Proceedings of ICRC 2001: 2143 © Copernicus Gesellschaft 2001

ICRC 2001

Measuring the abundances of ultra-heavy galactic cosmic rays through ultra long duration ballooning

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TIGER is a cosmic-ray detector consisting of several scintillator and Cherenkov light boxes and a scintillating fiber hodoscope. It will be able to measure the elemental abundances of GCRs with $26 \leq Z \leq 40$ and energies above 300 MeV/nucleon. TIGER will measure the individual abundances of the odd-Z elements between Z=30 and Z=40 for the first time. These odd-Z nuclei are important for distinguishing between the effects of first-ionization potential and volitilty in the injection process, for models of nucleosynthesis and constraining models of cosmic-ray propagation at short pathlengths. We will discuss some of the scientific questions we hope to be able to address with the TIGER mission

1 Introduction

The Trans Iron Galactic Element Recorder (TIGER) is a balloon-borne cosmic-ray instrument designed to measure the individual elemental abundances of galactic cosmic rays (GCRs) from $16 \leq Z \leq 40$. It is expected to provide the first individual elemental abundance measurements of odd-Z GCR nuclei with $30 < Z < 40$.

TIGER was selected as the first scientific payload to fly onboard an Ultra Long Duration Balloon (ULDB) in December of 2001. Due to the failure of the full scale ULDB balloon in its test earlier this year, we are instead planning to fly TIGER on a long duration balloon (LDB) flight in December 2001 from McMurdo Base in Antarctica. We hope to obtain a flight of approximately 30 days this year with a flight of two revolutions around the continent, followed by an additional flight in 2003.

TIGER also serves as an engineering model for the Energetic Trans-Iron Composition Experiment (ENTICE) module of the Heavy Nuclei Explorer (HNX) mission. (Binns, et. al., 2001) HNX has been selected for a mission concept study, now under way, for a NASA Small Explorer Mission. The objective of HNX is to measure the abundances of elements with $10 \leq Z \leq 100$.

2 Scientific Motivation

There is a general consensus that cosmic rays with an energy per nucleon less than about 10^{14} eV are accelerated by supernova shocks. The source of the material for the cosmic rays and the mechanism that injects them into the accelerator is still an outstanding question. From our present measurements of the GCR abundances we can infer the elemental abundances at the cosmic-ray source. If we compare the inferred cosmic-ray source abundances with the measured abundance of elements in our Solar System we find that the two are remarkably similar. However some of the elements at the cosmic-ray source are more abundant than in the solar system, which has led to two models of preferential acceleration. Each of these models points to a particular cosmic-ray material source.

It has been observed that the abundances of elements with a first ionization potential (FIP) less than about 10 eV are seen to be greater in the inferred cosmic-ray source than the

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measured solar system abundances. This observation led to the first model in which the GCR source material are particles in stellar atmospheres at temperatures of about 10^4 K where elements of low-FIP are more likely to be ionized than elements with a high-FIP. (Casse & Goret, 1978)

The second model suggests instead that the source is interstellar gas enriched by atoms sputtered off of interstellar dust grains. (Cesarsky & Bibring, 1981) In this model volatility governs cosmic-ray fractionation, and refractory elements are enhanced in the GCRs. Because most low-FIP elements are refractory, differentiation between these two models is difficult. There are a few rare elements that are low-FIP and volatile or semi-volatile that break this degeneracy. These elements include ^{32}Ge, ^{37}Rb, ^{50}Sn, ^{55}Cs, ^{82}Pb and ^{83}Bi. (Meyer, et. al., 1997)

TIGER will have sufficient collecting power and resolution to measure the abundances of both ^{32}Ge and ^{37}Rb. The elemental abundance of ^{32}Ge was measured by the HEAO-3 and Ariel-6 experiments and the result was suggestive of volatility being the governing factor in GCR fractionation. (Binns, et. al., 1989, Fowler et. al., 1987) More measurements, however, are needed to truly understand which is the governing mechanism. TIGER will help provide these measurements, though further measurements of the higher-Z GCRs will be needed for this question to be fully answered.

TIGER will also be able to provide a measurement of the elemental Co/Ni ratio. An earlier 23 hour flight of TIGER in 1997 was able to measure this ratio. The result suggested that most of the ^{59}Ni had not decayed suggesting a short time delay of less than $7.6*10^4$ years between nucleosynthesis and acceleration. (Sposato, et. al., 2000) This is in conflict with the definitive measurements by the ACE-CRIS instrument, which is able to measure the ^{59}Ni and ^{59}Co isotope abundances directly. (Wiedenbeck et. al., 1999) Due to the low statistics and limited resolution of the TIGER 1997 instrument there were large error bars on the TIGER Co/Ni measurement. The TIGER 1997 measurement was also made at a mean energy of about 2 GeV/nucleon while the ACE-CRIS measurement was made at energies of several hundred MeV/nucleon. The TIGER 2001 instrument will collect a sufficient number of particles to measure this element ratio as a function of energy for 300 Mev/nucleon < E < 7 GeV/nucleon which should help to resolve this issue.

3 The TIGER Instrument

TIGER was flown for 23 hours at float in September of 1997. This flight provided measurements of the GCR abundances and demonstrated that the TIGER instrument had the necessary resolution to measure GCRs heavier than iron as shown in Figure 1. We have refurbished and upgraded the TIGER instrument based on the results of the 1997 flight. TIGER consists of four plastic scintillation counters, two Cherenkov counters with radiators of different refractive indicies and a scintillating fiber trajectory detector (hodoscope). A cross-sectional view of the instrument is shown in Figure 2.

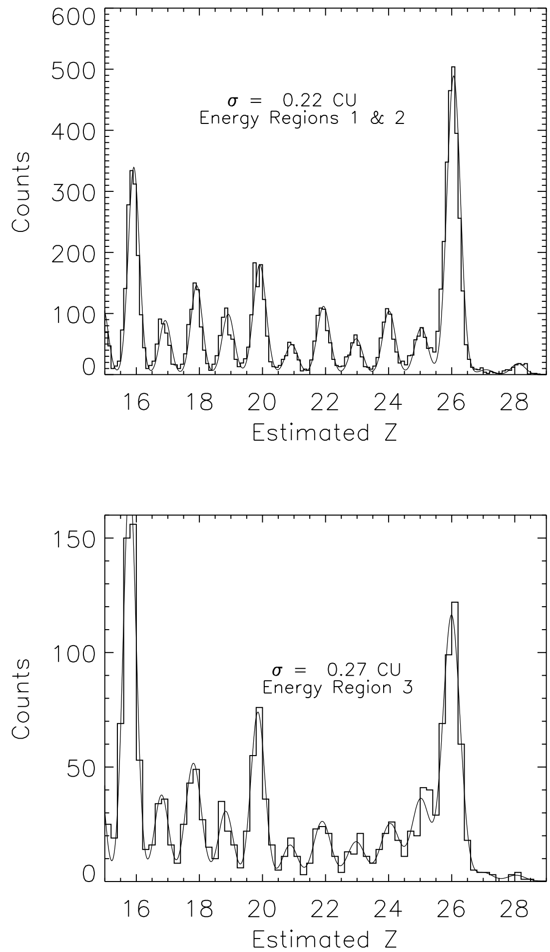

Figure 1. Charge Resolution for the 1997 TIGER instrument, which flew for one day out of Ft. Sumner New Mexico. The top plot shows the charge resolution for particles with energy less than 4.3 GeV/nucleon. The bottom plot shows the resolution for particles with energy greater than 4.3 GeV/nucleon. We expect to obtain better charge resolutions for the TIGER 2001 instrument.

The top three TIGER scintillator counters provide the primary dE/dx measurement while the bottom scintillator allows us to identify nuclei that have interacted in the detector. Each of these scintillation detectors is composed of a cast radiator 116 cm square and 0.8 cm thick made of BC-416, a blue-emitting scintillator. Four wavelength shifter bars (WLSBs) (Bicron BC482A) surround the perimeter of each scintillator. Particles traversing the scintillator cause blue scintillator light to be produced and emitted isotropically. A fraction of this light is totally internally reflected to the edges of the radiator where it enters the WLSB. The WLSB absorbs a large fraction of this light and re-emits it isotropically as green light. A portion of this re-emitted light is totally internally reflected and lightpiped to Hamamatsu R1924 photomulitiplier tubes

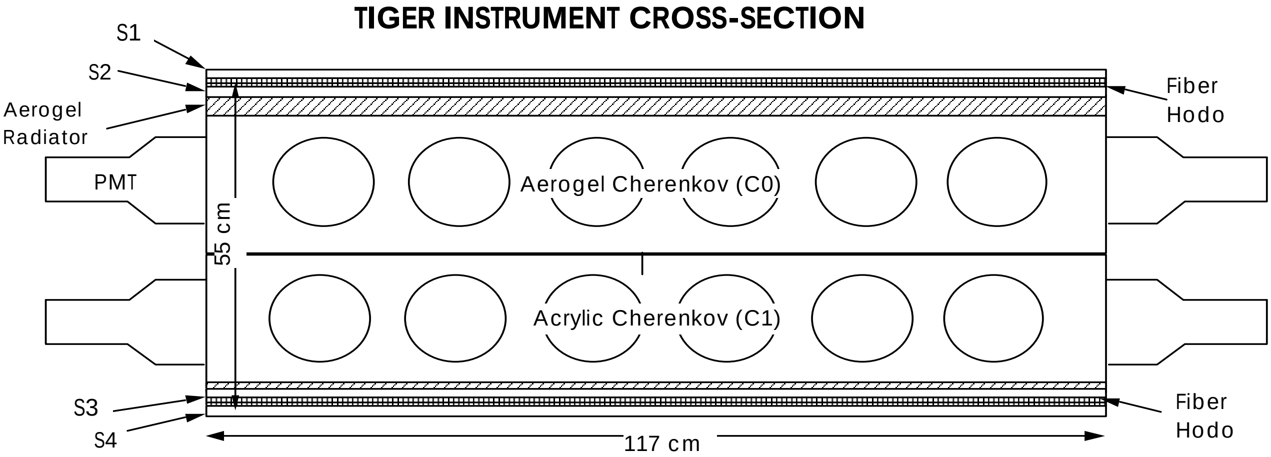

Figure 2. A cross-section of the TIGER Detector. S1 and S2 are the top scintillator detectors, S3 and S4 are the bottom scintillation detectors. The TIGER instrument is about 117 by 117 cm square and 55 cm high.

(PMTs) coupled to each the ends of the WLSB. This design allows us to measure the light from this 115 cm^2 detector with just eight one-inch-diameter PMTs. The analog signal from each PMT is amplified and digitized by a custom built pulse height analyzer (PHA) designed at Washington University.

The two Cherenkov detectors have radiators with different refractive indices. The top radiator is 3-cm-thick aerogel (n=1.04), while the bottom radiator is UVT acrylic (n=1.5) with blue waveshifter dye added. Each Cherenkov counter has a set of 24 RCA 83006 PMTs (5" diameter) placed around the edges (6 to a side). These tubes detect the Chrenkov light produced when a particle passes through the radiator. Each tube is individually pulse height analyzed. When used in conjunction with the scintillation counters we can obtain a measurement of an incident particle's charge and energy over the range 0.3 to 10 GeV/nucleon. This is due to the fact that while the signal from the Cherenkov and scintillator counters are proportional to Z^2, while the functional relation between the signal and velocity differ. Using two Cherenkov detectors with different refractive indices allows us to extend the range over which we can make a charge and velocity measurement.

The fiber hodoscope is composed of four 117cm x 117cm planes of scintillating optical fibers. When a high-energy particle transverses the detector it hits fibers in each of the four hodoscope planes. The fibers scintillate and a fraction of the light from them (about 5%) is lightpiped and detected by the Hamamatsu R1924 PMTs coupled to each end of the fibers. The fibers are 1mm square and grouped in tabs of six fibers giving us 196 tabs for each hodoscope plane. Rather than couple each fiber tab to a PMT, we use a coding scheme to decrease the total number of PMTs needed for readout. (Lawrence et. al., 1999) On one end of the hodoscope, tabs 1-14 are coupled to the first PMT, tabs 15-29 are coupled to the second tube, and so until all 196 tabs are coupled to 14 PMTs. On the other end we take tabs 1, 15, 29 etc. and couple them to the first PMT, tabs 2, 16, 30 etc. couple to the second PMT, and so on until all the tabs on the other edge are coupled to a second set of 14 PMTs. This coding scheme ensures that each fiber tab is read out by a unique pair of PMTs,
allowing us to read out the active area of all four of the hodoscope layers with only 112 PMTs (28 for each layer). Each tube is individually pulse height analyzed allowing us to precisely determine which fiber tab was hit. The four fiber planes yield an x and y measurement at the top and bottom of the detector which allows us to determine the straight line trajectory of a particle passing through the detector with position segments of 6mm width (corresponding to a resolution, σ = 1.7mm).

The TIGER electronics is composed of 192 pulse height Analyzers (PHAs), a relay control system, a housekeeping and calibration system, a high and low voltage power system and a PC104 CPU stack which provides I/O control for the PHAs, power control system, housekeeping and calibration. The CPU also interfaces with the ballooncraft scientific interface package (the SIP) through which we can send data to be sent to the ground or saved to a hard disk as well as receive commands from the ground. All of the TIGER electronics has been tested to ensure it functions over a wide temperature range (-40^{o}C to 50^{o}C). Furthermore, as we will be flying unpressurized, all electronics and the components of the high voltage system have been tested at ambient balloon altitude pressures (~3-6 mmHg). We have also done extensive ground testing of the detector readout electronics to ensure we understand its behavior as a function of temperature. Furthermore we have the ability to do an in-flight calibration by stimulating all detectors with blue LEDs.

The numbers of events that we expect to collect in a a 30 day flight in Dec. 2001 near solar maximum and the combined total number of events that we would expect to collect in the 2001 flight and a those subsequent 30 day flight in Dec. 2003 during the transition to solar minimum

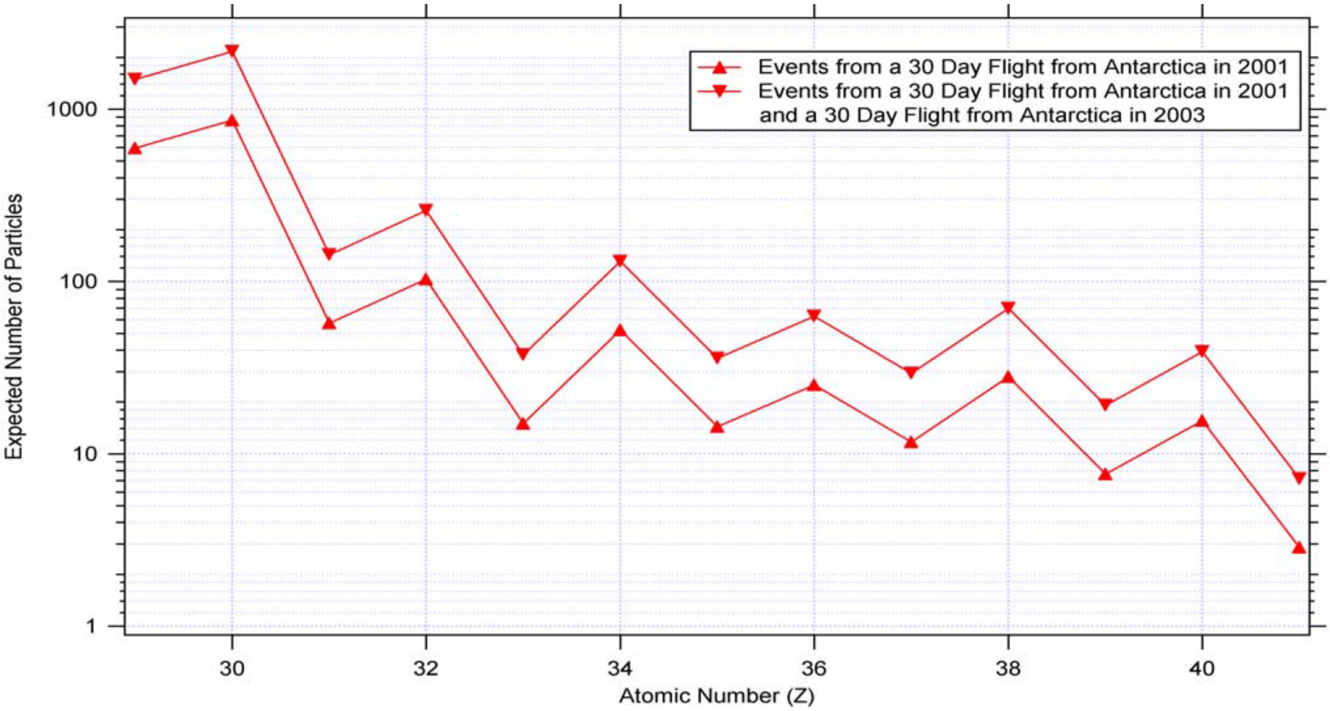

Figure 3. Expected number of events with Z between 29 and 41 expected for the TIGER 2001 instrument.

are plotted in Figure 3. The geometry factor of TIGER is ~$1.9 m^2 sr$. The numbers of particles in the second flight were estimated to be 1.5 times that obtained in the first flight at solar maximum. The events numbers are calculated using the HEAO-3 measurements for even-odd pairs of elements, with the even-odd ratios obtained from FIP adjusted solar system abundances propagated in a leaky box model. (Waddington, C.J., 2001) Events interacting in the instrument are not included in the estimates shown in Figure 3.

Acknowledgements. This research was supported by the National Aeronautics and Space Administration under grant NAG5-5078. J.T.L was further supported by a NASA GSRP grant NGT5-50240.

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