The Isotopic Composition of Iron, Cobalt, and Nickel in Cosmic-Ray Source Material

M.E. Wiedenbeck[1], W.R. Binns[2], E.R. Christian[3], A.C. Cummings[4], J.S. George[4], P.L. Hink[2], J. Klarmann[2], R.A. Leske[4], M. Lijowski[2], R.A. Mewaldt[4], E.C. Stone[4], T.T. von Rosenvinge[3], and N.E. Yanasak[1]

[1]*Jet Propulsion Laboratory, Pasadena, CA 91109, USA*
[2]*Washington University, St. Louis, MO 63130, USA*
[3]*NASA / Goddard Space Flight Center, Greenbelt, MD 20771, USA*
[4]*California Institute of Technology, Pasadena, CA 91125, USA*

Abstract

Measurements of the isotopic composition of iron-group elements in the energy range ~140–500 MeV/nucleon are reported from the Cosmic Ray Isotope Spectrometer carried aboard the Advanced Composition Explorer spacecraft. Calculations of the effects of interstellar propagation were carried out using recently published fragmentation cross sections to derive source abundances for stable isotopes of Fe, Co, and Ni. We report the resulting source composition, compare it with previous measurements and with abundances in other samples of matter, and discuss its implications for the nucleosynthesis of iron-group cosmic rays.

1. Introduction:

For understanding the nucleosynthetic origins of galactic cosmic rays, the abundances of the isotopes of Fe, Co, and Ni are of particular interest. These nuclides are formed in the late stages of stellar evolution and are ejected into the interstellar medium by supernova explosions. The relative abundances that result are sensitive both to the conditions in the pre-supernova star and to the explosion itself. In addition to their central role in stellar nucleosynthesis, primary nuclides with mass greater than 56 are important for cosmic ray studies because their abundances are only minimally contaminated by secondary production during interstellar transport.

However, accurate measurements of the abundances of iron group nuclei are difficult because adjacent isotopes have small relative mass separations ($< 2\%$) and, in many cases, very unequal abundances. Early measurements on ISEE-3 (Mewaldt et al., 1980; Leske 1993) established that the dominant isotopes of cosmic ray Fe and Ni are the same as in solar system material. To date, the only precise abundance measurements for the rarer iron-group nuclides have been made on Ulysses (Connell & Simpson, 1997).

The Cosmic Ray Isotope Spectrometer (CRIS) on the Advanced Composition Explorer (ACE) utilizes silicon detector telescopes plus a scintillating optical fiber trajectory system to carry out high precision studies of essentially all cosmic ray nuclides with $3 \leq Z \leq 30$ at energies ~ 50 to 500 MeV/nuc (Stone et al., 1998). In this paper we report CRIS measurements of the isotopes of Fe, Co, and Ni made during the first 16 months of operation following the ACE launch on 25 August 1997.

2. Observations:

Figure 1 shows the mass histograms from which isotope abundances were derived. The CRIS instrument collects particles over a large solid angle, accepting trajectories out to angles $\theta \gtrsim 60°$ from the detector normal. The mass resolution degrades slowly with increasing incidence angle due, for example, to increasing pathlength errors caused by multiple scattering. For iron-group isotopes the rms mass resolution is ~ 0.23 amu at small angles and increases to about twice this value for $\theta \simeq 45°$. Our analysis takes advantage of the large collecting power of CRIS to optimize the trade-off between resolution and statistics for the particular abundances being measured, as seen in Fig. 1. For isotopes of Fe and for ^{59}Ni, ^{61}Ni, and ^{62}Ni the requirement for high resolution is paramount, so only events

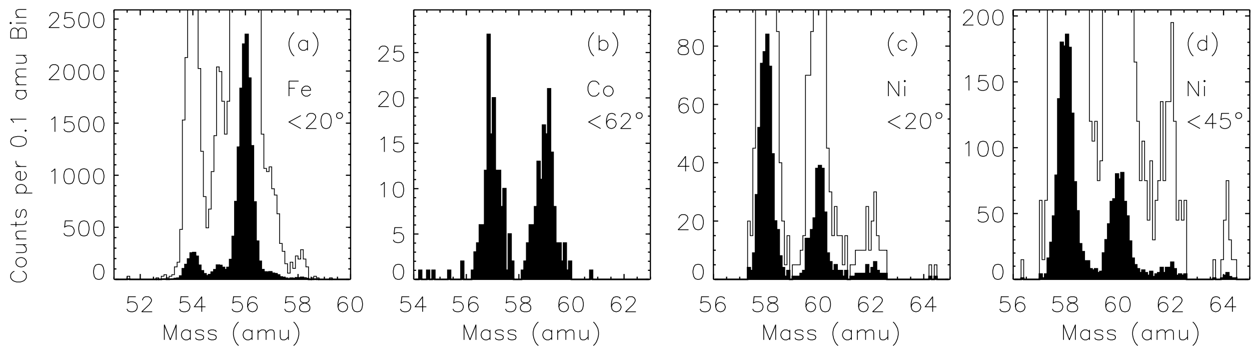

Figure 1. CRIS mass histograms. The element and the angle cut used are indicated on each panel. The light lines show the same data as the filled histogram, but with the vertical scales expanded by factors of 15 (panel a), 5 (panel c), and 15 (panel d) to better display the rare isotopes.

with $\theta < 20°$ have been used. Larger θ limits were employed for ^{57}Co, ^{59}Co, and ^{64}Ni where low abundances and 2 amu spacing make statistics more important.

The mass distributions were fit with a superposition of Gaussians taking into account the angular dependences of the observed count rates and mass resolution. Isotope fractions were derived from the fitted peak areas, with small corrections for differences in energy intervals and interaction losses. The elemental abundance ratios were derived from the relative normalizations obtained by fitting the measured energy spectra for Fe, Co, and Ni to a common spectral form.

Figure 2 shows the composition obtained from CRIS (filled points) together with values previously reported from Ulysses (Connell & Simpson, 1997). The error bars shown on the CRIS points represent a combination of the statistical errors and the uncertainties in fitting the mass peaks. Other possible systematic errors have not yet been fully investigated and are not taken into account in this preliminary analysis. In general, the abundances from CRIS and from Ulysses are in good agreement. The Ulysses ^{57}Fe abundance is greater than the CRIS value, possibly due to some residual spill over from ^{56}Fe in the former data set. The other notable difference is for ^{58}Fe, which is well resolved in both data sets. The origin of this difference, which is potentially important for interpreting the origins of iron-group cosmic rays, is not presently understood.

The solid horizontal lines in Fig. 2 show the composition of solar system material (Anders & Grevesse, 1989). The stable nuclides which should have negligible secondary contributions, ^{56}Fe, ^{58}Ni, ^{60}Ni, and ^{62}Ni, evidently have cosmic ray source abundances rather similar to solar system values.

3. Cosmic Ray Source Composition:

To derive source abundances we carried out a leaky-box propagation calculation using the parameters given by Leske (1993) and updated partial cross sections taking into account recent measurements of fragmentation of several iron-group nuclides (Webber et al., 1998a,b). This calculation successfully accounts for many of the dominantly-secondary nuclides in the interval $21 \leq Z \leq 25$. The points plotted in Figure 3 show the resulting cosmic-ray source composition relative to ^{56}Fe, normalized to the corresponding solar system values. A report of the ^{54}Fe source abundance is being deferred to a later publication after further investigation of the secondary contribution to this nuclide. This secondary correction is significant since ^{54}Fe can be produced by spallation of the abundant nuclide ^{56}Fe, and it is complicated by a contribution from the β^- decay of ^{54}Mn (Leske, 1993).

The most notable feature of the cosmic-ray source composition shown in Fig. 3 is its similarity to the composition of solar system matter. These two populations of material differ in their composition by no more than a few 10's of percent for the nine nuclides considered (including ^{56}Fe), even though the absolute abundances range over more than 3 orders of magnitude.

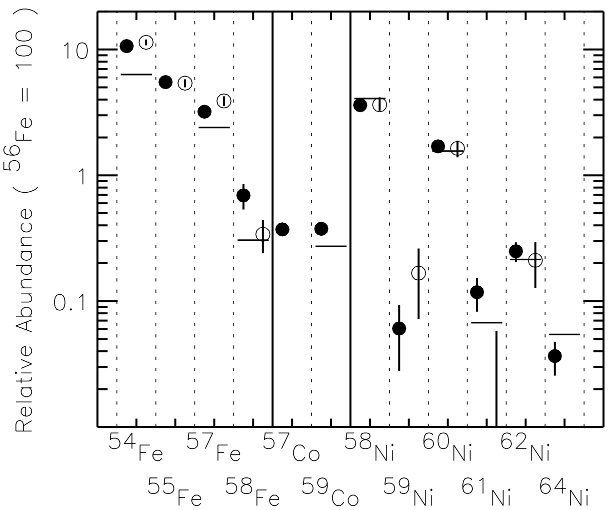

Figure 2. Comparison of isotope abundances observed with ACE/CRIS (filled points) to those from Ulysses (open points). The uncertainties shown on the CRIS points are a combination of statistical and fitting errors.

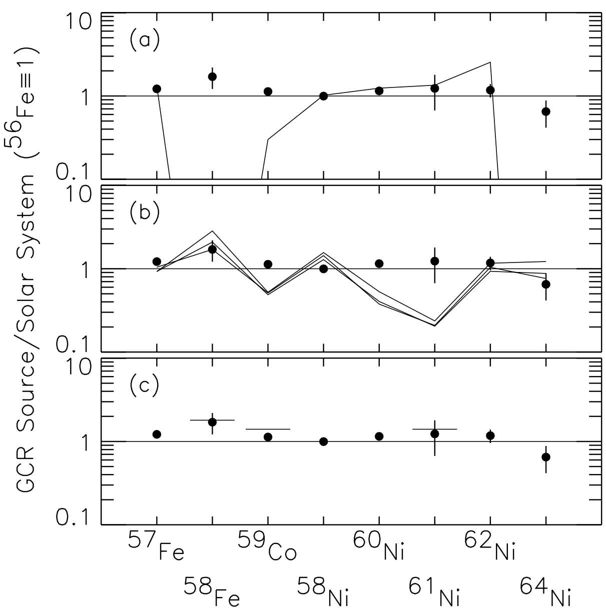

Figure 3. Comparison of derived GCR source abundances (filled points, normalized to ^{56}Fe=1) with various model calculations. Panel (a) SN II; panel (b) SN Ia; panel (c) Wolf-Rayet enriched ISM. See text for details.

Because of the great similarity between cosmic ray source and solar system compositions one can take advantage of the body of theoretical work which has been performed in an attempt to understand the nucleosynthetic origins of solar system matter. In Fig. 3 we compare the source abundances derived from CRIS with results from various nucleosynthesis calculations. In Fig. 3(a) the solid line shows the abundance pattern obtained by Nomoto et al. (1997) from calculations of the production and ejection of heavy nuclei from massive stars ($> 10 M_{\odot}$) which lead to core-collapse supernovae (Type II, Ib, or Ic, hereafter referred to collectively as SN II). They performed calculations for stars with initial masses between 13 and 70 $M_{\odot}$ (Tsujimoto et al., 1995) and then derived the yield from an ensemble of such stars weighted by a Salpeter initial mass function. A striking feature of their calculations is the prediction that SN II eject negligible amounts of the very neutron-rich species ^{58}Fe and ^{64}Ni (Thielemann, Nomoto, & Hashimoto, 1996), and therefore are unable to account for the observed abundances of these nuclides in cosmic rays.

Woosley & Weaver (1995) report results of an alternative set of calculations of yields of SN II from pre-supernova stars over a range of masses. Contrary to the Nomoto et al. (1997) results, they find that ^{58}Fe and ^{64}Ni are produced with solar-like abundances. While our analysis is based on the Nomoto et al. work, the reader is cautioned that the validity of some of our conclusions will remain in doubt until this important discrepancy between the theoretical calculations can be resolved.

In Fig. 3(b) the cosmic ray source composition is compared with calculated yields from Type Ia supernovae (SN Ia). These calculations by Nomoto et al. (1997) consider a variety of possible scenarios for the mass accretion onto a white dwarf that eventually leads to the explosion. The curves in Fig. 3(b) show their results for three models that consider nucleosynthesis by a deflagration wave that passes through the inner regions of a Chandrasekhar-mass white dwarf and subsequently leads to a detonation in the outer regions. The different curves correspond to different sets of model parameters that were considered.

SN Ia ejecta are composed primarily of iron-peak nuclei and are thought to have produced more than half of the Fe and Ni in solar system matter (Tsujimoto et al., 1995). Noting the similarity between cosmic ray and solar system composition, Meyer & Ellison (1999) have argued that cosmic ray source material must also have a substantial contribution from SN Ia. This point of view is supported by our isotope results, since the ^{58}Fe and ^{64}Ni that we observe are readily produced by SN Ia but not by SN II. This result provides an important constraint on the origin of cosmic rays related to the fact that SN Ia have progenitors with low masses and long evolutionary time scales ($\gtrsim$1 Gyr). Higdon, Lingenfelter, & Ramaty (1998) have suggested that cosmic rays are accelerated predominantly in superbubbles from supernovae ejecta which have not mixed with bulk interstellar matter. In such a model, cosmic rays should not contain a significant component originating in SN Ia because superbubbles disperse long before these low-mass stars can contribute. Thus it appears that such a superbubble origin cannot account for the observed cosmic ray composition.

Among the cosmic ray elements for which source isotopic composition has been precisely determined, only the ^{22}Ne/^{20}Ne ratio has been found to exhibit a large difference from solar system composition. Cassé & Paul (1982) proposed that this excess comes from the strong stellar winds of very massive ($\gtrsim 50 M_{\odot}$) stars in their Wolf–Rayet (WR) phase when their surfaces contain large excesses of the products of core helium burning, including ^{22}Ne and a variety of s-process nuclides. Prantzos et al. (1985) identified those s-process species that would be significantly enhanced if a large enough quantity of WR ejecta ($\sim$ 3%) were mixed with normal interstellar matter to produce the observed cosmic ray ^{22}Ne. Fig. 3(c) compares the isotopic enhancements that they predicted (horizontal lines) with the CRIS observations. At this point it is not possible to draw firm conclusions from this comparison: the ^{58}Fe abundance appears to favor the enhancement predicted by Prantzos et al. while the ^{59}Co abundance looks solar-like and ^{61}Ni is consistent with either possibility. With additional analysis it should be possible to reduce some of the abundance uncertainties, particularly for ^{58}Fe. However, the interpretation may remain questionable due to the possibility of significant uncertainties in the semi-empirical cross sections that are being used to calculate the secondary contributions to these nuclides. Direct measurements of the fragmentation of ^{60}Ni into ^{58}Fe and ^{59}Co may be necessary to conclusively test this model.

Acknowledgements: This research was supported by NASA at the California Institute of Technology (under grant NAG5-6912), the Jet Propulsion Laboratory, the Goddard Space Flight Center, and Washington University.

References

Anders, E. & Grevesse, N. 1989, Geoch. Cosmoch. Acta 53, 197
Cassé, M. & Paul, J.A. 1982 ApJ 258, 860
Connell, J.J. & Simpson, J.A. 1997, ApJL 475, L61
Higdon, J.C., Lingenfelter, R.E., & Ramaty, R. 1998, ApJL 509, L33
Leske, R.A. 1993, ApJ 405, 567
Mewaldt, R.A., Spalding, J.D., Stone, E.C., & Vogt, R.E. 1980, ApJ 236, L121
Meyer, J.-P. & Ellison, D.C. 1999, in *Proc. Conf. on LiBeB, Cosmic Rays, and Gamma-Ray Line Astronomy*, Astro. Soc. Pacific, to be published
Nomoto, K. et al. 1997, in *Thermonuclear Supernovae*, Ruiz-Lapuenta (ed.), (Kluwer:Dordrecht), pp. 349-378
Prantzos, N., Arnould, M., Arcoragi, J.P., & Cassé 1985, Proc. 19th ICRC (La Jolla) 3, 167.
Stone, E.C., et al. 1998, Space Sci. Rev., 96, 285
Thielemann, F.-K., Nomoto, K, & Hashimoto, M. 1996, ApJ 460, 408
Tsujimoto, T. et al. 1995, MNRAS 277, 945
Webber, W.R. et al. 1998a, ApJ 508, 949
Webber, W.R. 1998b, Phys. Rev. C 58, 3539
Woosley, S.E. & Weaver, T.A. 1995, ApJS 101, 181