Measurements of the Ultra-Heavy Galactic Cosmic-Ray Abundances between Z=30 and Z=40 with the TIGER Instrument.

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Abstract

The Trans-Iron Galactic Element Recorder (TIGER) instrument was launched in December 2001 from McMurdo, Antarctica. TIGER is a cosmic-ray telescope that uses four scintillation counters, two Cherenkov detectors and a scintillating fiber hodoscope to determine the charge (Z) and energy of a particle. During the 31.8 day flight it measured ≈100 ultra-heavy galactic cosmic-ray (GCR) events with $Z > 30$ and demonstrated charge resolution sufficient to resolve the individual elemental abundances in this region. The abundances of the Ultra-Heavy GCRs in this range can be used to distinguish between GCR source models. We present our measurements and discuss the implications for the GCR source.

1. Introduction and Scientific Motivation

It is generally believed that supernova shocks are the acceleration source for cosmic rays whose energy per nucleon is less than about 10^{14} eV. The exact source material from which cosmic rays are accelerated is still uncertain. Present measurements of the GCR abundances show that they are remarkably similar to the abundance of elements that we measure in our solar system. However, there are distinct differences for some elements between their GCR source and Solar System abundances. These differences suggest a preferential acceleration based on the first ionization potential (FIP) or on an element's volatility. Each of these models points to a different cosmic-ray material source [6].

Elements with FIP less than about 10 eV are more abundant in the cosmic-ray source compared with the solar system. This observation has led to the idea that GCRs may originate in stellar atmospheres in regions with temperatures at about 10^4K. Elements with a low FIP are more likely to be ionized and injected

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into the accelerator than elements with high FIP [7].

However, it has also been observed that the GCR elmental abundances can be ordered by their "volatility" [6]. In this model, the cosmic-ray source is interstellar gas enriched by atoms sputtered off of accelerated interstellar dust grains. The dust grains will have a higher rigidity at a given velocity than atoms and thus are more easily accelerated by supernova shocks. The elements that form these grains will therefore be enriched in the cosmic rays.

Since most low-FIP elements are refractory and most high-FIP elements are volatile, it is difficult to differentiate between these two models. There are a few elements that are both low-FIP and volatile or semi-volatile that break this degeneracy and can enable us to distinguish between models [6]. Several of these are ultra-heavy GCRs including $_{30}$Zn, $_{31}$Ga, $_{32}$Ge, $_{37}$Rb, $_{50}$Sn, $_{55}$Cs, $_{82}$Pb and $_{83}$Bi.

The best current measurements for GCRs over the range $30 \leq Z \leq 40$ come from the HEAO-C3/Ariel-6 results [2],[4]. Unfortunately these instruments lacked the charge resolution required to separate odd-Z and even-Z elements. In addition the HEAO-C2 experiment [3] provided a measurement for the lower part of this range but was very limited by statistics. The TIGER instrument was designed to have the necessary charge resolution to resolve elements in this region in order to make, for the first time, a measurement of the elemental abundances of all elements in this charge range.

2. The TIGER Instrument

TIGER is a balloon-borne cosmic-ray telescope consisting of four plastic scintillation detectors, two Cherenkov detectors and a scintillating fiber hodoscope. A cross section of the instrument is Figure 1. The scintillators are made of BC-416 (Saint-Gobain) of thickness of 0.8 cm. Each scintillator is read out by four wavelength shifter bars (WLSB) placed around the edges of the detector. A 2.5-cm-diameter Hammamatsu R1924 PMT is coupled to each end of each WLSB. The top Cherenkov detector, C0, has a 3 cm thick aerogel radiator with index of refraction n=1.04 and the bottom Cherenkov detector, C1, has an acrylic radiator made of BC-480 with thickness 1.2 cm and n=1.5. Each Cherenkov detector has twenty-four 12.7 cm diameter Burle S83006F PMTs. The hodoscope is made from 1-mm square scintillating optical fibers, bundled into 6-mm groups, coded and coupled to twenty-eight 2.5-cm-diameter Hammamatsu R1924 PMTs on each layer. The four layers of fibers, two on top and two on the bottom, provide an x-y location at the top and bottom of the detector with a calculated root-mean square position resolution of 0.17 cm.

This combination of detectors allows us to determine the charge and energy of a particle incident upon the instrument. The top two scintillation counters provide the primary dE/dx measurement while the bottom scintillation counters allow the identification of nuclei that interact in the instrument. The Cherenkov

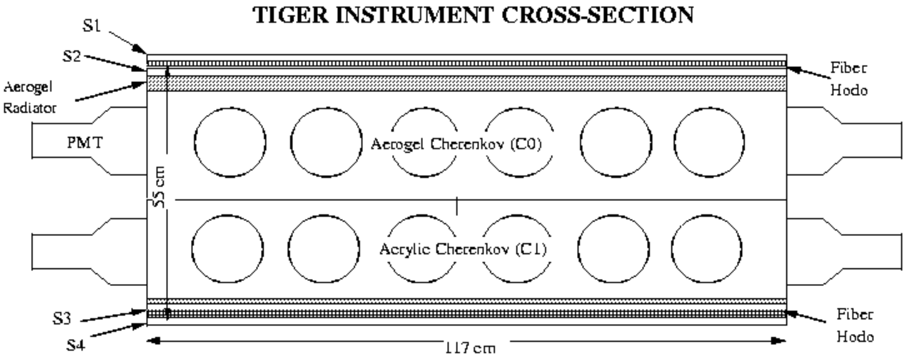

Fig. 1. TIGER Instrument Cross-section.

detectors with the scintillators and hodoscope determine the particle's charge and energy. Two Cherenkov detectors with different radiators are used to extend the energy range over which we can clearly resolve the charge and energy of particles. The scintillating fiber hodoscope allows us to determine the trajectory of a particle through the detector permitting pathlength and mapping corrections.

3. Results of the 2001 Flight

TIGER was launched on a long duration balloon (LDB) from McMurdo, Antarctica in December 2001. The flight lasted for a record 31.8 days at an average altitude of 118,000 feet. During the flight approximately 360,000 iron nuclei and 300 nuclei with $30 \leq Z \leq 40$ were measured.

Figure 2 is a charge histogram of data from this flight. Note that the y-axis scale on this plot changes at Z=29 since the ultra-heavy elements ($Z \geq 30$) are much less abundant than the lighter elements. We have very clearly resolved peaks in the heavy-element region. In the ultra-heavy region we see clear charge peaks for elements with Z=30, 31, 32 and 34. For heavier nuclei increased number of particles are needed to see peaks. We expect to increase our statistics with another flight planned for December 2003 in Antarctica.

The abundances of the elements for $30 \leq Z \leq 40$ were determined using a maximum likelihood fitting routine. These were corrected for interactions in the instrument and are compared in figure 3 to propagated abundances using Solar System source abundances [1] fractionated by FIP and volatility. The FIP fractionation model used is from Binns [2] while the Volatility fractionation is based on Meyer[6]. The propagation uses a weighted-slab leaky-box model [8]. These abundances are propagated through the ISM and to a depth of 5 g/cm^2 in the atmosphere.

From Figure 3, we see that the measured elemental abundances are in

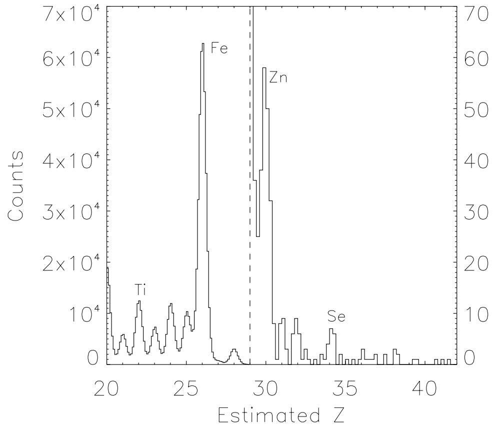

Fig. 2. Histogram of TIGER Data

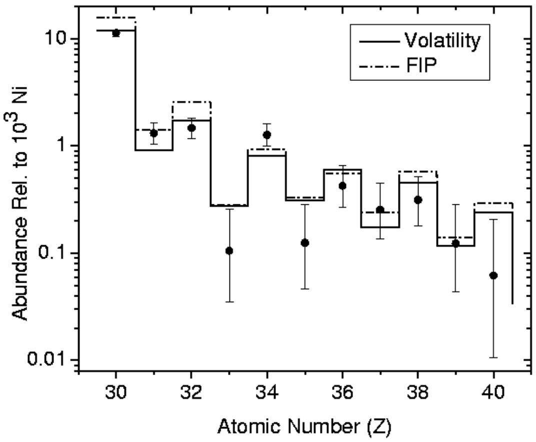

Fig. 3. Comparison of TIGER data to FIP and Volatility models.

good agreement with the propagated solar system abundances modified by FIP or volatility. In more detail, we see that the Z=30 and Z=32 abundances measured by TIGER are in good agreement with the volatility model. Z=31 agrees better with the FIP model, but is only ≈1.5 sigma from the volatility model. Overall those elements that distinguish between FIP and volatility models appear to favor volatility. However additional data are required to improve the statistical significance of our measurements. We are currently working on comparisons of our data with propagations using new solar system abundances [5] and updated FIP and volatility models. These will be presented at the conference.

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4. References

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