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The CALorimetric Electron Telescope (CALET) on the International Space Station

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Abstract

The CALorimetric Electron Telescope (CALET) space experiment, developed by Japan in collaboration with Italy and the United States, is a high-energy astroparticle physics mission installed on the International Space Station (ISS). The primary goals of the CALET mission include investigating on the possible presence of nearby sources of high-energy electrons, studying the details of galactic particle propagation and searching for dark matter signatures. During a two-year mission, extendable to five years, CALET can measure the flux of cosmic-ray electrons (including positrons) to 20 TeV, gamma-rays to 10 TeV and nuclei with $Z = 1$ to 40 up to 1,000 TeV. The instrument consists of two layers of segmented plastic scintillators for cosmic-ray charge identification (CHD), a 3 radiation length thick tungsten-scintillating fiber imaging calorimeter (IMC) and a 27 radiation length thick lead-tungstate calorimeter (TASC). CALET has sufficient depth, imaging capabilities and excellent energy resolution to allow for a clear separation between hadrons and electrons and between charged particles and gamma rays. The instrument was launched on August 19, 2015 to the ISS with the H-II Transfer Vehicle 5 (HTV-5) and installed on the Japanese Experiment Module-Exposed Facility (JEM-EF) on August 25. Since the start of operations in mid-October, 2015, a continuous observation has been going on mainly by triggering high energy (>10 GeV) showers without any major interruption. The number of triggered events above 10 GeV is nearly 20 million per month. By using the data obtained during the first two years, we give a summary of CALET observations: (1) Electron + Positron energy spectrum, (2) Proton and Nuclei spectrum, (3) Gamma-ray observation, with results of the performance study on orbit. We also present the results of observations of the electromagnetic counterparts to LIGO-VIRGO gravitational wave events and high-energy counterparts to GRB events measured with the CALET Gamma-ray Burst Monitor (CGBM).

Keywords: Astroparticle; Cosmic ray; Proton flux

1. Introduction

CALET is a space mission led by the Japanese Space Agency (JAXA) with the participation of the Italian Space Agency (ASI) and NASA. It was launched on August 19, 2015 with the Japanese carrier H-II and delivered to the ISS by the HTV-5 Transfer Vehicle, where it was installed on the Japanese Experiment Module Exposure Facility (JEM-EF).

The primary science goal of CALET (Torii et al., 2015, 2017) is to carry out high precision measurements of the electron spectrum with an accurate scan of the energy region already covered by previous experiments (Asaoka et al., 2017) and to extend it to the unexplored region above 1 TeV. The electron spectral shape might reveal the possible presence of nearby sources of acceleration.

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With excellent energy resolution (better than 2% for electrons above 100 GeV), proton rejection capability $>10^5$ and low background contamination, CALET is searching for possible signatures of dark matter in the spectra of both electrons and gamma rays.

Taking advantage of its capability of identifying cosmic rays with individual element resolution, CALET is also carrying out long term observations of light and heavy cosmic nuclei (Marrocchesi et al., 2017; Akaike et al., 2017) from proton to iron, measuring their spectral shape and relative abundance from a few tens of GeV to hundreds of TeV. In addition, it is currently chasing trans-iron elements (Rauch et al., 2017) up to Z ∼ 40.

2. CALET (CALorimetric Electron Telescope)

CALET (Fig. 1) is an all-calorimetric instrument designed to achieve a large proton rejection capability ($>10^5$) in electron measurements. It consists of IMC, a thin imaging calorimeter (3 X_0), followed by TASC, a 27 X_0 thick homogeneous calorimeter with 12 layers of lead-tungstate (PWO) logs. The IMC is a sampling calorimeter alternating thin layers of Tungsten absorber with 16 layers of 1 mm^2 square scintillating fibers that are individually read-out. Alternate layers are arranged along orthogonal directions both in IMC and TASC. The IMC can provide position information for tracking as well as image the early shower profile and reconstruct the incident direction of cosmic rays with good angular resolution (0.1° for electrons and better than 0.5° for hadrons) (Torii et al., 2015).

The instrument CAL (IMC + TASC) amounts to a total of 30 X_0 and ∼1.3 proton interaction length (λ_I) at normal incidence.

Charge identification of individual nuclear species is carried out by two independent sub-systems: one dedicated two-layered hodoscope of plastic scintillators (CHD) positioned at the top of CALET, and the IMC which provides a redundant charge determination via multiple dE/dx measurements from the fibers. Together, they can measure the charge Z of the incident particle over a wide dynamic range ($Z = 1$ to ~ 40) with sufficient charge resolution to resolve individual elements (Shimizu et al., 2011; Marrocchesi et al., 2011).

The geometrical factor of CALET is ∼ 0.12 m^2 sr and the total mass is 613 kg. The instrument is described in more detail elsewhere (Torii et al., 2015; Marrocchesi et al., 2012; Asaoka et al., 2017). Gamma-ray transients are detected by a dedicated Gamma-ray Burst Monitor (GBM) (Yamaoka et al., 2013).

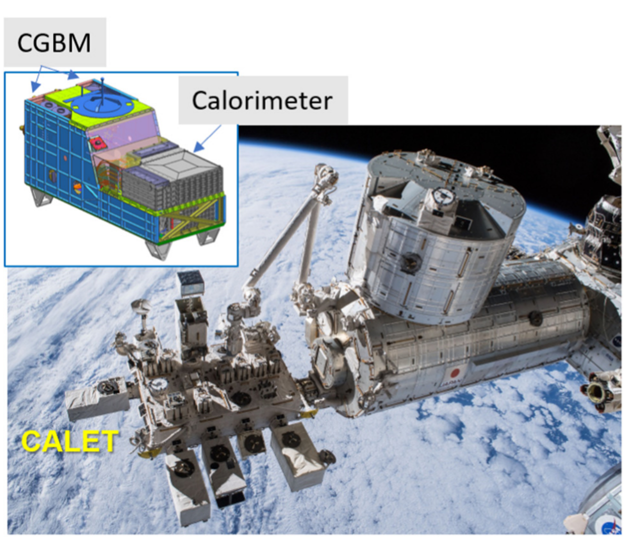


Fig. 1. JEM-EF and CALET installed on the JEM-EF of the ISS. The insert shows the CALET instrument with the main calorimeter and CALET Gamma-ray Burst Monitor (CGBM) (Yamaoka et al., 2013).

3. On-orbit operations

On-orbit operation of CALET are controlled via JAXA Ground Support Equipment (JAXA-GSE) in Tsukuba by the Waseda CALET Operations Center (WCOC) located at Waseda University, Tokyo. The data taken by the CALET instrument are transferred from the ISS to JAXA using NASA data relay system. The scientific operations of CALET are planned at WCOC (Asaoka et al., 2018) and the observation mode is controlled by scheduled command sequences that define the time profile of calibrations and data taking as well as the observation mode according to the orbital position of the ISS. Observation modes include a low-energy electron trigger operating at high geomagnetic latitude, a low-energy gamma-ray (LE-γ) trigger operating at low geomagnetic latitude, and an almost continuously active ultra-heavy ions trigger mode, during each ISS orbit. An always active high-energy (HE) trigger mode allows for a maximum exposure to high-energy electrons and other high-energy shower events. As of May 31, 2018, the total observation time was 962 days with a live time fraction ∼84% of the total time and ∼630 million events taken with the HE (E >10 GeV) trigger mode. Cumulative observation time has increased without significant interruption since scientific operation began in October 2015. Data transmission from JAXA-GSE to WCOC and data processing for scientific analysis at WCOC also proceeded smoothly.

4. Energy calibration

For an all-calorimetric instrument like CALET, energy calibrations are essential to achieve accurate flux measurements. Calibration uncertainties have to be carefully assessed and taken into account in the estimation of the actual energy resolution. Our energy calibration (Asaoka et al., 2017) procedures establish the values of the ADC-to-deposited-energy conversion factors, enforce a linear energy response over each gain range (TASC has four gain ranges for each channel), and provide a seamless transition among neighboring ranges. The calibration of the lower gain interval is particulary important for the spectrum measurements in the TeV range. Position and temperature

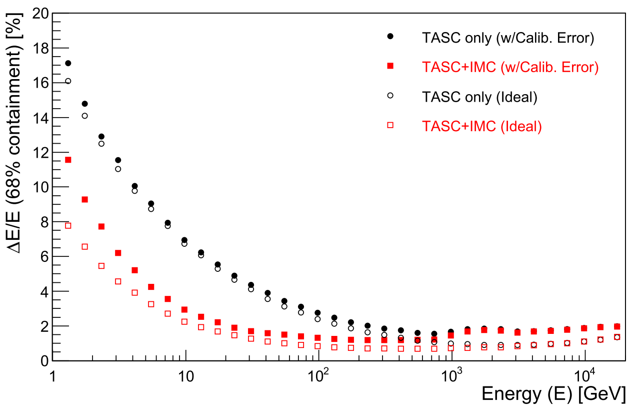


Fig. 2. Energy resolution for electron measurements (Asaoka et al., 2017).

dependence as well as temporal gain variations are corrected for by the calibration procedure (Adriani et al., 2017).

As a result, a very high resolution of 2% or better is achieved for electrons above 20 GeV (Asaoka et al., 2017) as shown in the top panel of Fig. 2. It should be noted that even with such a detailed calibration, the limiting factor for CALET energy resolution is the calibration uncertainty, as the intrinsic resolution of the instrument is close to 1%.

5. Direct measurements on the ISS with CALET

5.1. Inclusive electron spectrum

The CALET collaboration published a first electron paper reporting the measurement of the spectrum in the energy range from 10 GeV to 3 TeV (Adriani et al., 2017). Soon after, the DArk Matter Particle Explorer (DAMPE) collaboration published their all-electron spectrum in the energy interval from 25 GeV to 4.6 TeV (Ambrosi et al., 2017). The latter publication was followed by many papers speculating about the origin of a peak-like structure near 1.4 TeV in the DAMPE data.

Recently, an updated version of the CALET all-electron spectrum using 780 days of flight data and the full geometrical acceptance was published covering the energy range from 11 GeV to 4.8 TeV (Adriani et al., 2018). Fig. 3 shows the updated spectrum obtained with CALET using the same energy binning as in our previous publication (Adriani et al., 2017), except for adding one extra bin at the high energy end. The width of each bin is shown as a horizontal bar, the statistical errors as vertical bars, while the gray band is representative of the quadratic sum of statistic and systematic errors. A comprehensive study of the systematic uncertainties was performed as described in Refs. (Adriani et al., 2017, 2018) and Supplemental Material therein.

Taking the currently available experimental data at face-value we notice that:

- the all-electron spectrum data seem to fork into two groups of measurements: AMS-02 + CALET and Fermi/LAT + DAMPE, with good consistency within each group, but with only marginal overlap between the two groups, possibly indicating the presence of unknown systematic errors;
- CALET spectrum is consistent with AMS-02 below ~1 TeV where both experiments have a good electron

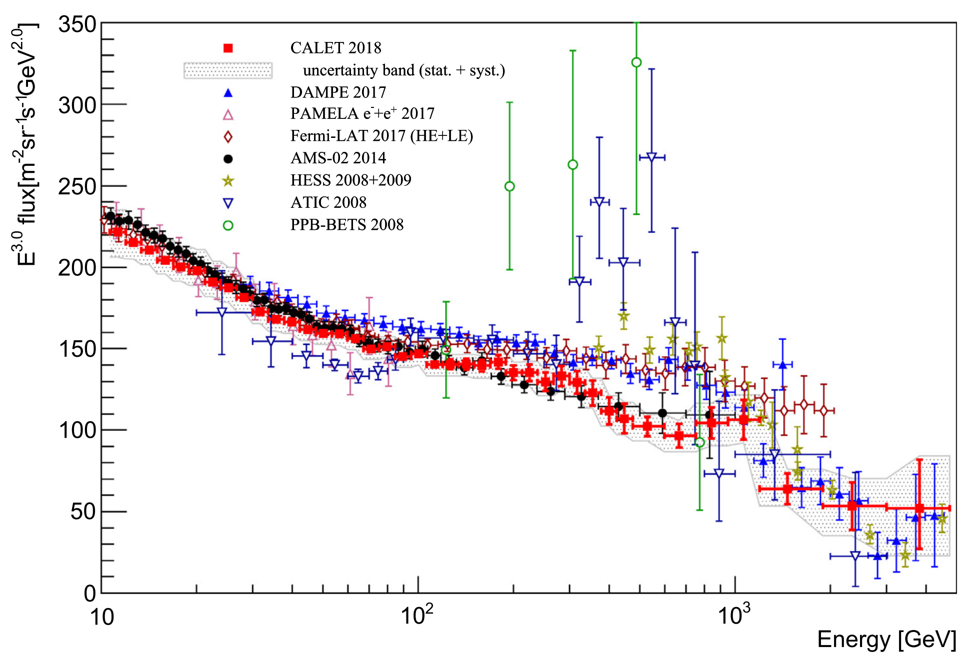


Fig. 3. Cosmic-ray all-electron spectrum measured by CALET from 10.6 GeV to 4.75 TeV (Adriani et al., 2018). The gray band indicates the quadratic sum of statistical and systematic errors (not including the uncertainty on the energy scale). Also plotted are direct measurements in space including (Ambrosi et al., 2017; Adriani et al., 2017; Abdollahi et al., 2017; Aguilar et al., 2014; Chang et al., 2008; Yoshida et al., 2008) and from ground-based experiments (Aharonian et al., 2008, 2009).

identification capability albeit using different detection techniques;

- CALET observes a flux suppression above ~1 TeV consistent with DAMPE within errors;
- No peak-like structure was found at 1.4 TeV in CALET data, irrespective of energy binning.

After rebinning with the same set of energy bins as DAMPE, an inconsistency between the two measurements emerges with a 4σ significance. The latter includes the systematic errors quoted from both experiments. Possible binning related effects in the CALET all-electron spectrum were also investigated by introducing a shift by 1/4 of the bin width. The deviation ascribed to the binning is well below our energy dependent systematic uncertainty or statistical fluctuations. Therefore, bin-to-bin migration and related effects turn out to be negligible compared with our estimated systematic uncertainties, as expected from the estimated CALET energy resolution of 2% above 20 GeV. The solid curves in Fig. 3 show the energy dependent systematic uncertainty band.

5.2. Cosmic-ray nuclei spectra

Direct measurements of the high-energy spectra of each element present in the flux of charged cosmic rays provide information complementing electron observations with additional insight into cosmic-ray acceleration and propagation phenomena (Marrocchesi, 2017). CALET is carrying out extensive measurements of the energy spectra, relative abundances and secondary-to-primary ratios of elements from proton to iron and above.

In particular, CALET is investigating the intermediate energy region from 200 GeV/A to 800 GeV/A where a deviation from a single power-law has been observed for both proton and helium spectra by CREAM (Ahn et al., 2010; Yoon et al., 2011, 2017), PAMELA (Adriani et al., 2011, 2013) and confirmed with high statistics measurements by AMS-02 (Aguilar et al., 2015) that reported a similar behavior also for Li and other light nuclei. CALET is performing an accurate scan of this energy region to verify the hypothesis of a progressive hardening of the proton spectrum by measuring accurately the dependence of the spectral index as a function of energy.

By correlating the charge measurements from the two layers of CHD (Fig. 4) and the independent charge measurement by IMC, well separated charge peaks emerge on top of a low background for individual elements.

Taking advantage of the excellent charge identification capability and wide charge span, preliminary results from the current analysis of nuclei have been presented on protons (Marrocchesi et al., 2017) and heavier nuclei (Akaike et al., 2017, 2018) including the spectra of carbon, oxygen, neon, magnesium, silicon and iron as shown in Fig. 5 as a function of kinetic energy per particle.

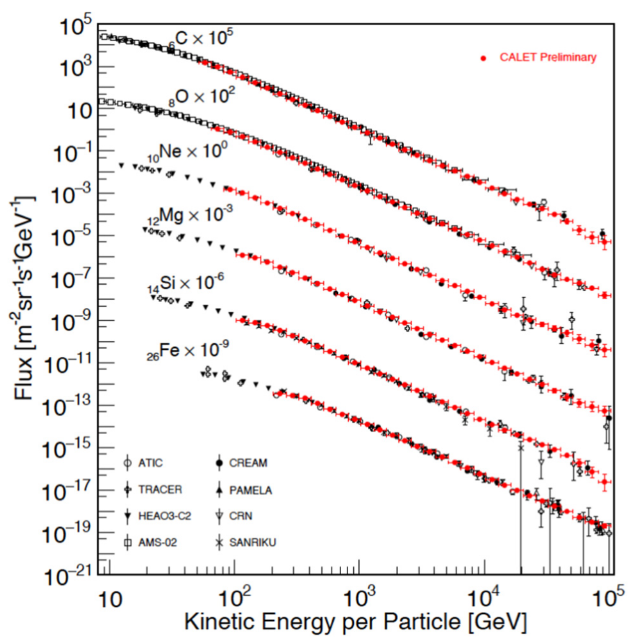


Fig. 5. Preliminary energy spectra of carbon, oxygen, neon, magnesium, silicon and iron as a function of kinetic energy per particle compared with previous observations. Only statistical errors are shown.

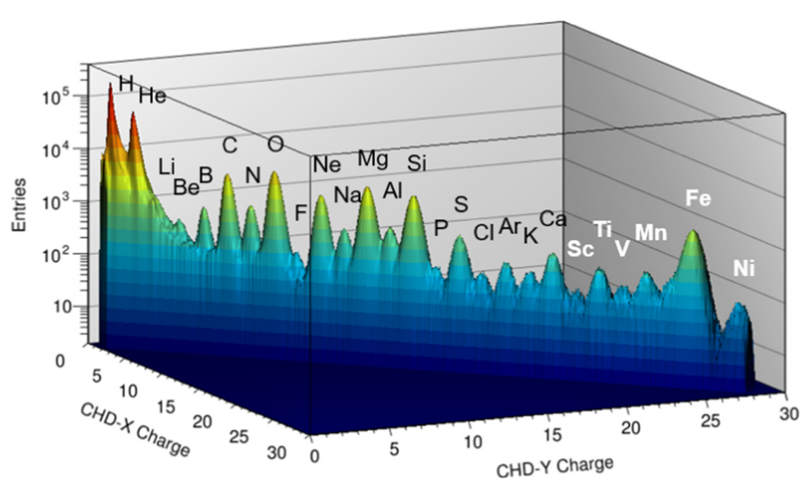


Fig. 4. Charge identification capability of CHD shown as a scatter plot of the charge measured by the two layers.

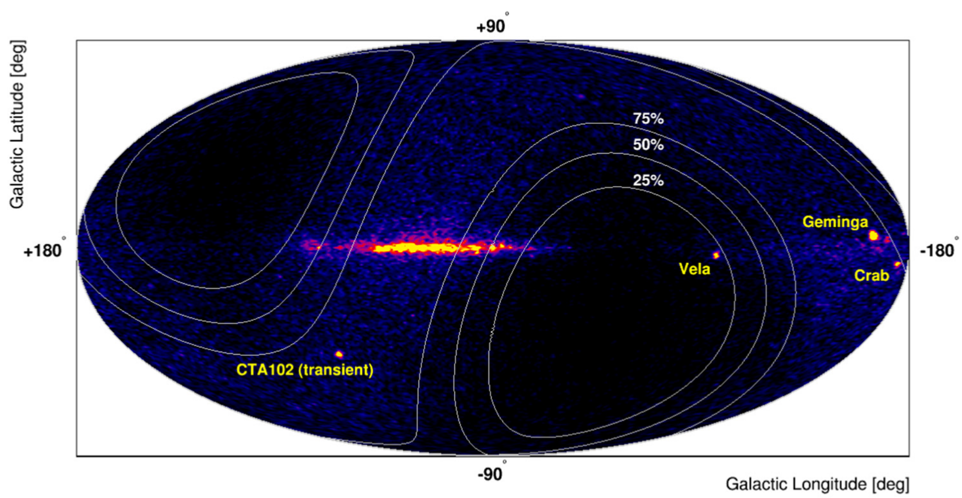
5.3. Observation of gamma-rays

CALET can identify gamma-rays and measure their energies up to the TeV region. Both CHD and the first IMC layers are used in the offline analysis as anti-coincidence against incoming charged particles, taking advantage of the high granularity of the IMC. In addition to the HE trigger, CALET uses a LE-γ trigger extending the sensitivity to gamma rays with primary energies down to $\sim$1 GeV. This dedicated trigger is activated only at low geomagnetic latitudes (to avoid an increase of the dead-time) and it is also enabled whenever a gamma-ray burst is triggered onboard by the CGBM.

The gamma-ray data from the first 24 months of on-orbit scientific observations allowed a complete characterization of the performance of the calorimeter (Cannady et al., 2018). Optimization of the event selection criteria and the determination of the effective area, Point Spread Function (PSF) and absolute pointing accuracy lead to the observation of bright point sources and the study of diffuse components.

CALET gamma-ray sky seen with LE-γ trigger is shown in Fig. 6 (top panel), where both the galactic emission and bright gamma-ray sources are clearly identified. Fig. 6 (bottom panel) shows the projection of the observed and expected number of photons onto the galactic latitude for the galactic plane region $|l| < 80^{\circ}$. The observations were tested against Fermi/LAT data by comparing the expected number of photons calculated using Fermi flux map and CALET's exposure in the same region of the sky, after taking into account the screening effects due to the presence of ISS structures in our field-of-view. A very good consistency was found which was taken as a confirmation of the CALET sensitivity.

Gamma-ray transients were detected by the dedicated CGBM instrument which collected, as expected (Yamaoka et al., 2017), an average of nearly 60 GRBs per year in the energy range of 7 keV–20 MeV. About 20% of them were classified as short GRBs. A search for GeV-energy gamma-ray counterparts detected by other instruments was carried out by checking the CAL data at the reported trigger times based on CGBM, Swift, and



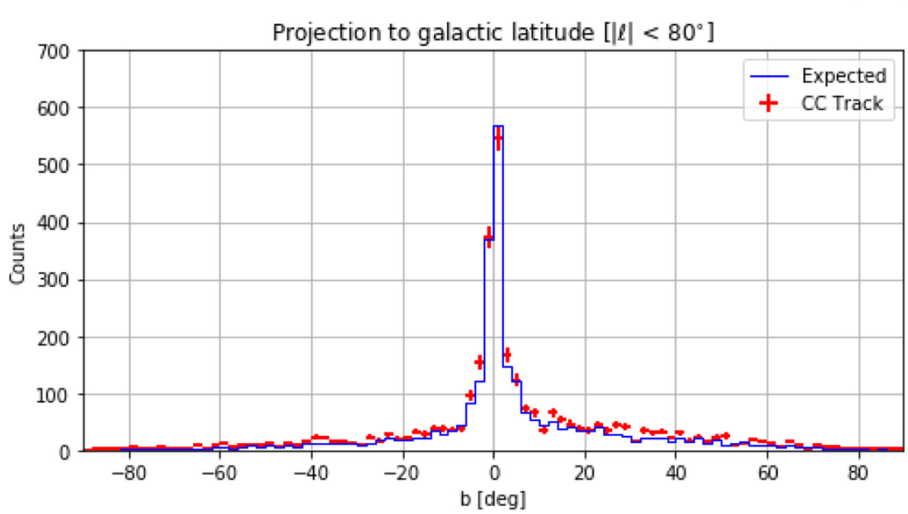


Fig. 6. (*Top*) Gamma-ray sky map shown in a Mollweide projection of galactic coordinates. White contours show the relative level of exposure compared to the maximum on the sky. (*Bottom*) Projection of the observed and expected number of photons onto galactic latitude for the galactic plane region $|l| < 80^{\circ}$ for the energy range from 1 to 100 GeV.

Fermi/GBM triggers. No significant counterparts have been detected at this stage for timescales ranging from 1 s to 1 h (Cannady et al., 2018). Combined analyses of CGBM and calorimeter were performed for the search of counterpart emission related to gravitational wave events. In particular, for GW151226 upper limits on X-ray and gamma-ray counterparts were established (Adriani et al., 2016). A review of the search results with the CALET calorimeter during the LIGO/Virgo's Observation Run 2 has been published recently (Adriani et al., 2018).

6. Summary and perspectives

CALET was successfully launched on Aug. 19, 2015. The instrument performance has been very stable during all the scientific observation period from Oct. 13, 2015. CALET measurements of the electron spectrum (Adriani et al., 2017, 2018) were published in two papers, the latter with improved statistics and extended energy range from 11 GeV to 4.8 TeV. In perspective, the extension to five years (or more) of CALET electron observations is expected to increase the available statistics by a factor $\sim$3 thereby contributing to a better understanding of the detector and a possible reduction of the systematic errors. This will make possible a refined search for possible spectral features in the region from a few hundred GeV to $\sim$1 TeV, which are currently not significant.

Preliminary results on protons (Marrocchesi et al., 2017), as well as primary and secondary nuclei up to $Z = 26$ and their ratios (for example, boron to carbon) (Akaike et al., 2017, 2018) were presented at this conference, demonstrating CALET's wide energy span from 1 GeV to 1 PeV and its excellent charge identification capability. The relative abundance of the ultra heavy nuclei up to $Z = 40$ has also been preliminarily analyzed (Rauch et al., 2017).

The performance of the gamma-ray measurements has been characterized (Cannady et al., 2018) confirming CALET's capability to observe gamma rays in the energy range from $\sim$1 GeV to above 100 GeV. CALET's current results on the search of electromagnetic counterparts to gravitational wave events (Adriani et al., 2016, 2018) confirm the great potential of follow-up observations during the upcoming LIGO/Virgo's third observation run (Observation Run 3).

High statistics detection of MeV electrons originating from the radiation belt (Kataoka et al., 2016) allowed the study of relativistic electron precipitation. This is one of the topics of Space Weather studies which were added as additional observational targets for CALET after the start of on-orbit operations.

The so far excellent performance of CALET and the outstanding quality of the data suggest that a 5-year (or more) observation period will most likely improve our current knowledge of cosmic-ray phenomena.

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