

Direct Measurement of the Spectral Structure of Cosmic-Ray Electrons + Positrons in the TeV Region with CALET on the International Space Station

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Detailed measurements of the spectral structure of cosmic-ray electrons and positrons from 10.6 GeV to 7.5 TeV are presented from over 7 years of observations with the CALorimetric Electron Telescope (CALET) on the International Space Station. The instrument, consisting of a charge detector, an imaging calorimeter, and a total absorption calorimeter with a total depth of 30 radiation lengths at normal incidence and a fine shower imaging capability, is optimized to measure the all-electron spectrum well into the TeV region. Because of the excellent energy resolution (a few percent above 10 GeV) and the outstanding e/p separation (10^5), CALET provides optimal performance for a detailed search of structures in the energy spectrum. The analysis uses data up to the end of 2022, and the statistics of observed electron candidates has increased more than 3 times since the last publication in 2018. By adopting an updated boosted decision tree analysis, a sufficient proton rejection power up to 7.5 TeV is achieved, with a residual proton contamination less than 10%. The observed energy spectrum becomes gradually harder in the lower energy region from around 30 GeV, consistently with AMS-02, but from 300 to 600 GeV it is considerably softer than the spectra measured by DAMPE and Fermi-LAT. At high energies, the spectrum presents a sharp break around 1 TeV, with a spectral index change from -3.15 to -3.91 , and a broken power law fitting the data in the energy range from 30 GeV to 4.8 TeV better than a single power law with 6.9 sigma significance, which is compatible with the DAMPE results. The break is consistent with the expected effects of radiation loss during the propagation from distant sources (except the highest energy bin). We have fitted the spectrum with a model consistent with the positron flux measured by AMS-02 below 1 TeV and interpreted the electron + positron spectrum with possible contributions from pulsars and nearby sources. Above 4.8 TeV, a possible contribution from known nearby supernova remnants, including Vela, is addressed by an event-by-event analysis providing a higher proton-rejection power than a purely statistical analysis.

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Introduction.—Direct measurements of high-energy electron and positron cosmic rays (hereafter, all-electron CRs) have advanced significantly since the 2000s with state-of-the-art detectors in space, some of which continue to operate increasing the collected statistics and, correspondingly, the precision of the spectrum. Based on these observations, it has widely been recognized that the all-electron spectrum cannot be described by a single power law in the range from the 10 GeV to the TeV region. In particular, the energy spectrum above 1 TeV is expected to show a break due to the radiative cooling process with an energy loss rate proportional to E^2 . As a result, only nearby (< 1 kpc) and young

($< 10^5$ yr) sources can contribute to the flux above 1 TeV if the sources are supernova remnants (SNRs) as it is commonly believed. The pioneering works [1–7] pointed out a possible break of the electron spectrum above 1 TeV, suggesting that precise measurements of the spectrum in the TeV region could lead to the identification of nearby sources. Recently, several authors interpreted the observed spectral break above 1 TeV assuming this scenario (for example, Refs. [8–11]). Also, a direct probe of the escape mechanism from SNR is discussed, for example, in Ref. [12].

The calorimetric electron telescope (CALET) is a space experiment installed at the Japanese Experiment Module–Exposed Facility (JEM-EF) on the International Space Station (ISS) for long term observations of cosmic rays and optimized for the measurement of the all-electron spectrum [13]. The first result on the all-electron spectrum by CALET was published in the energy range from 10 GeV

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to 3 TeV, the first ever significant observation reaching into the TeV region [14]. Subsequently, an updated spectrum was published with a factor ~ 2 larger statistics by using more than 2 years of flight data and the full geometrical acceptance in the high-energy region [15]. The observed energy spectrum above ~ 1 TeV suggests a flux suppression consistent within the errors with the results of dark matter particle explore (DAMPE) [16].

Although calorimeters as CALET and the DAMPE [17] are not able to measure the polarity of charge, magnet spectrometers, such as the payload for antimatter matter exploration and light nuclei astrophysics (PAMELA) [18] and the alpha magnetic spectrometer (AMS-02) [19], measured separately the positrons and the electrons, and found an increase of the positron fraction above 10 GeV. The fraction reaches a maximum ($\sim 15\%$) around 300 GeV and decreases to a level of a few percent near 1 TeV. The results require a primary source component of the positrons in addition to the generally accepted secondary origin. Candidates for such primary sources range from astrophysical (pulsar) to exotic (dark matter). Since these primary sources emit electron-positron pairs, it is expected that the shape of the all-electron spectrum would reflect the presence of the primary source component of electrons and positrons, in the corresponding energy range above 10 GeV.

In this paper, we present the CALET all-electron spectrum with a further increase in statistics by a factor ~ 3.4 since the last publication [15], using 2637 days of flight data from October 13, 2015 to December 31, 2022. The spectrum integrates 7.02 million electron (+positron) events above 10.6 GeV up to 7.5 TeV. Combining the CALET all-electron spectrum and the positron measurements up to 1 TeV by AMS-02, we attempt a consistent interpretation of both spectra based on contributions from pulsars and nearby SNR sources. Based on this interpretation, the obtained spectrum in the TeV region is tested for indications of contributions from the nearby sources, foremost Vela, by estimating the number of electron candidates above 4.8 TeV obtained with an event-by-event analysis with a residual proton contamination probability less than 10% [20].

Instrument.—CALET is a fully active calorimeter optimized for electron observations from 1 GeV up to 20 TeV. It consists of a charge detector (CHD), a 3 radiation-length thick imaging calorimeter (IMC), and a 27 radiation-length thick total absorption calorimeter (TASC). It has a field of view of approximately 45° from zenith and a geometrical factor of $1040 \text{ cm}^2 \text{ sr}$ for high-energy electrons. The IMC induces the start of the shower development for electromagnetic particles while suppressing nuclear interactions in order to maximize the proton rejection power for the electron candidates, and provides the direction of incident particles. It is composed of 7 layers of tungsten absorbers interleaved with scintillating fiber belts read out individually with 64-anode PMTs. The TASC installed below the IMC measures the energy of shower particles caused by the

interactions of the incident particles in the IMC. It is a tightly packed lead-tungstate (PbWO_4 ; PWO) hodoscope, allowing for a nearly total containment of TeV-electron showers. The CHD, placed at the top of the detector to identify the charge of the incident particle, is comprised of a pair of plastic scintillator hodoscopes arranged in two orthogonal layers.

With the precise energy measurements from total absorption of electromagnetic showers, it is possible to derive the electron spectrum well into the TeV region with a straightforward and reliable analysis. A more complete description of the instrument is given in Ref. [21].

Observation and calibrations.—Since the start of scientific operations, CALET observations have been carried out continuously without any serious incident and with downtime less than a few days during each interruption. The live time fraction, dominated by the data acquisition dead time (nearly 5 ms per event) is nearly 86%, including runs for calibration and the high trigger rate for low energy particles (> 1 GeV) [23]. The total live time was so 1.927×10^8 sec.

CALET carries out precise energy measurements over a very wide dynamic range from 1 GeV to 1 PeV by exploiting the read-out system of the TASC, which implements four gain ranges for each channel, providing excellent energy resolution even in the TeV region. Our energy calibration includes the evaluation of the conversion factors between analog-to-digital converter units and energy deposits, ensuring linearity over each gain range and provides a seamless transition between neighboring gain ranges [24]. The absolute calibration of energy is done by using the energy deposit of penetrating protons and/or helium particles detected at the highest gain.

Temporal gain variations occurring during long duration observations are also corrected by the calibration procedure. The errors at each calibration step, such as the correction of position and temperature dependence, consistency between energy deposit peaks of noninteracting protons and helium, linear fit error of each gain range, and gain ratio measurements, as well as slope extrapolation, are included in the estimation of the energy resolution. As a result, an excellent energy resolution of 2% or better is achieved above 20 GeV up to over 10 TeV. The calibrations are checked monthly to confirm the instrument stability, and the spectra of deposited energies in TASC using four gain ranges are compared among each other for consistency.

Data analysis.—The analysis has been carried out on the data collected with a high-energy shower trigger [23] in the full detector acceptance, by an updated procedure to reduce the proton background in the TeV region, compared with the analysis described in Ref. [15]. A Monte Carlo (MC) program was used to simulate physics processes and detector response based on the simulation package EPICS [25] (EPICS9.20/COSMOS8.00). Using MC event samples of electrons and protons, event selection and event reconstruction efficiencies, energy correction factors, and

background contamination were derived. An independent analysis based on GEANT4 [26] was performed, and differences between the MC models are included in the systematic uncertainties. The GEANT4 simulation employs the hadronic interaction models FTFP-BERT as the physics list, while DPMJET3 [27] is chosen as the hadronic interaction model in the EPICS simulation.

We use the “electromagnetic shower tracking” algorithm [28] to reconstruct the shower axis of each event, taking advantage of the electromagnetic shower shape and IMC imaging capabilities. As input for the electron identification, well-reconstructed and well-contained single-charged events are preselected by (i) an offline trigger confirmation, (ii) a geometrical condition, (iii) a track quality cut to ensure reconstruction accuracy, (iv) a charge selection using CHD, (v) a requirement based on the longitudinal shower development, and (vi) on the lateral shower consistency with that expected for electromagnetic cascades.

In addition to fully contained events, the events incident from the IMC sides and exiting through the sides of TASC are used for analysis above 476 GeV [15]. For events not crossing the CHD, we use the energy deposit of the first hit IMC layer to determine their charge. The path length inside TASC is required to be longer than the vertical depth of TASC, i.e., 27 radiation lengths. The energy of incident electrons is reconstructed using an energy correction function which converts the energy deposit of TASC and IMC into primary energy for each geometrical condition. The absolute energy scale was calibrated and shifted by +3.5% [14] as a result of a study of the geomagnetic cutoff. Since the full dynamic range calibration [24] was carried out with a scale-free method, its validity holds regardless of the absolute scale uncertainty. The systematic uncertainties are described in detail in the Supplemental Material [20].

In order to identify electrons and to study systematic uncertainties in the electron identification, we applied two methods: a simple two-parameter cut below 476 GeV and a multivariate analysis above. The latter is based on boosted decision trees (BDTs) optimized in the energy interval above (below) 949 GeV, using 13 (9) parameters, respectively. Calculation of event selection efficiencies, BDT training, and estimation of proton background contamination are carried out separately for each geometrical condition and combined in the end to obtain the final spectrum. Considering that the lower energy region is dominated by systematics in our analysis, and therefore more statistics would not significantly improve the precision of our data, only fully contained events are included in the lower energy region below 476 GeV.

An example of a BDT response distribution in the $754 < E < 949$ GeV bin including all acceptance conditions is shown in Fig. 1. The BDT response distributions for the TeV region are shown in Fig. S1 of the Supplemental Material [20]. In the final electron sample, the contamination ratios of protons are 5% up to 1 TeV, and less than 10%

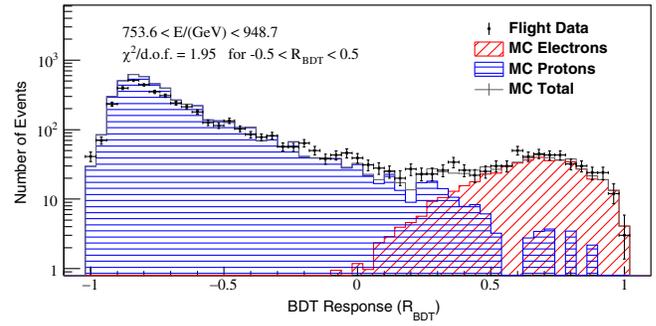


FIG. 1. An example of BDT response distributions in the $754 < E < 949$ GeV bin, including all acceptance conditions.

in the 1–7.5 TeV region, while keeping a constant high efficiency of 80% for electrons.

By using the data obtained with the low energy trigger (1 GeV threshold), the high energy trigger efficiency was verified, considering only the events observed in the rigidity cutoff region below 6 GV. Two independent analyses were carried out by separate groups inside the CALET Collaboration, using different event selections and acceptance of the event geometries. The results of the two analyses are consistent with each other within the errors over the entire energy region.

Results.—Figure 2 shows the all electron spectrum obtained in this analysis using the observed events with statistics increased by a factor 3.4 since the last publication [15]. The error bars along the horizontal and vertical axes indicate the bin width and statistical errors, respectively. The gray band is representative of the quadratic sum of statistical and systematic errors, using the same definition as in Ref. [15].

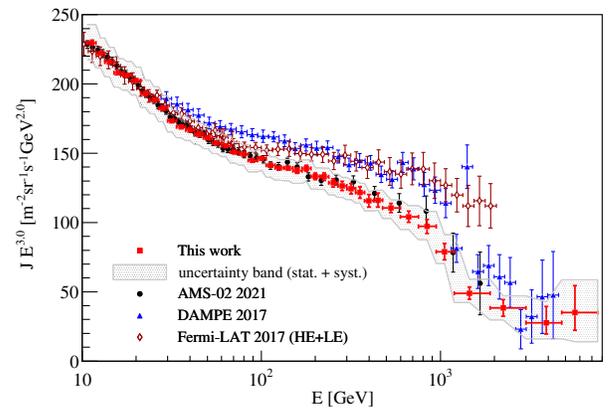


FIG. 2. Cosmic-ray all-electron spectrum measured by CALET from 10.6 GeV to 7.5 TeV using the same energy binning as in our previous publication below 4.8 TeV [15], where the gray band indicates the quadratic sum of statistical and systematic errors (not including the uncertainty on the energy scale). Also plotted are other direct measurements in space [16,29,30] for comparison. The enlarged figure is shown in Fig. S4 in the Supplemental Material [20].

Systematic errors include errors in the absolute normalization and energy dependent ones. The energy dependent errors include those obtained from BDT stability, trigger efficiency in the low-energy region, tracking dependence, dependence on methods of charge identification and of electron identification, as well as MC model dependence. Conservatively, all of them are included in the total error estimate in Fig. 2, and a breakdown of the contributions from each source and their specific energy dependence is given in the Supplemental Material [20]. Utilizing this additional data, our all-electron spectrum in combination with the positron-only measurement by AMS-02 can provide essential information for investigating spectral features as possible signatures of dark matter and/or astrophysical sources.

Comparing with other recent experiments in space (AMS-02, Fermi-LAT, and DAMPE), the CALET spectrum shows good agreement with AMS-02 data up to 2 TeV. In the energy region from 30 to 300 GeV, the fitted power-law spectral index, -3.14 ± 0.02 , is roughly consistent with the values quoted by other experiments within errors. However, the CALET spectrum appears to be softer compared to DAMPE and Fermi-LAT, and the flux measured by CALET is lower than that seen by DAMPE and Fermi-LAT, starting near 60 GeV and extending to near 1 TeV, indicating the presence of unknown systematic effects. Moreover, the flux in the 1.4 TeV bin of DAMPE's spectrum, which might imply a peak structure, is not compatible with CALET results at a significance level of 4.8σ using the same energy binning as DAMPE, including all systematic errors from both experiments. In Fig. S5 [20], we show the CALET all-electron spectrum in DAMPE's binning for reference.

In Fig. 3, we fit the differential spectrum in the energy range from 30 GeV to 4.8 TeV with a smoothly broken

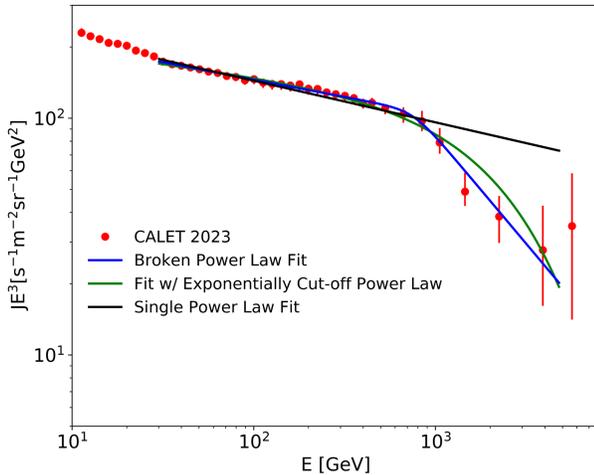


FIG. 3. All-electron spectrum measured by CALET from 10.6 GeV to 7.5 TeV, and the fitted results in the energy range from 30 GeV to 4.8 TeV, with a broken power law, an exponentially cutoff power law and a single power law. The error bars represent statistical and systematic uncertainties except normalization. See text for the details of the fits by power laws.

power-law model (blue line) [31]. The model is defined as: $J(E) = C(E/100 \text{ GeV})^\gamma [1 + (E + E_b)^{\Delta\gamma/s}]^{-s}$, where E_b is the break energy, while γ is the power index below E_b and $\Delta\gamma$ is the difference in the power index below and above E_b . The fitted spectrum steepens from $\gamma = -3.15 \pm 0.01$ by $\Delta\gamma = -0.77 \pm 0.22$ at energy $E_b = 761 \pm 115 \text{ GeV}$ with the break smoothness parameter (s) fixed to 0.1 which fits our data well, with $\chi^2 = 3.6$ and 27 degrees of freedom (NDF).

A single power-law fit over the same energy range (black line) gives $\gamma = -3.18 \pm 0.01$ with $\chi^2/\text{NDF} = 56/29$, which means that a broken power law is favored with 6.9σ significance over a single power law. An exponentially cutoff power law [30] (green line) with a power index of -3.10 ± 0.01 below a cutoff energy of $2854 \pm 305 \text{ GeV}$ fits also our data well, with $\chi^2/\text{NDF} = 12/28$ and a significance of 6.6σ over the single power law.

Discussion.—In the following we discuss a possible interpretation of the CALET energy spectrum over the whole energy range. We have incorporated the measured AMS-02 positron flux [29], source and propagation parameters suggested in Ref. [32], and results from the numerical propagation code DRAGON [33] to construct a possible model that fits the CALET all-electron measurements. Figure 4 shows the prediction of our example model compared to the CALET results. The positron flux of AMS-02 is fitted with contributions from secondaries (red dashed line) + several pulsars (red dotted line), while the all-electron flux is fitted with the sum of electron and positron flux from the pulsars (black dotted line), in addition to secondaries + distant SNRs (black dashed line) with a cutoff at 1 TeV. In this model we follow a hypothesis that the positron excess is caused by a primary source of

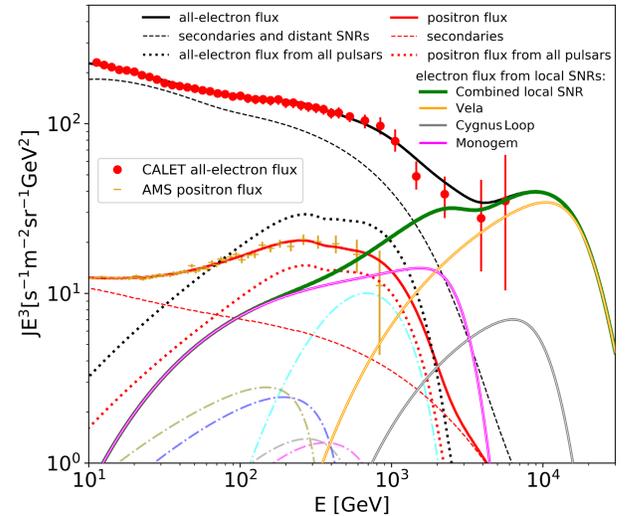


FIG. 4. Possible spectral fit over the whole region of CALET observations, including pulsars and nearby SNR sources as individual sources, with the Vela SNR dominating in the TeV region. See details in text.

$e^- + e^+$ pairs, for which we include the only contribution from pulsars neglecting more exotic sources as dark matter. In the range from about 30 GeV to 1 TeV, this $e^- + e^+$ pair source significantly influences the all-electron spectrum. Above 1 TeV, we include the nearby SNRs, Vela (orange solid line), Cygnus Loop (gray solid line), and Monogem (magenta solid line) as the dominant sources [7], with their combined contribution (green line). The best fit yields an energy output of 0.8×10^{48} erg in electron cosmic rays above 1 GeV for each nearby SNR.

The spectra of the nearby SNRs and secondaries (e^- , e^+) are calculated using DRAGON [33], which is also used to define the propagation parameters via calculation of the nuclei spectra, concurrently providing spectra of the secondary electrons and positrons forming part of the background. This whole-region model for the interpretation of the all-electron spectrum and its implications for the possible contribution of nearby sources is discussed in more detail in Ref. [32]. For the fitting shown in Fig. 4, statistical and systematic errors are added up quadratically, the cutoff energy for the near SNR source spectrum is 100 TeV, and the propagation conditions labeled as “Model X” in Ref. [32] are used. The predicted number of events with the best fit is 11.0 (4.2) electrons above 4.8 TeV (7.5 TeV). A fit of the model without the three nearby SNRs and a smooth extension of the power-law spectrum to the TeV-region [Fig. S6 [20] has similar fit quality and predicts 4.6 (1.0) events]. The observed numbers of electron candidates obtained by the event-by-event analysis are 9 (4) above 4.8 TeV (7.5 TeV), compatible with the expected contribution from the nearby SNRs. A study on the significance while taking the errors into account will be published elsewhere. The electron selection above 4.8 TeV using an event-by-event analysis is discussed in detail in the Supplemental Material [20].

Conclusion.—We have extended our previous result [15] of the CALET all-electron spectrum with an approximate increase of the statistics by a factor 3. The all-electron energy spectrum over the entire region is fitted using the positron flux measured by AMS-02 and the expected contribution of the known astrophysical sources including nearby pulsars and SNRs. In the TeV region the data show a break of the spectrum compatible with the DAMPE results. The accuracy of determining the break’s sharpness and position, and of the spectral shape above 1 TeV, are improved by the better statistics. The observed 9 electron candidates above 4.8 TeV are consistent with an estimation of the electron flux from the nearby SNRs based on an interpretation model. Further observations are needed to reach a final conclusion.

Extended CALET operations approved by JAXA/NASA/ASI in March 2021 through the end of 2024 (at least) will bring a further increase of the statistics and a reduction of the systematic errors based on the analysis.

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