CALET
Calorimetric Electron Telescope

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CALET Collaboration Team

CALET Payload

Launched on Aug. 19th, 2015 by the Japanese H2-B rocket
Emplaced on JEM-EF port #9 on Aug. 25th, 2015
(JEM-EF: Japanese Experiment Module-Exposed Facility)

- Mass: 612.8 kg
- JEM Standard Payload Size:
  1850mm (L) × 800mm (W) × 1000mm (H)
- Power Consumption: 507 W (max)
- Telemetry:
  Medium 600 kbps (6.5GB/day) / Low 50 kbps
ISS: a Cosmic Ray Observatory in Low Earth Orbit

AMS Launch
May 16, 2011

JEM-EF

ISS-CREAM Launch
August 14, 2017

CALET Launch
August 19, 2015

P. S. Marrocchesi
CALET instrument in a nutshell

Field of view: ~ 45 degrees (from the zenith)  Geometrical Factor: ~ 1,040 cm² sr (for electrons)

CALET: a unique set of key instruments

- **CHD**: a dedicated charge detector + multiple dE/dx sampling in the IMC allow to identify individual nuclear species (Δz~0.15-0.3 e).
- **IMC**: a high granularity (1mm) imaging pre-shower calorimeter accurately identifies the arrival direction of incident particles (~0.1°) and the starting point of electromagnetic showers.
- **TASC**: a thick (~30 X₀), fully active calorimeter allows to extend electron measurements into the TeV energy region with ~2% energy resolution.

Combined, they separate electrons from the abundant protons (rejection > 10⁵.).

Simulated Shower Profile

**Gamma-ray 10 GeV**

**Electron 1 TeV**

**Proton 10 TeV**
# CALET Instrument overview

## CHD (Charge Detector)
- **Measure**: Charge (Z=1-40)
- **Geometry (Material)**: Plastic Scintillators: 28 paddles, 14 paddles x 2 layers (X,Y)
  - Paddle Size: 32 x 10 x 450 mm³
- **Readout**: PMT+CSA

## IMC (Imaging Calorimeter)
- **Measure**: Tracking, Particle ID
- **Geometry (Material)**: Scintillating Fibers: 448 x 16 layers (X,Y)
  - 7 W layers (3X₀): 0.2X₀ x 5 + 1X₀ x 2
  - Scifi size: 1 x 1 x 448 mm³
- **Readout**: 64-anode PMT+ ASIC

## TASC (Total Absorption Calorimeter)
- **Measure**: Energy, e/p Separation
- **Geometry (Material)**: PWO logs: 16 x 12 layers (x,y): 192 logs
  - Log size: 19 x 20 x 326 mm³
  - Total Thickness: 27 X₀, ~1.2 λᵣ
- **Readout**: APD/PD+CSA
  - PMT+CSA (for Trigger)@top layer

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**Figure**: Diagram showing the components of the CALET instrument, including CHD, IMC, and TASC modules. Each module is described with its specific materials, layer configurations, and readout methods.
◊ CALET **tracking** takes advantage of the IMAGING capabilities of IMC thanks to its granularity of 1 mm with Sci-fibers **readout individually**.

**Example**: A **multi-prong event** due to an interaction of the primary particle in the CHD is very well imaged by the IMC.
**TASC Energy Measurement: wide Dynamical Range 1-10^6 MIPs**

The whole dynamic range was calibrated by **UV laser irradiation** on ground:
1. The linearity of each gain range is confirmed in the range of 1.4-2.5%.
2. Each channel covers from 1 MIP to 10^6 MIPs.

<table>
<thead>
<tr>
<th></th>
<th>APD-H</th>
<th>APD-L</th>
<th>PD-H</th>
<th>PD-L</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.4%</td>
<td>1.5%</td>
<td>2.5%</td>
<td>2.2%</td>
</tr>
</tbody>
</table>

The correlation between adjacent gain ranges is calibrated by using **in-flight data** in each channel.

**Example of energy distribution in one PWO log**
Some nearby sources, e.g. Vela SNR, are likely to have unique signatures in the electron energy spectrum at the TeV scale (Kobayashi et al. ApJ 2004)

**CALET: Cosmic-Ray Nuclei Spectra in the Multi-TeV region**

- Proton spectrum to $\approx 900$ TeV
- He spectrum to $\approx 400$ TeV/n
- Spectra of C,O,Ne,Mg,Si to $\approx 20$ TeV/n
- B/C ratio to $\approx 4 - 6$ TeV/n
- Fe spectrum to $\approx 10$ TeV/n

CALET energy reach (5 years)
# Main Scientific Objectives

<table>
<thead>
<tr>
<th>Scientific Objectives</th>
<th>Observation Targets</th>
<th>Energy Range</th>
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</table>
| CR Origin and Acceleration             | Electron spectrum p→Fe individual spectra  
Ultra Heavy Ions (26 < Z ≤40)  
Gamma-rays (Diffuse + Point sources) | 1 GeV - 20 TeV  
10 GeV - 1000 TeV  
> 600 MeV/n  
1 GeV - 1 TeV |
| Galactic CR Propagation                | B/C and sub-Fe/Fe ratios                                                              | Up to some TeV/n                  |
| Nearby CR Sources                      | Electron spectrum                                                                    | 100 GeV - 20 TeV                  |
| Dark Matter                            | Signatures in electron/gamma-ray spectra                                              | 100 GeV - 20 TeV                  |
| Solar Physics                          | Electron flux (1 GeV-10 GeV)                                                         | < 10 GeV                          |
| Gamma-ray Transients                   | Gamma-rays and X-rays                                                                 | 7 keV - 20 MeV                    |

- Electron observation in 1 GeV - 20 TeV is achieved with high energy resolution due to design optimization for electron detection. **Search for Dark Matter and Nearby Sources**
- Observation of cosmic-ray nuclei will be performed in energy region from 10 GeV to 1 PeV. **Unravelling the CR acceleration and propagation mechanism(s)**
- Detection of transient phenomena in space by stable observations. **Gamma-ray bursts, Solar flares, e.m. counterpart from GW sources, ...**
Observations with High Energy Trigger (>10GeV)


- The exposure, $S\Omega T$, has reached to $\sim 76.0 \text{ m}^2 \text{ sr day}$ for electron observations by continuous and stable operations.
- Total number of triggered events is $\sim 570 \text{ million}$ with a live time fraction of 85.0%.

Accumulated observation time (live, dead)  

Accumulated triggered event number

<table>
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<tr>
<th>Time [hr]</th>
<th>12000</th>
<th>14000</th>
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<tr>
<td>Date [ymmdd UT]</td>
<td>16101</td>
<td>16040</td>
<td>16070</td>
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</table>

Live Time: 85.0%

Total Number: $5.68 \times 10^8$ events

$6.53 \times 10^5$ events/day ($\sim 7.6 \text{ Hz}$)
Examples of Observed Events

- **Proton, ΔE=2.89 TeV**
- **Fe, ΔE=9.3 TeV**
- **Electron, E=3.05 TeV**
- **Gamma-ray, E=44.3 GeV**
ISS orbit @ 2017/08/29 5:25UT
ISS ran through SAA.
CHD count rate jumped up to \( \sim 3 \times 10^5 \) Hz from \( \sim 3 \) Hz, but the HE trigger rate remained stable.

Trigger/Count Rate @ 2017/08/29

HE trigger was not affected by SAA thanks to high energy threshold (>10 GeV).
(Energies of the trapped particles are too low to make a trigger for the observations.)

⇒ Observation is continuously carried out even at SAA!
Position and Temperature Calibration, and Long-term Stability

Example of position dependence correction

![Graph showing position dependence correction](image1)

Examples of temperature change correction

![Graph showing temperature change correction](image2)

Active Thermal Control System (ATCS) on ISS can provide very stable thermal condition during Long-term observations: $\Delta t \sim$ a few degrees

Energy Resolution for Electrons by On-orbit Calibration

Fine energy resolution of 2% or better was obtained above 20GeV.

![Graph showing energy resolution](image3)

Electron / Proton Separation

Simple Two Parameter Cut

**$F_E$:** Energy fraction of the bottom layer sum to the whole energy deposit sum in TASC

**$R_E$:** Lateral spread of energy deposit in TASC-X1

Cut Parameter $K$ is defined as follows:

$$K = \log_{10}(F_E) + 0.5 \frac{R_E}{\text{cm}}$$

Boosted Decision Trees (BDT)

In addition to the two parameters in the left, TASC and IMC shower profile fits are used as discriminating variables

BDT Response using 9 parameters
Stability of resultant flux are intensively studied in the large parameter space (i.e., viable choices to derive spectrum)

- Normalization:
  - Live time
  - Radiation environment
  - Long-term stability
  - Quality cuts

- Energy dependent:
  - Tracking
  - charge ID
  - electron ID (K-Cut vs BDT)
  - BDT stability (vs efficiency & training)
  - MC model (EPICS vs Geant4)

N.B. Energy scale uncertainty is not included in this analysis.
Secondary component is estimated using azimuthal distributions.

- Performed in three different cutoff rigidity regions.
- Correction factor was found to be **1.035** compared to MIP calibration.

[Y.Asoka, E1.5-0023-18] [S.Miyake, E1.5-0027-18]
Cutoff Rigidity Measurements and Comparison with Calculation

- Performed in three different cutoff rigidity regions.
- Correction factor was found to be 1.035 compared to MIP calibration.

Since universal energy-scale calibration between different instruments is very important, we adopt the energy scale determined by rigidity cutoff to derive our spectrum.
Inclusive ($e^+e^-$) Electron Energy Spectrum [10 GeV, ~3TeV]

- Geometry Condition: $S\Omega = 570.3$ cm$^2$sr (Fully Contained: 55% for all acceptance)
- Live Time: 2015/10/13–2017/06/30 (x 0.85) $\Rightarrow T = 4.57 \times 10^7$ sec
- Exposure: $S\Omega T = 2.64 \times 10^6$ m$^2$ sr sec (less than 20% of full analysis for 5 years)


Energy resolution: $< 2\% @ >$ 20 GeV

- CALET incl. systematic uncertainty
- Fermi-LAT 2017 (HE+LE)
- AMS-02 2014
- PAMELA $e^-$+$e^+$
- HESS 2008+2009
Measurements of the electron spectrum

Comparison of CALET with DAMPE and other experiments in space

first published spectrum by CALET (red points)
in restricted (fiducial) acceptance $S\Omega = 570.3$ cm$^2$sr
$\sim 55\%$ of full acceptance  
Live time $= T = 4.57 \times 10^7$ s

CALET: PRL 119 (2017) 181101, 3 November 2017
DAMPE: Nature 552 (2017) 63, 7 December 2017

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Extended Measurement by CALET

Approximately doubled statistics above 500GeV by using full acceptance of CALET

CALET: Phys. Rev. Lett. 120, 261102, June 2018
DAMPE: Nature 552 (2017) 63, 7 December 2017

Energy [GeV]

CALET 2018
uncertainty band (stat. + syst.)

DAMPE 2017

PAMELA e⁻+e⁺ 2017

Fermi-LAT 2017 (HE+LE)

AMS-02 2014

HESS 2008+2009

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1. CALET spectrum is consistent with AMS02 data below 1 TeV.

2. Present measurements cluster into 2 groups: **AMS02 + CALET** and **FERMI + DAMPE** possibly indicating the presence of unknown systematic errors.

3. Above 1 TeV CALET observes a **flux reduction** consistent with DAMPE within errors.

5. No peak-like structure at 1.4 TeV is observed in CALET data irrespective of energy binning.
Comparison of CALET and DAMPE

Is there a peak-like spectral structure at 1.4 TeV?

arXiv:1711.10995

Many papers speculating about the tentative peak which is not mentioned in the original paper

arXiv:1711.11579

arXiv:1712.00869

Fermi-LAT 2010

AMS-02 2014

HESS 2008+2010

arXiv:1711.11012

Energy [GeV]
Charge Identification of Nuclei with CHD and IMC

Single element selection for p, He and light nuclei is achieved by CHD+IMC charge analysis.

Charge separation in B to C : ~7 σ

CHD charge resolution (2 layers combined) vs. Z

Charge separation in B to C : ~5 σ

IMC Charge resolution using multiple dE/dx measurements from the scintillating fibers.

Non-linear response to Z² is corrected both in CHD and IMC using a halo model.

*) Plots are truncated to better show the elemental separation.
Preliminary Flux of Primary Components

Flux measurement:

\[ \Phi(E) = \frac{N(E)}{S\Omega \epsilon(E) T \Delta E} \]

- N(E): Events in unfolded energy bin
- S\Omega: Geometrical acceptance
- T: Live time
- \epsilon(E): Efficiency
- \Delta E: Energy bin width

Observation period:
2015.10.13 – 2017.10.31 (750 days)
Selected events: ~13 million
Preliminary Energy spectra of Carbon and Oxygen (2 independent CALET analyses)

**Broken Power Law fit**
- $C = 13.23 \pm 0.37$
- $\gamma = -2.604 \pm 0.008$
- $\Delta \gamma = 0.200 \pm 0.057$
- $E_0 = 232 \pm 55$
- $s = 0.020$
- $\chi^2/ndf = 18.5/16$

**Single Power-Law fit**
- $C = 12.55 \pm 0.30$
- $\gamma = -2.588 \pm 0.006$
- $\chi^2/ndf = 38/19$

**Broken Power Law fit**
- $C = 12.82 \pm 0.35$
- $\gamma = -2.605 \pm 0.007$
- $\Delta \gamma = 0.34 \pm 0.11$
- $E_0 = 387 \pm 185$
- $s = 0.020$
- $\chi^2/ndf = 9.85/16$

**Single Power-Law fit**
- $C = 12.38 \pm 0.06$
- $\gamma = -2.596 \pm 0.001$
- $\chi^2/ndf = 27.5/19$

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**[Y.Akaike, E1.5-0028-18]**

**[P.Maestro, E1.5-0024-18]**
Preliminary Boron-to-Carbon Flux Ratio

Systematic uncertainties:
- window range for charge selection
- charge selection by CHD or IMC
- charge selection by CHD or CHD/IMC
- hadron interaction model: DPMJET3 or EPOS, QGSJET2
- initial assuming spectra for energy unfolding
- long-term stability
- Exp/MC of Beam test (E=150GeV/c)

$^{10}\text{B} : ^{11}\text{B} = 3:7$
Preliminary Spectra of Nuclei with **Even** Atomic Number \( (Z = 10 \div 16) \)

[Y.Akaike, E1.5-0028-18]
Preliminary Spectra of Nuclei with Even Atomic Number (Z = 18 ÷ 28)

[Y.Akaike, E1.5-0028-18]
CALET measures the relative abundances of ultra heavy nuclei through $^{40}$Zr

CALET has a special UH CR trigger utilizing the CHD and the top 4 layers of the IMC that:
- has an expanded geometry factor of \( \sim 4000 \text{ cm}^2\text{sr} \)
- has a very high duty cycle due to low event rate

Data analysis
- Event Selection: Vertical cutoff rigidity > 4GV & Zenith Angle < 60 degrees
- Contamination from neighboring charge are determined by multiple-Gaussian fit
CALET $\gamma$–ray Sky (>1GeV)

Instrument characterized using EPICS simulations

- Effective area $\sim 400\ \text{cm}^2$ above 2 GeV
- Angular resolution $< 2^\circ$ above 1 GeV ($< 0.2^\circ$ above 10 GeV)
- Energy resolution $\sim 12\%$ at 1 GeV ($\sim 5\%$ at 10 GeV)

Simulated IRFs consistent with 2 years of flight data

Consistency in signal-dominated regions with Fermi-LAT

Residual background in low-signal regions

Flux validation with pulsars (under investigation)

See also: E1.17-0009-18 (Mori & Asaoka)
**Hard X-ray Monitor (HXM)**

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<tr>
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<th>HXM (x2)</th>
<th>SGM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector (Crystal)</td>
<td>LaBr₃(Ce)</td>
<td>BGO</td>
</tr>
<tr>
<td>Number of detector</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Diameter [mm]</td>
<td>61</td>
<td>102</td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>12.7</td>
<td>76</td>
</tr>
<tr>
<td>Energy range [keV]</td>
<td>7-1000</td>
<td>100-20000</td>
</tr>
<tr>
<td>Energy resolution@662 keV</td>
<td>~3%</td>
<td>~15%</td>
</tr>
<tr>
<td>Field of view</td>
<td>~3 sr</td>
<td>~2π sr</td>
</tr>
</tbody>
</table>

- **Effective area [cm²]**
  - HXM x 2
  - SGM

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**CALET Gamma-ray Burst Monitor (CGBM)**

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Examples of CGBM light curves

- As of Sept 2017, 74 GRBs confirmed by other missions
- 63 Long (85%), 11 Short (15%) - Average rate ~ 37 GRBs/year

[S.Ricciarini, E1.17-00xx-18]
90% CL Upper limits for GW counterpart search

No event survived. Backgrounds are negligible.

- For GW151226 CALET-CAL observation constrains 15% of LIGO localization map by 90% upper limit flux of $9.3 \times 10^{-8}$ erg cm$^{-2}$ sec$^{-1}$ (1-10 GeV)
- For GW170104, GW170608, GW170814 no constrain on any portion of LIGO probability

[M.Mori, E1.17-0022-18]

As of Feb. 28, 2018, total observation time is 870 days with live time fraction to total time close to 85 %. Nearly 570 million events collected with high energy (>10 GeV) trigger.

Accurate calibrations have been performed with non-interacting p & He events + linearity in the energy measurements established up to $10^6$ MIP.

Preliminary analysis of nuclei, electrons (+ positrons) and gamma-rays have successfully been carried out and spectra obtained in the energy range:

- proton: $50 \text{ GeV} \sim 100 \text{ TeV}$, helium: $10 \text{ GeV} - 20 \text{ TeV/n}$, C-Fe: $300 \text{ GeV} \sim 100 \text{ TeV}$,
- B/C ratio: $20 \text{ GeV/n} - 1 \text{ TeV/n}$, All electrons: $10 \text{ GeV} \sim 4.5 \text{ TeV}$.

Preliminary analysis of UH cosmic rays up to $Z=40$.

CALET’s CGBM detected 74 GRBs in the energy range $7 \text{ keV} - 20 \text{ MeV}$. Follow-up observations of the GW events were carried out.

The so far excellent performance of CALET and the outstanding quality of the data suggest that a 5-year observation period is likely to provide a wealth of new interesting results.