Status and Performance of the CALorimetric Electron Telescope (CALET) on the International Space Station

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for the CALET Collaboration

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32) National Institute of Polar Research, Japan
33) The University of Tokyo, Japan

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The CALorimetric Electron Telescope, CALET, project is a Japan-led international mission for the International Space Station, ISS, in collaboration with Italy and the United States.

The CALET payload is launched by the Japanese carrier, H-II Transfer Vehicle 5 (HTV5) and robotically attached to the port #9 of the Japanese Experiment Module – Exposed Facility (JEM-EF) on the International Space Station.

Mission Life (Target): 5 years
Launch Date: Aug. 19, 2015

Gamma - Ray Burst Monitor
Calorimeter
## CALET Overview

### Calorimeter
- Charge Detector (CHD)
- Imaging Calorimeter (IMC)
- Total Absorption Calorimeter (TASC)

### Gamma–ray burst monitor (CGBM)
- Hard X–ray Monitor (HXM)
  - LaBr$_3$: 7keV–1MeV
- Soft γ–ray Monitor (SGM)
  - BGO: 100keV–20MeV

### Data process and Telemetry
- Mission Data Controller (MDC)
  - Data process, Telemetry, Trigger
- HV–BOX (by Italian Contribution)
  - High voltage power supply
    - (PMT:68ch, APD:22ch)

### Support sensors
- Advanced Stellar Compass (ASC)
  - Directional measurement
- GPS Receiver (GPSR)
  - Time stamp on events (<1ms)
CALET is now on the ISS!

① **August 19th:** After a successful launch of the Japanese H2-B rocket by the Japan Aerospace Exploration Agency (JAXA) at 20:50:49 (local time), CALET started its journey from Tanegashima Space Center to the ISS.

② **August 24th:** The HTV-5 Transfer Vehicle (HTV-5) is grabbed by the ISS robotic arm.

③ **August 24th:** The HTV-5 docks to the ISS at 6:28 (EDT).

④ **August 25th:** CALET is emplaced on port #9 of the JEM-EF and data communication with the payload is established.

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CALET Science Goals

The CALET mission will address many of the outstanding questions of High Energy Astrophysics, such as the origin of cosmic rays, the mechanism of CR acceleration and galactic propagation, the existence of dark matter and nearby CR sources.

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<th>Observation Targets</th>
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<td>Electron spectrum into trans-TeV region</td>
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<td>Dark Matter *</td>
<td>Signatures in electron/gamma energy spectra in the several GeV – 10 TeV range</td>
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<td>Cosmic-ray Origin and Acceleration</td>
<td>p-Fe energy spectra up to $10^{15}$ eV and trans-iron elements (Z=26-40) at a few GeV</td>
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<td>Cosmic–ray Propagation in the Galaxy</td>
<td>B/C ratio above TeV/nucleon</td>
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<td>Solar Physics</td>
<td>Electron flux below 10 GeV</td>
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*) See e.g. H.Motz “Dark matter sensitivity of CALET” talk at DM session on 27 Oct.
Electron & Positron Origins and Production Spectrum

Astrophysical Origin

Shock Wave Acceleration in SNR

Accelerations in PWN

Power Law Distribution with a Cutoff

\[ dN/dE \propto E^{-2\alpha} \exp(-E/E_c) \]

Log(dN/dE)

Log(E)

Typical Distribution Depending on the Mass and Type of DM

(dN/dE) vs. E

(i) Monoenergetic: Direct Production of e+e- pair

(ii) Uniform: Production via Intermediate Particles

(iii) Double Peak: Production by Dipole Distribution via Intermediate Particles

Dark Matter Origin

Evolution of the Universe

Constitutes of the Universe

- Dark Energy 73%
- Dark Matter 25%
- Hydrogen, Helium 4%
- Star 0.5%
- Neutrino 0.3%
- Heavy Element 0.03%

Annihilation of Dark Matter (WIMP)

\[ \chi \chi \rightarrow e^+e^- \]

Typical Distribution Depending on the Mass and Type of DM

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Nearby Sources of Electrons in the TeV region

\[ \frac{\partial}{\partial t} f(t, \varepsilon, x) = \begin{cases} D(\varepsilon) \nabla^2 f & \text{Diffusion} \\ \frac{\partial}{\partial \varepsilon} \left[ b \varepsilon^2 f \right] & \text{Energy loss by IC & synchro.} \\ q(t, \varepsilon, x) & \text{Injection} \end{cases} \]

\[ b \sim 10^{-16} \text{GeV}^{-1}\text{s}^{-1} \]

\[ D(\varepsilon) \sim 5.8 \times 10^{28} \text{cm}^2\text{s}^{-1} \left(1 + \frac{\varepsilon}{4\text{GeV}}\right)^{1/3} \]

\[ T(\text{age}) = 2.5 \times 10^5 \times (\text{TeV}/E) \text{ yr} \]

\[ R(\text{distance}) = 600 \times (\text{TeV}/E)^{1/2} \text{ pc} \]

\[ > 1 \text{ TeV Electron Source:} \]
- Age < a few $10^5$ years
  - very young comparing to ~$10^7$ year at low energies
- Distance < 1 kpc
  - nearby source

Source (SNR) Candidates:
- Vela
- Cygnus Loop
- Monogem

Unobserved Sources?
CALET Main Target: Identification of Electron Sources


Expected flux for 5 year mission

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Expected Flux</th>
</tr>
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<tbody>
<tr>
<td>&gt; 10</td>
<td>$\sim 2.7 \times 10^7$</td>
</tr>
<tr>
<td>&gt; 100</td>
<td>$\sim 2.0 \times 10^5$</td>
</tr>
<tr>
<td>&gt; 1000</td>
<td>$\sim 1.0 \times 10^3$</td>
</tr>
</tbody>
</table>

Expected Anisotropy from Vela SNR

~10% @1TeV

Identification of the unique signature from nearby SRNs, such as Vela, in the electron spectrum by CALET
CALET Main Target: Identification of Electron Sources


<table>
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<th>Expected flux for 5 year mission</th>
<th>&gt; 10 GeV</th>
<th>~ 1.8 x 10^7</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;100 GeV</td>
<td>~ 1.3 x 10^5</td>
<td></td>
</tr>
<tr>
<td>&gt;1000 GeV</td>
<td>~ 6.5 x 10^2</td>
<td></td>
</tr>
</tbody>
</table>

Expected Anisotropy from Vela SNR

~10% @1TeV

Identification of the unique signature from nearby SRNs, such as Vela, in the electron spectrum by CALET
TeV $e^\pm$ spectrum can prove the CR escape!


- Electron spectrum from Vela SNR/PSR ($d=290$pc, $t_{age}\sim10^4$yr, $E_{tot}=10^{48}$erg)
- Only $e^\pm$ with $\varepsilon_e>\varepsilon_{esc}(t_{age})$ can run away from the SNR.

➔ Low Energy Cutoff

- 5yr obs. by CALET ($S\Omega T=220$m$^2$sr days) may detect it.

Direct Evidence of Escape-Limited Model for CR accelerators (=SNR)!
Detection of High Energy Gamma-rays

Performance for Gamma-ray Detection

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>4 GeV-10 TeV</td>
</tr>
<tr>
<td>Effective Area</td>
<td>600 cm$^2$ (10 GeV)</td>
</tr>
<tr>
<td>Field-of-View</td>
<td>2 sr</td>
</tr>
<tr>
<td>Geometrical Factor</td>
<td>1100 cm$^2$sr</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>3% (10 GeV)</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>0.35° (10 GeV)</td>
</tr>
<tr>
<td>Pointing Accuracy</td>
<td>6’</td>
</tr>
<tr>
<td>Point Source Sensitivity</td>
<td>$8 \times 10^{-9}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Observation Period (planned)</td>
<td>2015-2020 (5 years)</td>
</tr>
</tbody>
</table>

*) Trigger efficiency included below 10 GeV
**) 100 % efficiency over 5 GeV

Simulation of Galactic Diffuse Radiation

~5,700 photon* are expected per one year

~1,700 photon* from extragalactic γ-background (EGB) each year

Simulation of point source observations in one year

Vela: ~ 300 photons above 5 GeV**

Geminga: ~150 photons above 5 GeV**
Crab: ~ 100 photons above 5 GeV**
Monochromatic gamma-ray signals from WIMP dark matter annihilation would provide a distinctive signature of dark matter, if detected. Since gamma-ray line signatures are expected in the sub-TeV to TeV region, due to annihilation or decay of dark matter particles, CALET, with an excellent energy resolution of 2 - 3 % above 100 GeV, is a suitable instrument to detect these signatures.

Simulated gamma-ray line spectrum for 2yr from neutralino annihilation toward the Galactic center with m=820GeV, a Moore halo profile, and BF=5
• Hardening in the p and He at 200 GV observed by PAMELA
• p and He spectra have different slopes in the multi TeV region (CREAM)
• Acceleration limit by SNR shock wave around 100 TeV/Z?

- All primary heavy nuclei spectra well fitted to single power-laws with similar spectral index (CREAM, TRACER)
- However hint of a hardening from a combined fit to all nuclei spectra (CREAM)

At high energy (>10 GeV/n) the B/C ratio measures the energy dependence of the escape path-length, ~E⁻δ, of CRs from the Galaxy
Data below 100 GeV/n indicate δ~0.6. At high energy the ratio is expected to flatten out (otherwise CR anisotropy should be larger than that observed)
Ultra heavy nuclei abundances provide information on CR site and acceleration mechanism

CHD resolution is \( \sim \) constant above 600 MeV/n \( \Rightarrow \) Charge ID from saturated \( dE/dx \)

No need to measure energy \( \Rightarrow \) No passage through TASC \( \Rightarrow \) Large acceptance \( \sim 0.4 \, \text{m}^2\text{sr} \)

The energy threshold cut is based on the vertical cutoff rigidities seen in orbit

CALET should collect in 5 years \( \sim 10 \) times the statistics of TIGER, w/o corrections for residual atmosphere overburden

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Field of view: ~45 degrees (from the zenith)
Geometrical Factor: 0.12 m$^2$sr (for electrons)

- The unique feature of CALET is its thick (~30 $X_0$), homogeneous calorimeter that allows to extend electron measurements into the TeV energy region with excellent energy resolution (~2-3%), coupled with a high granularity imaging pre-shower calorimeter to accurately identify the arrival direction of incident particles (~0.1°) the starting point of electro-magnetic showers. Combined, they powerfully separate electrons from the abundant protons: rejection power (~10$^5$).
- A dedicated charge detector + multiple dE/dx track sampling in the IMC allow to identify individual nuclear species ($\Delta z \sim 0.15-0.3$).

### CALET Instrument Characteristics

<table>
<thead>
<tr>
<th>Function</th>
<th>CHD (Charge Detector)</th>
<th>IMC (Imaging Calorimeter)</th>
<th>TASC (Total Absorption Calorimeter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor (Absorber)</td>
<td>Plastic Scintillator: 14 × 1 layer (x,y) Unit Size: 32mm x 10mm x 450mm</td>
<td>SciFi: 448 x 8 layers (x,y) = 7168 Unit size: 1mm$^2$ x 448 mm Total thickness of Tungsten: 3 $X_0$</td>
<td>PWO log: 16 x 6 layers (x,y) = 192 Unit size: 19mm x 20mm x 326mm Total Thickness of PWO: 27 $X_0$</td>
</tr>
<tr>
<td>Readout</td>
<td>PMT+CSA</td>
<td>64 -anode PMT(HPK) + ASIC</td>
<td>APD/PD+CSA PMT+CSA (for Trigger)@top layer</td>
</tr>
</tbody>
</table>

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CALET Expected Performance by Simulations – electrons & gamma-ray –

Angular resolution for gamma ray (10GeV-1TeV): \( \sigma = 0.2-0.3 \text{ deg} \)

Proton rejection power at 1TeV: \( \approx 1.3 \times 10^5 \) with 88% efficiency for electrons

Geometrical factor for electrons: \( \approx 1200 \text{ cm}^2 \text{sr} \)

Energy resolution for electrons (>10GeV): \( \sigma/m = \approx 2\% \)

Gamma-ray detection efficiency against electrons

Electron Contamination(%)

Left: detection efficiency of gamma-rays with electron discrimination power \( 3.54 \times 10^{-4} \) (90% CL): >95% in 10-900 GeV
Right: electron contamination in galactic diffuse gamma-rays: 10% @10GeV – 1%@TeV
CERN Beam Test using the STM

Schematic Side View of the Beam Test Model

Charge Detector: CHD

Imaging Calorimeter: IMC

Total Absorption Calorimeter: TASC

The Beam Test Model at CERN SPS H8 Beam Line
CERN-SPS beam tests

Electron shower transition curve in TASC

Energy distribution

Angular resolution for electrons
Proton rejection power for 85% survival probability of electrons
• beam test: $6.45 \times 10^{-4}$
• simulation: $4.88 \times 10^{-4}$

The beam test results are consistent with simulation within statistical errors.
Heavy Ion Beam Test @ CERN 2014 & 2015

CHD Experiment @CERN-SPS

Charge resolution:
\[ \sigma_Z = 0.15e(@B) - 0.30e(@Fe) \]

Energy deposit vs. Beam energy

150A GeV/c Argon Fragments

Preliminary

Energy resolution vs. Charge of Incident particle (Beam energy)
Calorimeter Flight Components

- CHD-FEC
- IMC-FEC
- TASC-FEC

- CHD
- IMC
- TASC

**Plastic Scintillator**

**Scintillating Fiber**

**Scintillator (PWO)**

14 x 1 layer (x,y) = 28
32mm x 10mm x 450mm

448 x 8 layers (x,y) = 7168
1mm² x 448 mm

16 x 6 layers (x,y) = 192
19mm x 20mm x 326mm

CFRP Structure

TASC (Completed)
System Test of Proto-Flight Model

- Acoustic test, Thermal-Vacuum test and EMC test were successfully carried out at Tsukuba Space Center (JAXA)

- After final system function test, the payload was transferred to the launching site, Tanaegashima Space Center, for launch with HTV5.
Data Downlink Using TDRSS and DRTS

NASA Link
Real-Time Connection
> 50 % (max. 17 hr/day)

TDRSS

JAXA Link

DRTS
(Data Relay Test Satellite)
JAXA ICS Link
Real-Time Connection
~20 % (5 hr/day)

TSK

White Sands Complex,
NM, USA

NASA MSFC

Waseda CALET Operations Center

Data Archive Center

International Collaboration Organization (Italy, USA)

CALET

Scientific Operations and Data Analysis in Collaboration with International Team at Waseda CALET Operations Center (WCOC)

Operation at Tsukuba Space Center for monitoring

CALET Operations Center

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General Alerts of Transients by CGBM

Waseda CALET Operations Center
See Y. Asaoka Poster #594

MSFC/NASA

TDRSS  DRTS

CGBM data
- TH: Timing Histogram
- PH: Pulse height Histogram
- GRB triggered data

JAXA
Tsukuba SC

CALET Grnd Sys. in UOA

CALET on ISS

LIGO-Virgo MOU

Counterpart search
Further follow up observations in longer EM wavebands

CGBM Data Processing in
Waseda CALET Operations Center (WCOC)

GCN, ATel, Web

- GCN:
  Gamma-ray Coordinates Network
- ATel:
  Astronomer’s Telegram

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The long-duration GRB 151006A (Kocevski et al., GCN Circ. 18398; Cummings et al., GCN Circ. 18409; Roberts & Meegan, GCN Circ. 18404; Golenetskii et al., GCN Circ. 18413; Bhalerao et al., GCN Circ. 18422) triggered the CALET Gamma-Ray Burst Monitor (CGBM) at 09:54:59.97 UT on 6 October 2015. The clear burst signal was detected by the Soft Gamma-ray Monitor (SGM; 30 keV - 20 MeV) which is a scintillation detector utilizing a BGO crystal. Due to a large incident angle of the event, no signal was detected by the Hard X-ray Monitor (HXM; 7 keV - 1 MeV) which is a scintillation detector composed of a LaBr3(Ce) crystal.

The SGM light curve shows two spikes peaking at T₀-2s and T₀+2s, and the emission ending around T₀+~60s. The T90 duration measured by the SGM data is 63 +/- 5 s (30 - 1000 keV). Currently, CALET is in the commissioning phase.

We predict two-three GRB events per month, and the detection coincident with CALET-Calorimeter and MAXI on JEM are expected.
~1TeV electron (candidate) observed!

(converted to MIP by calibration on ground)

1 event per a few days expected
Conclusions and Summary

✧ CALET is a space-based calorimeter designed to perform cosmic ray measurement, mainly aimed at the electron component.

✧ Its main instrument is a deep \((27 \times X_0)\), homogeneous, segmented PWO calorimeter and a fine imaging calorimeter \((3 \times X_0)\), which provides both an excellent energy resolution and a high e/p rejection power.

✧ CALET will investigate the spectrum of many cosmic ray species in a broad energy range, providing valuable information for indirect DM search, and study acceleration and propagation mechanisms.

✧ The CALET was launched by the Japanese carrier, HTV-5, to the Japanese Experiment Module (Kibo) on the ISS on Aug. 19, 2015 for 5-year observation. At present, commissioning of each component was being carried on, and the science operation has started from Oct. 5.

Stay tuned !!!!
Dark Matter or Pulsar by CALET Observation

Decay of Dark Matter (LSP)

Expected $e^+ + e^-$ spectrum by **Lightest Super Symmetry Particle (LSP) (black line)** after 5-year CALET measurement (red dots), which is consistent with present data of positron excess and $e^+ + e^-$ spectrum.

- Parameters assigned to PWN in random walk to match AMS-02 data => 100 cases
  - ATNF : $R < 2$ kpc, Age $< 10^6$ year (40 pulsars)
  - Spectra of nearby PWN simulated with DRAGON

- By using 500 CALET 5-yr samples:
  - **The fine structure (e.g black line)** is observable by CALET thanks to the high energy resolution
  - **Single pulsar hypothesis (dotted line)** can be rejected by more than $5\sigma$ for most cases
Overview of Expected Limits for Selected Dark Matter Candidates

Annihilation Case
5 year CALET Observation (+ AMS e⁺/e⁻ ratio)
Background: Single Pulsar + secondary

- e⁺+e⁻ - channel: Largest improvement (up to factor 10) for e⁺+e⁻ - channel and (up to factor 5) for LKP – hard drop in spectrum at mass of Dark Matter particle – well detectable by CALET due to high statistics in TeV region
- τ⁺+τ⁻ - channel: spectrum most similar to pulsar - could so far explain all the positron excess – weaker limit than for μ⁺+μ⁻ and dent where pulsar and Dark Matter annihilation spectrum together give best fit.

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Proton rejection power of $10^5$ can be achieved with IMC and TASC shower imaging capability.

Charge of incident particle is determined to $\sigma_z = 0.15 - 0.3$ with the CHD.
Overview of Trigger modes for CALET

**High Energy Shower Trigger (HE)**
- High energy electrons (10GeV ~ 20TeV)
- High energy gamma rays (10GeV ~ 10TeV)
- Nuclei (a few10GeV~000TeV)

**Low Energy Shower Trigger (LE)**
- Low energy electron at high latitude(1GeV ~ 10GeV)
- GeV gamma-rays originated from GRB (1GeV ~)
- Ultra heavy nuclei (combined with heavy mode)

**Single Trigger (Single)**
- For detector calibration: penetrating particle (mainly protons and helions)

**Auto Trigger (Pedestal/Test Pulse)**
- For calibration: ADC offset measurement (Pedestal), FEC’s response measurement (Test pulse)

(*) In addition to above 3 trigger modes, heavy modes are defined for each of the above trigger mode. They are omitted here for simple explanation.

Predominantly, timestamped changes of trigger setting are described in schedule command file. It makes possible to take pedestals, penetrating particles, low energy electrons at high latitude, and other dedicated data in addition to the most important high energy shower data.
Operation Procedure

- **Optimization of observation condition**
  - Stable and continuous data taking to accumulate HE electron events is the primary and the most important task of the nominal operation.
  - Need to schedule calibrations runs (pedestal, penetrating p/He)
  - We can think of other trigger mode as long as it does not affect high energy electron data statistics to maximize the outcome

- **Every day observation plan**
  - realization with schedule command file
    - changing of observation mode

---

Pedestal data acquisition
Schedule file: sequence of time and command
• Summarized in terms of WCOC role in CALET operations
• Interfaces to JAXA corresponding to each role of WCOC