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New results obtained from CALET observations after 8 years of data collection on the International Space Station

Sandro Gonzi[a,b,c,*] **for the CALET collaboration**

[a] *University of Florence, Department of Physics and Astronomy, Via Giovanni Sansone 1, 50019 Sesto Fiorentino, Italy*

[b] *National Institute for Nuclear Physics INFN, Division of Florence, Via Bruno Rossi 1, 50019 Sesto Fiorentino, Italy*

[c] *National Research Council CNR, Institute of Applied Physics IFAC, Via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy*

E-mail: sandro.gonzi@unifi.it

The Calorimetric Electron Telescope (CALET) is a cosmic-ray observatory operating since October 2015 on the International Space Station. The primary scientific goals of the CALET mission include the investigation of the mechanism of cosmic-ray acceleration and propagation in the Galaxy and the detection of potential nearby sources of high-energy electrons and potential dark matter signatures. The CALET instrument can measure the inclusive spectrum of cosmic electrons and positrons up to about 20 TeV. In addition, it can measure the energy spectra and elemental composition of cosmic-ray nuclei from H to Fe and the abundance of trans-iron elements up to about 1 PeV. Finally, it can monitor the gamma-ray sky up to about 10 TeV, search for signals from gravitational-wave event candidates, and observe gamma-ray burst events. In this contribution the on-orbit performance of the instrument and the main results obtained during the first 8 years of operation will be reported and discussed.

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*Speaker

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1. Introduction

The CALorimetric Electron Telescope (CALET) [1] is a space experiment operating onboard the International Space Station (ISS) for long-term observations of both charged and neutral cosmic radiation. The international space mission conducting the experiment is led by the Japan Aerospace Exploration Agency (JAXA), with contributions from the Italian Space Agency (ASI) and the National Aeronautics and Space Administration (NASA). Launched into orbit on August 19, 2015, by the Japanese H-IIB carrier and delivered to the ISS via the automated H-II Transfer Vehicle (HTV), CALET was installed on the Japanese Experiment Module - Exposed Facility (JEM-EF) external platform. Initially designed for a five-year mission, its operations have now been extended until the end of the ISS's expected lifetime in 2030. CALET's advanced technical capabilities enable it to tackle key open questions in high-energy cosmic-ray physics, such as the origin of cosmic rays, the mechanisms behind their galactic acceleration and propagation, the potential existence of nearby sources, and the search for dark matter signals. With its excellent energy resolution and high proton-rejection power, CALET's primary scientific objective is to perform precise measurements of the inclusive spectrum of cosmic electrons and positrons up to 1 TeV, with the ability to explore higher energy regions up to 20 TeV. In addition, CALET measures the energy spectra and elemental composition of cosmic-ray nuclei, from hydrogen to iron, and can detect trans-iron elements at energies approaching the PeV scale - the highest ever directly observed. The instrument is also capable of monitoring the gamma-ray sky within an energy range of 1 GeV to 10 TeV, observing gamma-ray bursts, and searching for signals from gravitational wave event candidates counterparts. CALET also contributes to solar modulation studies by observing electrons and protons in the 1-10 GeV energy range, as well as detecting MeV electrons from the radiation belt, providing valuable data for space weather monitoring. This paper discusses the on-orbit performance of the instrument and presents the main scientific results obtained during the first eight years of operation.

2. The CALET mission: detector, performance and operation

The CALET experiment consists of two primary detectors: the main calorimeter (CAL) and the CALET Gamma-ray Burst Monitor (CGBM). The main detector [2] is a fully calorimetric instrument with a total vertical thickness equivalent to 30 radiation lengths (X_0) and 1.3 proton interaction lengths (λ_I) for particles at normal incidence. The total instrument has a field of view of about 45° from zenith and a geometrical factor of about 1040 cm^2 sr for high-energy electrons. At the top of the instrument is the CHarge Detector (CHD), which consists of two orthogonal layers of segmented plastic scintillator hodoscopes. The CHD is responsible for reconstructing the charge of the incoming particle. Central to the instrument is the IMaging Calorimeter (IMC), a 3 X_0 sampling calorimeter that alternates thin tungsten absorber layers with layers of individually read-out scintillating fibers. This allows the IMC to track the trajectory and reconstruct the early shower profile of the incident particle, while also providing an independent charge measurement through multiple energy-loss sampling. Positioned at the bottom of the instrument is the Total AbSorption Calorimeter (TASC), a 27 X_0 segmented calorimeter made of tightly packed lead-tungstate (PWO) crystals. The TASC is designed to absorb almost the entire energy of TeV-scale electron showers. The CGBM [3] includes two types of detectors: the Hard X-ray Monitor (HXM),

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which uses lanthanum bromide ($LaBr_3$(Ce)) crystal scintillators to cover the energy range of 7-1000 keV, and the Soft Gamma-ray Monitor (SGM), utilizing Bismuth Germanate Oxide (BGO) crystal scintillators to detect energies between 100 keV and 20 MeV. The CALET design achieves an electromagnetic shower energy resolution of approximately 2% above 20 GeV and a proton rejection factor of around 10^5, enabling the precise study of high-energy phenomena with well-established and robust analysis techniques.

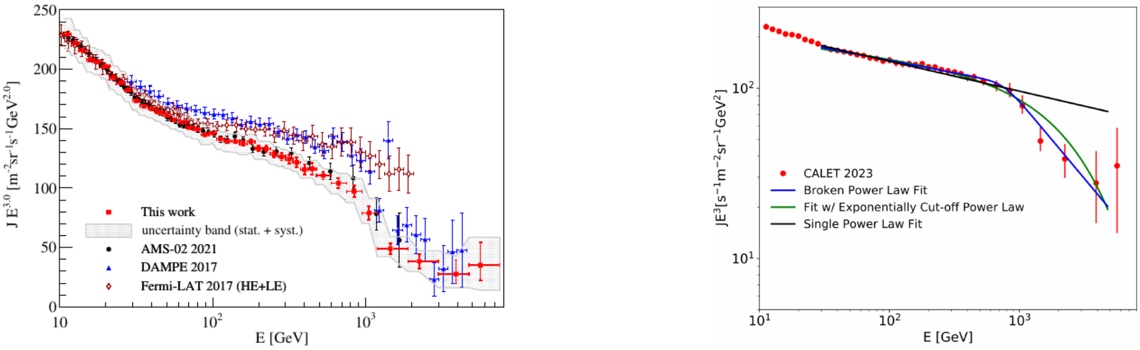
The CALET mission has maintained highly stable operations thanks to the collaboration between the JAXA Ground Support Equipment (JAXA-GSE) and the Waseda CALET Operations Center (WCOC) [4]. A continuously active High-Energy (HE) trigger mode ensures maximum exposure to high-energy electrons and other shower events with energies above 10 GeV. Additional modes include a Low-Energy (LE) trigger at the highest geomagnetic latitudes, a low-energy gamma-ray (LE-γ) trigger at lower geomagnetic latitudes, and an Ultra-Heavy (UH) trigger that operates almost continuously except during high-latitude calibrations, which involve detecting minimum ionizing particles and are conducted for three hours each day. As of April 30, 2024, the total observation time reached 3,123 days, with a live-time fraction of 86% during this period, corresponding to over 2.07 billion events recorded in HE trigger mode. Monte Carlo (MC) simulations, which replicate the detailed detector configuration, physics processes, and signal response, are based on the EPICS [5] simulation package, carefully tuned and validated using accelerator beam test data. An independent analysis using FLUKA [6, 7] and GEANT4 [8] is also conducted to evaluate systematic uncertainties.

3. Results

This section presents the main recent results obtained by CALET on the all-electron (i.e., electrons and positrons), proton, and helium spectra. A detailed discussion of the most significant findings from the analyses of boron, carbon and oxygen [9, 10], iron [11, 12], nickel [13], ultra heavy nuclei [14], gamma-ray sky map [15], gamma-ray bursts observations and searches of gravitational waves counterparts [16], as well as solar modulation effects [17, 18], can be found in other publications.

3.1 All-electron spectrum

Figure 1a shows the all-electron spectrum measured by CALET from 10.6 GeV to 7.5 TeV [19], compared with Fermi-LAT [20], DAMPE [21] and AMS-02 [22]. The CALET spectrum shows a good agreement with AMS-02 data up to 2 TeV, where both experiments have a good electron identification capability, albeit using different detection techniques. In the energy region from 30 to 300 GeV, the fitted power-law spectrum index, -3.14 ± 0.02, is roughly consistent with the values quoted by other experiments within the errors. The CALET spectrum, however, appears to be softer compared to Fermi-LAT and DAMPE, and the flux observed by CALET is lower than these two experiments, starting near 60 GeV and extending to near 1 TeV, possibly indicating the presence of unknown systematic errors. In the energy region above 1 TeV, CALET observes a flux suppression that aligns with DAMPE within the errors. This observed break is consistent with models in which only nearby (<1 kpc) and young (<10^5 years) sources, such as supernova remnants (SNRs), contribute to the flux beyond 1 TeV.

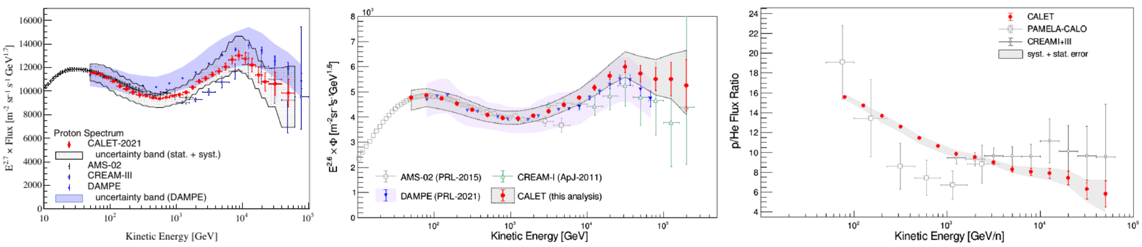


(a) all-electron spectrum. **(b)** fits on the all-electron spectrum.

Figure 1: some remarkable results obtained from CALET measurement of the cosmic-ray all-electron spectrum [19] compared with those achieved by other direct measurements in space [20–22].

To quantitatively analyze the spectral steepening, the all-electron spectrum has been fitted using various fitting functions. The best result is obtained performing the fit in the energy range of 30 GeV to 4.8 TeV with a single broken power law (SBPL) function defined as follows: $\Phi(E) = C(E/100\ \mathrm{GeV})^{\gamma}[1 + (E/E_b)^{\Delta\gamma/s}]^{-s}$ where $\Phi(E)$ is the flux as a function of the energy E, C is a normalization factor, γ is the spectral index, $\Delta\gamma$ is the spectral variation due to the spectral steepening, E_b is the steepening break energy, s is the break smoothness parameter. Figure 1b shows the data with statistical errors and the best-fit function. The best-fit parameters are: $\gamma = -3.15\pm0.01$, $\Delta\gamma = -0.77 \pm 0.22$, $E_b = 761 \pm 115$ GeV, $s = 0.1$ (fixed), with $\chi^2/\mathrm{dof} = 3.6/27$.

3.2 Proton and helium spectra



(a) proton spectrum. **(b)** helium spectrum. **(c)** proton-to-helium ratio.

Figure 2: some remarkable results obtained from CALET measurement of the cosmic-ray proton [23] and helium [27] spectra compared with those achieved by other direct measurements [24–26, 28–30, 32, 33].

Figure 2a shows the proton spectrum measured by CALET from 50 GeV to 60 TeV [23], compared with AMS-02 [24], CREAM-III [25] and DAMPE [26]. The spectrum is in good agreement with the rigidity spectra measured by magnetic spectrometers in the sub-TeV region, and it is also consistent, within the errors, with the measurements carried out with calorimetric instruments at higher energies. The analysis confirms the presence of a spectral hardening at a few hundred GeV with significance of more than 20 σ (statistical error) and observes a spectral softening around 10 TeV.

Figure 2b shows the helium spectrum measured by CALET from 40 GeV to 250 TeV [27], compared with CREAM-I [28], AMS-02 [29] and DAMPE [30]. Also in this case, the spectrum is in good agreement with the rigidity spectra measured by magnetic spectrometers in the sub-TeV region, and it is consistent, within the errors, with the measurements carried out with calorimetric instruments at higher energies. The analysis observes a spectral hardening from a few hundred GeV to a few tens TeV with a significance of more than 8 σ (statistical error) and also observes the onset of a spectral softening above a few tens of TeV.

Differences between the proton and helium spectra can contribute important constraints on acceleration models [31]. Figure 2c shows the measured proton-to-helium flux ratio compared with results of previous CREAM [25] and PAMELA (calorimeter analysis) [32, 33].

4. Summary and future prospects

The performance of the CALET instrument aboard the ISS has remained exceptionally stable throughout its entire scientific observation period, which began in October 2015. During its first eight years of operation, CALET has provided valuable new data on cosmic-ray spectra, including measurements of the all-electron spectrum up to 7.5 TeV - crucial for investigating nearby sources and potential dark matter signatures. It has also measured the proton spectrum up to 60 TeV and the helium spectrum up to 250 TeV. In addition, CALET has updated the analyses of various elements, including boron, carbon, oxygen, iron, nickel, and ultra-heavy nuclei. It has also delivered a gamma-ray sky map, observed gamma-ray bursts, and conducted searches for gravitational wave counterparts and solar modulation effects. In March 2021, the mission was extended by JAXA, ASI and NASA through the end of 2024, with an additional extension approved until 2030. As data collection continues, improved statistics will allow for refined spectral analyses, extended measurements to higher energies, and deeper insights into cosmic-ray phenomena.

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