Refractory Nuclides in the Cosmic-Ray Source

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Abstract

New observations of the abundances and energy spectra of the isotopes of Mg, Al, and Si from ACE/CRIS are used to extend our previous results on the composition of refractory nuclides in cosmic-ray source material. For the 18 nuclides considered for elements between Mg and Ni, relative source abundances are generally consistent with solar-system values to within 20%. The ^{58}Fe abundance, taken relative to ^{28}Si, is found to have the largest difference from solar, a factor of ~ 1.6. We suggest that the compositional similarity between the cosmic-ray source and the solar system can be understood in terms of acceleration of cosmic-ray refractories out of a well-mixed sample of interstellar matter.

1. Introduction

Comparison of the abundances of nuclides found in cosmic-ray source material with those in the solar system indicates a remarkable similarity between these two samples of matter. This is particularly true when the comparison is restricted to refractory nuclides, which appear to have undergone minimal elemental fractionation relative to one another in cosmic rays. Recent studies of Fe-group [4,7-9] and Ca [8-10] isotopes have provided comparisons for 12 dominantly-primary nuclides. Earlier work on Mg and Si [6 and refs. therein] showed that the isotopic make-up of these elements also differs little from solar system composition. In this paper we combine source abundances derived from observations of Mg, Al, and Si by the Cosmic-Ray Isotope Spectrometer (CRIS) on the Advanced Composition Explorer (ACE) with those previously obtained for heavier nuclides to produce a more nearly complete picture of the nuclidic composition of refractories in the cosmic-ray source.

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2. Observations and Source Abundances

The data set covers the period from mid-December 1997 through April 2000, when galactic cosmic-ray intensities were close to their solar-minimum values. Analysis procedures are discussed in [8]. Figure 1 shows the mass histograms for Mg, Al, and Si measured in the energy interval $\sim$ 110–330 MeV/nuc.

Isotopic energy spectra near Earth were derived by combining elemental energy spectra (available from http://www.srl.caltech.edu/ACE) with isotopic fractions derived from mass histograms such as those shown in Fig. 1 partitioned into six separate energy intervals.

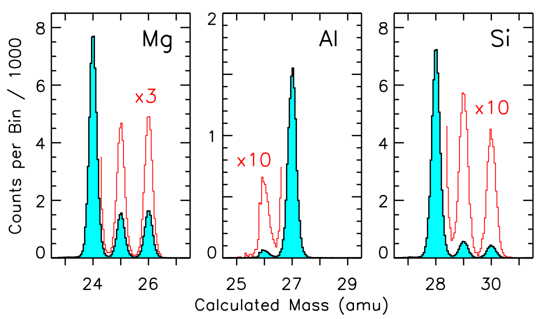

Fig. 1. ACE/CRIS mass histograms for Mg, Al, and Si. The unshaded curves have vertical scales expanded by the indicated factors to better show the separation of the minor isotopes. The radioactive isotope ^{26}Al, which is produced by fragmentation of heavier cosmic rays and not used in the present study, is discussed in [13].

To obtain source abundances we used a leaky-box model of interstellar propagation together with a solar-modulation model, as described in [9]. Source abundances for dominantly-primary nuclides were adjusted to make the calculated spectra at Earth agree with the energy spectra of individual isotopes obtained from the ACE/CRIS data. Figure 2 compares the resulting cosmic-ray source abundances with solar-system abundances [1]. The error bars take into account statistical and systematic errors in the measurements, but not uncertainties it the model calculations.

Of the 18 nuclides included in this comparison, only ^{58}Fe is found to have an abundance relative to ^{28}Si that differs by more than a factor of 1.5 from the solar-system value. When uncertainties are taken into account, all of the other abundances are consistent with being within 20% of the solar values.

3. Discussion

It is generally believed that the solar system condensed from interstellar gas and dust that contained contributions from the ejecta of a wide range of stellar objects [12]. For example, Fe-group nuclides are thought to originate mainly from a mix of type II and type Ia supernovae. The progenitors of SN II are stars more massive than 8 $M_{\odot}$, which are rather short-lived, while SN Ia come from low-mass stars, some of which existed for a significant fraction of the age of the Galaxy.

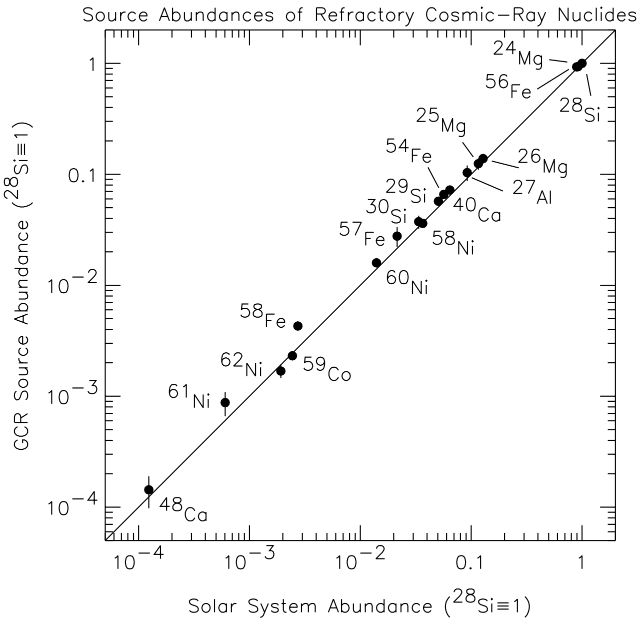

Fig. 2. Comparison of derived cosmic-ray source abundances of refractory nuclides with solar-system abundances [1]. Error bars associated with some of the GCR source values are smaller than the plotted points.

The isotopes of intermediate-mass elements, Mg, Al, and Si are thought to be synthesized primarily in intermediate mass stars, ~ 8–$12M_{\odot}$, and ejected when these objects shed portions of their outer envelope in the asymptotic-giant-branch (AGB) phase of their evolution. A recent spectroscopic study of Mg isotopic abundances in low-mass cluster-stars [14] found large star-to-star differences, with ^{26}Mg/^{24}Mg ranging from 0.08 to 0.74. This suggests a high degree of compositional variability among the AGB ejecta that contributed to the formation of these low-mass stars.

Given the wide range of abundance ratios that are apparently present in the objects that contributed material to the solar-system and to the cosmic-ray source, it is remarkable that these two samples of galactic matter resemble one another so closely. Such similarity might be simply accounted for if both populations sampled large enough volumes of the interstellar medium (ISM) that they truly reflected the *average* composition, taking account of all the types of stellar objects that eject heavy nuclei.

If the cosmic-ray source is, indeed, a well-mixed sample from the contemporary ISM, then the cosmic-ray isotope measurements can provide new information on the isotopic composition of refractory elements in the ISM. This information is complementary to spectroscopic observations of isotopic abundances in the Galaxy, which are presently limited to elements that occur in molecules either in the ISM (primarily volatiles such as H, C, N, O [11]) or in the atmospheres of certain relatively-cool stars (e.g., Mg [14]). In addition, by considering measured gradients of elemental [2] and isotopic [11] composition in the Galaxy it may be possible to obtain constraints on the regions in the ISM from which cosmic-rays observed at Earth are being accelerated.

Improved galactic chemical evolution calculations will be important for understanding under what conditions the small compositional differences between cosmic-ray source and solar system could have originated, given that the two samples of the ISM were taken ~ 4.5 Gyr apart.

The similarity between cosmic-ray source and solar abundances does not necessarily extend to the volatile elements. In fact, some models of cosmic-ray origin propose that the acceleration of refractories, which reside in grains in the ISM, is qualitatively different from the acceleration of volatiles [5]. The large enhancement of the ^{22}Ne/^{20}Ne ratio in cosmic rays is well established [3 and refs. therein] and it has been suggested that an admixture of cosmic-ray material injected by Wolf-Rayet stars could account for both the ^{22}Ne excess and possibly smaller excesses of certain neutron-rich isotopes, including ^{58}Fe.

Determinations of the isotopic make-up of other volatile elements other than Ne are presently limited by the required large corrections for secondary contributions to the observed abundances of the minor isotopes. In addition, it is difficult to precisely correct for the chemical fractionation that occurs prior to acceleration in order to obtain relative abundances of volatile elements in the underlying source population.

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4. References

1. Anders, E. and Grevesse, N. 1989, Geoch. Cosmoch. Acta, 53, 197.
2. Andrievsky, S.M. et al. 2002, A&A, 381, 32.
3. Binns, W.R. et al., 2001, AIP Conf. Proc. 598, 257.
4. Connell, J.J. and Simpson, J.A. 1997, ApJL, 475, L61.
5. Meyer, J.-P., Drury, L.O'C. and Ellison, D.C. 1997, ApJ 487, 182.
6. Simpson, J.A. and Connell, J.J. 2001, Space Sci. Rev., 97, 337.
7. Wiedenbeck, M.E. et al. 2000, AIP Conf. Proc. 528, 363.
8. Wiedenbeck, M.E. et al. 2001, AIP Conf. Proc. 598, 269.
9. Wiedenbeck, M.E. et al. 2001, Space Sci. Rev. 99, 15.
10. Wiedenbeck, M.E. et al. 2001, Proc. 27th ICRC (Hamburg), 5, 1679.
11. Wilson, T.L. 1999, Rep. Prog. Phys, 62, 143.
12. Woosley, S.E. and Weaver, T.A. 1995, ApJ Supp., 101, 181.
13. Yanasak, N.E. et al. 2001, ApJ, 563, 768.
14. Yong, D. et al. 2003, A&A, 402, 985.