plus SN ejecta summed over all elements. In their calculation, most of the ^{22}Ne comes from the WR outflows, not the SN ejecta. Higdon and Lingenfelter conclude that "the ^{22}Ne abundance in the GCRs is not anomalous but is a natural consequence of the superbubble origin of GCRs in which the bulk of GCRs are accelerated by SN shocks in the high-metallicity, WR wind and SN ejecta enriched, interiors of superbubbles". In addition, they assert that the measured value of the ^{22}Ne/^{20}Ne ratio provides evidence for a superbubble origin of GCRs.

We have examined other isotope ratios at the cosmic-ray source, inferred from our CRIS observations and others, as an additional test of the superbubble model of the origin of cosmic rays. These ratios are then compared with modeling calculations of WR outflow that provide predictions of isotope ratios in addition to $^{22}Ne/^{20}Ne$. These model results do not include explicit core-collapse SN ejecta contributions to those ratios as was the case for the Higdon and Lingenfelter work on the neon isotopes described above.

We use here the models of Meynet and Maeder (2003) for massive stars with metallicity Z=0.02, and with rotational equatorial velocities at the surface on the Zero Age Main Sequence of either 0 or 300 km/s. The models with rotation give results consistent with the observed number ratio of WR to O-type stars in the solar neighborhood. They are also consistent with the observed ratio of type Ib/c to type II SNe, and for the existence of a small, but observable, fraction of WR stars with both H and He-burning products at their surface. This good agreement of the modeling results with observations is achieved not only for the rotating Z=0.02 models but also for different metallicities (Meynet and Maeder 2005). While these results do not pertain directly to the comparisons that we will make below, they do provide an independent validation of the rotating stellar models. The non-rotating models, however, have difficulties in reproducing the above observational constraints.

Based on these models, an extended nuclear reaction network is solved in order to follow the evolution of the abundances of the nuclides in the WR winds. We then calculate for each model star the amounts of each nuclide ejected in the wind between the Zero Age Main Sequence and the end of the WR phase. This mixture is referred to as the WR wind material.

For each WR model star, we find what mixture of WR outflow with material of solar-system (solar-wind) composition will give the $^{22}Ne/^{20}Ne$ ratio found by CRIS for the GCR source. The fraction (p) of WR material that is required for each case is shown in Table 1. The very large p values required for the rotating 85 and 120 $M_\odot$ stars relate to the fact that they have a very long WN phase. As a result of this, they lose enormous amounts of CNO processed material that is not ^{22}Ne-enriched. Except for these two cases, the mixing fractions in Table 2 are similar to that derived by Higdon and Lingenfelter (0.18±0.05) described above. The large p-values predicted for the $M \geq 85\ M_\odot$ stars are not a problem, however, since these very massive stars are expected to be much rarer than the lower mass ones if one adopts a Salpeter-type Initial Mass Function (IMF) (Salpeter 1955), which predicts that the number of stars born at each time with an initial mass M is proportional to $M^{-2.35}$.

WR Initial Mass ($M_\odot$)	No Rotation WR Fraction (p)	Rotation WR Fraction (p)
40	---	0.22
60	0.20	0.16
85	0.12	0.44
120	0.16	0.37

Table 1. The mass fraction of ejecta from WR stars required to normalize each model to the CRIS $^{22}Ne/^{20}Ne$ ratio. A non-rotating 40 $M_\odot$ initial mass star does not go through the WR phase.

The ratios of other isotopes that result from the WR mix with material of solar-system composition that are required to match the $^{22}Ne/^{20}Ne$ ratio are shown in Figure 3 for non-rotating and rotating models respectively. The results of these models are compared with the GCR source ratios inferred from CRIS and other observations. The plotted neon point (closed circle) is the source ratio inferred from our propagation described above. The points for heavier elements are also from CRIS results (Wiedenbeck et al. 2001a and 2003). Ulysses Mg and Si data (Connell and Simpson 1997) are in good agreement with our CRIS results, while their $^{58}Fe/^{56}Fe$ ratio (Connell 2001) is significantly lower than the CRIS value. A possible reason for this discrepancy for Fe has been suggested by Wiedenbeck et al. (2001b). We have not plotted their data point since the error bars are large. The solid diamonds plotted for the lighter elements are mean values of GCR source abundances, divided by the Lodders (2003) solar-system abundances, and weighted by their published uncertainties, obtained from Ulysses (Connell and Simpson 1997), ISEE-3 (Krombel and Wiedenbeck 1988; Wiedenbeck and Greiner 1981), Voyager (Lukasiak et al. 1994) and HEAO-C2 (Engelmann et al. 1990). The plotted error bars are weighted means from these experiments. The mean values are obtained from these experiments as follows: $^{12}C/^{16}O$—Ulysses and HEAO-C2 (note that these are actually element ratios that have not been corrected for the small fraction of neutron-rich C and O isotopes present at the source); $^{14}N/^{16}O$—ISEE-3, Voyager, and HEAO-C2; N/Ne—Ulysses and HEAO-C2. All ratios plotted here are relative to the Lodders (2003) solar-system abundances.

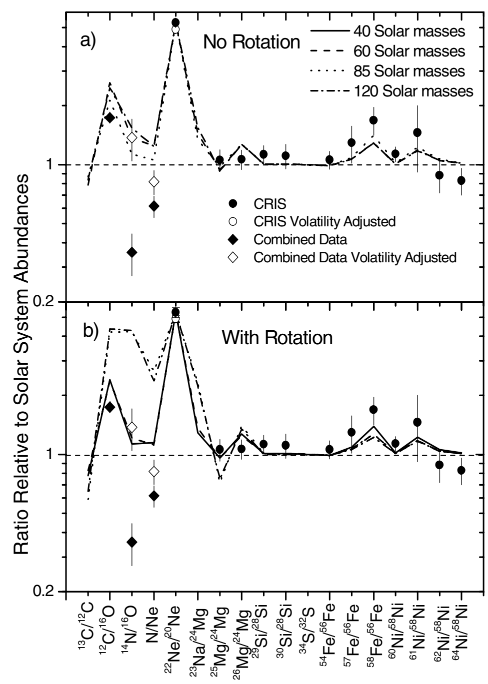

Figure 3. Comparison of CRIS data and data from other experiments with WR calculations.

For nuclei heavier than neon, we see that the WR models are in generally good agreement with data (within about 1.5 sigma), except for the high-mass (85 and 120 solar masses) rotating star models that predict a deficiency in the $^{25}Mg/^{24}Mg$ ratio, which is not observed. The observed enhancement of $^{58}Fe/^{56}Fe$ is roughly consistent with the enhancement of this ratio predicted by the models. The GCR data do not show any significant enhancement of the $^{26}Mg/^{24}Mg$, although the models do show some enhancement at the level of <1.5 standard deviations. Moreover, the cross-section used in the WR models for the reaction $^{22}Ne(\alpha,\gamma)^{26}Mg$ has a significant uncertainty (Angulo et al. 1999), and decreasing this cross-section within the range of its uncertainty brings the $^{26}Mg/^{24}Mg$ ratio into agreement with the GCR result.

For elements lighter than neon, there is usually only a single isotope for which source abundances can be obtained with precision sufficient to constrain the models. The ratios that we have compared are therefore for different elements. This makes comparisons more complicated since atomic fractionation effects may be important for some ratios. Comparing the plotted data for nuclei lighter than neon with modeling predictions, initially ignoring elemental fractionation effects, in Figures 3a and 3b the measured

$^{12}C/^{16}O$ source ratio is much larger than in the Solar System and is in qualitative agreement with the WR models for non-rotating stars, and rotating stars with initial masses of 40 and 60 $M_{\odot}$.

The measured $^{14}N/^{16}O$ ratio is, however, smaller by more than a factor of two than for the model calculations and for the Solar System. This small ratio cannot be caused by the simple mixing of WR material with solar-system abundances. It is likely that at least part of the explanation is elemental and mass fractionation of the GCR source material. Cassé & Goret (1978) recognized that elements with a low first-ionization potential (FIP) had a GCR source to solar-system abundance ratio that was substantially enhanced over those with a high-FIP. An alternative model (Epstein 1980; Cesarsky and Bibring 1981) suggested that since most of the elements with low-FIP for which GCR source abundances had been determined were refractory, while those with high-FIP were volatile, then the material of GCRs might preferentially originate in interstellar dust. More recent work by Meyer et al. (1997) and Ellison et al. (1997) has given support to a model in which the GCR fractionation is governed by volatility. The refractory elements are enriched in the GCRs, in this model, since they sputter off accelerated dust grains, and are thus more easily accelerated by SN shocks.

Although atomic or molecular oxygen is highly volatile, nearly a quarter of the oxygen in the ISM is believed to exist in refractory compounds (Lodders 2003). In the Meyer et al. and Ellison et al. models, the fraction of any element that exists as a refractory, whether in molecular or atomic state, should be preferentially injected into the GCRs. A significant but poorly known fraction of carbon, which is refractory in its elemental form, exists in the ISM as a volatile in molecules such as CO (Meyer et al. 1997). On the other hand, nitrogen exists primarily as a gas and neon exists entirely in the gas state. So both the $^{12}C/^{16}O$ and the $^{14}N/^{16}O$ GCR ratios should be corrected for this effect to have a strictly valid comparison.

We can make a rough adjustment to the $^{14}N/^{16}O$ ratio since the fraction of ^{14}N and ^{16}O that exists in the solid state in the pre-solar nebula has been estimated. According to Lodders (2003), 23% of oxygen in the pre-solar nebula is in the solid state. Meyer et al. (1997) show that the GCR source to solar-system abundance ratio for the refractory elements is approximately a factor of 13 larger than for nitrogen. In addition, even for volatile elements they point out that there appears to be a systematic enhancement in the abundance of heavy volatiles compared to light volatiles and they estimate the dependence of this enhancement on mass (A) as $A^{0.8\pm0.2}$. Assuming that the oxygen in grains are injected into the GCRs with an efficiency 13 times that of the gas phase fraction and, in addition, make an adjustment for the differing mass of ^{14}N and ^{16}O for the volatile oxygen fraction, then the $^{14}N/^{16}O$ GCR source ratio should be increased by a factor $(0.23\times13)+0.77\times(16/14)^{0.8}=3.85$ to obtain the ratio for the source material prior to acceleration. This adjusted ratio is plotted as an open diamond in Figure 3.

The $^{12}C/^{16}O$ ratio is more difficult to correct since the fraction of carbon that is in the solid state in the ISM is poorly known. Therefore we have not attempted this adjustment.

The effect of fractionation based on volatility should be reduced if we look at the ratio of elements such as N/Ne that exist almost entirely in the volatile state in the ISM. In Figure 3 we have plotted the measured N/Ne ratio as a solid diamond and see that it is nearly 40% lower than for solar-system abundances. The N/Ne ratio has been adjusted for the mass dependent enhancement and plotted as an open diamond in Figure 3. The $^{22}Ne/^{20}Ne$ ratio has also been adjusted for mass dependence and the adjusted ratio is plotted as an open circle.

After these adjustments are applied the $^{14}N/^{16}O$ and N/Ne ratios are in much better agreement with both the WR modeling results and solar system abundances. These adjusted ratios should be regarded as approximate values, however, showing that ratios previously thought to be inconsistent with solar-system abundances may very well be consistent if GCRs are properly fractionated on the basis of volatility and mass (Meyer et al. 1997; Ellison et al. 1997). Because these adjustments are model dependent in nature, the values quoted throughout the paper for the $^{22}Ne/^{20}Ne$ source ratio do not include this adjustment.

Although it might be argued that the hot superbubble interior does not provide a setting in which refractory elements can exist in the solid state, thereby making adjustments based on element volatility inconsistent with a superbubble origin of cosmic rays, in fact approximately 30% of WR stars are known to be dusty, although the formation of dust in this hot environment is not understood (Marchenko et al. 2002). Therefore the inclusion of fractionation based on volatility in a model of superbubble origin of cosmic rays appears to be reasonable.

After adjustments for elemental fractionation, we see that the CRIS data combined with those from other experiments show an isotopic composition that is very similar to the one obtained by mixing about 20% of WR wind material with about 80% of material of solar-system composition. The largest ratios predicted by the WR models (including fractionation adjustments where possible), $^{12}C/^{16}O$, $^{22}Ne/^{20}Ne$, and $^{58}Fe/^{56}Fe$ are in fact observed. All other measured ratios are in reasonable agreement with small or insignificant differences from WR model predictions. We take this agreement as evidence, in addition to that already obtained from previous measurements of the $^{22}Ne/^{20}Ne$ ratio (see references in section 2), that WR star ejecta is likely an important component of the cosmic-ray source material.

The WR models discussed above do not explicitly assume that the GCR origin is in superbubbles. However, the arguments made by Higdon and Lingenfelter (2003) that most WR stars reside in superbubbles, as do most core-collapse SNe, would appear to indicate that the predominant site of injection of WR material into the GCR source material is in superbubbles. A clear corollary to this conclusion is that the same shocks that accelerate the WR ejecta within the superbubble must also accelerate SN ejecta. Therefore the picture that emerges from these data alone is that superbubbles would appear to be the site of origin and acceleration of at least a substantial fraction of GCRs.

Recent discoveries of TeV γ-ray sources by the ground-based High Energy Gamma-Ray Astronomy (HEGRA) and High Energy Stereoscopic System (HESS) telescopes clearly indicates that cosmic-ray acceleration to high energies is occurring at those sites. Currently, a total of 15 TeV gamma-ray sources have been identified. A number of these have been shown to be spatially coincident with SNRs in our galaxy (Aharonian, et al. 2005a). In addition, three of these sources are spatially coincident with OB associations. The source TeV J2032+4130 is spatially coincident with Cygnus OB2 (Aharonian et al. 2005b), and HESS J1303-631 and PSR B1259-63/SS2883 are spatially coincident with Cen OB1 (Aharonian et al. 2005c). Furthermore, the Wolf-Rayet star θ-Mus is a member of this OB association (Aharonian et al. 2005c). In addition, HESS J1804-216 coincides spatially with SNR G8.7-0.1 "which is known to be associated with molecular gas where massive star formation is taking place" (Aharonian, et al. 2005a). These discoveries of sources of TeV γ-rays, some of which are spatially coincident with OB associations, strengthen our conclusion obtained from relatively low-energy galactic cosmic rays, that superbubbles are the source of at least a substantial fraction of galactic cosmic rays.

5. Summary

Our CRIS measurements have led to an improved value for the $^{22}Ne/^{20}Ne$ source abundance ratio that is a factor of 5.3±0.3 greater than for the solar wind. Comparing measurements from CRIS and from other experiments with stellar model predictions shows that for non-rotating and $M<85\ M_\odot$ rotating WR models, the three isotope ratios predicted to be most enhanced relative to the solar system, $^{12}C/^{16}O$, $^{22}Ne/^{20}Ne$, and $^{58}Fe/^{56}Fe$, are indeed present in the GCRs. All other measured ratios are in reasonable agreement with small or insignificant differences from WR model predictions, which are very similar to solar-system abundances, provided that volatility fractionation of elemental source abundances according to the model of Meyer et al. (1997) is included.

We take this agreement as evidence, in addition to that previously suggested by earlier measurements of the $^{22}Ne/^{20}Ne$ ratio, that WR star ejecta is likely an important component of the cosmic-ray source material.

Since most WR stars reside in superbubbles, as do most core-collapse supernovae, superbubbles must be the predominant site of injection of WR material into the GCR source material. Therefore the picture that emerges from these data is that superbubbles would appear to be the site of origin and acceleration of at least a substantial fraction of GCRs.

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References
Aharonian, F., et al. 2005a, Science, 307, 1938
Aharonian, F., et al. 2005b, A&A, 431, 197
Aharonian, F., et al. 2005c, Sub. to A&A, http://xxx.lanl.gov/PS_cache/astro-ph/pdf/0505/0505219.pdf
Anders, E, & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Angulo, C. et al. 1999, Nucl. Phys. A, 656, 3
Binns, W. R., et al. 2001, in AIP Proc. 598, Sol. and Gal. Comp., ed. Wimmer-Schweingruber, R. F., (New York:AIP), 257
Binns, W.R., et al. 2005, ApJ in Press
Cassé, M & Goret, P. 1978, ApJ, 221, 703
Cassé, M., & Paul, J. A. 1982, ApJ, 258, 860
Cesarsky, C. J., & Bibring, J. P. 1981, in IAU Symp. 94, ed. Setti, G., Spada, G., & Wolfendale, A. W. (Dordrecht: Kluwer Acad. Pub.), 361
Connell, J. J., & Simpson, J. A. 1997, 25th Int. Cosmic Ray Conf. (Durban), 3, 381
Connell, J. J. 2001, Space Sci. Revs., 99, 41
Dessart, L., Crowther, P. A., Hillier, D. J., Willis, A. J., Morris, P. W., & van der Hucht, K. A. 2000, MNRAS, 315, 407
DuVernois, M. A., Garcia-Munoz, M., Pyle, K. R., Simpson, J. A., & Thayer, M. R. 1996, ApJ, 466, 457
Ellison, D. C., Drury, L. O'C., & Meyer, J. -P. 1997, ApJ, 487, 197
Epstein, R. I. 1980, MNRAS, 193, 723
Engelmann, J. J., et al. 1990, AA, 233, 96
Geiss, J. 1973, 13th Int. Cosmic Ray Conf., 5, 3375
Garcia-Munoz, M., Simpson, J. A., & Wefel, J. P. 1979, ApJ, 232, L95
Higdon, J. C., Lingenfelter, R. E., & Ramaty, R. 1998, ApJ, 509, L33
Higdon, J. C., & Lingenfelter, R. E. 2003, ApJ, 590, 822
Kafatos, H., Bruhweiler, F., & Sofia, W. 1981, 17^{th} Int. Cosmic Ray Conf. (Paris), 2, 222
Knödlseder, J., Cerviño, M., Le Duigou, J. –M, Meynet, G., Schaerer, D., & von Ballmoos, P. 2002, AA 390, 945
Krombel, K. E. & Wiedenbeck, M. E. 1988, ApJ, 328, 940
Lodders, K. 2003, ApJ, 591, 1220
Lukasiak, A., Ferrando, P., McDonald, F. B., & Webber, W. R. 1994, ApJ, 426, 366
Maeder, A. & Meynet, G. 1993, A&A., 278, 406
Maeder, A. 2000, New Astron. Revs., 44, 291
Maehl, R., Hagen, F. A., Fisher, A. J., & Ormes, J. F. 1975, 14th Int. Cosmic Ray Conf., 1, 367
Marchenko, S.V., Moffat, A.F.J., Vacca, W.D., Cote, S., and Doyon, R. 2002, ApJ, 565, L59
Mewaldt, R. A., Spalding, J. D., Stone, E. C., & Vogt, R. E. 1980, ApJ, 235, L95
Meyer, J. P., Drury, L., & Ellison, D. C. 1997, ApJ, 487, 182
Meynet, G., & Maeder, A. 2003, A&A, 404, 975
Meynet, G., & Maeder, A. 2005, A&A, 429, 581
Nugis, T., & Lamers, H. J. G. L. M. 2000, A&A, 360, 227
Olive, K. A., & Schramm, D. N. 1982, ApJ, 257, 276
Prantzos, N., Doom, C., Arnould, M., de Loore, C. 1986, ApJ, 304, 695
Prantzos, N., Arnould, M., Arcoragi, J.-P. 1987, ApJ, 315, 209
Reeves, H. 1978 in Protostars and Planets, ed. Gehrels, T., (Tucson: University of Arizona Press) 399
Salpeter, E. E. 1955, ApJ, 121, 161
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&A, 96, 269
Soutoul, A., & Legrain, R. 1999, 26th Int. Cosmic Ray Conf. (Salt Lake City), 4, 180

Soutoul, A., & Legrain, R. 2000, in AIP Proc. 528, ACE 2000 Symposium, ed. Mewaldt, R. A., Jokipii, J. R., Lee, M. A., Möbius, E., & Zurbuchen, T. H. (New York:AIP), 417
Stone, E. C., & Wiedenbeck, M. E. 1979, ApJ, 231, 606
Stone, E. C., et al. 1998, Space Sci. Rev., 86, 285
Streitmatter, R. E., Balasubrahmanyan, V. K., Protheroe, R. J., & Ormes, J. F. 1985, A&A, 143, 249
Streitmatter, R.E., and Jones, F.C., 2005, 29th Int. Cosmic Ray Conf. (Pune) To be published.
Van Marle, A.J., Langer, N. & Garcia-Segura, G, 2005, submitted to Astronomy and Astrophysics
Webber, W. R., Lukasiak, A., & McDonald, F. B. 1997, ApJ, 476, 766
Wiedenbeck, M. E., & Greiner, D. E. 1981, Phys. Rev. Lett., 46, 682
Wiedenbeck, M. E., et al. 2001a, in AIP Proc. 598, Sol. and Gal. Composition, ed. Wimmer-Schweingruber, R. F. (New York:AIP), 269
Wiedenbeck, M. E., et al. 2001b, Adv. Space Res., 27, 773
Wiedenbeck, M. E., et al. 2003, 28th Int. Cosmic Ray Conf. (Tsukuba), 4, 1899
Woosley, S. E., & Weaver, T. A. 1981, ApJ, 243, 651
Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181