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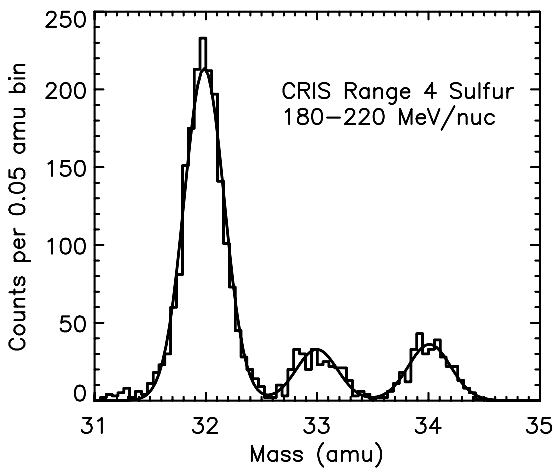
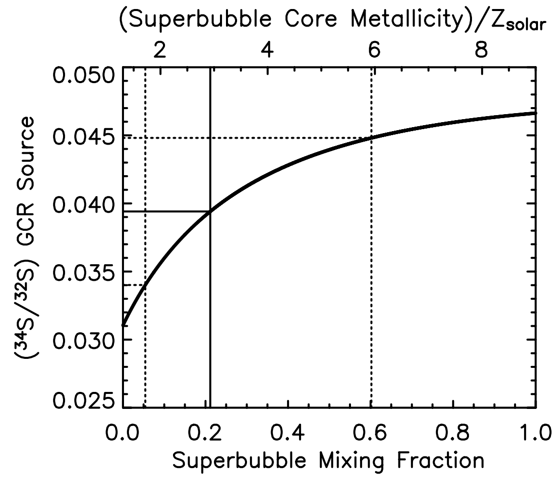
Superbubble Origin of Galactic Cosmic Rays Supported by Supernova-Produced Isotopes





The source of Galactic cosmic rays (GCRs) is a long-standing unsolved problem in high-energy astrophysics. The five-fold enrichment of ^{22}Ne seen in the GCRs supports the theory that these high-energy nuclei originate in the cores of hot, rarified regions known as superbubbles that form around associations of massive OB stars. The high-precision measurements of neon isotopes made by the Cosmic Ray Isotope Spectrometer (CRIS) aboard ACE (see previous ACE News items #74 & #95) are consistent with a model in which the contribution of material ejected from the stars in these OB associations and accelerated to cosmic ray energies is ~20% of the GCR seed population, with the rest made up of material from the interstellar medium (ISM). This mixing of older ISM and metal-rich stellar ejecta results in a calculated GCR source metallicity (fraction of elements heavier than helium) of 2.7 times solar metallicity. The enrichment of ^{22}Ne is due to the winds of Wolf-Rayet stars. The freshly synthesized material in the superbubble core consists of matter ejected from supernovae explosions in addition to Wolf-Rayet wind material. If the GCR source material is indeed a mix of ~20% ejecta material and ~80% ISM as derived from Wolf-Rayet wind dominated GCR species like ^{22}Ne, the isotopic makeup of GCR nuclei that are mainly produced in supernova explosions should reflect this same composition.

Approximately 90% of the sulfur isotopes ^{32}S and ^{34}S and argon isotopes ^{36}Ar and ^{38}Ar in the core of a superbubble are produced by core-collapse supernovae. The calcium isotopes ^{40}Ca and ^{44}Ca in a superbubble are also produced in bulk by supernovae (~90% and ~65%, respectively). These isotopes are present in the Galactic cosmic rays and are measured precisely by CRIS (see S isotopes in the left-hand figure above). Their abundances at the GCR source are determined by modeling the effects of cosmic ray propagation through the Galaxy and solar system. By using CRIS observations of similar mass isotopes which are thought to be absent from the GCR source (^{33}S and ^{42}Ca, for example), the effects of Galactic propagation on the abundances of the sulfur, argon, and calcium isotopes can be derived and their source abundances are determined with unprecedented accuracy.

Isotope ratios in the superbubble core as a function of ISM/ejecta mixing fraction, or equivalently, metallicity, were derived using theoretical calculations of Wolf-Rayet winds and supernovae yields by Woosley and Weaver and by Goriely. The ^{34}S/^{32}S ratio at the GCR source is shown in the right-hand figure: the horizontal solid line is the derived GCR source ratio and the dotted lines are the uncertainties in this ratio. For the superbubble core material to reflect the sulfur isotopic composition seen in the GCRs, the mixing fraction must be ~21%, corresponding to a metallicity of ~2.9 times solar. The ensemble of isotope ratios ^{34}S/^{32}S, ^{38}Ar/^{36}Ar, and ^{44}Ca/^{40}Ca give a mixing fraction of $18\%^{+26\%}_{-14\%}$ which corresponds to a metallicity of $2.7^{+3.9}_{-2.1}$ times solar. This amount of mixing derived by supernova-produced S, Ar and Ca isotopes is consistent with that determined from Wolf-Rayet produced ^{22}Ne. Taken together, these results verify two major ingredients of the material predicted to be accelerated at the GCR source, lending credence to the superbubble origin of Galactic cosmic rays.

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