

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

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The Calorimetric Electron Telescope (CALET), launched to the ISS in August 2015 and in continuous operation since, measures cosmic-ray (CR) electrons, nuclei, and gamma rays. CALET, with its 27 radiation length deep Total Absorption Calorimeter (TASC), measures particle energy, allowing for the determination of spectra and secondary to primary ratios of the more abundant CR nuclei through ^{28}Ni , while the main charge detector (CHD) can measure Ultra-Heavy (UH) CR nuclei through ^{40}Zr . Previous CALET UHCR analyses used a special high duty cycle ($\sim 90\%$) UH trigger that does not require passage through the TASC and used time- and position-dependent detector response corrections based on ^{14}Si and ^{26}Fe and an angle-dependent geomagnetic cutoff rigidity selection to show abundances of even nuclei in agreement with SuperTIGER and ACE-CRIS. The work shown here further improves upon those results by restricting UH events to those that pass through both the TASC and CHD. While this constraint does reduce the number of events to $\sim 1/6$ of the original UH trigger analysis, the loss of statistics is compensated by improvements in event selection from an energy-binned charge determination and minimum deposited energy that substitutes for the previous minimum geomagnetic rigidity selection. The results shown here represent 7 years of observation for the abundances of elements from $Z=10$ to $Z=40$ relative to ^{26}Fe and are compared to previous measurements from ACE-CRIS, SuperTIGER, and HEAO-3.

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1. Introduction

The CALorimetric Electron Telescope (CALET) on the International Space Station (ISS) is a Japanese led astroparticle observatory that was launched on August 19, 2015 and has been collecting scientific data since October 13, 2015. As its name suggests, 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) 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) and cosmic-ray nuclei (up to 1,000 TeV). In addition, there is the CALET Gamma-ray Burst Monitor (CGBM), which can make simultaneous observations with the calorimeter. [1]

The main calorimeter instrument is comprised of three detector systems, shown in more detail in Fig. 1a and 1b. At the top of CALET is the charge detector (CHD), which is comprised of an x and a y layer, each layer having 14 scintillator paddles. These paddles all are 32 mm wide by 10 mm thick by 450 mm long. Right below the CHD is the imaging calorimeter (IMC), which is 156.5 mm tall, and made of 8 layers of both x and y scintillating fibers that are 1 mm wide squares and 448 mm long. In between the fiber layers of the IMC are a combined 3.0 radiation lengths (X_0) of tungsten arranged such that the first 5 layers are $0.2X_0$ thick and the bottom two are each $1.0X_0$ thick. At the bottom of the instrument stack is the total absorption calorimeter (TASC). The TASC is made of 6 x and y layers of 16 lead tungstate (PWO) scintillator logs. Each of these logs are 19 mm wide, 20 mm tall, and 326 mm long. Combined these logs give the TASC a total depth of $27X_0$.

The CHD, along with the IMC, provides the primary particle charge identification. All three detectors are utilized for track reconstruction, but that is primarily based on the IMC, while the particle energy is determined from the calorimeters, with most of the determination based on TASC measurements.

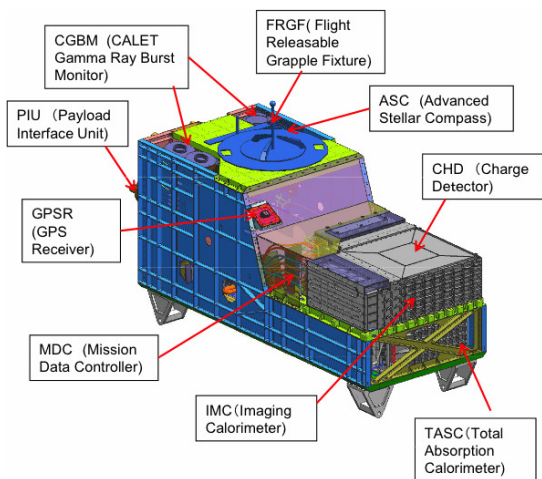


Figure 1(a): CALET instrument package detailing locations of the various CALET subsystems.

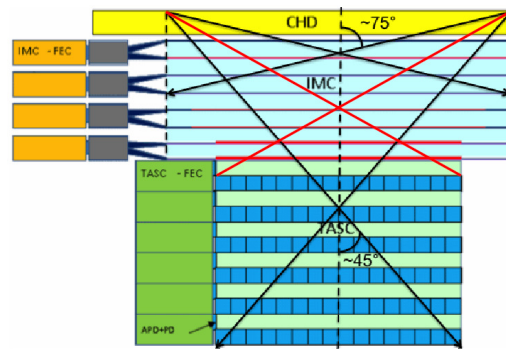


Figure 1(b): CALET side-view showing CHD, IMC, and TASC detector placement with the maximum acceptance angles for detection. The maximum acceptance angle (75°) for the UH trigger analysis is shown in black and in red for the TASC analysis (45°).

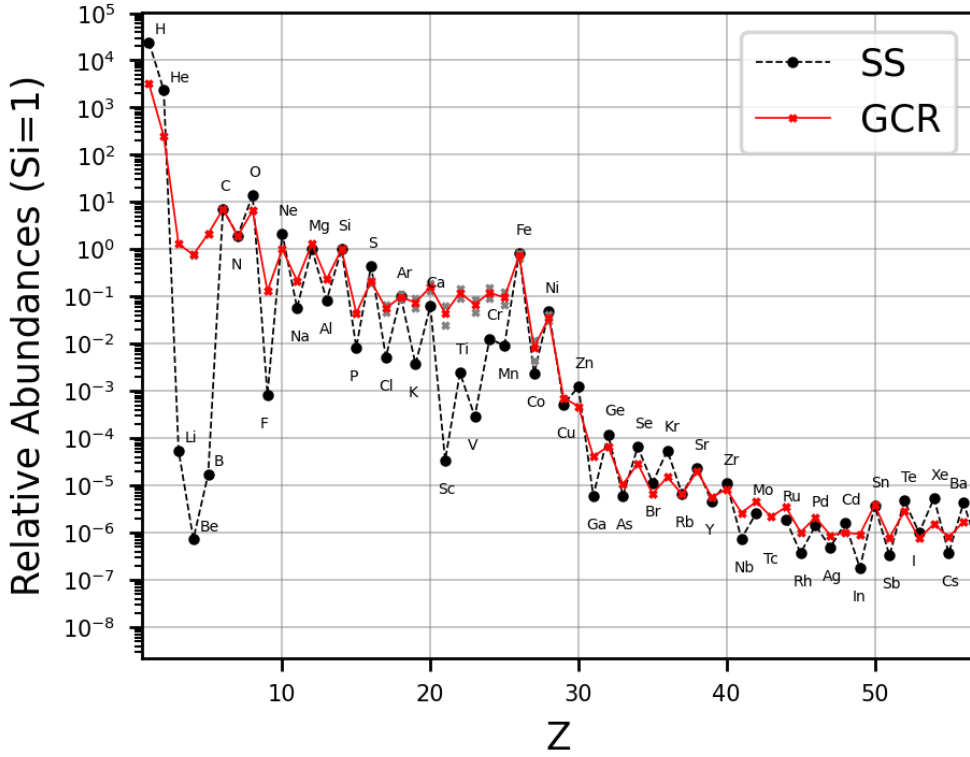


Figure 2: Solar System (SS) [2] and Galactic cosmic-ray (GCR) relative abundances at 2 GeV/nuc. Red line depicts average GCR data, sourced for $1 \leq Z \leq 2$ from [3], $Z=3$ from [4], $4 \leq Z \leq 28$ from [5], and $16 \leq Z \leq 56$ from [6] normalized to ^{14}Si . Grey dots depict overlapping measurements from [5] and [6].

2. Ultra-Heavy Cosmic Rays

The measurement of ultra-heavy cosmic rays (UHCRC), ^{30}Zn and higher charge elements, provides insight into the origins of cosmic rays. In Fig. 2, the relative abundances of cosmic rays elements ($1 \leq Z \leq 56$) with energies of 2 GeV/nucleon are compared to 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 by cosmic ray spallation between source and detection and by acceleration efficiencies. In the cosmic rays we see that ^{26}Fe is $\sim 5 \times 10^3$ times less abundant than ^1H , and that the UHCRC with charges $30 \leq Z \leq 40$ are $\sim 10^5$ times less abundant than ^{26}Fe . Single-element resolution UHCRC measurements have so far only been made by a small number of instruments. For balloon borne measurements these go up to ^{40}Zr by TIGER [7] and up to ^{56}Ba by SuperTIGER [8] at GeV/nuc energies, while the single element space based measurements only go up to ^{38}Zr by the ACE-CRIS [14] instrument at hundreds of MeV/nuc.

These experiments find that UHCRC composition shows enhancement in material produced in massive stars, both from stellar outflows during the stars' lives and in the ejecta from supernovae. This suggests that a significant fraction of the cosmic rays may originate in OB associations, which is where the majority of supernovae 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 UHCRC observations can help constrain the relative contributions of supernovae

and binary neutron star mergers to the heavy r-process elements.

Our CALET observations contribute to the statistics of the UHCR data set and complement other existing measurements. The ultra-heavy (UH) event trigger on CALET, which requires events only pass through the CHD and top half of the IMC, has collected UHCR statistics similar to those achieved in the first flight of the balloon-borne SuperTIGER instrument. CALET also observes a similar energy range to TIGER and SuperTIGER, but requires corrections for different systematic effects. The balloon based observations must be corrected for energy losses and nuclear interactions that occur in the atmosphere, while ISS based measurements are subject to screening by Earth's geomagnetic field. Comparatively, UHCR observations made by ACE-CRIS occur outside the geomagnetic field in a complementary lower energy range. So while ACE-CRIS and SuperTIGER instruments only measure down to ${}_5\text{B}$ and ${}_{10}\text{Ne}$, respectively, CALET's measurements of cosmic-ray abundances in the $13 \leq Z \leq 44$ charge range provide complementary measurements and a check of the cross calibrations of other instruments.

3. Data, corrections, and screens

As stated prior, the UH trigger requires events only pass through the CHD and top half of the IMC. If one chooses to perform analysis on the full UH trigger dataset you need to use the minimum geomagnetic cutoff as a proxy for energy. This method was shown at the previous ICRC in [10]. Here we explore usage of a subset of data that requires UH particles to pass through part of the TASC. In either case, before we can perform analysis, we need to perform some minor secondary corrections on the data set.

The CALET instrument already has a number of corrections applied to the dataset, however these corrections are optimized for the main analysis, with the bulk of the corrections being applied to the electron and helium fluxes. Since the UH analysis events have significantly different detected energies, we need to perform our own set of secondary corrections to optimize the UH region. To do this we do corrections based on position and event date of detection.

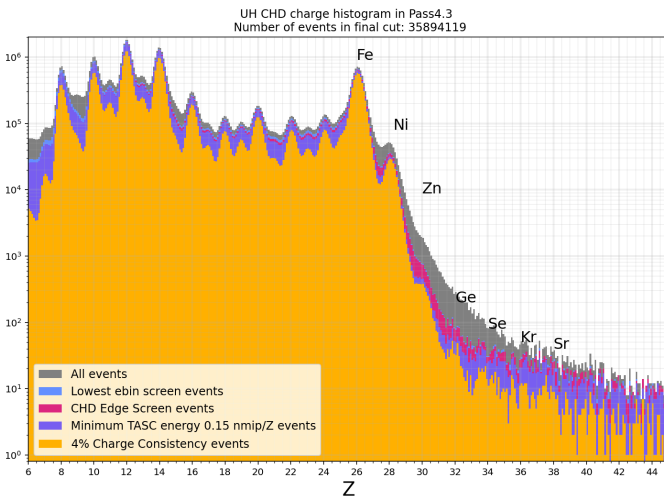


Figure 3: The TASC UH dataset, with successive screens applied. A minimum TASC Edep of 1.53 nmip to remove the lowest 3 energy bins, a screen on the event location, a minimum TASC Edep/Z, and the 4 percent charge consistency screen.

The position corrections are derived by dividing each CHD paddle into 42 segments (with length $\sim 1/3$ of paddle width). For each individual paddle segment we perform a Gaussian fit on ${}_{26}\text{Fe}$ and ${}_{14}\text{Si}$ events to determine the local mean energy for those elements. We then take these local means and find the ratio of the full layer means for both ${}_{26}\text{Fe}$ and ${}_{14}\text{Si}$ respectively. We then plug these ratios into a function to smoothly transition between those correction factors allowing for a seamless

correction that can be applied to all UH events. The time corrections are performed similarly, with the "local" segments being defined as increments in time where there are a minimum 600 events in each paddle. This results in time correction bins being approximately 3 days in length.

Since the last ICRC, work has continued on the analysis of the subset of data of events that pass through the TASC with the 45° acceptance angle shown in Fig. 1b, which provides each event with energy information. This comes in the form of deposited energy as a function of number of minimum ionizing particles (nmip). While this value is not an exact energy, as that requires a reconstruction of every event, it does suffice as a value that allows for separation of events into groups of energy. After the grouping of events by deposited energy we perform a Tarle model charge assignment [9] on each deposited energy bin, and remerge the bins.

After all corrections are performed, we perform a number of event selection screens. In this analysis shown here we perform cuts for an overall minimum deposited energy and the deposited energy by charge. These two cuts are applied to remove low energy events that cause a smearing of charge. Additionally, we apply a charge consistency cut requiring that the calculated CHD charge for both x and y layers is within 4%. We also apply a screen on position, removing the events closest to the edge of CHD, and a screen on time to account for a few bad time bins where the ISS displayed abnormal behavior.

The successive effects of these cuts are shown in Fig. 3. For further details on how all of these corrections have been implemented and on how each screen is determined please see our complementary ICRC on *Optimizing Selection Criteria for the CALET Ultra-Heavy Cosmic Ray Analysis*. [11]

4. Determination of Abundances

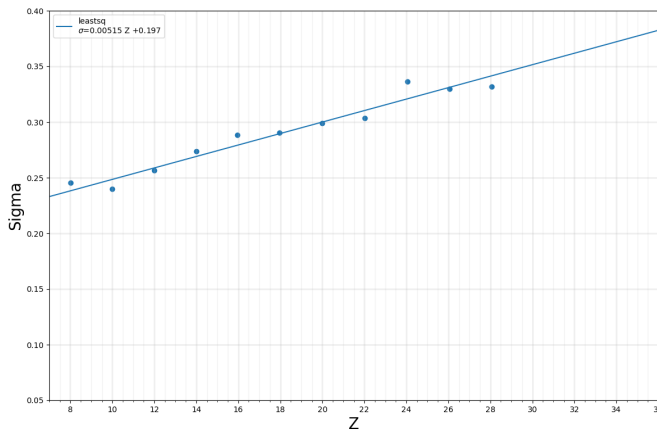


Figure 4: Linear fit on the sigmas from the initial fit. Successive fits are required to have peak width be within 2 percent of the best fit function shown here.

From this fit we take the peak widths of all even peaks and perform a linear fit on the even peaks $8 \leq Z \leq 28$. In the second iteration of the multigaussian we add the constraint that all peak sigmas must be within 2% of the linear best fit. From this second fit we record the final sigmas and peak positions. After this is the third and final fit, where only peak amplitudes are allowed to vary. The results of this fit are shown in Fig. 5.

To find abundances for the UH analysis we use a similar methodology to one originally implemented in the SuperTIGER analysis. [6] This methodology has us perform multiple iterations of a maximum-likelihood Gaussian fit that add in constraints based on prior fit information. The first iteration of the fit is applied to all $Z \leq 50$ with the only constraint of full integer spacing between all peaks. From this fit we take the peak widths of all even peaks and perform a linear fit on the even peaks $8 \leq Z \leq 28$. In the second iteration of the multigaussian we add the constraint that all peak sigmas must be within 2% of the linear best fit. From this second fit we record the final sigmas and peak positions. After this is the third and final fit, where only peak amplitudes are allowed to vary. The results of this fit are shown in Fig. 5.

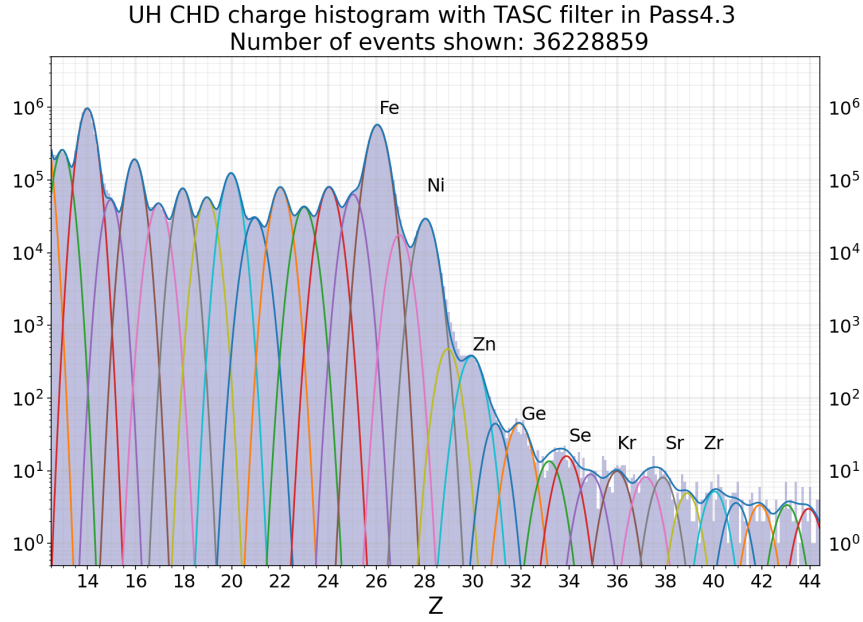


Figure 5: Here we show the results of the multigaussian fit procedure for the TASC UH abundances. The number of events within the full fit is roughly identical to the number in the histogram (<1% difference between fit and histogram in the UH region)

To determine the total error on the fit we combine three error sources in quadrature. First, is the error returned from the fit itself, second is the statistical error derived by Gehrels [?], and finally a variational error derived from the choice in screens used. To get this third error source, we repeat the final step in the fitting routine on a set of alternative histograms. Some of these histograms are shown in Fig 6a and possess slightly different screens: a change in minimum Edep/Z and/or maximum percent difference. We take the results of each fit and take the difference in abundances

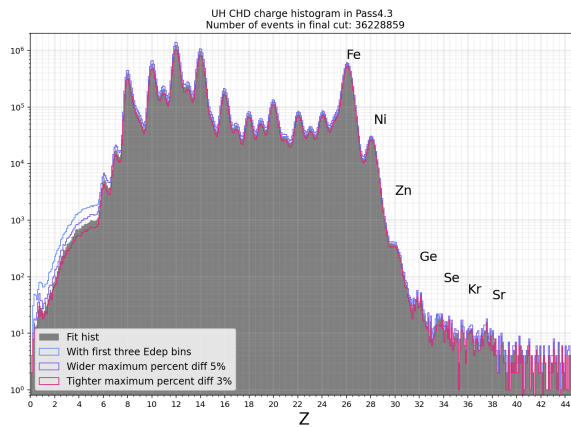


Figure 6(a): Example histograms for derivation of variational error. The histograms above explore differences in the Edep screen and changes in the percent difference between CHDX and CHDY.

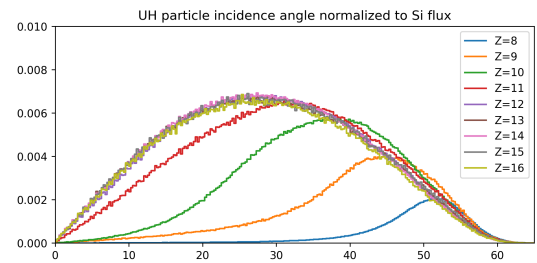


Figure 6(b): Incidence event angle with a weighted normalization to the ^{14}Si flux to show minimum acceptance angle changes with Z. 0° is vertical entry and bin size is 0.25° .

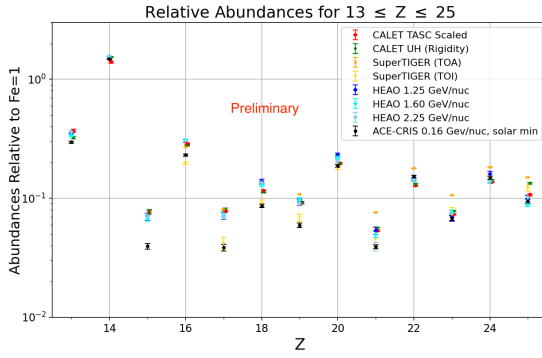


Figure 7(a): Abundances for $Z < 26$ compared to abundances from HEAO-3-C2 for 1.25 to 2.25 GeV/nuc [5], ACE-CRIS [13], and both SuperTIGER top of instrument [8] and top of atmosphere [6]. The CALET UH abundances derived via a rigidity cutoff is in red.

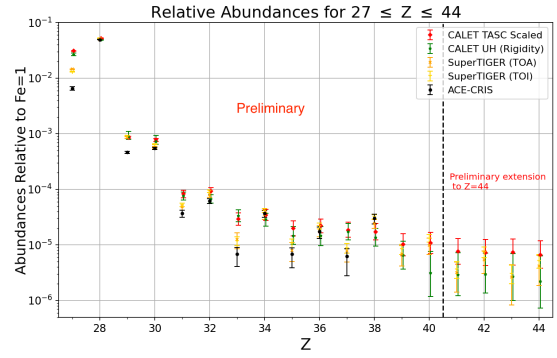


Figure 7(b): CALET UH Abundances for $Z > 26$ compared to the abundances from ACE-CRIS [14] and both SuperTIGER top of instrument [8] and top of atmosphere [6]. The CALET UH abundances derived via a rigidity cutoff is in red.

between the alternative and original histogram in Figure 5. We use the maximum differences in positive and negative relative abundances as the error.

After this we also correct the abundances for low Z by comparing and if needed normalizing lower Z peaks to the geometry factor of ^{14}Si . This is to account for systematic effects caused by the UH trigger, as low Z events entering at shallower angles are able to exceed the UH-Trigger minimum. By exploring how event count for Z changes with incident angle in Fig 6b, we can rescale low Z peaks to what they may have been without the UH trigger.

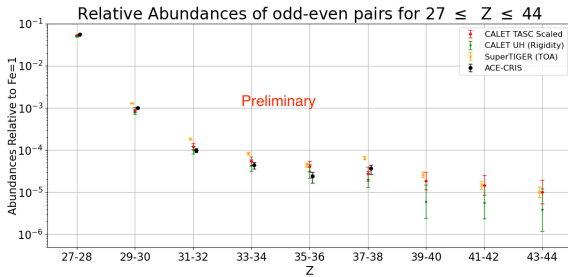


Figure 8: The relative abundances of the Odd-Even element pairs compared to abundances from ACE-CRIS [14] and SuperTIGER. [6] The CALET UH abundances derived via a rigidity cutoff is in red.

In these plots we can see good consistency between the space-based measurements and CALET. We note that there are some minor differences from SuperTIGER, but these may be caused by the atmospheric corrections. The current work done in [15] shows a revised atmospheric correction that may bring SuperTIGER's results to be in line with CALET.

5. Conclusions

Abundances from CALET UH-trigger and TASC UHCR analyses continue to agree with previous CALET results and other instrument measurements. After 7.5 years, CALET continues to

After these steps have been performed, we are able to plot the relative abundances in Figures 7a and 7b. In these plots we compare the results of this analysis to previous results shown from ACE-CRIS, HEAO-3-C2 and SuperTIGER. For SuperTIGER both the published top-of-instrument values and a set of preliminary top-of-atmosphere values are shown. We also provide a comparison to the older analysis method most recently shown in [10] that uses the UH trigger in conjunction with geomagnetic cutoff screen.

output excellent data, 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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