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Cosmic Ray Neon, Wolf-Rayet Stars, and the Origin of GCRs

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The abundances of neon and other refractory isotopes in the galactic cosmic rays (GCRs) have been measured by the Cosmic Ray Isotope Spectrometer (CRIS) aboard the ACE spacecraft. We have derived the ^{22}Ne/^{20}Ne ratio at the cosmic-ray source and obtain a ratio of 0.387 ± 0.007 (stat.) ± 0.022 (syst.), which corresponds to enhancement by a factor of 5.3±0.3 over that in the solar wind. We compare our ACE-CRIS data, 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 observed in the GCRs. Since WR stars are evolutionary products of OB stars, and most OB stars exist in OB associations that form superbubbles, the good agreement of our data with WR models suggests that superbubbles are the likely source of at least a substantial fraction of GCRs.

1. Introduction

Several 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). A number of models have been proposed to explain the large ^{22}Ne/^{20}Ne ratio. The most widely accepted mechanism 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 be due to 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 wind enrichment of He-burning products, especially carbon and oxygen. Also, at the beginning 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.

2. Measurements

The CRIS instrument (Stone et al. 1998) consists of four stacks of silicon 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^2sr and the total vertical thickness of silicon is 4.5 cm. The precision with which angle is measured by the fiber hodoscope is ≤ 0.1°.

The neon data were collected from 1997 Dec. 5 through 1999 Sept. 24 and are a selected, high-resolution data set. Events were selected with trajectory angles ≤25º relative to the detector normal and particles stopping within 750 μm of the single surface of each silicon wafer having a dead layer were excluded from analysis. Nuclei that interacted in CRIS were rejected by using the bottom silicon anticoincidence detector, by requiring consistency in charge estimates, and by rejecting particles with trajectories that exit through the side of a silicon stack.

The average mass resolution for neon that we obtained 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 $\sim 4.6 \times 10^4$. This Figure also shows histograms of F and O isotopes that are used in a "tracer" propagation to obtain the $^{22}Ne/^{20}Ne$ ratio at the cosmic rays source.

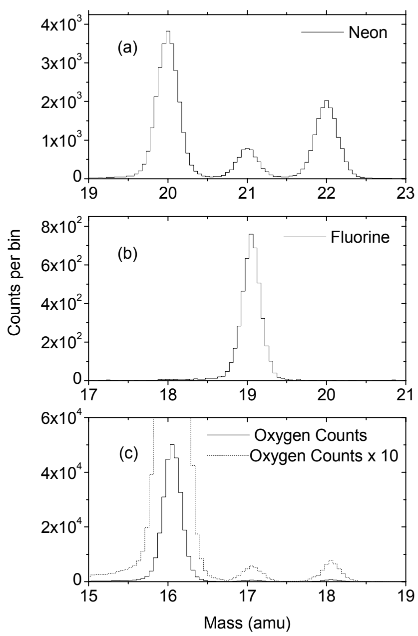

Figure 1-Mass histograms of neon, fluorine, and oxygen isotopes

3. Source Composition

To obtain the $^{22}Ne/^{20}Ne$ abundance ratio at the comic-ray source from the ratio observed, we have used the "tracer method" of Stone and Wiedenbeck (1979), which utilizes 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 such "tracer" isotopes. 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).

This analysis, combining the results derived using the three tracer isotopes gives an overall $^{22}Ne/^{20}Ne$ ratio of 0.387 ± 0.007 (stat.) $\pm$ 0.022 (syst.). This corresponds to a ratio relative to solar system of $(^{22}Ne/^{20}Ne)_{GCRS}/(^{22}Ne/^{20}Ne)_{SW}$ ratio of 5.3 ± 0.3.

4. Superbubble and Wolf-Rayet Models of Galactic Cosmic Ray Origin

Most core-collapse supernovae (SNe) in our galaxy (~90%) are believed to occur in OB associations that form superbubbles within giant molecular clouds (Higdon & Lingenfelter, 2003). Additionally, most WR stars are located in OB associations and many of their O and B star constituents evolve into WR's. These massive stars have short lifetimes, typically a few million years, and the WR phase is typically a few hundred thousand years (Meynet & Maeder 2003). It seems almost certain that pre-supernova WR wind material will be accelerated either by the SN shock from the evolved WR star that initially ejected the material or by nearby SNe from short-lived O and B stars. The mass of the neon isotopes synthesized and ejected in superbubbles by massive stars in their WR and core-collapse SN phases has been calculated by Higdon and Lingenfelter (2003). They estimated that a mass fraction, 18±5%, of WR plus SN ejecta must be mixed with ISM material of solar-system composition in the superbubble core to obtain the $^{22}Ne/^{20}Ne$ ratio reported in an earlier analysis of the CRIS results (Binns et al.

2001). They 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". Additionally, they suggest 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 a further test of the superbubble model of the origin of cosmic rays. In Figure 2 we show these ratios and compare them with modeling calculations of WR outflow (Meynet and Maeder 2003) for metallicity Z=0.02 and initial rotational equatorial velocities at the stellar surface of either 0 or 300 km/s. For each WR model star, the mixture (by mass) of WR star outflow with material of solar-system (solar-wind) composition required to give the ^{22}Ne/^{20}Ne ratio measured by CRIS for the GCR source was calculated. Table 1 shows the mass fraction (p) of the total cosmic ray source material that is required from the WR star since its initial formation for each case. The mixing fractions in Table 1 are similar to the value of 0.18±0.05 derived by Higdon and Lingenfelter. The high p-values predicted for the $M \geq 85\ M_\odot$ stars are not a problem since these very massive stars are much rarer than the lower mass stars.

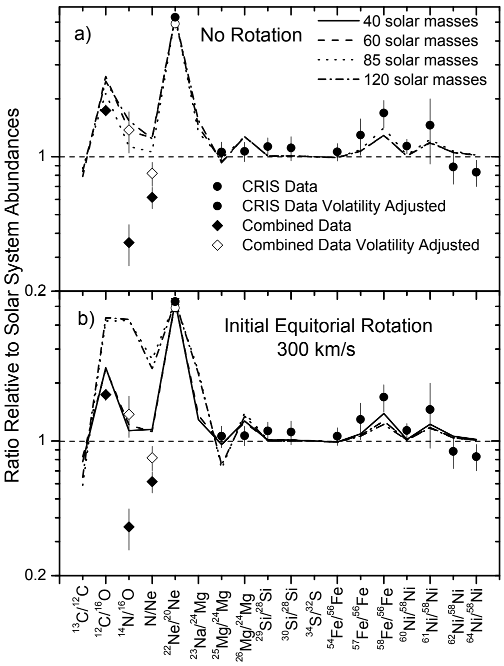

Figure 2--Comparison of CRIS and other data with WR calculations

Table 1

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

The closed circles in Figure 2 are CRIS results (See Wiedenbeck et al. 2001 and 2003 for elements heavier than neon). Ulysses Mg and Si data (not plotted; 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. The lighter elements are plotted as solid diamonds and are mean values of GCR source abundances, relative to solar system, 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 error bars are based on weighted means from these experiments. The ratios are relative to the Lodders (2003) solar-system abundances.

For nuclei heavier than neon, the WR models are in reasonable agreement with data, with the exception of 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.

For elements lighter than neon, there is usually only a single isotope for which source abundances can be obtained with sufficient precision to constrain the models. Therefore the ratios compared are for different elements. This makes comparisons more complicated since atomic fractionation effects may be important for some ratios. We see in Figures 2a and 2b that the measured $^{12}C/^{16}O$ source ratio is much larger than in the Solar System and is in qualitative agreement with WR models for non-rotating stars, and rotating stars with initial masses of 40 and 60 $M_{\odot}$. It is in disagreement with models of the heavier rotating stars.

However, the experimental $^{14}N/^{16}O$ ratio is smaller by more than a factor of two than for the model calculations and for the Solar System. It is likely that at least part of the explanation is elemental and mass fractionation of the GCR source material. Recent work by Meyer et al. (1997) and Ellison et al. (1997) has given support to a model in which GCR fractionation is governed by volatility.

Although atomic or molecular oxygen is highly volatile, ~23% of the oxygen in the ISM is believed to exist in refractory compounds, e.g. in silicates (Lodders 2003). Thus in the Meyer et al. and Ellison et al. models, that fraction of the oxygen should be preferentially injected into the GCRs. Additionally, a significant 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). Nitrogen exists primarily as a gas. 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 14N/16O ratio since the fraction of 16O that exists in the solid state in the pre-solar nebula has been estimated. Meyer et al. (1997) show that the GCR source to solar-system abundance ratio for the refractory elements is roughly a factor of 13 larger than for nitrogen. They also point out that, even for volatile elements there is a systematic enhancement in the abundance of heavy volatiles compared to light volatiles. They estimate the mass dependence of this enhancement as $A^{0.8\pm0.2}$, where A is the atomic mass. The ratio adjusted for this fractionation is plotted as an open diamond in Figure 2. The $^{12}C/^{16}O$ ratio is more difficult to correct since the fraction of carbon that is in the volatile state in the ISM is poorly known. Therefore we have not attempted this adjustment. We have adjusted the N/Ne ratio for the mass dependent enhancement and plotted it as an open diamond in Figure 6. The $^{22}Ne/^{20}Ne$ ratio has similarly been adjusted for mass dependence and the adjusted ratio is plotted as an open circle.

The adjusted $^{14}N/^{16}O$ and N/Ne ratios are in much better agreement with both the solar system and WR modeling results. Note that these adjusted ratios should be regarded as approximate values showing that ratios previously thought to be inconsistent with solar-system abundances may be consistent if GCRs are fractionated on the basis of volatility and mass, and fractionation is properly taken into account.

We see that after adjustments for elemental fractionation, the CRIS data and data from other experiments show an isotopic composition 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), $^{12}C/^{16}O$, $^{22}Ne/^{20}Ne$, and $^{58}Fe/^{56}Fe$ are in fact observed. We take this agreement as evidence 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.

5. Acknowledgements

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