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Progress on Ultra-Heavy Cosmic-Ray Analysis with CALET on the International Space Station

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Abstract

The Calorimetric Electron Telescope (CALET), launched to the International Space Station in August 2015 and continuously operating since, measures cosmic-ray (CR) electrons, nuclei and gamma-rays. CALET utilizes its main calorimeter charge detector to measure CR nuclei from $_{1}$H to $_{40}$Zr. In order to maximize the acceptance of the rare ultra-heavy (UH) CR above $_{30}$Zn, a special high duty cycle (~90%) UH trigger is used that does not require passage through the 27 radiation length deep Total Absorption Calorimeter (TASC). This provides a 6× increase in geometry factor allowing CALET to collect in 5 years a UHCR dataset with statistics comparable to those from the first flight of the balloon-borne SuperTIGER instrument but without the need for atmospheric corrections. Previous CALET UHCR analyses using time and position corrections based on $_{26}$Fe and a geomagnetic vertical cutoff rigidity selection have shown abundances of even nuclei in agreement with SuperTIGER. To further improve resolution and maximize statistics, a trajectory dependent geomagnetic rigidity selection has been employed here with further work being done to implement a Cash-Karp Runge-Kutta ray tracing method for an improved determination of effective cutoff rigidities. Additional work has also been done to analyze events from the smaller dataset of events that pass through the TASC, which provides energy information and a better charge assignment that will provide higher resolution UH measurements, albeit with lower statistics.

CALET Instrument

The main science objective of CALET is to directly measure the total cosmic-ray electron flux (e^{-}+e^{+}) to the highest energies (1 GeV to 20 TeV) [2, 3, 4, 5, 6] with the main calorimeter (CAL), shown in the CALET instrument package in Fig. 1a. The calorimeter is also capable of measuring gamma rays (10 GeV to 10 TeV) [7, 8, 9] and cosmic-ray nuclei (up to 1,000 TeV) [10, 11, 12, 13, 14].
The instrument is comprised of three detector systems: (Fig. 1b)

- The charge detector (CHD), comprised of an x and y layer with 14 scintillator paddles. Each paddle is 32 mm wide by 10 mm thick by 450 mm long. Provides the primary particle charge identification.
- Below that layer is the imaging calorimeter (IMC), which is 156.5 mm tall and made of 8 layers of x and y scintillating fibers that are 1 mm square and 448 mm long. Utilized for track reconstruction
- The total absorption calorimeter (TASC). This is made of 6 x and y layers of 16 lead tungstate (PWO) scintillator logs which gives a determination of particle energy.

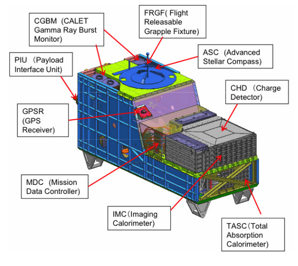

Figure 1(a): CALET instrument package detailing location of various CALET subsystems.

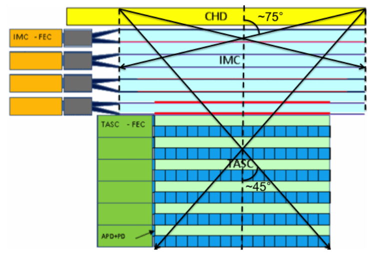

Figure 1(b): CALET side-view showing CHD, IMC, and TASC detector placement with the maximum acceptance angles for detection. In the UH trigger analysis this is 75°and in the TASC analysis this is 45°.

Acknowledgments

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Ultra Heavy Cosmic Rays

The measurement of ultra-heavy cosmic rays (UHCR), $_{30}$Zn and higher charge elements, provides insight into the origins of cosmic rays. In Fig. 2, the relative abundances of elements ($1 \leq Z \leq 40$) for cosmic rays with energies of 2 GeV/nucleon are compared with the Solar System (SS) abundances normalized to $_{14}$Si. These two samples of galactic matter are nominally consistent, with most of the differences accounted for through both cosmic ray spallation between source and detection and by acceleration efficiencies. In the cosmic rays we see that $_{26}$Fe is ~5×10^{3} times less abundant than $_{1}$H, and that the UHCR with charges $30 \leq Z \leq 40$ are ~10^{5} times less abundant than $_{26}$Fe. Single-element resolution UHCR measurements have so far only been made up to $_{40}$Zr by the TIGER [15] and made up to $_{56}$Ba by SuperTIGER [17] balloon-borne instruments at GeV/nuc energies, and up to $_{40}$Zr by the ACE-CRIS [18] space based instrument at hundreds of MeV/nuc. The UHCR composition shows enhancement in material produced in massive stars, both from stellar outflows during the stars' lives and in the ejecta from supernova. This suggests that a significant fraction of the cosmic rays originate in OB associations, which is where the majority of supernova that are believed to accelerate the galactic cosmic rays occur. The fact that the cosmic-ray source appears to be enhanced in massive star material compared to SS would suggest that UHCR observations can help constrain the relative contributions of supernovas and binary neutron star mergers to the heavy r-process elements.

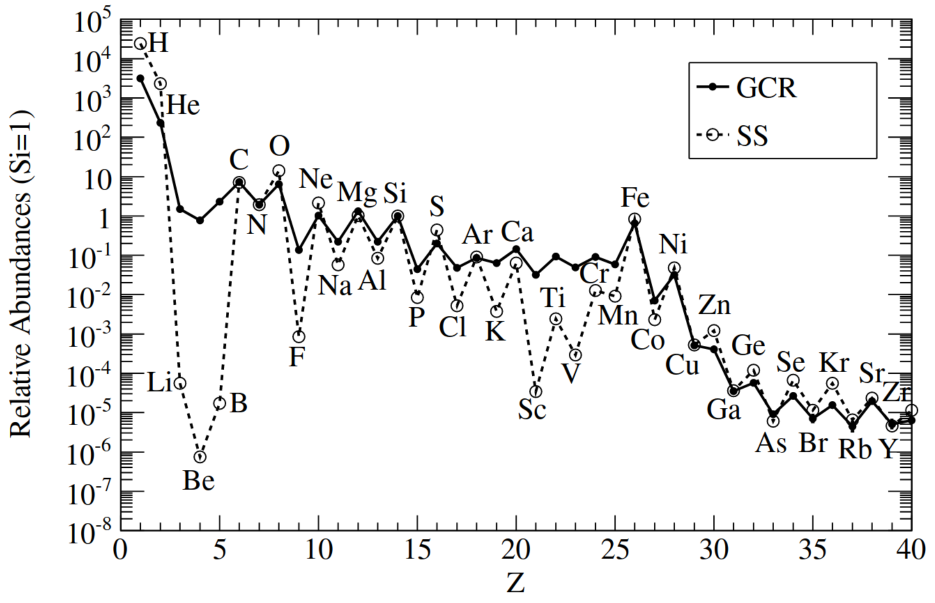

Figure 2: Solar System (SS) [19] and Galactic cosmic-ray (GCR) relative abundances at 2 GeV/nuc. GCR data is sourced for $1 \leq Z \leq 2$ from [20], Z = 3 from [21], $4 \leq Z \leq 28$ from [22], Z = 29 from [15], and $28 \leq Z \leq 40$ from [16] and normalized to $_{14}$Si.

Rigidity Results

A model for the geomagnetic field has been implemented that provides the field strength as a function of time, latitude, longitude, and altitude, and then takes in the angle of detection in the frame of the Earth's magnetosphere to provide an angle-dependent minimum rigidity for all CALET UH events.
These calculated rigidity values are then used in the overall UH analysis.

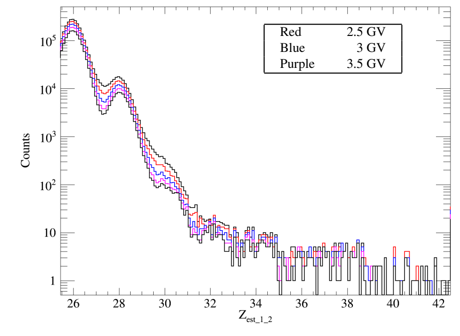

Figure 3(a): Variation in Z due to different minimum cutoff rigidity, bin size in 0.1 units of charge. Minimum cutoff rigidity ranges from 2-4 GV with 2.5 in red, 3 GV in blue, and 3.5 GV in purple.

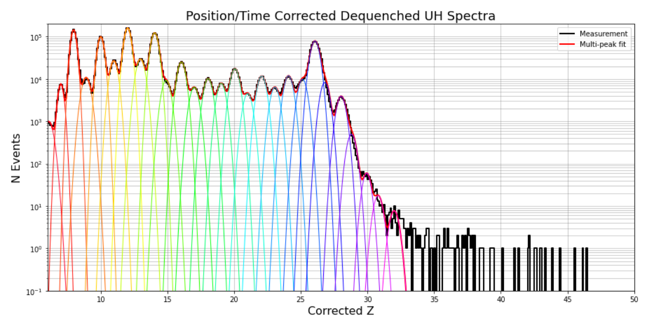

Figure 3(b): Charge histogram produced through L-Shell determination of rigidity. Minimum rigidity threshold of 4 GV bin size in 0.1 units of charge.

TASC Analysis

Since the last ICRC, work has begun on a complementary analysis via the data set of events that pass through the TASC, which provides each event with an energy. In this analysis cuts are done for:

- minimum total deposited TASC energy
- minimum TASC first x and third x layer energy
- charge consistency between CHD x and y of $\leq$ 2.00%

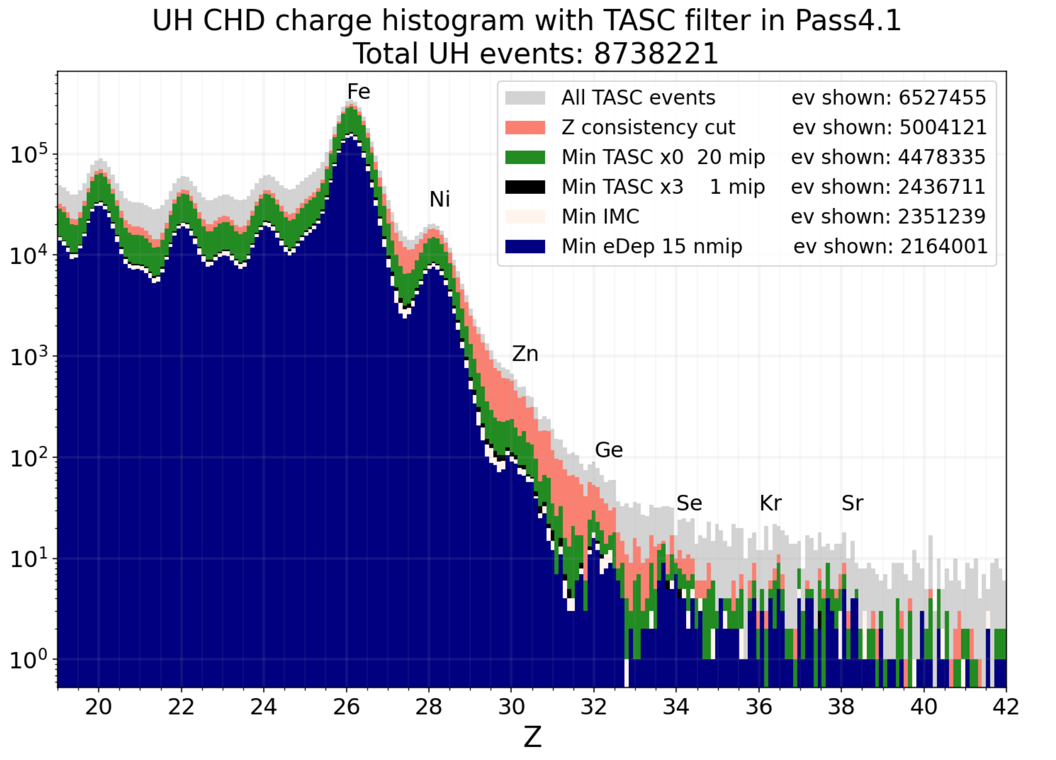

Figure 4: A charge histogram showing what each successive cut on the TASC data-set does step-by-step from a charge consistency cut that requires both x and y layers to be within 2.00%, cuts on multiple layers of the TASC and IMC, as well as a minimum TASC energy.

A Tarle model charge assignment [25] is done and the abundances are then determined by a multiple-Gaussian fit with integer charge means shown in Fig. 5a. By comparison with the histograms in Figs. 3a and 3b, you can see that there is an improved resolution of higher charge peaks without much of a loss in statistics, and in Fig. 5b the relative abundances of the odd-even pairs ($_{27}$Co & $_{28}$Ni, $_{29}$Cu & $_{30}$Zn, etc.) are compared to both ACE-CRIS's preliminary top-of-instrument [18] and SuperTIGER's top-of-atmosphere abundances [26]. Future work on this will incorporate time and position corrections similar to the those done for the CHD in the UH-trigger analysis and do a charge assignment by bins of deposited energy in the TASC.

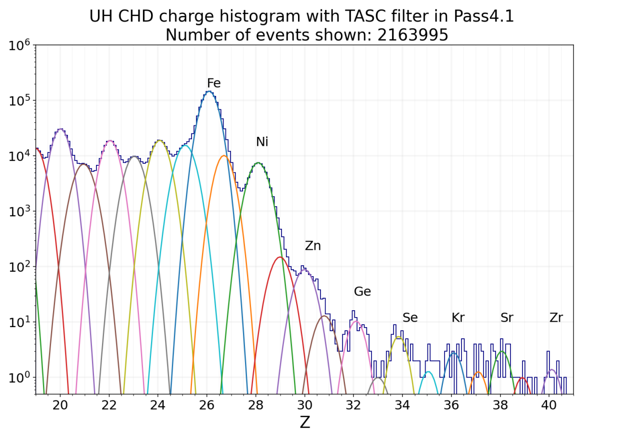

Figure 5(a): UHCR TASC analysis histogram with multiple gaussian fitting, bin size in 0.1 units of charge.

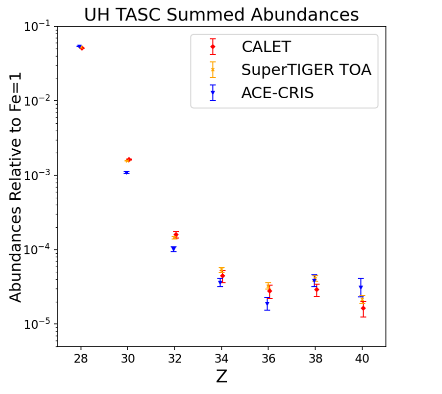

Figure 5(b): Comparison of the relative abundances of the summed odd-even pairs with SuperTIGER[26] and ACE-CRIS[18] for Z between $27 \leq Z \leq 40$. Errors bars are statistical only.

Conclusions

Preliminary abundances from CALET UH-trigger and TASC UHCR analyses continue to agree with previous CALET results and other instrument measurements. CALET continues to output excellent data from the International Space Station, and it is expected to continue operating for several more years. This further data-collection will allow improved statistics for CALET to contribute to the total UHCR data set, and complement the measurements made by other balloon and space-borne instruments.

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