Measurement of the Proton Spectrum with CALET on the ISS

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for the CALET Collaboration

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CALET Payload

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) x 800mm (W) x 1000mm (H)
- Power: 507 W (max)
- Telemetry: Medium 600 kbps (6.5GB/day)
Cosmic Ray Observations aboard the ISS and CALET program

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

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

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 electro-magnetic showers. Scifi + Tungsten absorbers: 3 $X_0$ (=0.2 $X_0 \times 5 + 1.0 X_0 \times 2$)

- **TASC**: thick (27 $X_0$) homogeneous PWO calorimeter allowing to extend electron measurements into the TeV energy region with ~2% **energy resolution**.

- **Combined** (30 $X_0$, 1.2 $\lambda_p$) they separate electrons from the abundant protons (rejection > $10^5$).

Simulated Shower Profile

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Examples of Observed Events

Multi-prong background event (interaction in CHD)

**Electron, E=3.05 TeV**

**Proton, ΔE=2.89 TeV**

**Iron, ΔE=9.3 TeV**

**Gamma-ray, E=44.3**
## CALET Instrument overview

<table>
<thead>
<tr>
<th>CHD (Charge Detector)</th>
<th>IMC (Imaging Calorimeter)</th>
<th>TASC (Total Absorption Calorimeter)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measure</strong></td>
<td><strong>Tracking, Particle ID</strong></td>
<td><strong>Energy, e/p Separation</strong></td>
</tr>
<tr>
<td><strong>Geometry (Material)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic Scintillators: 28 paddles</td>
<td>Scintillating Fibers: 448 x 16 layers (X,Y)</td>
<td>PWO logs: 16 x 12 layers (x,y): 192 logs</td>
</tr>
<tr>
<td>14 paddles x 2 layers (X,Y)</td>
<td>Scifi size: 1 x 1 x 448 mm(^3)</td>
<td>log size: 19 x 20 x 326 mm(^3)</td>
</tr>
<tr>
<td>Paddle Size: 32 x 10 x 450 mm(^3)</td>
<td>7 Tungsten layers : 0.2(X_0) x 5 + 1(X_0) x 2</td>
<td>Total Thickness: 27 (X_0), (~1.2\ \lambda_1)</td>
</tr>
<tr>
<td><strong>Readout</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMT+CSA</td>
<td>64-anode PMT+ ASIC</td>
<td>APD/PD+CSA PMT+CSA (for Trigger)@top layer</td>
</tr>
</tbody>
</table>

**Reference**

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Energy Measurement in a wide dynamic 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>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>
</tr>
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</table>

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

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

Example of energy distribution in one PWO log

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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 ~116 m$^2$ sr day for electron observations under continuous and stable operations.
- Total number of triggered events is ~1.8 billion with a live time fraction of ~84%.

Accumulated observation time (live, dead)

![Graph showing accumulated observation time with live time fraction of 84.2%]

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

![Graph showing distribution of deposit energies with a peak around 1 PeV]

- 151013-190531
- 1.78x10$^9$ Events
- Only statistical errors presented

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Position and Temperature Calibration + Long-term Stability

Example of position dependence correction

Example of temperature change 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

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:

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

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
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.

Deviation from Z² response is corrected both in CHD and IMC using a core + halo ionization model (Voltz)

Combined CHD-IMC proton-Helium charge-ID
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

1. Subranges of 50—500 GeV, 1-10 TeV can be fitted with single power law function, but not the whole range (significance > 3σ).
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.

- Study flux stability via scan of parameter space
  - 
  - Radiation environment
  - Long-term stability
  - Quality cuts

**Energy independent** (normalization)

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

4.1%

**Energy dependent**

- MC model dependence
- Track consistency with TASC energy deposits
- Shower development requirement in IMC
- Charge identification
- Energy unfolding
- Beam test related uncertainties

**Energy scale uncertainty**

- beam test with < 400 GeV protons
- beam test with 150 GeV/n Ar fragments
- ground test with laser (response linearity)

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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.

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 ion fragments. Linearity of 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!
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