An overview of CALET observations after 3 years at ISS

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for the CALET Collaboration

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CALET Payload

- **Kounotori (HTV) 5**

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

- **FRGF (Flight Releasable Grapple Fixture)**

- **ASC (Advanced Stellar Compass)**

- **GPSR (GPS Receiver)**

- **MDC (Mission Data Controller)**

- **Calorimeter**

**Launched on Aug. 19th, 2015** by the Japanese H2-B rocket

**Emplaced on port #9 of JEM-EF (Japanese Experiment Module Exposed Facility) on Aug. 25th**

- **Mass:** 612.8 kg  JEM Standard Payload
- **Size:** 1850mm (L) × 800mm (W) × 1000mm (H)
- **Power:** 507 W (max)
- **Telemetry:** Medium 600 kbps (6.5GB/day)
Main CALET science objectives:

- **Electron observation** in 1 GeV - 20 TeV range. Design optimized for electron detection: high energy resolution and large e/p separation power + e.m. shower containment. Detailed study of spectral shape. Search for Dark Matter and Nearby Sources

- **Observation of cosmic-ray nuclei** in the energy region from 10 GeV to 1 PeV. Unravelling the CR acceleration and propagation mechanism(s)

- **Detection of transient phenomena** in space Gamma-ray bursts, e.m. GW counterparts, Solar flares, Space Weather

<table>
<thead>
<tr>
<th>Scientific Objectives</th>
<th>Observation Targets</th>
<th>Energy Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR Origin and Acceleration</td>
<td>Electron spectrum&lt;br&gt;Individual spectra of elements from proton to Fe&lt;br&gt;Ultra Heavy ions (26 &lt; Z ≤ 40)&lt;br&gt;Gamma-rays (Diffuse + Point sources)</td>
<td>1 GeV - 20 TeV&lt;br&gt;10 GeV - 1000 TeV&lt;br&gt;600 MeV/n&lt;br&gt;1 GeV - 1 TeV</td>
</tr>
<tr>
<td>Galactic CR Propagation</td>
<td>B/C and sub-Fe/Fe ratios</td>
<td>Up to some TeV/n</td>
</tr>
<tr>
<td>Nearby CR Sources</td>
<td>Electron spectrum</td>
<td>100 GeV - 20 TeV</td>
</tr>
<tr>
<td>Dark Matter</td>
<td>Signatures in electron/gamma-ray spectra</td>
<td>100 GeV - 20 TeV</td>
</tr>
<tr>
<td>Solar Physics</td>
<td>Electron flux (1 GeV-10 GeV)</td>
<td>&lt; 10 GeV</td>
</tr>
<tr>
<td>Gamma-ray Transients</td>
<td>Gamma-rays and X-rays</td>
<td>7 keV - 20 MeV</td>
</tr>
</tbody>
</table>
CALET instrument in a nutshell

Field of view: ~ 45 degrees (from the zenith) | Geometrical Factor: ~ 1,040 cm²sr (for electrons)

1 TeV electron shower

CALET: a unique set of key instruments

- **CHD**: a dedicated charge detector + multiple dE/dx sampling in the IMC allow the identification of individual nuclear species (charge resolution ~0.15-0.3 e).

- **IMC**: high granularity (1mm) imaging pre-shower calorimeter to accurately reconstruct the arrival direction of incident particles (~0.1°) and the starting point of electromagnetic showers. Scifi + Tungsten absorbers: 3 X₀ (=0.2 X₀ x 5 + 1.0 X₀ x 2)

- **TASC**: thick (27 X₀) homogeneous PWO calorimeter allowing to extend electron measurements into the TeV energy region with ~2% energy resolution.

- **Combined** (30 X₀, 1.2 λ₁) they separate electrons from the abundant protons (rejection > 10⁵).

Simulated Shower Profile

- **Gamma-ray 10 GeV**
- **Electron 1 TeV**
- **Proton 10 TeV**

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Examples of Observed Events

Multi-prong background event (interaction in CHD)

Proton, $\Delta E=2.89$ TeV

Iron, $\Delta E=9.3$ TeV

Electron, $E=3.05$ TeV

Gamma-ray, $E=44.3$ GeV

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CALET Instrument overview

<table>
<thead>
<tr>
<th>Measure</th>
<th>CHD (Charge Detector)</th>
<th>IMC (Imaging Calorimeter)</th>
<th>TASC (Total Absorption Calorimeter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry (Material)</td>
<td>Plastic Scintillators: 28 paddles 14 paddles x 2 layers (X,Y) Paddle Size: 32 x 10 x 450 mm³</td>
<td>Scintillating Fibers: 448 x 16 layers (X,Y) Scifi size: 1 x 1 x 448 mm³ 7 Tungsten layers : 0.2X₀ x 5 + 1X₀ x 2 Total Thickness: 3X₀</td>
<td>PWO logs: 16 x 12 layers (x,y): 192 logs log size: 19 x 20 x 326 mm³ Total Thickness: 27X₀, ~1.2λₐ</td>
</tr>
<tr>
<td>Readout</td>
<td>PMT+CSA</td>
<td>64-anode PMT+ASIC</td>
<td>APD/PD+CSA PMT+CSA (for Trigger)@top layer</td>
</tr>
</tbody>
</table>

Measure: Charge (Z=1-40)  
Tracking, Particle ID  
Energy, e/p Separation  

Geometry (Material):  
Plastic Scintillators: 28 paddles 14 paddles x 2 layers (X,Y) Paddle Size: 32 x 10 x 450 mm³  
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Readout:  
PMT+CSA  
64-anode PMT+ASIC  
APD/PD+CSA PMT+CSA (for Trigger)@top layer
**Energy Measurement in a wide dynamic range 1-10^6 MIPs**

MIP calibration determines the conversion factor from ADC unit to the energy.

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>1.4%</td>
<td>1.5%</td>
<td>2.5%</td>
<td>2.2%</td>
<td></td>
</tr>
</tbody>
</table>

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

<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>0.1%</td>
<td>0.7%</td>
<td>0.1%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Example of energy distribution in one PWO log
Observations with High Energy Trigger (>10GeV)

- Observation with High Energy Trigger for 1327 days: Oct.13, 2015 – May 31, 2019
- The exposure, $S\Omega T$, has reached $\sim 116$ m$^2$ sr day for electron observations under continuous and stable operations.
- Total number of triggered events is $\sim 1.8$ billion with a live time fraction of $\sim 84\%$.

**Accumulated observation time (live, dead)**

**Distribution of deposit energies ($\Delta E$) in TASC**

- Live Time Fraction: 84.2%
- Only statistical errors presented

**Graphs**

- High Energy Trigger (1327 days)
- Total Observation Time (1.13x10^9 sec)
- Live Time (9.65x10^8 sec)
- Dead Time (Fraction 14.7%)

**Data**

- 151013-190531
- 1.78x10^9 Events

**Graphs**

- LE-HE Trigger Trigger region region
- All Particles
- 1 PeV

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Position and Temperature Calibration + Long-term Stability

Example of position dependence correction

![Graph showing correction curves before and after correction]

Examples of temperature change correction

![Graph showing changes in Beta Angle over time before and after correction]

Active Thermal Control System (ATCS) on ISS provides very stable thermal conditions 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 for electrons


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Electron / Proton Discrimination

**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 on the left, TASC and IMC shower profile fits are used as discriminating variables.

**BDT Response using 9 parameters**

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**Figures:**

- Left: Distribution of $K$ parameter with Flight Data and MC simulations for $126.2 < E/\text{GeV} < 200.0$
- Right: Distribution of BDT Response with Flight Data and MC simulations for $126.2 < E/\text{GeV} < 200.0$

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**References:**

- [151013 - 170331] $T_{\text{live}} = 3.89 \times 10^7 \text{sec} (10812.2\text{hr})$
- 126.2 < $E/\text{GeV}$ < 200.0

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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.

![Before Correction Graph](image1)

**BEFORE CORRECTION**

- Secondary component is estimated using azimuthal distributions.

**AFTER CORRECTION**

- Energy scale correction factor (Tracer/Data E ratio) compared to MIP calibration.

Y. Asaoka, COSPAR 2018 E1.5-0023-18
[S. Miyake, COSPAR 2018 E1.5-0027-18]
Stability of resultant flux analyzed by scanning parameter space

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

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

**Total Systematic Uncertainty**
- Electron ID (K-Cut vs BDT)
- MC Model (Geant4 vs EPICS)

**Systematic Uncertainty**
- Tracking (KF vs EM)
- Charge Selection

**BDT-cut Stability**
- total systematic uncertainty band
Direct measurements of the electron spectrum

Comparison of CALET with DAMPE and other experiments in space

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

first published spectrum by CALET (red points)
in restricted (fiducial) acceptance $S\Omega = 570.3 \text{ cm}^2\text{sr}$
$\sim 55\%$ of full acceptance  Live time = $T = 4.57 \times 10^7 \text{ s}$
- CALET spectrum is consistent with AMS02 data below 1 TeV.
- Present measurements cluster into 2 groups: AMS02 + CALET and FERMI + DAMPE possibly indicating the presence of unknown systematic errors.
- Above 1 TeV CALET observes a flux reduction consistent with DAMPE within errors.
- No peak-like structure at 1.4 TeV is observed in CALET data irrespective of energy binning.
Direct measurement of proton spectrum by CALET

CALET covers the range 50 GeV to 10 TeV with THE SAME INSTRUMENT confirming the existence of proton spectral hardening with a deviation from a single power law by more than 3σ.

CALET Collaboration, Phys. Rev. Lett. 122, 181102
Highlighted as “Editor’s Suggestion”
Spectral Behavior of Proton Flux

smooth transition of the power-law spectral index from $-2.87 \pm 0.06$ (including solar modulation effects in the lower energy region) to $-2.56 \pm 0.04$ (1–10 TeV)

1. Subranges of 50–500 GeV, 1-10 TeV can be fitted with single power law function, but not the whole range (significance > 3\sigma).
2. Progressive hardening up to the TeV region was observed.
3. “smoothly broken power-law fit” gives power law index consistent with AMS-02 in the low energy region, but shows larger index change and higher break energy than AMS-02.
Direct measurements of proton spectrum to date

- **p and He below 100 GeV**: % level agreement of magnetic spectrometers (BESS-TeV, PAMELA, AMS02)
- Good agreement of PAMELA and AMS-02 on p and He spectra below a few hundred GeV.
- The next challenge is the region from **10 TeV to 100 TeV** being explored by balloon-borne (e.g., ATIC, CREAM) and space instruments (CALET, DAMPE, NUCLEON).

To date, published results in this region have large errors.
Single element selection for p, He and light nuclei is achieved by CHD+IMC charge analysis.

Combined CHD-IMC proton-Helium charge-ID

Deviation from $Z^2$ response is corrected both in CHD and IMC using a core + halo ionization model (Voltz)
Preliminary fluxes of primary elements

Carbon and Oxygen

Ne, Mg, Si, S, Ca, Fe
Preliminary Spectra of Z-even Nuclei from Ar to Ni (Z = 18-28)

(Y. Akaike, COSPAR 2018 E1.5-0028-18)

[Image of graphs showing spectra for different elements: 18Ar, 22Ti, 26Fe, 20Ca, 24Cr, 28Ni]
Preliminary Energy spectra of Carbon and Oxygen

(2 independent CALET analyses)

Broken Power Law fit
C = 13.23 ± 0.37
γ = -2.604 ± 0.008
Δγ = 0.200 ± 0.057
E₀ = 232 ± 55
s = 0.020
χ²/ndf = 18.5/16

Single Power-Law fit
C = 12.55 ± 0.30
γ = -2.588 ± 0.006
χ²/ndf = 38/19

Broken Power Law fit
C = 12.82 ± 0.35
γ = -2.605 ± 0.007
Δγ = 0.34 ± 0.11
E₀ = 387 ± 185
s = 0.020
χ²/ndf = 9.85/16

Single Power-Law fit
C = 12.38 ± 0.06
γ = -2.596 ± 0.001
χ²/ndf = 27.5/19
Boron-to-carbon flux ratio (Preliminary)

\[ ^{10}\text{B} : ^{11}\text{B} = 3:7 \]

Source of systematic uncertainties:
- Trigger efficiency
- Charge consistency cuts
- Track width selection
- Window range for charge identification
- Background model of p and He spectra
- Initial assuming spectra for energy unfolding
- Energy correction based on beam test results
- Difference of beam test model and flight model
- Long term stability
Ultra Heavy Nuclei (Preliminary Measurements for 26 < Z ≤ 40)

CALET measures the relative abundances of nuclei above Fe through $^{40}\text{Zr}$

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

шей The CALET UH element ratios relative to $^{56}\text{Fe}$ show good agreement with SuperTIGER and ACE abundances.

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Instrument characterized using EPICS simulations

- **Effective area** ~400 cm² above 2 GeV
- **Angular resolution** < 2° above 1 GeV (< 0.2° above 10 GeV)
- **Energy resolution** ~12% at 1 GeV (~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)**

[N.Cannady, COSPAR 2018 E1.17-0009-18]
### CALET Gamma-ray Burst Monitor (CGBM)

#### Hard X-ray Monitor (HXM) vs. Soft Gamma-ray Monitor (SGM)

<table>
<thead>
<tr>
<th></th>
<th>HXM (x2)</th>
<th>SGM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector (Crystal)</td>
<td>LaBr$_3$(Ce)</td>
<td>BGO</td>
</tr>
<tr>
<td>Number of detectors</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>

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**Effective area [cm$^2$]**

- **HXM x 2**
- **SGM**

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**CALET Gamma-ray Burst Monitor (CGBM)**
As of June 2019:

- **159 GRBs** detected
- **140 Long (88%)**
- **19 Short (12%)**

Average rate $\sim 43$ GRBs/year
Complete Search Results for GW Events during O1 & O2


<table>
<thead>
<tr>
<th>Event</th>
<th>Type</th>
<th>Mode</th>
<th>Sum. LIGO prob.</th>
<th>Obs. time</th>
<th>Upper limits</th>
<th>Ener. Flux</th>
<th>Lum. Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>cm^{-2} s^{-1}</td>
<td>erg s^{-1}</td>
</tr>
<tr>
<td>GW150914</td>
<td>BH-BH</td>
<td>LE</td>
<td>15%</td>
<td>T_0-525 - T_0+211</td>
<td>9.3 \times 10^8</td>
<td>1.0 \times 10^{-6}</td>
<td>6.4 \times 10^{-6}</td>
</tr>
<tr>
<td>GW151226</td>
<td>BH-BH</td>
<td>LE</td>
<td>15%</td>
<td>T_0-525 - T_0+211</td>
<td>9.3 \times 10^8</td>
<td>1.0 \times 10^{-6}</td>
<td>6.4 \times 10^{-6}</td>
</tr>
<tr>
<td>GW170104</td>
<td>BH-BH</td>
<td>HE</td>
<td>30%</td>
<td>T_0-60 - T_0+60</td>
<td>6.4 \times 10^{-6}</td>
<td>6.2 \times 10^{50}</td>
<td></td>
</tr>
<tr>
<td>GW170608</td>
<td>BH-BH</td>
<td>HE</td>
<td>0%</td>
<td>T_0-60 - T_0+60</td>
<td>Out of FOV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GW170814</td>
<td>BH-BH</td>
<td>HE</td>
<td>0%</td>
<td>T_0-60 - T_0+60</td>
<td>Out of FOV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GW170817</td>
<td>NS-NS</td>
<td>HE</td>
<td>0%</td>
<td>T_0-60 - T_0+60</td>
<td>Out of FOV</td>
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</tbody>
</table>

- CALET can search for EM counterparts to LIGO/Virgo triggers
- All O1 and O2 triggers checked – no signal in CGBM or CAL
- Upper limits set for GW151226 for CGBM+CAL in 2016 paper
- Upper limits for the CAL set using refined LE selection for triggers to-date in the 2018 paper

As of May 31, 2019 total observation time is 1327 days with live time fraction to total time close to 84%. Nearly 1.8 billion events collected with low (> 1 GeV) + high energy (>10 GeV) triggers.

In-flight calibrations with p & He events + CERN beam tests with e, p and fragmented ions + linearity in the energy measurements established up to $10^6$ MIP.

Measurement of electron+positron spectrum in 11 GeV - 4.8 TeV range using full acceptance Observation of a flux reduction above 1 TeV.

Direct measurement of proton spectrum in 50 GeV – 10 TeV energy range. Spectral hardening observed above a few hundred GeV.

Preliminary analysis of primary elements up to Fe and secondary-to-primary ratios.

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

Study of diffuse and point sources with gamma-rays. Follow-up observations of GW events in X-ray and gamma-ray bands. CALET’s CGBM detected 159 GRBs in the energy range 7 keV-20 MeV.

After an initial period of 2 years CALET observation time has been extended to 5 years at least.
Thank you for your attention!
CALET Collaboration Team


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