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ELEMENTARY PARTICLES AND FIELDS
Experiment

CALET Results after Three Years on Orbit on the International Space Station

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Abstract—The CALorimetric Electron Telescope (CALET) is an astroparticle physics experiment installed on the International Space Station since August 2015. The CALET mission was conceived to address several outstanding questions of high-energy astroparticle physics, like indirect detection of dark matter, the origin of cosmic rays (CRs), their mechanisms of acceleration and galactic propagation, the presence of possible nearby astrophysical CR sources. That can be achieved by precise measurements of the fluxes of CR electrons and γ rays up to the unexplored region above 1 TeV, and the energy spectra and composition of CR nuclei from a few tens of GeV to hundreds of TeV. In order to perform these observations, the instrument combines a thick total absorption PWO crystal calorimeter for energy measurement, a scintillator hodoscope for charge identification and thin imaging tungsten-scintillating fiber calorimeter providing accurate particle tracking and complementary charge measurement. In this paper, we will present an overview of the main CALET results based on the data collected in the first three years of the mission.

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1. INTRODUCTION

CALET (CALorimetric Electron Telescope) is a space-based detector developed by an international collaboration led by the Japanese Space Agency (JAXA) with the participation of the Italian Space Agency (ASI) and NASA. The primary goal of CALET is to search for possible clues of the presence of astrophysical sources of high-energy electrons near the Earth and signatures of dark matter, by measuring accurately the flux of cosmic-ray (CR) electrons (including positrons) and γ rays up to 20 TeV. In addition to that, CALET will also investigate the origin of cosmic rays and the mechanisms of acceleration and propagation in the Galaxy, by measuring the energy spectra and elemental composition of each chemical species from H to Fe in cosmic rays with unprecedented statistics up to the highest energies ever directly observed (approaching 10^{15} eV), and the abundance of trans-iron elements at few GeV/amu up to about $Z = 40$ [1–3].

2. THE CALET INSTRUMENT

CALET is an all-calorimetric instrument designed to measure electrons and gamma rays with an excellent energy resolution, providing high discrimination against hadronic cascades.

It consists of three detectors: a CHarge Detector (CHD), a finely segmented pre-shower IMaging Calorimeter (IMC), and a Total AbSorption Calorimeter (TASC), made of 12 layers of lead–tungstan (PWO) logs. The CHD consists of a pair of plastic scintillator hodoscopes, capable of identifying CRs with individual element resolution up to $Z = 40$ [4]. The IMC consists of 7 tungsten plates interleaved with double layers of 1 mm^2 cross-section scintillating fibers (SciFi), read out individually and arranged along orthogonal directions in each layer. It provides accurate particle tracking and redundant CR identification by multiple specific ionization (dE/dx) sampling [5]. The total thickness of the instrument is equivalent to 30 X_0 and 1.3 proton interaction length (λ_I). The geometrical factor is 0.12 m^2 sr and the total weight is 613 kg. A more complete description of the instrument can be found in the Supplemental Material (SM) of [6].

3. ON-ORBIT OPERATIONS AND CALIBRATIONS

The CALET instrument was launched on August 19, 2015 to the International Space Station (ISS) with the Japanese rocket H-II Transfer Vehicle 5 (HTV-5) and installed on the Japanese Experiment Module-Exposed Facility (JEM-EF) of the ISS on August 25, for a 5-year mission. The on-orbit commissioning phase aboard the ISS was successfully completed in the first days of October 2015, and since then the instrument has been taking science data continuously without any major interruption [7]. On-orbit operations 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.

As of May 31, 2018, the total observation time was 1327 days with a live time fraction ~84% of the total time and ~1.8 billion events taken with the onboard high-energy (HE) trigger mode, conceived to ensure maximum exposure to electrons above 10 GeV and other high-energy shower events.

Energy calibration of each channel of CHD, IMC, and TASC is performed by using penetrating proton and He particles, selected in-flight by a dedicated trigger mode. Raw signals are corrected for non-uniformity in light output, gain differences among the channels, position and temperature dependence as well as temporal gain variations [8]. In addition, correlations among the four gain ranges for each TASC channel are calibrated with flight data, and responses from neighboring ranges are linked to provide a seamless transition. In this way, a dynamic range of more than six orders of magnitude is achieved, allowing to observe from singly-charged minimum ionizing particles to 1-PeV showers.

4. RESULTS

4.1. Inclusive Electron Spectrum

CALET is best suited for observation of possible fine structures in the all-electron spectrum up to the TeV region. The 30 X_0-thick calorimeter allows full containment of elecron showers even at TeV

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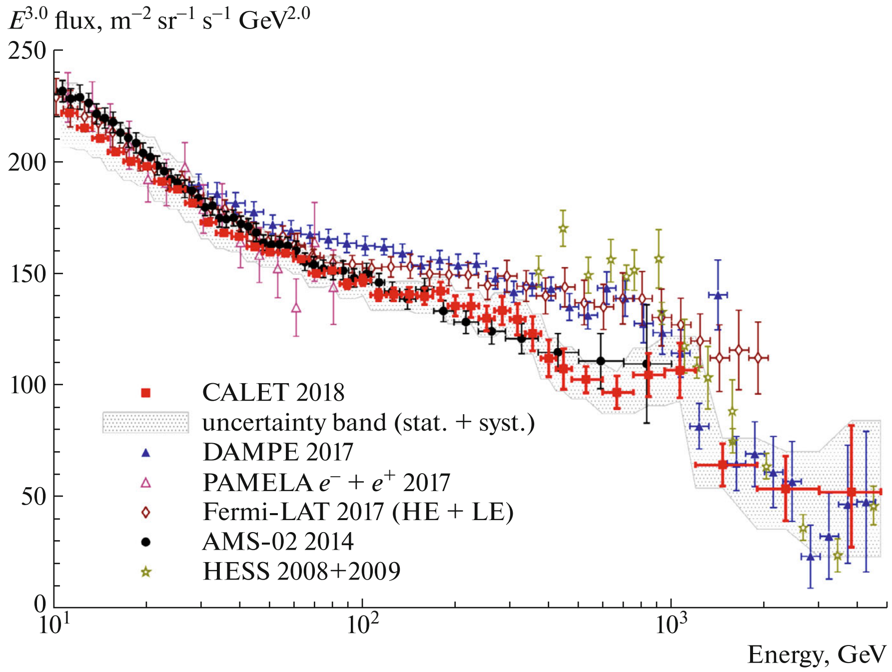

Fig. 1. Cosmic-ray all-electron spectrum measured by CALET from 11 GeV to 4.8 TeV [9]. The width of each bin is shown as a horizontal bar, the statistical errors as vertical bars, while the gray band indicates the quadratic sum of statistical and systematic errors (not including the uncertainty on the energy scale). Also plotted are direct measurements in space including [10–13] and from ground-based experiments [14, 15].

scale, with excellent energy resolution (<2% at energy above 20 GeV), while proton showers, with equivalent energy deposit, are characterized by large energy leakage out of the bottom part of the TASC. This feature is used to easily separate electrons from protons. Morever, the rejection power against proton is significantly improved by exploiting the capability of the TASC and IMC to image the longitudinal and lateral shapes of electromagnetic and hadronic cascades.

Two papers about CR electrons were published so far by the CALET collaboration [6, 9]. A constant electron identification efficiency of 70% was achieved above 30 GeV (where the HE trigger is fully efficient), with a proton contamination level of 2–5% below 1 TeV and ~10–20% above. In Fig. 1, the updated electron spectrum measured by CALET in the energy interval between 11 GeV and 4.8 TeV is shown [9]. In this second analysis the full geometrical acceptance was used at high energy [9], resulting in doubled statistics at $E > 475$ GeV and one additional energy bin between 3 and 4.8 TeV with respect to the first analysis [6], though the spectra from the two papers are perfecly consistent bin-by-bin within the errors.

The CALET electron spectrum is consistent with AMS-02 data [10] below 1 TeV, where both experiments have a good electron identification capability albeit using different detection techniques. It is, instead, significantly softer than the spectra reported by Fermi/LAT [11] and DAMPE [12] in the energy region from 300 to 600 GeV, possibly indicating the presence of unknown systematic errors. CALET observes a flux suppression above ~1 TeV consistent with DAMPE within errors. CALET does not observe any significant evidence for a narrow spectral feature in the energy region around 1.4 TeV, where, instead, the flux in the DAMPE spectrum seems to imply a peak structure, which triggered several theoretical speculations. The results in this energy region are incompatible at a level of 4σ significance, including the systematic errors from both experiments.

4.2. Proton Spectrum and Heavy Nuclei

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. Following the recent observations of a spectral hardening in proton, helium as well as in carbon and oxygen spectra [16–20], it becomes of particular interest to investigate the region of transition for each nuclear species and measure accurately the energy dependence of the spectral index.

The CALET collaboration recently published results of the proton spectrum measured over the wide energy range from 50 GeV to 10 TeV for the first time

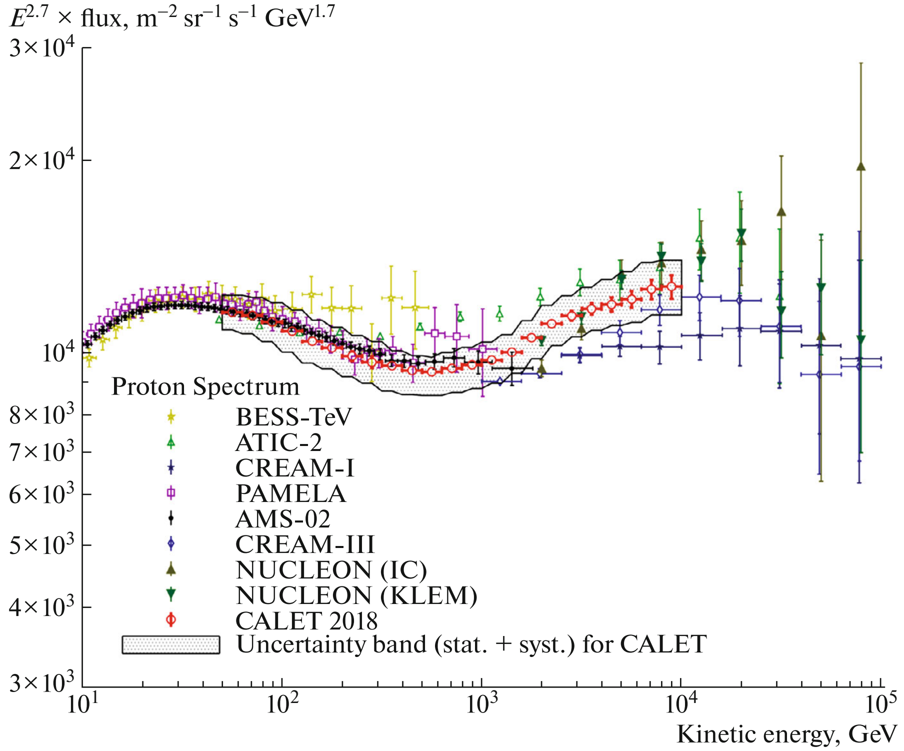

Fig. 2. Cosmic-ray proton spectrum measured by CALET from 50 GeV to 10 TeV [21]. The gray band indicates the quadratic sum of statistical and systematic errors. Also plotted are recent direct measurements [16, 22–26].

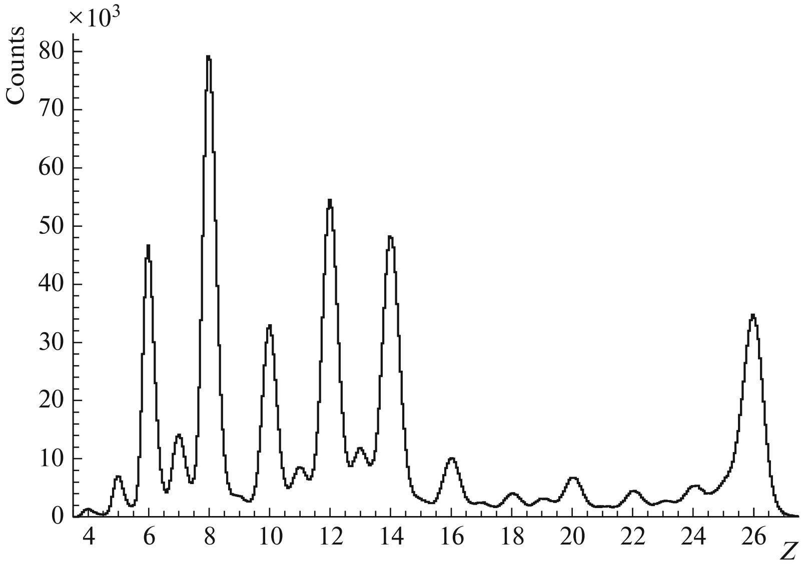

Fig. 3. Charge distribution in the elemental range from Be to Fe, as measured by the combined CHD layers using a subset of FD.

with a single instrument in space (Fig. 2). Possible sources of systematic uncertainties (like hadronic interaction modeling, energy scale calibration, tracking and charge identification) were studied in detail, resulting in a total systematic uncertainty less than 10% over the whole energy range [21]. The CALET proton spectrum is consistent with AMS-02 data [16] below 1 TeV and CREAM-III data [22] in the high-energy region. It shows a very smooth transition of the power-law spectral index from -2.81 ± 0.03 in the energy region 50-500 GeV to -2.56 ± 0.04 between 1 and 10 TeV, thereby confirming the existence of

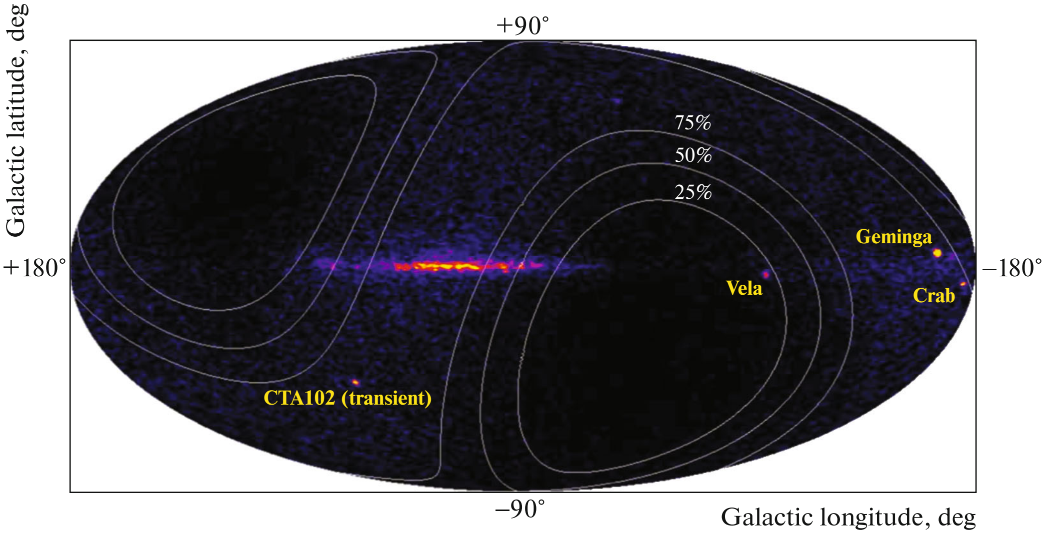

Fig. 4. Gamma-ray sky map shown in a Mollweide projection of galactic coordinates [30]. White contours show the relative level of exposure compared to the maximum on the sky. The Crab, Geminga, and Vela pulsars are clearly visible, as is a flare of the AGN CTA 102.

a spectral hardening at a few hundreds of GeV and providing evidence of a deviation from a single power-law by more than 3σ.

Taking advantage of its wide dynamic range, large thickness and excellent charge identification capability (an example of charge distribution obtained with the CHD is shown in Fig. 3), CALET is carrying out extensive measurements of the energy spectra, relative abundances and secondary-to-primary ratios of cosmic-ray nuclei. Preliminary results were presented on the primary heavy component of cosmic rays and B/C flux ratio in [17, 28].

4.3. Observation of Gamma-Rays

CALET can identify gamma rays and measure their energies up to the TeV region. In the offline analysis, signals in the CHD and IMC upper layers are used to veto charged particles, while gamma-ray candidates are required to deposit more energy in the bottom IMC layers than in the layer where pair conversion takes place. In order to extend the gamma-ray sensitivity down to ~1 GeV, a dedicated Low-Energy (LE) trigger is used at low geomagnetic latitudes (to avoid an increase of the dead time), in addition to the HE trigger. This trigger mode is also enabled whenever a gamma-ray burst is triggered onboard by the CALET Gamma-ray Burst Monitor (CGBM) [29].

The calorimeter response to gamma rays was characterized in terms of effective area, angular resolution and Point Spread Function (PSF) by comparing simulations and data from the first two years of observations. The gamma-ray sky observed by CALET using the LE-γ trigger is shown in Fig. 4. Measured signals from gamma-ray bright point sources and diffuse galactic emission were found to be in agreement with simulated results and expectations from Fermi-LAT data [30].

Source spectra for Crab, Geminga, and Vela pulsars measured by CALET were tested for consistency with parameterized LAT spectra, as shown in Fig. 5, demonstrating the sensitivity of the calorimeter to observe bright, persistent sources.

CALET can also detect gamma-ray transients by means of the dedicated CGBM, which can measure the duration and spectral parameters of gamma-ray bursts (GRB) in the energy range of 7 keV–20 MeV. As of June 2019, 159 GRBs have been detected, 12% of which were classified as short GRBs, with an average rate of ~43 GRBs/year.

Combined analyses of the CGBM and calorimeter were performed to search for electromagnetic counterparts of gravitational waves (GW) triggered by LIGO/Virgo. Possible signals compatible with gamma-ray emission were searched for in the calorimeter and CGBM data in time intervals of tens of seconds centered on the reported trigger times of GW151226, GW170104, GW170608, GW170814, and GW170817 events. No signal was detected for all GW events; upper limits on gamma-ray emission were set for GW151226 (CAL + CGBM) and GW170104 (CAL), while GW170608, GW170814, GW170817 turned out to be out of the CALET field-of-view [31, 32].

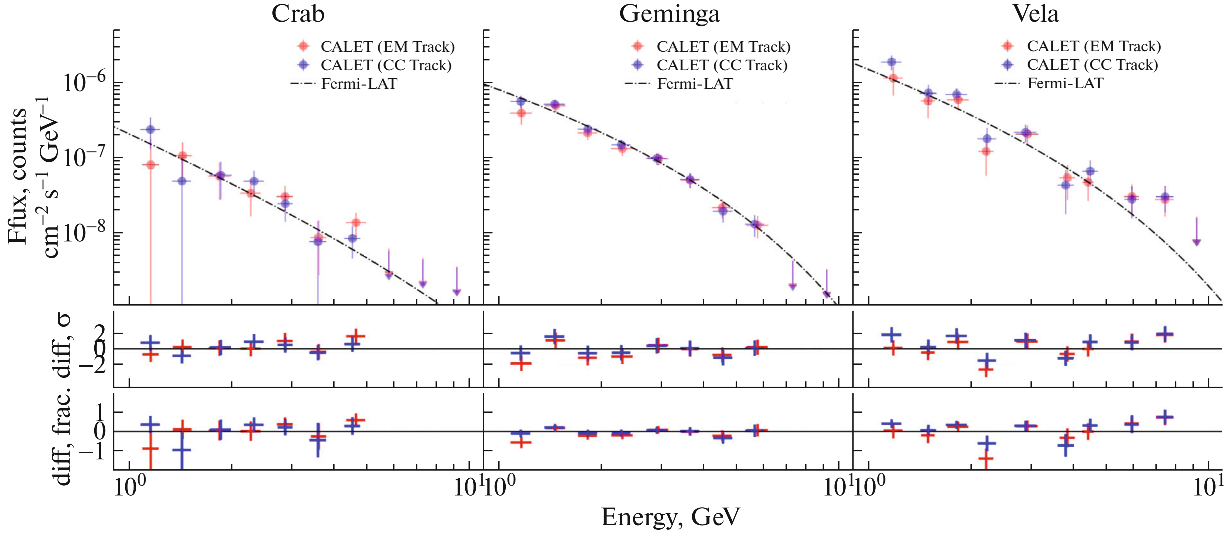

Fig. 5. Source spectra for Crab, Geminga, and Vela as measured by CALET [30]. The lower panels in each plot show the difference between the CAL observations and the Fermi-LAT parameterization in units of CAL error (top) and fractional difference (bottom).

5. SUMMARY AND PERSPECTIVES

CALET has been taking data continuously since October 2015, showing remarkable stability of the instrument and excellent performance. As of May 31, 2019, the total observation time is 1327 days and nearly 1.8 billion events have been collected with high energy trigger.

The electron spectrum was published up to 4.8 TeV, suggesting a flux reduction above 1 TeV [6, 9]. The expected statistics in five years of observations (a factor ∼3 more than the published data) and a better understanding of systematic uncertainties, will allow us to investigate accurately possible spectral features in the electron spectrum and flux break above 1 TeV.

The CALET wide energy span and excellent charge identification capability allow us to measure nuclei in cosmic rays from proton to iron up to the PeV scale. The proton spectrum was published by the CALET collaboration up to 10 TeV; the spectral index variation as a function of energy was measured confirming a clear flux hardening at a few hundred GeV [21]. Measurements of the energy spectra and composition of primary and secondary nuclei are ongoing.

The CALET capability of observing the diffuse component and bright point-sources in the gamma-ray sky was demonstrated [30], as well as its great potential to perform follow-up observations in the X-ray and gamma-ray band of GW events during the upcoming LIGO/Virgo third observation run [31, 32].

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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