Abundance measurements of Zn, Ga, Ge, & Se from the Cosmic Ray Isotope Spectrometer (CRIS) experiment on the Advanced Composition Explorer (ACE) satellite

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Abstract. **The cosmic ray elemental abundances of $_{30}$Zn, $_{31}$Ga, $_{32}$Ge, and $_{34}$Se provide important tests of the model of the OB-association origin of galactic cosmic rays that has resulted from previous ACE measurements of the neon and iron isotopes and which appears to be confirmed by elemental abundances of Zn, Ga, Ge, and Se measured by the balloon-borne Trans-Iron Galactic Element Recorder (TIGER). These ultra-heavy (Z≥ 30) nuclei are very rare and require an instrument with a large product of geometrical factor and exposure time. We have measured these abundances using the CRIS instrument, which has a geometrical factor of about 250 cm^{2}sr, on the NASA-ACE spacecraft. Over the 11+ years since launch in 1997 we have collected ~400 nuclei with Z≥ 30 over the energy range of ~150 to 600 MeV/nucleon. These measured abundances relative to iron are presented and compared with those from the TIGER and HEAO-3 experiments. Our measurements are in reasonable agreement with the TIGER results and are consistent with an OB association origin of galactic cosmic rays.**

***Keywords*: cosmic rays–Galaxy:abundances**

I. INTRODUCTION

Measurements of the isotopic abundances of neon, iron, and other elements by the ACE-CRIS experiment have led to the conclusion that the source of the material and acceleration of most galactic cosmic rays (GCR) is very likely in associations of massive stars called OB associations [1], [2]. These isotopic abundances are consistent with source material that is about 20% outflow from massive stars and 80% interstellar material with solar system composition. Abundance measurements from other experiments have been used to show that elements that exist primarily as dust grains (refractory elements) in interstellar space are accelerated preferentially compared to elements that exist primarily as gas (volatile elements) in space and that there is a mass dependence for the volatile elements, but not for the refractory elements [3]. Recently a new measurement of the elemental abundances of $_{30}$Zn, $_{31}$Ga, $_{32}$Ge, and $_{34}$Se by the balloon-borne Trans-Iron Galactic Element Recorder (TIGER) instrument has shown that a striking improvement in the ordering of the refractory and volatile elements can be obtained by normalizing the abundances to the 20%/80% mix mentioned above, rather than to solar system abundances. The TIGER collaboration has taken this as a confirmation of the OB association origin of most GCRs [4]. In the work reported here, we have analyzed more than 11 years of data from the ACE-CRIS experiment to obtain preliminary elemental abundances for nuclei from $_{30}$Zn to $_{34}$Se. These measured abundances are compared with the previously measured TIGER and HEAO-3 C2 abundances.

II. EXPERIMENT

The CRIS instrument [5] consists of four stacks of silicon detectors (4.5 cm total thickness of silicon) to measure 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 energy range covered for nuclei with Z≥ 30 is ~150-600 MeV/nuc. The geometrical factor is ~250 cm^{2}sr. The precision with which angle is measured by the fiber hodoscope is ~0.1 degrees.

III. MEASUREMENTS

In Figure 1 we show a histogram of events from the CRIS instrument collected over a period of time of ~11.3 years beginning Sept. 1, 1997. For this time period, we have collected ~400 nuclei with Z≥ 30. These are preliminary data and may contain systematic biases that can be removed with further analysis. The data are finely binned and show isotope peaks for $_{26}$Fe through $_{30}$Zn with possible peaks beginning to form at $_{31}$Ga. The inverted triangles show the expected position of the isotopes of each element obtained by fitting the measured isotope peaks for iron through zinc with a quadratic function and then extrapolating to higher charge. We note that the CRIS experiment does not directly measure the charge of the stopping particle, but the product of the two measured quantities, dE/dx and E_{tot}, is approximately proportional to AZ^2 in the non-relativistic limit. This accounts for the differing position of the isotopes of a given charge on the "charge estimate" scale and shows that elements with several stable isotopes are expected to cover a larger range in apparent charge than elements with only 1 or 2 stable isotopes (e.g., compare Ga with Ge). To obtain element abundances, we have made cuts for each charge at the mid-point between the heaviest isotope of a given element and the lightest isotope of the next heavier element. In Figure 2 we plot these same data as in Figure 1, but with coarser binning, that better shows the element peaks for nuclei heavier than zinc.

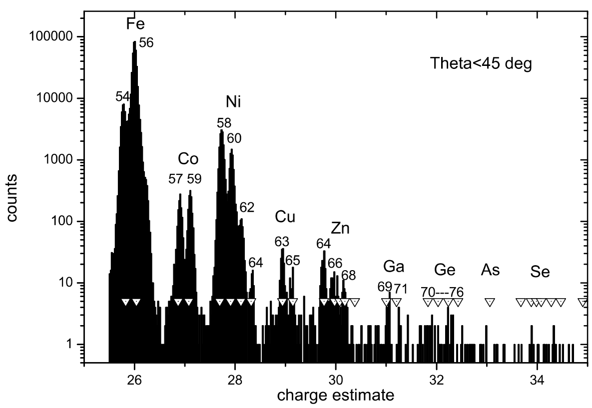

Fig. 1. Histogram of events with estimated charge from $_{26}$Fe to $_{34}$Se using fine binning. Isotope peaks are clearly visible through $_{30}$Zn with possible peaks beginning to form for $_{31}$Ga. The inverted open triangles indicate the expected locations of isotope peaks based on extrapolations from the $_{26}$Fe to $_{30}$Zn isotope peak positions (see text).

Figure 3 shows the abundances relative to iron for our CRIS data and compares it to the TIGER [4] and HEAO-3 C2 [6] data. We see that CRIS abundances agree well with TIGER for $_{30}$Zn, $_{31}$Ga, and $_{34}$Se, but $_{32}$Ge is significantly higher. They agree with the HEAO-3 Zn abundance but are higher for Ga and Ge. The solid line on the plot shows the solar system abundances [7]. As is the case for the TIGER and HEAO-3 data, the Ga and Ge abundances are approximately equal, in distinct contrast to Solar System abundances. Since they are both considered to be volatile elements, thus tending to take the form of gas in the interstellar medium, their volatile or refractory nature cannot account for their nearly equal abundances. Likewise, their first-ionization-potentials are very similar, so that cannot account for their abundances either. We note that the energy ranges of the particles detected by the TIGER and HEAO-3 C2 experiments are both $\sim\geq 800$ MeV/nuc, which differs from the lower CRIS energy range.

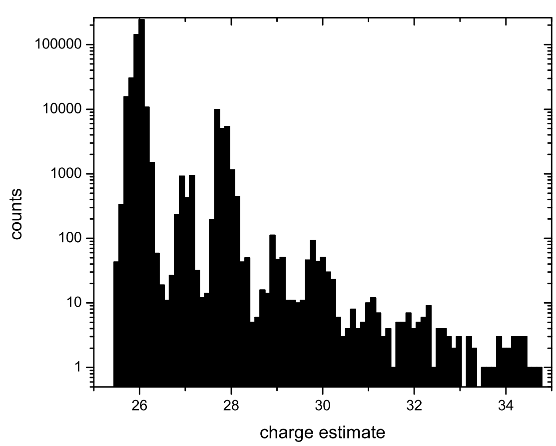

Fig. 2. Data plotted are the same as in Figure 1, but with coarser binning so that the element peaks for Z> 30 can be seen more easily.

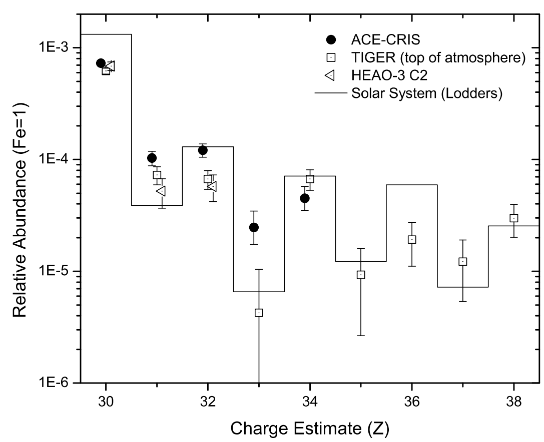

Fig. 3. The abundances relative to iron are shown for ACE-CRIS (closed circles), TIGER (open squares), and HEAO-3 C2 (open triangles). The solid line represents Solar System abundances taken from [7].

Woosley and Heger [8] have calculated the combined outflow of material from massive stars with initial masses ranging from 12 to 120 solar masses, after weighting the ejecta by a Salpeter initial-mass-function (IMF). This represents the outflow expected in OB associations, where most massive stars reside. They plot the element production factor relative to Solar System abundances as a function of charge and find that the element most enhanced in this environment is Ga. This may account for the enhancement in the Ga/Ge ratio that CRIS, TIGER, and HEAO-3 observe.

The TIGER collaboration has found that when their derived source abundances are plotted relative to the 20%/80% mix noted above (with the 20% outflow from massive stars calculated from [8]) instead of relative to solar system abundances, a much improved ordering and separation of volatile and refractory elements is obtained [4] compared to that presented in [3]. The

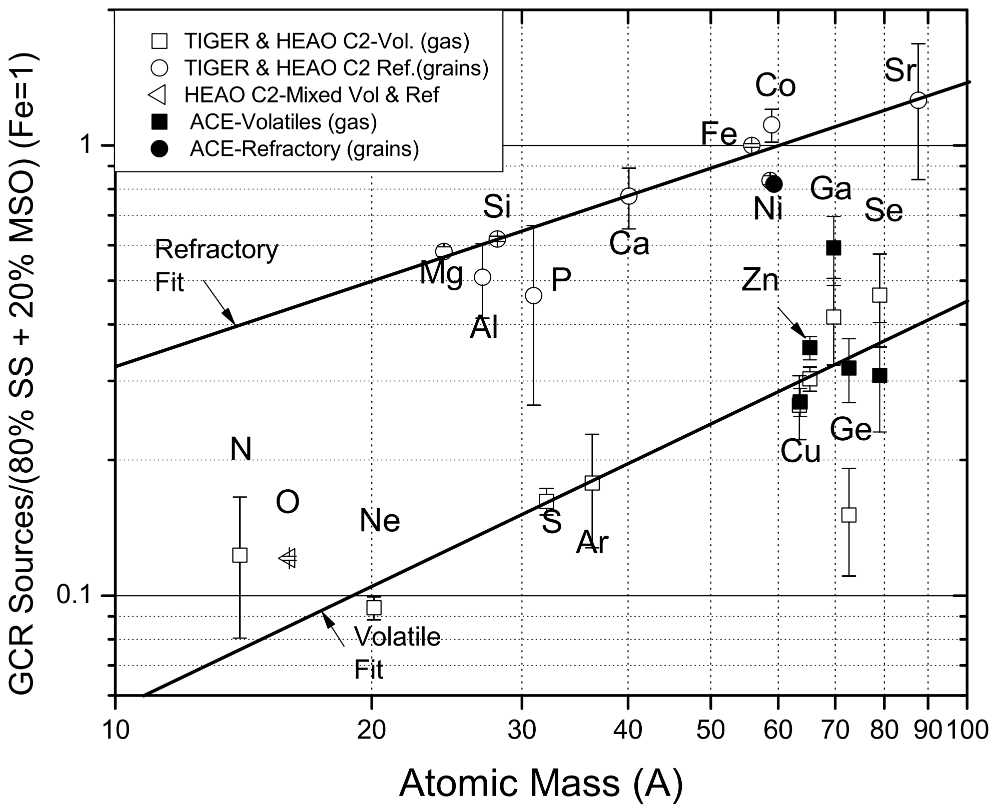

Fig. 4. The galactic cosmic ray source abundances obtained by propagation back to the source relative to a mix of 20% of material from the outflow from massive stars (MSO) and 80% solar system (SS) material is plotted vs. atomic mass. Closed square and round symbols are ACE-CRIS abundances for volatile and refractory elements, respectively. Open square and round symbols are TIGER and HEAO-3 C2 abundances [4] for volatile and refractory elements, respectively. The error bars on the CRIS data are statistical only. The solid lines are fits to the TIGER and HEAO-3 C2 volatile and refractory element abundances [4].

data obtained by TIGER, combined with the earlier data presented in [6], are shown in Figure 4 as open symbols. The elements which are classified as volatiles are shown as open circles and the refractories as open squares. The CRIS data are plotted as closed squares for volatiles and as a closed circle for the single refractory element, nickel. All abundances are normalized to iron=1.0. The straight lines that are shown are power laws fit to the TIGER and earlier data [4]. We see that the CRIS abundances agree very well with TIGER abundances for Ni, Cu, Zn, Ga, and Se within the errors. As was previously noted, Ge appears to have a higher abundance in the CRIS data than for TIGER. The effect of this is to move Ge up onto the fitted line, where in the TIGER data Ge falls significantly below the fitted line. The CRIS Ga data point, although in statistical agreement with the TIGER measurement, lies significantly above the volatile element line.

IV. Conclusions

In general, the CRIS data are in good agreement with TIGER on the crucial points. These are 1) the abundances of Ga and Ge are approximately equal, likely resulting from s-process enhancement in massive star outflow [9], and 2) the CRIS data generally confirm the improved ordering of volatile and refractory elements when abundances are compared to the 20%/80% mix. We conclude that the CRIS data presented here tend to confirm the OB association origin of most galactic cosmic rays.

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