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Observation of ^{60}Fe in the Galactic Cosmic Rays

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The Cosmic Ray Isotope Spectrometer (CRIS) on the ACE spacecraft has been measuring the isotopic composition of Galactic Cosmic Rays (GCRs) since August 1997. Using selected data from the past seventeen years, we have a set of 2.95×10^5 ^{56}Fe nuclei in the energy interval ~240 to ~470 MeV/nucleon with excellent mass resolution characterized by $\sigma = 0.24$ amu. In this data set we have detected fifteen well resolved ^{60}Fe nuclei. ^{60}Fe is β^- unstable with a half-life of 2.6 million years. The detection of these radioactive nuclei permits us to set an upper limit of a few million years on the time between nucleosynthesis of these nuclei and their acceleration to cosmic-ray energies. A lower limit of $\sim 10^5$ years was established by the CRIS observation that the electron-capture isotope ^{59}Ni is essentially absent in the GCRs. These two limits bracket the nucleosynthesis-to-acceleration time to a range that is consistent with the emerging evidence that the bulk of GCRs are accelerated in associations of massive stars (OB associations).

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1. Introduction

Using seventeen years of data from the Cosmic Ray Isotope Spectrometer (CRIS) [1] on the Advanced Composition Explorer (ACE) spacecraft [2], we have examined the isotopic distribution of Fe nuclei in the Galactic cosmic rays. With excellent mass resolution of σ = 0.24 amu, we identify 15 well resolved events of ^{60}Fe in a set with 2.95 x 10^5 events of ^{56}Fe. Since ^{60}Fe has a half-life of 2.62 Myr [3] and only a very small fraction of the ^{60}Fe we observe could be produced in the interstellar medium by fragmentation of heavier nuclei, detection of this isotope in the cosmic rays is evidence that cosmic-ray acceleration occurs within several million years of the nucleosynthesis of these nuclei. By comparing our observed ^{60}Fe/^{56}Fe ratio with the ratio produced in nucleosynthesis models of massive star evolution, we derive a conservative upper limit on the time between nucleosynthesis and acceleration of 10 Myr.

Previously, CRIS data demonstrated a lack of ^{59}Ni in the cosmic rays [4]. This isotope decays with a half-life of 7.6 x 10^4 years, but only by electron capture; so it is essentially stable once it is accelerated to cosmic-ray energies where it is stripped of its orbital electrons. Its lack in the cosmic rays is evidence that at least 10^5 years must elapse between nucleosynthesis and cosmic-ray acceleration. This leads to the conclusion that the supernova in which the nucleosynthesis occurs cannot be the supernova whose shock wave accelerates the material to cosmic-ray energies [4][5].

The fact that cosmic-ray acceleration occurs within a few million years of nucleosynthesis, but not in the same supernova where the Fe-group nuclei are synthesized requires that there are at least two nearby supernovae separated by only a few million years. This need for nearby supernovae closely spaced in time strongly suggests acceleration in associations of massive stars (OB associations). Thus our observation of ^{60}Fe gives strong support for the emerging understanding [6] that OB associations are the primary environment for acceleration of Galactic cosmic rays.

In section 2 of this paper we present the CRIS data from which we determine the ^{60}Fe/^{56}Fe ratio near Earth. In section 3 we calculate the ratio at the acceleration source, taking account of the decay of ^{60}Fe, using characteristics of cosmic-ray propagation in the galaxy that have been derived from CRIS data on beta-decay secondary cosmic rays [7]. In section 4 we derive an upper limit to the time between nucleosynthesis and cosmic-ray acceleration. In section 5 we make a more general comparison between the ^{60}Fe/^{56}Fe ratio at the acceleration source and the production ratio calculated in two different models of nucleosynthesis [8][9]. In section 6 we summarize the conclusions we draw from this work.

2. Observation of Fe isotopes near Earth

Figure 1 displays the CRIS data for isotopic composition of Fe taken during solar quiet times during the seventeen-year period from 4 December 1997 to 28 September 2014. To optimize the mass resolution, data in this plot were confined to cosmic-ray trajectories with angles to the instrument normal less than 30°, and to cosmic rays stopping in the fourth to the eighth silicon detectors, corresponding to energies of Fe at the top of the instrument in the interval ~240 to ~470 MeV/nucleon. We required consistency among mass calculations using various combinations of detector signals. In this plot we see 15 events at mass 60, well resolved from the much more abundant stable isotopes of mass 54, 55, 56, 57, and 58. With a Gaussian fit we find that there are 2.95 x 10^5 events in the ^{56}Fe peak.

As evidence that at most one of the 15 events at ^{60}Fe could be spill-over from the ^{58}Fe peak, we present in Figure 2 the corresponding mass histogram of Co, displaying a very sharp upper-mass edge to the ^{59}Co peak. We note that the number of events at ^{59}Co is similar to the number at ^{58}Fe, and there is only one event at ^{61}Co that could be a high-mass spill-over from ^{59}Co. We thus conclude that of the 15 events at ^{60}Fe, 1 ± 1 of them could be a spill-over from ^{58}Fe.

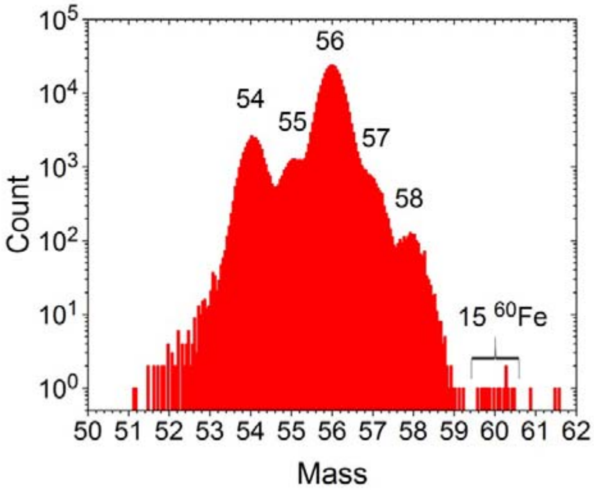

Figure 1. Mass histogram of Fe.

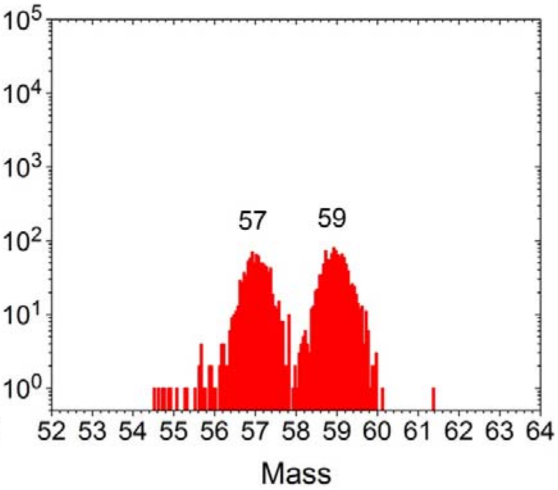

Figure 2. Mass histogram of Co.

We estimate that one of the ^{60}Fe we observed could be of secondary origin, resulting from interstellar nuclear interaction of heavier cosmic rays, primarily ^{62}Ni and ^{64}Ni. This estimate comes from using semi-empirical cross-sections for ^{60}Fe production along with cosmic-ray propagation parameters derived from beta-decay secondaries observed by CRIS [7].

Thus we have observed 13 ± 3.8(stat.) ± 1(syst.) = 13 ± 4.8 primary ^{60}Fe with 2.95 x 10^5 ^{56}Fe, giving a primary ^{60}Fe/^{56}Fe ratio near Earth of 4.4 ± 1.6 x 10^{-5}.

3. Extrapolation of the ^{60}Fe/^{56}Fe ratio back to the acceleration source

The CRIS observation of the beta-decay secondary cosmic rays – ^{10}Be, ^{26}Al, ^{36}Cl, and ^{54}Mn – has been well explained by a simple leaky-box model of cosmic-ray propagation in the Galaxy characterized by a mean confinement time in the galaxy τ_{esc} = 15.0 ± 1.6 Myr and an average interstellar hydrogen number density n_H = 0.34 ± 0.04 H atoms cm^{-3} [7].

In the context of a simple leaky-box steady-state galactic propagation (ignoring interstellar energy loss), if Q represents abundance at the acceleration source, and N represents primary abundance near Earth, then

$$Q_{60}/Q_{56} = (N_{60}/N_{56}) \text{ x } (\tau_{56}/\tau_{60})$$

where $1/\tau_{56} = 1/\tau_{esc} + 1/\tau_{int56}$

and $1/\tau_{60} = 1/\tau_{esc} + 1/\tau_{int60} + 1/\tau_{decay60}$

The mean lifetime for loss by nuclear interaction with the interstellar medium is $\tau_{int} = \lambda/(n_H\, m_H$ v). From the Westphal et al. [10] mass-changing cross-sections the interaction mean free paths in interstellar gas (90% H 10% He by number), are λ_{60} = 2.80 g/cm^2 and λ_{56} = 2.95 g/cm^2.

We took a mean value of the interstellar velocity, v, of 0.787c for ^{56}Fe and 0.782c for ^{60}Fe. These estimates of mean velocity are based on the fact that the energies at the detector were ~240 to ~470 MeV/nucleon, with a mean value of 367 MeV/nucleon, and taking into account an average value of the estimated energy loss due to modulation in the Solar System. The Fe data presented here were taken over a 17-year period, during which the level of modulation varied substantially between minima and maxima of solar activity. We estimate this energy loss using a spherically symmetric model of modulation as discussed by Fisk [11] and characterized by a parameter ϕ, which we derived from the measured shape of the Fe energy spectrum for each 27-day Bartels rotation period throughout the 17-year period. The value of ϕ varied between ~250 MV and ~1000 MV; an average ϕ over this period, weighted according to the number of observed Fe events in each 27-day period was ϕ = 453 MV, corresponding to an energy loss of 210 MeV/nucleon for ^{56}Fe and 196 MeV/nucleon for ^{60}Fe**.** Thus we have τ_{int56} = 6.96 ± 0.82 Myr and τ_{int60} = 6.64 ± 0.78 Myr.

The mean lifetime for radioactive decay of ^{60}Fe at rest is 3.78 ± 0.06 Myr (the 2.62 ± 0.04 Myr half-life [3] divided by ln2). In calculating $\tau_{decay60}$ for the equations above, we must take account of Lorentz factor γ, which is 1.604 for v = 0.782c, thus we have $\tau_{decay60}$ = 1.604 x (3.78 ± 0.06 Myr) = 6.06 ± 0.09 Myr, giving τ_{56} = 4.75 ± 0.41 Myr and τ_{60} = 2.62 ± 0.13 Myr.

So our observed ^{60}Fe/^{56}Fe ratio near Earth of (0.44 ± 0.16) x 10^{-4} implies a ^{60}Fe/^{56}Fe ratio at the cosmic-ray acceleration source of (0.80 ± 0.30) x 10^{-4}.

4. An upper limit to the time between nucleosynthesis and cosmic-ray acceleration

Calculations by Woosley & Heger [8] and by Chieffi & Limongi [9] give the production of ^{60}Fe and ^{56}Fe by massive stars of various initial masses. These calculations give very different results for, *R*, the ^{60}Fe/^{56}Fe ratio produced by non-rotating stars of various masses. From [8] *R* varies between 0.9 x 10^{-4} from the most massive stars (~100 M_{sun}) to 11.6 x 10^{-4} from the least massive OB stars (~12 M_{sun}), while [9] gives *R* that varies between 33 x 10^{-4} from massive stars (~80 M_{sun}) to 0.1 x 10^{-4} from low-mass OB stars (~13 M_{sun}).

There is strong evidence both from the overabundance of ^{22}Ne in the cosmic rays compared with its abundance in the Solar System [12] and from the cosmic-ray abundances of elements with atomic number between 30 and 40 [13] that the cosmic-ray source is a mixture of ~20% outflow and ejecta from massive stars and ~80% old material with a composition that matches the Solar-System. Since that old material would have no ^{60}Fe, we would expect the ^{60}Fe/^{56}Fe ratio in the source material to be ~0.2*R*.

To calculate an upper limit on the time between nucleosynthesis and cosmic-ray acceleration, we make the extreme assumption that only the massive stars ~80 M_{sun} contribute to the massive star outflow and that the calculation of [9] is correct. In that case *R* = 33 x 10^{-4}, and so the source material for the cosmic rays would have a ^{60}Fe/^{56}Fe ratio of 6.6 x 10^{-4}. Taking our best value for the ratio at the time of cosmic-ray acceleration we would calculate the time between nucleosynthesis and acceleration of 3.78 Myr x ln(6.6/0.80) = 8.0 Myr; or taking the lower error bar on our ratio at acceleration, we would calculate 3.78 Myr x ln(6.6/0.50) = 9.8 Myr. Since it is rather unlikely that only those stars with mass ~80 M_{sun} contribute to the cosmic rays, this value of 10 Myr is a very conservative upper limit. It is likely that the time between massive-star nucleosynthesis and acceleration is less than this value.

Combining this upper limit with the lower limit of 100 kyr inferred from the lack of ^{59}Ni in the cosmic rays [4] implies that cosmic-ray acceleration occurs in regions where at least two nearby supernovae (one that synthesizes the Fe-group elements and another that accelerates them) occur within a few million years. In a typical OB association supernovae occur at a rate of approximately one per million years. Indeed it is in such associations of massive stars that such a frequency of nearby supernovae is most likely to be found.

Thus the CRIS observations of ^{60}Fe in the cosmic rays, combined with the earlier CRIS observation of the lack of ^{59}Ni in the cosmic rays, gives strong support for OB associations being the primary source of Galactic cosmic rays.

5. A more realistic comparison between the production ratio and acceleration ratio

Rather than assuming that only the stars with mass ~80 M_{sun} contribute to the cosmic rays, it is more realistic to assume that the cosmic rays we observe have contributions from supernovae accelerating interstellar material over the life of OB associations. Figure 3 shows *R*(*t*), the massive-star-outflow ^{60}Fe/^{56}Fe ratio accumulated in the interstellar medium of an OB association as a function of time during the life of the association, using the production ratio of these two isotopes as a function of stellar mass from either [8] or [9]. (The plot here for [9] is for their non-rotating models. Their rotating models give results that lie between the plots here.) In deriving these curves, stellar masses were distributed according to the Salpeter Initial-Mass Function [14]. The stellar life as a function of stellar mass [15], and the decay of ^{60}Fe were taken into account. Using the calculations of [8], *R*(*t*) varies from a maximum of 4.5 x 10^{-4} between 4 and 5 Myr after the birth of the OB association to ~1.2 x 10^{-4} near the end of the association's life. Using the calculations of [9], it varies from 3 x 10^{-3} at ~3.5 Myr to ~10^{-5} near the end.

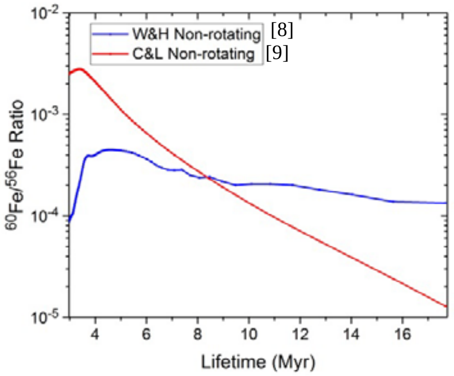

Figure 3. *R*(*t*), the massive-star-outflow ^{60}Fe/^{56}Fe ratio in the interstellar medium of an OB association

Calculating the mean of *R*(*t*), weighted according to the relative supernova rate in an OB association as a function of association age [15], which falls by about a factor of two from early in the association's life to late in its life, gives 5.8 x 10^{-4} using [9] and is 2.4 x 10^{-4} using [8]. Again taking account of the ~80% dilution with old material in which there is no surviving ^{60}Fe we would expect a ^{60}Fe/^{56}Fe ratio at the acceleration source of 11.6 x 10^{-5} using [9] and 4.8 x 10^{-5} using [8]. The value (8.0 ± 3.0) x 10^{-5}, derived from our observation in section 3 above, lies midway between these two nucleosynthesis-model values. The value derived from [8] is barely below our experimental lower limit, while the value derived from [9] is barely above our experimental upper limit. We take the difference between the result using [8] and that using [9] as indicative of the substantial uncertainty in these nucleosynthesis calculations.

Thus we see that our observed ^{60}Fe/^{56}Fe ratio is consistent with the model in which Galactic cosmic rays are primarily accelerated in OB associations over the life of the associations.

6. Conclusion

The observation of the rare radioactive isotope ^{60}Fe by the CRIS instrument on the ACE spacecraft was possible only because of the exquisite mass resolution of CRIS and the remarkably long lifetime of this instrument and this spacecraft. This observation of ^{60}Fe in the cosmic rays, combined with the earlier CRIS observation of the lack of ^{59}Ni in the cosmic rays, implies that cosmic-ray acceleration must occur in a region of the Galaxy where supernovae occur with a frequency of at least one every few million years, thus giving strong support that OB associations are the primary source of Galactic cosmic rays.

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