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Results from CALorimetric Electron Telescope (CALET) Observations of Gamma-rays on the International Space Station

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The CALorimetric Electron Telescope (CALET) cosmic ray detector on the International Space Station (ISS) has been in operation since its launch in 2015. The main instrument, the CALorimeter (CAL), is optimized to observe high-energy electrons up to TeV energies, but its three-storied, composite and thick detector enable us to discriminate gamma rays from overwhelming background of charged cosmic rays. Thus, it is monitoring the gamma ray sky from 1 GeV up to 10 TeV with a field of view of about 2 sr, but the exposure is somewhat non-uniform because of the limitation imposed by the inclination angle (51.6 degree) of the ISS orbit. In this paper we report results from gamma ray observations obtained during its mission for more than seven years with increased statistics compared with previous reports. They include properties of the Galactic diffuse gamma rays, spectra of bright Galactic point sources, and light curves of extragalactic active galactic nuclei, which show good consistencies with Fermi-LAT observations of which energy range overlaps with CALET.

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1. Introduction

The CALorimetric Electron Telescope (CALET) mission [1], which was successfully launched and installed on the Japanese Experiment Module (JEM) 'Kibo'-Exposed Facility of the International Space Station (ISS) in 2015 August, has been operational without any serious faults up to the time of this writing (2023 June). The main target of CALET is observation of high-energy cosmic rays, especially electrons, in the energy range from ~ 1 GeV to tens of TeV, but its fine detector structure allows us to observe high-energy gamma-rays from ~ 1 GeV to ~ 10 TeV. Details of our analysis to extract gamma-ray candidates are described in refs. [2, 3].

In this paper, we report updated results from gamma ray observations obtained during its mission for about eight years with increased statistics compared with previous reports. They include properties of the Galactic diffuse gamma rays, spectra of bright Galactic point sources, which show good consistencies with Fermi-LAT observations of which energy range overlaps with CALET. Also we breifly describe our efforts to increase high-energy sensitivies above 100 GeV by developing an improved gamma-ray selection process.

2. CALET detector

CALET consists of two scientific instruments: the Calorimeter (CAL) and the CALET Gamma-ray Burst Monitor (CGBM). The CAL is the main instrument, which is capable of observing high-energy electrons from ~ 1 GeV to ~ 20 TeV, protons, helium, and heavy nuclei from ~ 10 GeV to 1000 TeV and gamma-rays from ~ 1 GeV to ~ 10 TeV. The field of view (FOV) of CAL is ~ 45° from the zenith direction. It consists of three main components: the CHarge Detector (CHD), the IMaging Calorimeter (IMC), and the Total AbSorption Calorimeter (TASC). Details of the detector is described elsewhere [4]. Here we just mention that we have two trigger modes of the CALET/CAL related to gamma-ray observation: a high-energy (HE) mode with an energy threshold ~ 10 GeV used in normal operation irrespective of geomagnetic latitude, and a low-energy gamma-ray (LE-γ) mode with a threshold ~ 1 GeV, activated when the geomagnetic latitude is below 20° and following a CGBM burst trigger (see ref. [4] for details on our trigger scheme).

3. Gamma-ray analysis

We apply a gamma-ray selection by tracking pair creation events in IMC for the flight data [2]. The gamma-ray event selection used in this analysis is described in detail in ref.[3]. We require the tracks cross the CHD (full area) to the TASC-top (except for the 2 cm margin around the outside, so that reliable reconstruction of events is possible, and apply cuts to select electromagnetic showers. Finally we select gamma-ray candidates with no hits in CHD. Incident gamma-ray energies were estimated based on the deposited energy in CAL (mainly in TASC) considering the geometry conditions.

The CAL gamma-ray performance and initial CAL gamma-ray results for steady sources are described in ref. [3] using simulation study and compared with flight data. The energy resolution and the angular resolution for gamma rays are estimated as 3 % and 0.4°, respectively, at 10 GeV [3], and the energy dependence of its energy resolution is plotted in Fig. 1, which shows its good performance in the high-energy region thanks to the thick calorimetric configuration of CAL.

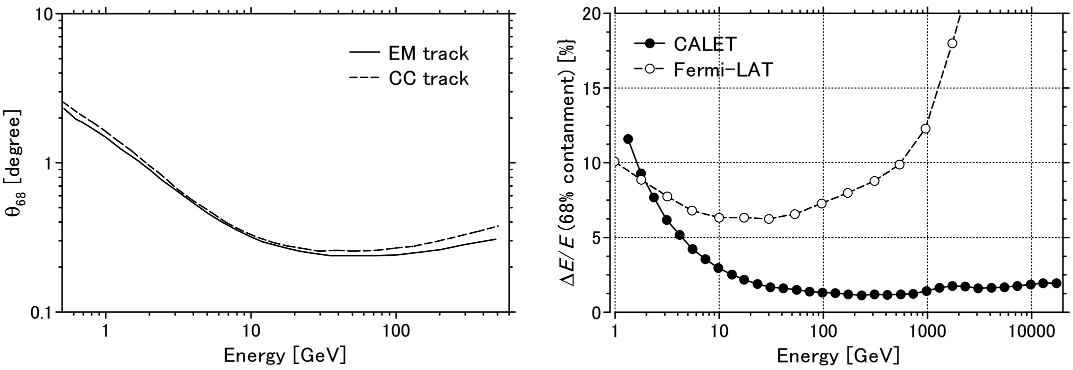

Figure 1: (*Left*) Angular resolution of CALET for gamma rays as a function of energy, averaged over various shower starting points in IMC [3]. θ_{68} is the half angle of the cone in which 68% of gamma rays are contained. 'EM Track' is an algorithm developed for electron analysis and optimized for HE triggers, and 'CC Track' is another one developed specifically for low-energy (1–10 GeV) gamma-rays. (*Right*) Energy resolution of CALET as a function of energy [8], compared with that of Fermi-LAT (P8R3SOURCE_V2, Total) [9].

According to the simulation study that has generated events around the instrument isotropically, we estimate that the highest gamma-ray efficiency is achieved around 10 GeV with an efficiency of 50% relative to a geometrical factor of about 400 cm^2 sr, which is the 100% efficiency case, by applying the event selections described above. The effective areas for various incident angles are shown in Fig.7 (left) as a function of energy.

Since CALET is attached to the exposed facility of the JEM on the ISS, gamma-ray observation with CAL suffers from secondary gamma rays produced in interactions of high-energy cosmic rays with various structures of the ISS surrounding the detector. Some structures, such as the ISS truss and the JEM, are fixed to the ISS, and we can easily cut those secondary gamma rays by limiting our field-of-view. However, moving structures, such as solar panels and robotic arms, produce time-varying backgrounds for gamma ray observation. In our previous analysis, we simply rejected events coming from the field-of-view affected by moving structures [3]. We have developed moving filter algorithms to reject time-varying portions of our field-of-view by taking account of moving structures, whose operational data are supplied by JAXA, operating the 'Kibo' module, in order to maximize our exposure for cosmic gamma rays.

As a result of the improved structure cut, the exposure which can be used for gamma-ray analysis is significantly increased. For example, in the LE-γ trigger mode, the fraction of survival after the cut increased from $\sim$ 60% to > 90% around the peak region of the exposure map (around 3 GeV). See ref.[5, 6] for details of the cut for gamma rays and also ref.[7] for general discussion on environment for detectors on ISS.

4. Results

We analyzed the CALET/CAL data acquired between November 2015 to December 2022. The top panel of Fig.2 shows the skymap of gamma-ray intensities for LE-γ triggers (> 1 GeV) and the lower panel show that for HE triggers (> 10 GeV). Note that the CAL exposures, superimposed as

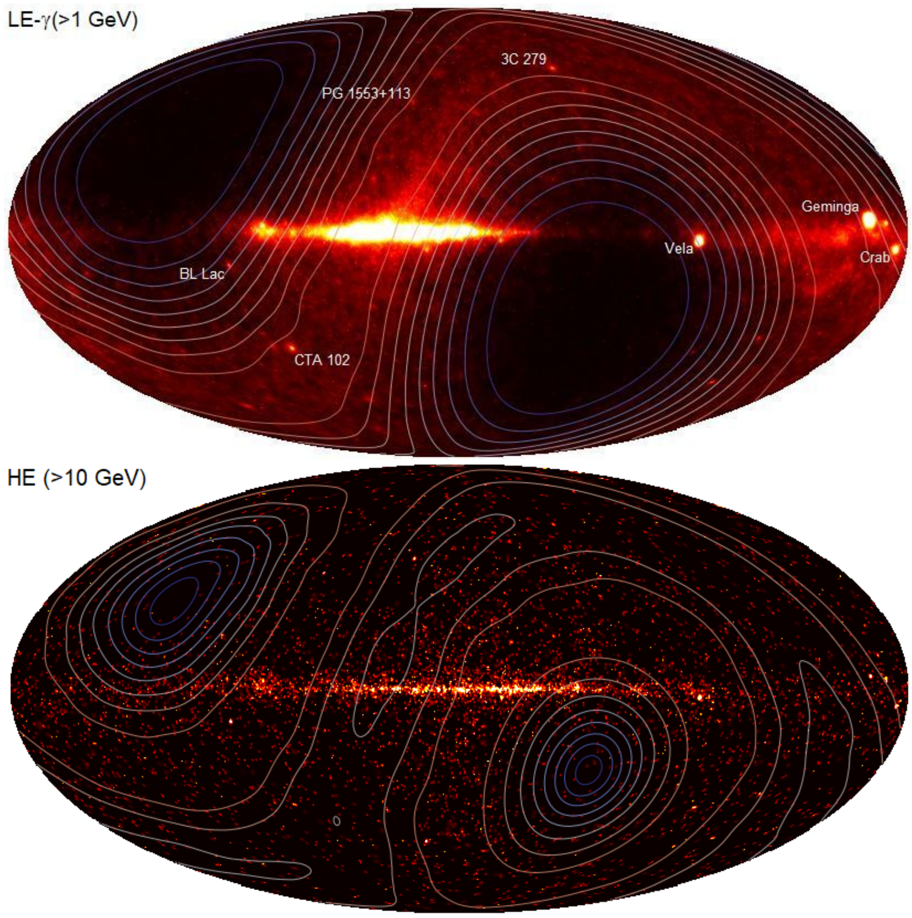

Figure 2: Skymaps showing gamma-ray intensities observed by CALET/CAL in galactic coordinates. The upper panel shows the skymap for LE-γ triggers ($>$ 1 GeV) and the lower panel shows that for HE triggers ($>$ 10 GeV). Superimposed contours show relative exposures.

contours, are not uniform over the celestial coordinates because of inclination angle (51.6°) of the ISS orbit and our triggering schemes. One can see these skymaps match nicely with those shown by Fermi-LAT, considering the non-uniform exposures.

We can easily identify 23 point sources in the skymaps (Fig. 2), but the significance level of the detection of each source is still under evaluation. Fig. 3 shows the spectra of Crab, Geminga and Vela, for examples, compared with the parametrized spectra given by the Fermi-LAT collaboration [10–12]. One can see they are consistent each other within statistical errors. Operating for more than 7 years, CALET is also working as a sky monitor for variable sources. As an example, a light curve of CTA 102, which is a flat-spectrum radio quasar ($z = 1.037$) flared in 2017, is shown in Fig. 4.

Fig. 5 shows comparison of the Galactic plane (diffuse plus discrete sources) spectra ($|b| < 8°$) and the off-Galactic plane spectra ($|b| > 10°$) taken with CALET/CAL and Fermi-LAT. The left panel shows a plot for LE-γ data and the right panel for HE data. We plotted the spectra for LE-γ and HE data separately since the exposures and the tracking algorithms are different, which means they contain different systematic errors. Also, note that these spectra are plotted without removing

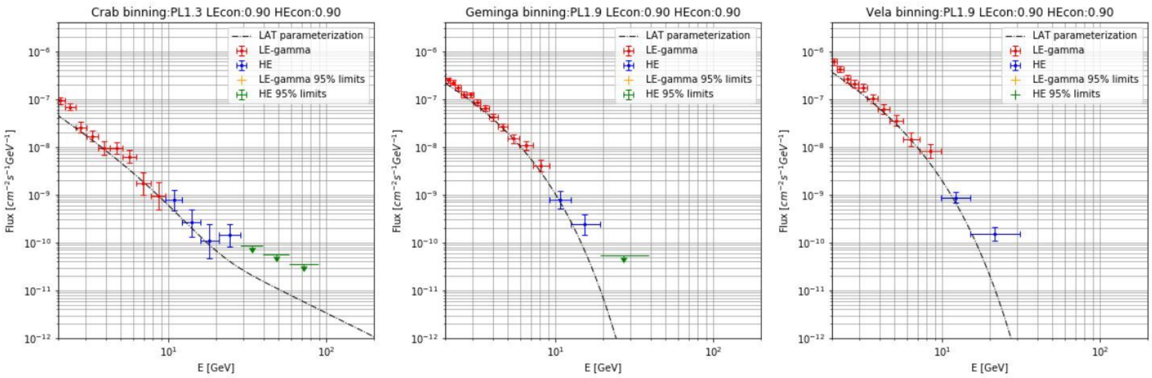

Figure 3: Compasion of energy spectra of some point sources (Crab, Geminga and Vela) observed by CALET and parametrized spectra given by the Fermi-LAT collaboration [10–12].

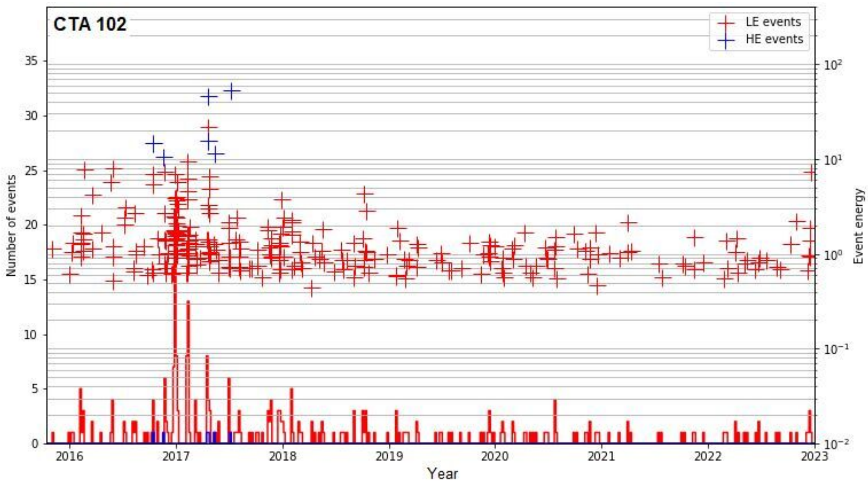

Figure 4: Light curve of CTA 102. Histograms show number of events in scale of the left axis and crosses show energies of individual events in scale of the right axis.

discrete source contributions. One can see good match for the Galactic plane spectra, but some overestimates below about 10 GeV and underestimates above that energy can be seen in the CAL off-plane spectra, which suggests there might be some unaccounted effects at this level in the CAL analysis. We will investigate these effects further.

5. Improvements to increase high-energy sensitivity

At higher energies ($\gtrsim$ 100 GeV), charge selection with CHD becomes contaminated with backscattered secondary particles (see Fig.6 for an example) and the current selection procedure often reject such events. New selection has been developed to mitigate such effects. It is defined to use looser cuts in CHD and incorporating the first two layers of IMC for charged primary rejection. Preliminary results using similated events show significant increase in effective area above $E_\gamma > 100$ GeV as shown in Fig. 7. We are testing the selection and contamination of charged particle. It will be implemented in all flight-data analysis soon. Details of this new selection are discussed elsewhere [13].

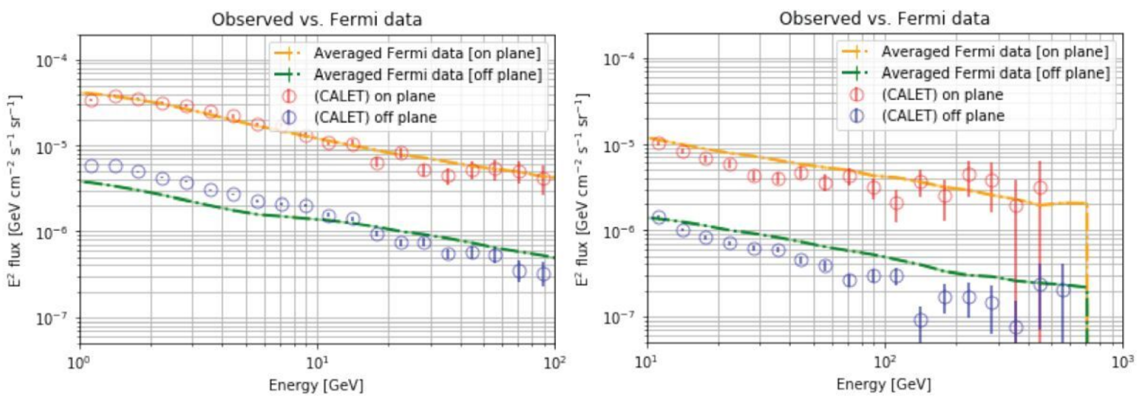

Figure 5: The Galactic plane (diffuse plus point-sources) spectra ($|b| < 8°$) and the off-Galactic plane spectra ($|b| > 10°$) taken with CALET and Fermi-LAT. The left panel shows a plot for LE-γ data and the right panel for HE data.

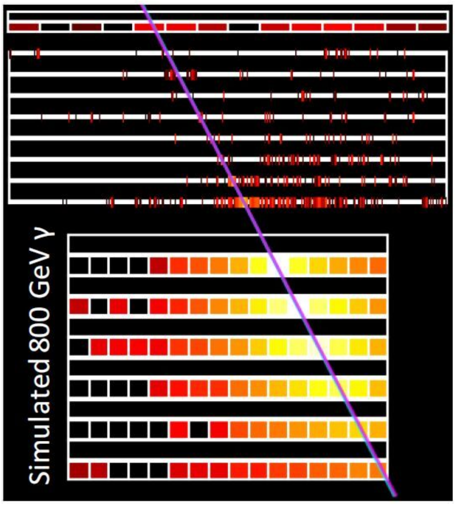

Figure 6: A simulated 800-GeV gamma-ray event incident on the CALET calorimeter. Energy losses in each component (CHD, IMC and TASC from the top) are color-coded and a line shows the incident gamma-ray position and direction.

6. Summary

CALET has been taking data for more than 7.5 years on the ISS and is in good health. Operations of CALET has been approved until end of 2024, are possible for even longer.

We analyzed data from CALET calorimeter to extract gamma-ray events and some of the results (or preliminary results) have been already reported, including: (1) search for counterparts of gravitational wave candidates reported from LIGO/Virgo Observing run 3 [14, 15] (See [16] for prospects for Observing run 4), (2) Galactic and extra-galactic point sources [6], (3) Galactic diffuse emission and dark matter line searches [17], and (4) Solar and space weather phenomena [6].

Improvement to the photon selection is being implemented, which is effective especially at high energies, using information from IMC more extensively to keep gamma rays apart from

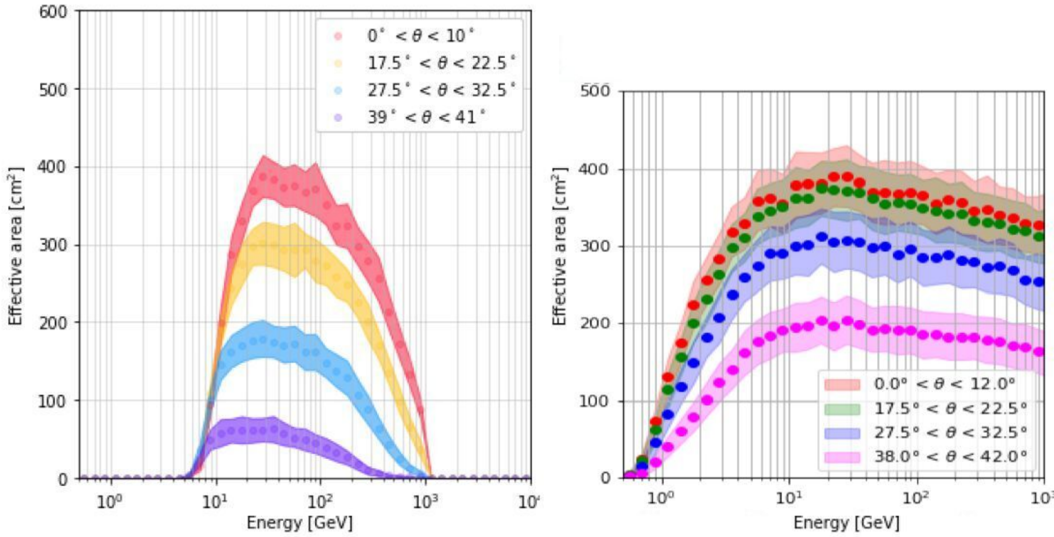

Figure 7: Effective area of CALET/CAL for gamma-rays with the standard analysis (for HE triggers, left) and with the improved analysis (right) plotted against gamma-ray energies and some ranges in zenith angles. One can see significant increase of effective area above 100 GeV [13].

background cosmic rays. Revised geometrical acceptance allows for high-energy sensitivity at larger zenith angles. Preliminary results indicate a factor 3 increase in effective area at 500 GeV for normal incidence, and much larger for larger zenith angles. This new selection will enhance the above-mentioned investigations further. Details of this improvement are described in ref.[13].

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