Measurements of the elemental abundances of ultra-heavy galactic cosmic rays from Cu through Sr from the CRIS experiment on the ACE satellite

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Abstract: The Cosmic Ray Isotope Spectrometer (CRIS) instrument was launched on the Advanced Composition Explorer (ACE) satellite in August 1997 and has been collecting data steadily since that time. The large geometrical factor of CRIS, combined with the very long exposure time and the extended solar minimum, has enabled us to measure the cosmic ray composition of the more abundant elements from Zn (Z=30) up to Sr (Z=38). We have collected a total of ~700 nuclei heavier than Ni (Z=28) with energies in the range of ~175 to 535 MeV/nucleon. In this paper we report the elemental composition measurements and compare them with those obtained from the Trans-Iron Galactic Element Recorder (TIGER) experiment and with models of cosmic ray origin. We obtain generally good agreement with the TIGER data and find that both the refractory and volatile element abundances exhibit a mass dependence, as was observed in the TIGER experiment.

Keywords: Element composition of cosmic rays. Ultra-heavy cosmic rays.

1 Introduction

The elemental and isotopic composition of Galactic cosmic rays (GCRs) at their source is generally quite similar to the Solar System (SS) abundances [1]; however, recent observations have firmly established differences between the GCR and SS abundances, which point to the origin of GCRs in massive star (OB) associations at the cores of superbubbles. Excesses of ^{22}Ne and ^{58}Fe have been precisely measured by the Cosmic Ray Isotope Spectrometer (CRIS) on the ACE spacecraft and interpreted as indicating a source composed of a mixture of approximately 80% material of SS composition and 20% material of the composition expected from the outflow of massive stars [2]. The elemental composition of GCRs with atomic number (Z) greater than 28 measured with the Trans-Iron Galactic Element Recorder (TIGER) balloon-borne instrument have also shown deviations from SS abundances that point to that same 80%-20% mixture [3].

Earlier reports of results [4, 5, 6] from the CRIS instrument were limited to elements with Z ≤ 30, the region for which that instrument was primarily designed. Now, with the benefit of over 13 years of accumulated CRIS data, we report preliminary results extending the measurements to $_{38}$Sr and significantly improving their statistical precision. In this paper we report on the elemental composition in the interval 30 ≤ Z ≤ 38, and in an accompanying paper [7] the isotopic composition for elements with 29 ≤ Z ≤ 32 is reported.

2 Instrument

The CRIS instrument consists of four stacks of silicon detectors with total thickness 4.5 cm to measure energy-loss rate (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, mass, and energy. The instrument is described in detail in [8]. The energy interval for which we report data is governed by the requirement that nuclei penetrate at least into the third silicon detector but stop before reaching the ninth detector. As a result the energy interval varies slightly from element to element. At $_{26}$Fe the energy interval is 161 to 440 MeV/nuc; at $_{30}$Zn it is 174 to 480 MeV/nuc; and at $_{38}$Sr it is 192 to 536 MeV/nuc.

3 Measurements

Figure 1 displays a histogram of the charge estimate for events identified as having Z ≥ 26, from 4 December 1997 to 2 April 2011 excluding only intervals when the CRIS instrument was disabled due to large fluxes of solar energetic particles, as described in [5]. Events shown were selected to have good agreement between the multiple charge estimates made on each particle using different combinations of the silicon signals for dE/dx and residual energy (E_R) [8], a good trajectory indicated by a good fit to a straight line in the three scintillating fiber hodoscope planes, and incidence angle < 45°. Additionally, events that stopped in or near the "dead layer" of the silicon detectors were rejected [8]. This figure demonstrates excellent resolution of individual elements.

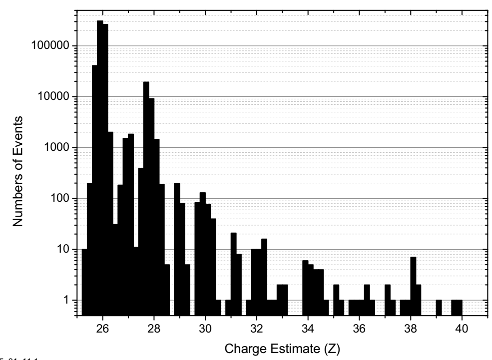

Figure 1. Observed number of events vs assigned charge.

We have derived preliminary element abundances as follows: We counted the number of events in each element peak, simply making cuts at the valleys between the peaks. To determine abundances relative to Fe we applied three factors. (1) The probability of losing an event due to a fragmentation interaction in the instrument increases with increasing nuclear mass; so observed numbers were multiplied by a factor ranging from 1.014 for Cu to 1.059 for Sr. (2) The width of the energy interval in which we made these measurements increases with increasing atomic number, and the mean energy at which the measurement is made moves along the energy spectrum; the combination of these effects leads to a correction to the observed numbers of events with a multiplicative factor ranging from 0.953 for Cu to 0.888 for Sr. (3) The CRIS instrument was designed with nuclei of Z ≤ 28 as the primary objective, so some of the heavier elements were lost from the data analysis as a result of pulse-height-analyzer saturation. Careful modeling of the instrument response resulted in a correction factor that varied steeply with Z for Z > 31. No correction was necessary for Z ≤ 31. For heavier nuclei a correction factor was needed that ranged from 1.008 at Z = 32 to 1.345 at Z = 36 to 1.771 at Z = 38.

In Figure 2 we display (solid circles) the resulting element abundances at the top of the instrument, and for comparison we show the top-of-atmosphere results from the TIGER Antarctic balloon flights [3] (solid squares) and for 30 ≤ Z ≤ 32 from the C2 instrument on the HEAO3 spacecraft [9]. We note that both the TIGER and the HEAO3-C2 measurements were at higher energies than the CRIS measurements presented here. The TIGER data were for all energies greater than 0.9 GeV/nuc at the top of the atmosphere, and the HEAO3-C2 data were similarly for energies greater than 0.9 GeV/nuc. (Also plotted for reference are the SS abundances from [1].) We note that there is good agreement between these new CRIS abundances and those determined by TIGER. (We have no ready explanation for the difference between these two measurements at $_{34}$Se.) Also we note that the two sets of data have similar statistical uncertainties. TIGER had fifty days of data and a very broad energy interval with an instrument of ~1 m^2 area, while CRIS has more than thirteen years of data in a relatively narrow energy interval with an instrument of ~ 300 cm^2 area.

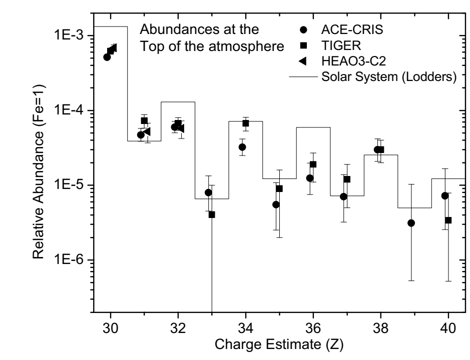

Figure 2. Element abundances relative to Fe. Data points show GCR abundances outside the atmosphere and histogram shows SS abundances.

4 Results

Rauch et al. [3] demonstrated that the TIGER results indicated that the GCR source abundances could be explained as a mixture of ~80% material of SS composition and ~20% material typical of the outflow of massive stars (MSO) as calculated by [10], which has been modified by selection effects in the acceleration mechanism. Those selection effects favor refractory elements over volatile elements by a factor of about four and systematically favor more massive elements. Since the abundances presented here from CRIS agree well with those from TIGER, these CRIS results lead to essentially the same conclusion.

Figure 3 is adapted from figure 9 of [3]. The data from that figure 9 are plotted here as open symbols, and the new CRIS data have been added as solid circles and solid squares. The GCR source (GCRS) abundances used here for A ≤ 56 are from HEAO3-C2 [11]. (For the prelimary results presented here, GCRS abundances are derived from the CRIS observations applying the same correction factors derived for correcting TIGER top-of-atmosphere results to the GCRS, as described in [3].) The dashed lines in this figure are the fits to the TIGER data for A ≥ 56 and HEAO3-C2 data that were presented in [8]. The solid lines are similar power-law fits using the CRIS data and ignoring the TIGER data. (We still use here the HEAO3-C2 data for A ≤ 56. Source abundances for A ≤ 56 from CRIS would not significantly change the fit, and will be presented in the updated version of this paper.)

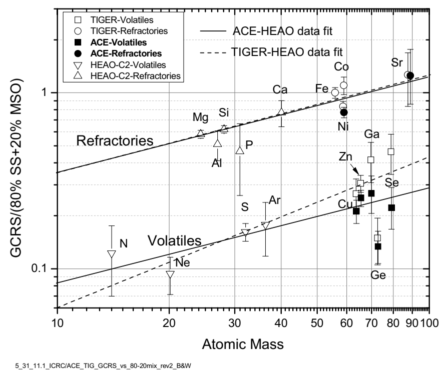

Figure 3. GCR Source abundances relative to the 80%-20% mix described in the text.

The fit to the refractory elements is essentially unchanged by the CRIS data. The fit to the volatile elements using the CRIS data gives a power-law dependence on atomic mass very similar to that of the refractory elements. The significance of these slopes in the context of cosmic-ray acceleration models remains to be investigated. However, the difference between the volatile-element slope derived from TIGER and the slope derived from CRIS (primarily resulting from the difference in $_{34}$Se abundances in the two measurements) is probably an indication of the uncertainty in the precise value of this slope.

Acknowledgements

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