SuperTIGER Ultra-Heavy Galactic Cosmic Ray Atmospheric Propagation Corrections and Uncertainty Analysis

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Abstract

The SuperTIGER (Super Trans-Iron Galactic Element Recorder) balloon-borne ultra-heavy galactic cosmic-ray (UHGCR) detector has flown twice in the stratosphere over Antarctica at altitudes up to $\sim$130,000 ft. Corrections for propagating through the last $\sim$0.5% of the atmosphere are based on those developed for the preceding TIGER instrument. Changes due to nuclear interactions are determined by finding top of the atmosphere (TOA) elemental abundances that yield those measured in the instrument after solving networks of equations for all elements with partial and total charge changing cross sections stepping through fine slabs of material. Varying rates of energy loss in the atmosphere for different elements yield different TOA minimum energies for the acrylic Cherenkov detector threshold ($\sim$350 MeV/nuc). TOA abundances corrected for nuclear interactions for each element are scaled with the fraction of the integral energy spectrum for its TOA minimum energy, using the iron spectrum for the UHGCR. Statistical uncertainties are derived at the TOA by shifting the abundance of each element individually up and down by the measured uncertainty in the instrument and calculating the TOA abundance of that element. Systematic uncertainties previously were estimated by simultaneously shifting the partial and then the total cross sections for all elements up and down by their uncertainties and finding TOA abundances compared to the nominal values. Here we present a plan for a Monte Carlo study of the systematic impact of simultaneously randomly varying atmospheric propagation parameters over many trials to find the normal range of variation in the resulting TOA element abundances. Total and partial charge changing cross sections for each element are individually varied in each sampling.

TIGER and SuperTIGER Flight Trajectories

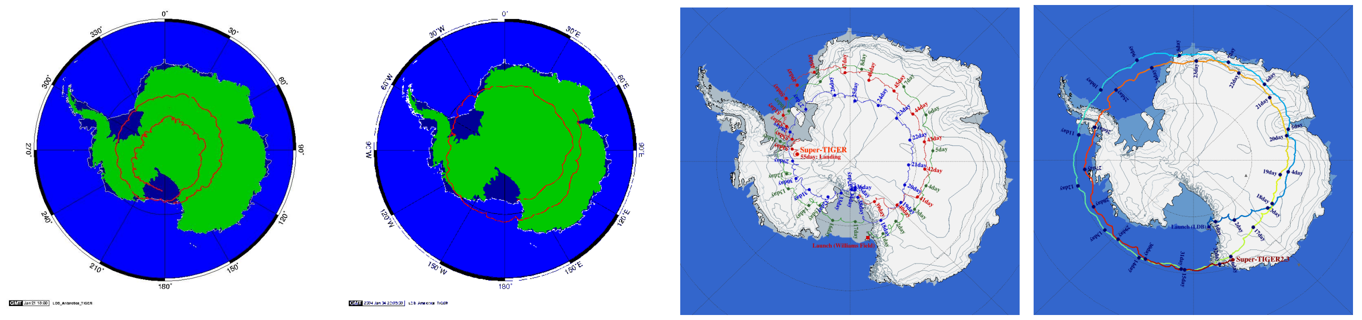

Figure 1: Left to right: TIGER 2001 from Dec 21, 2001 – Jan 21, 2002 for 32 days with 3.7×10^5 $_{26}$Fe, TIGER 2003 from Dec 27, 2003 – Jan 4, 2004 for 18 days with 2.5×10^5 $_{26}$Fe, SuperTIGER 2012 from Dec. 8, 2012 - Feb. 1, 2013 for 55 days with 5.38×10^6 $_{26}$Fe, and SuperTIGER 2019 from Dec. 15, 2019 - Jan. 17 2020 for 32 days with 1.3×10^6 $_{26}$Fe. The UHCR statistics scale with iron.

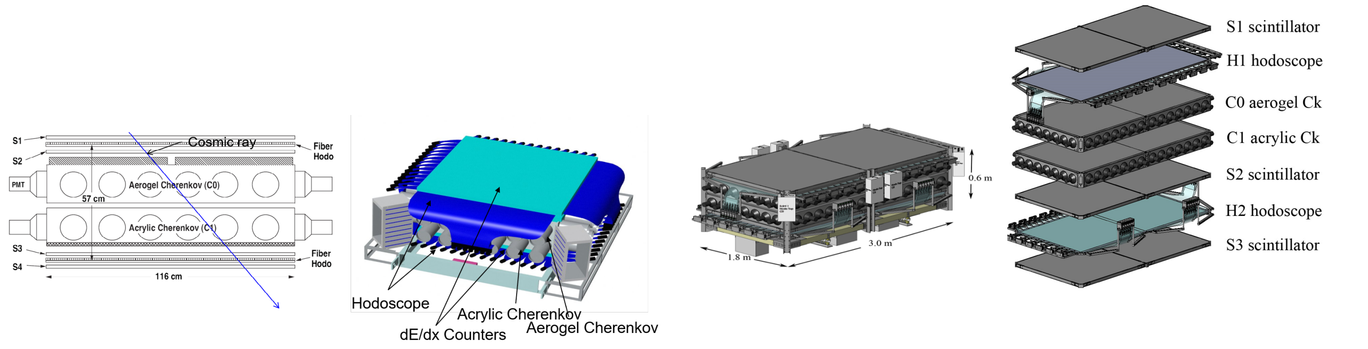

Figure 2: Left to right: TIGER stack, TIGER technical model, one of two SuperTIGER modules, and SuperTIGER module expanded view.

The 2001 TIGER flight had a leaky balloon, and the 2019 SuperTIGER flight took a northerly route and spent a lot of time over the ocean, both of which led to lower altitudes. The inactive material above the top scintillator detectors was modeled with an equivalent depth of atmosphere in the propagation corrections, with 1.31 g/cm^2 for TIGER and 0.1 g/cm^2 for SuperTIGER.

TIGER Altitude Profiles

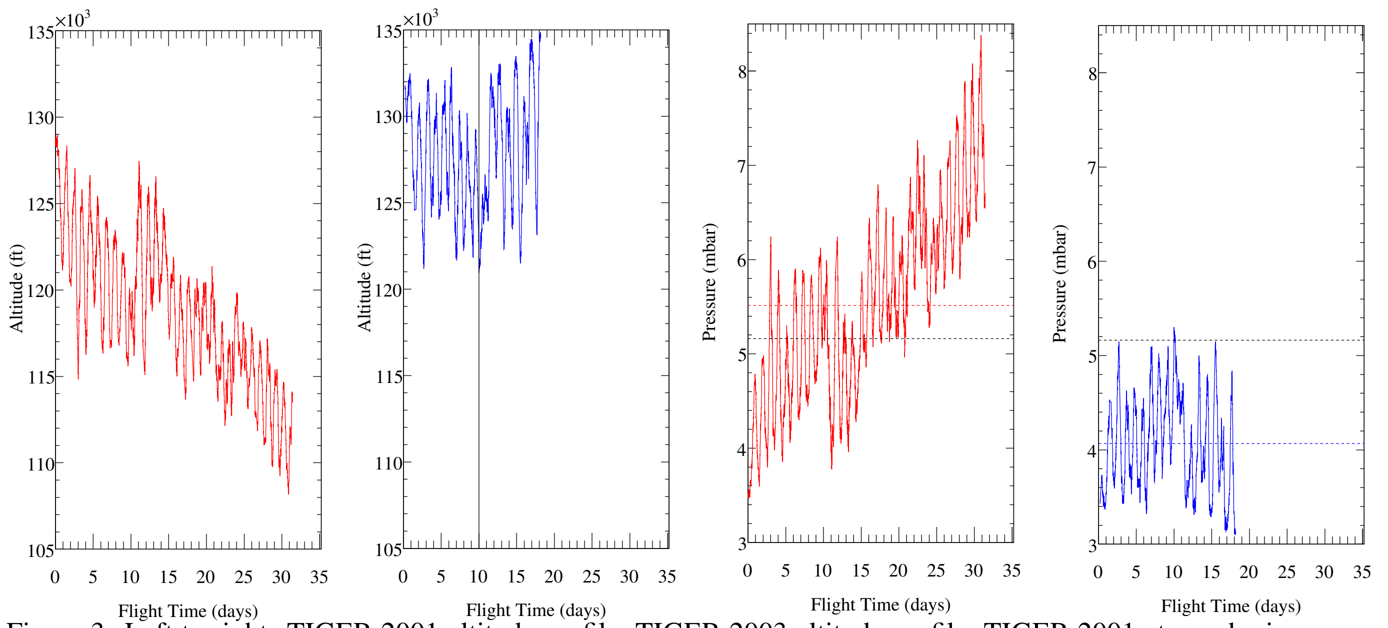

Figure 3: Left to right: TIGER 2001 altitude profile, TIGER 2003 altitude profile, TIGER 2001 atmospheric pressure profile, and TIGER 2003 atmospheric profile.

Due to the limited statistics of the observed UHCR the atmospheric propagation corrections for TIGER [4, 5] and SuperTIGER [1, 2, 6] have been performed with a mean overburden. The average overburden in the TIGER analysis from both flights is shown by the black dashed line.

Charge Changing Cross Sections

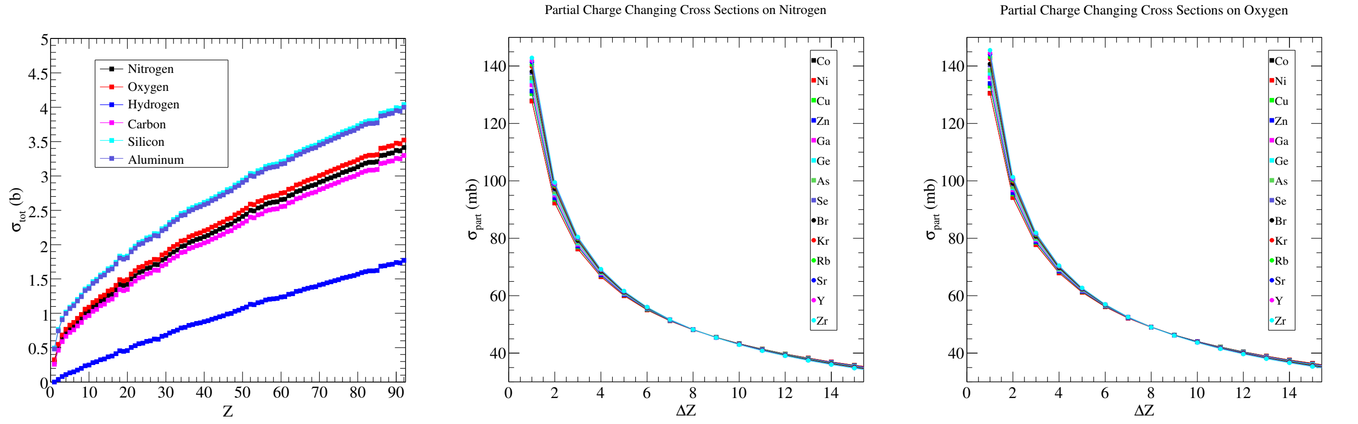

Figure 4: Left to right charge changing cross sections: total and partial on $^{14}_{7}$N and $^{16}_{8}$O.

The total charge changing cross sections are given by $\sigma_{tot}(P,T) = \pi[R_P + R_T - (3.20 \pm 0.05)]^2$, where P and T refer to the projectile and target nuclei, and R_P and R_T are their respective nuclear radii [3]. The partial charge changing cross section is given by

$$\sigma_{\Delta Z}(A_P, A_T, K, \Delta Z) = p_1(A_P^{1/3} + A_T^{1/3} - p_2)(1 + p_3/K)|\Delta Z|^{-p_4[1+A_P^{1/3}/p_5+A_T^{1/3}/p_6+p_7/K]}. \quad (1)$$

The parameters for this equation are taken from Table VIII in the paper [3], and are reproduced in here. The arguments of this equation are the mass numbers of the projectile and target nuclei, A_P and A_T, the charge change of the projectile, ΔZ, and the total kinetic energy of the projectile, K. For the TIGER analysis a value of $K = 2A$ GeV was selected as representative of the average cosmic-ray energies in the atmosphere, and for SuperTIGER $K = 3.1A$ GeV. The proposed Monte Carlo study of the systematic uncertainties in TOA abundances will allow parameters to vary within their ranges for each cross section used in the propagation. Requiring this poster so far in advance of the conference in a particularly busy time means that all I can do is tease the ultimate Monte Carlo study where parameters will be allowed to simultaneously vary randomly. I show results from sensitivity studies where single parameters are varied (atmospheric depth and cross section energy) or cross sections are all shifted up and down by their stated uncertainties.

parameter	value
p_1	21.2 ± 0.5 mb
p_2	1.08 ± 0.15
p_3	$(0.485 \pm 0.014)A$ GeV
p_4	0.094 ± 0.013
p_5	1.11 ± 0.02
p_6	10.8 ± 1.6
p_7	$(0.85 \pm 0.03)A$ GeV
χ^2_ν	2.84
N	1741

TIGER Propagation Systematic Dependencies

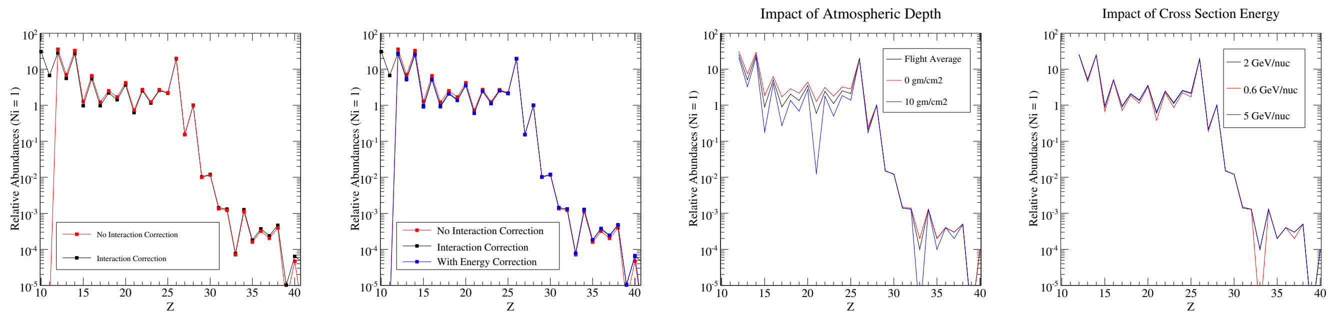

Figure 5: Left to Right: impact of atmospheric interaction corrections on TIGER abundances, impact of interaction corrections with energy loss correction on TIGER TOA abundances, sensitivity of TIGER TOA abundances to atmospheric depth, and sensitivity of TIGER TOA abundances to interaction cross section energy.

SuperTIGER Propagation Systematic Dependencies

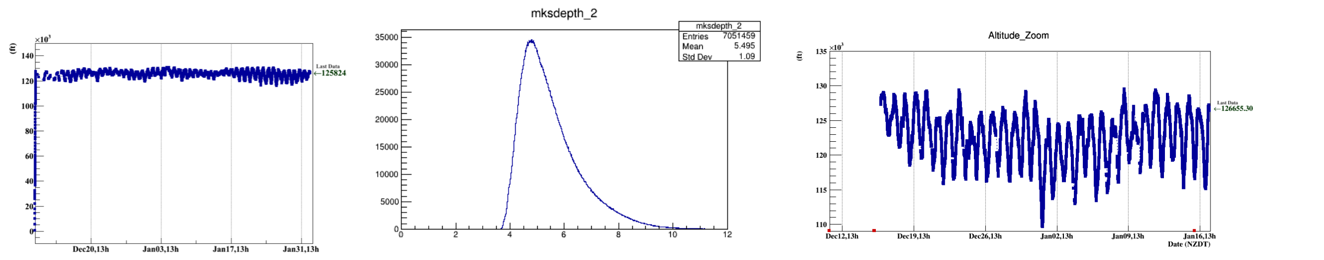

Figure 6: Left to Right: SuperTIGER 2012 altitude profile, SuperTIGER 2012 atmospheric overburden distribution, and SuperTIGER 2019 altitude profile at float.

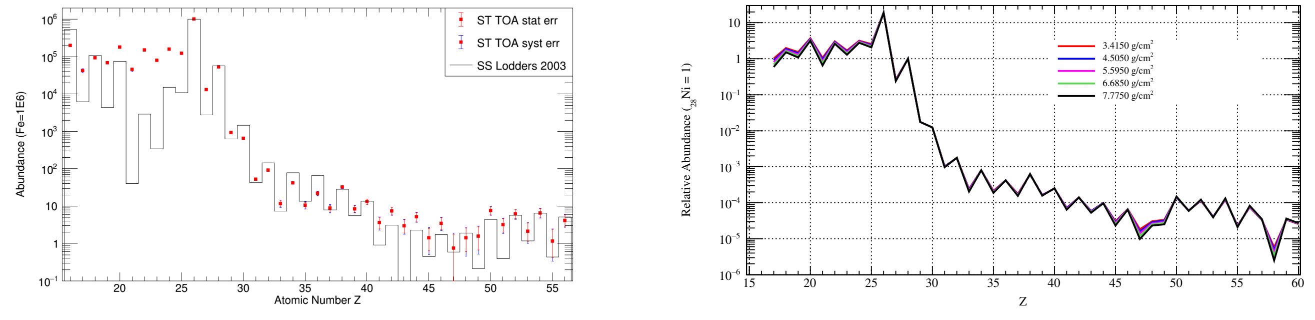

Figure 7: Left to Right: SuperTIGER 2012 TOA relative abundances with systematic error bars based on scaling cross sections up and down by their uncertainties, SuperTIGER 2012 atmospheric propagation correction dependence on assumed depth.

References

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