The Calorimetric Electron Telescope (CALET) for High Energy Astroparticle Physics on the International Space Station

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Abstract: The CALET space experiment, currently under development by Japan in collaboration with Italy and the United States, will measure the flux of Cosmic Ray electrons (including positrons) to 20 TeV, gamma rays to 10 TeV and nuclei with Z=1 to 40 up to 1,000 TeV during a five year mission. These measurements are essential to investigate possible nearby astrophysical sources of high energy electrons, study the details of galactic particle propagation and search for dark matter signatures. The instrument consists of a module to identify the particle charge, a thin imaging calorimeter (3 radiation lengths) with tungsten plates interleaving scintillating fiber planes, and a thick calorimeter (27 radiation lengths) composed of lead tungstate logs. CALET has the depth, imaging capabilities and energy resolution necessary for excellent separation between hadrons, electrons and gamma rays. The instrument is currently being prepared for launch, during the 2014 time frame, to the International Space Station (ISS) for installation on the Japanese Experiment Module - Exposed Facility (JEM-EF).

Keywords: electrons, calorimeter, neraby sources, dark matter, ISS

1 Introduction

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. CALET provides the highest energy direct measurements of the cosmic ray electron spectrum in order to observe discrete sources of high energy particle acceleration in our local region of the Galaxy. CALET will, furthermore, address many outstanding questions including (1) the nature of the sources of high energy particles and photons, through the high energy spectrum, (2) the details of particle transport in the Galaxy, and (3) signatures of dark matter, in either the high energy electrons or gamma ray spectrum. It will also be capable of monitoring gamma ray transients and solar modulation. Figure 1 shows JEM/EF and the CALET instrument attached, and Fig. 2 presents a schematic overview of the CALET instrument.

The unique feature of CALET is its thick, fully active calorimeter that allows measurements well into the TeV energy region with excellent energy resolution, coupled with a fine imaging upper calorimeter to accurately identify the starting point of electromagnetic showers. CALET will have excellent separation between hadrons and electrons and between charged particles and gamma rays. It will provide unparalleled energy resolution and broad sky coverage to probe the High Energy Universe. It is in the TeV region that we anticipate being able to observe, for the first time, an unambiguous signature of energetic particles (electrons) accelerated in specific sources in our local region of the Galaxy and then propagating to Earth.

The hadronic data provide another channel through which the details of particle acceleration in supernova remnants or other sources will be investigated. Combining, for the first time, high energy, high resolution measurements of electrons, protons, helium, and high-Z particles provides a new tool to investigate cosmic accelerators in the high energy universe.

Moreover, some theories predict that potential dark matter particles (Kaluza-Klein particles from extra-dimension theories, or neutralinos predicted by supersymmetric theories) may have masses in the hundreds of GeV to TeV range. The characteristic signatures of the annihilation/decay of such particles in both the electron and gamma ray spectra can only be observed at the high energies reached by CALET.

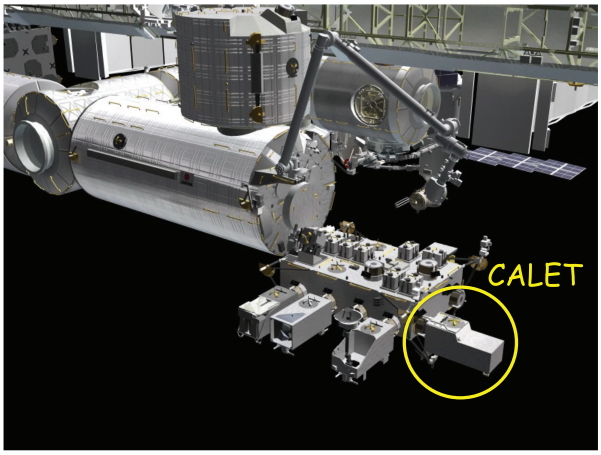

Figure 1: Japanese Experiment Module-Exposure Facility and CALET attached at the ♯ 9 port (as of 2014).

2 CALET Instrument

To effectively address these scientific issues, a large exposure detector, sensitive to $>$ 100 GeV electrons, protons and heavy ions, is needed. CALET is expected to satisfy these requirements. CALET is optimized to provide a precise measurement of the cosmic ray energy spectrum of electrons up to greater than 10 TeV, of protons, helium and other heavy ions up to several hundred TeV as well as complementary diffuse gamma ray spectrum measurements up to several TeV.

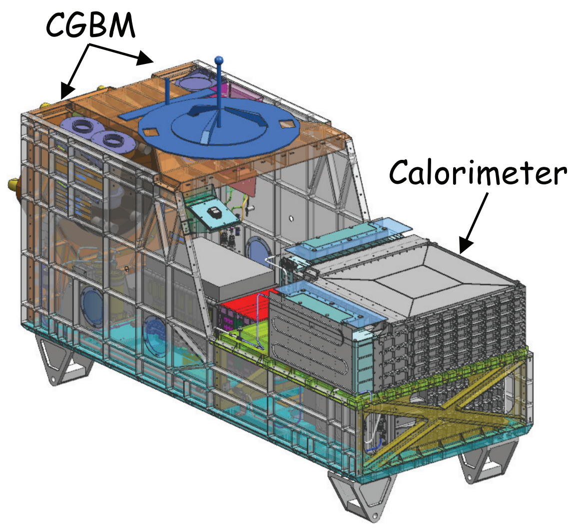

Figure 2: Overview of CALET instrument.

2.1 Main Detector: Calorimeter

The calorimeter consists of a single particle telescope that operates in event-by-event mode. It is composed of three subcomponents, the Charge Detector, CHD, the Imaging Calorimeter, IMC and the Total Absorption Calorimeter, TASC, that collectively provide event identification and background suppression. The total weight of the system will be 650 kg, and the detector has the absorber thickness of 30 radiation lengths (X_0) and 1.3 proton interaction lengths (λ), and the effective geometrical factor for high energy electrons of 1,200 cm^2 sr. A conceptual instrument design for CALET is shown in Fig. 3 with a simulated shower profile produced by an electron with an energy of 1 TeV. The

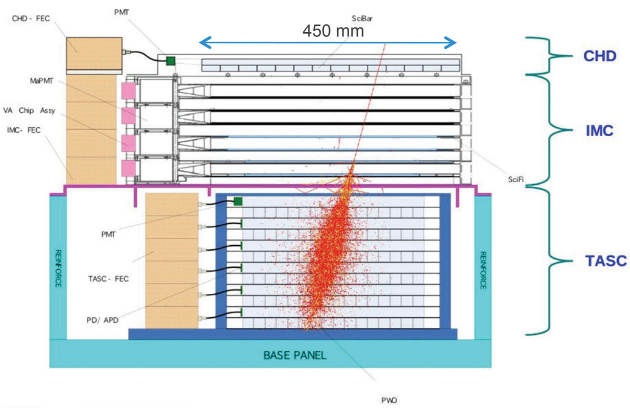

Figure 3: A schematic side view of the main calorimeter (size in mm). An example of a simulation event for a 1 TeV electron is over-written to illustrate the shower development in the calorimeter.

CHD is placed at the top of the instrument. It consists of two layers of 14 plastic scintillator paddles arranged alternately along X and Y directions, for a total of 28 paddles. The single paddle dimensions are 32(W) $\times$10(H) $\times$ 450 (L) mm^3; the CHD layers thus cover an area of 45.0$\times$45.0 cm^2. Relativistic particles traversing a paddle lose, by ionization, an amount of energy proportional to the square of their electric charge (dE/dx $\propto Z^2$). The generated scintillation light is collected and read out by a photomultiplier tube (PMT). Charge identification capabilities of CHD have been measured by exposing it on an ion beam at GSI facility [1] and CERN-SPS , giving a charge resolution ranging from 0.15 electron charge units (e) for B to 0.30-0.35 e for Fe.

The IMC consists of 7 layers of tungsten plates each separated by 2 layers of 1 mm square cross section scintillating fiber (SciFi) belts arranged in the X and Y direction and capped by an additional X,Y SciFi layer pair. The dimensions of the IMC are about 45 cm by 45 cm, while the total thickness of the IMC is 3 X_0. The first 5 tungsten-SciFi layers sample the particle at 0.2 X_0 and the following 2 layers are 1.0 X_0 deep. This provides the precise measurement to 1) separate the incident particles, 2) precisely determine the starting point for the shower, and 3) determine the incident particle trajectory. The readout for the SciFi layers consists of 64-anode Hamamatsu R7600-M64 photomultiplier tubes (MA-PMT).

The TASC measures the development of the electromagnetic shower to 1) determine the total energy of the incident particle and 2) separate electrons and gamma rays from hadrons. The TASC is composed of 12 layers of Lead Tungstate (PWO) "logs" where each log has dimensions of 20(H) $\times$ 19(W) $\times$ 326(L) mm^3. The logs are wrapped on five sides for optical isolation and, for each layer, are assembled next to each other in two rows with the unwrapped face outward. The top layer is used for triggering, and a PMT for readout is attached to the unwrapped log face. A photodiode and avalanche photodiode packages (PD/APD) are used for the readout of the other layers. There are 16 such logs in each layer. Alternate layers are orientated 90 degrees to each other to provide an X,Y coordinate for tracking the shower core. Finally, the PD/APD readout electronics (PreAMP+AMP) boxes are assembled on each face of the TASC. The total area of the TASC is about 1,060 cm^2 and the vertical thickness is about 27 X_0.

2.2 Performance of Calorimeter

The calorimeter is designed specifically for precise measurements of the cosmic ray electron energy spectrum over the range 1 GeV to 20 TeV. A necessary requirement, therefore, is to be able to efficiently identify high energy electrons among the "sea" of background cosmic ray hadron events. Combining the particle identification results from both IMC and TASC yields an electron detection efficiency above 80 % and a proton rejection factor of 1 in 10^5 by using the shower imaging capability as illustrated in Fig. 4 With the expected proton rejection factor, CALET will provide accurate measurements of the energy spectrum above 1 TeV ($\Delta E \sim 2$ %) whether individual sources are evident or not. Recent results of simulation studies on the CALET performance are described in Akaike *et al*. [2] by comparing with the CERN-SPS beam test results. A prototype CALET detector, bCALET-2, with a geometry factor of $\sim$ 320 cm^2

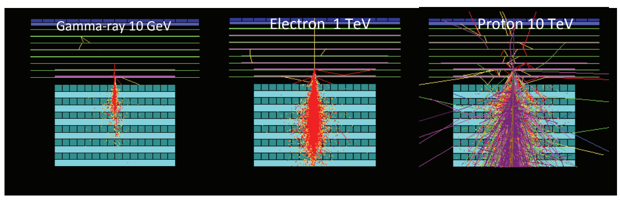

Figure 4: Examples of shower profiles by simulation.

sr, was constructed for a balloon experiment. The flight data demonstrated that the prototype worked well and observed the electron and gamma-ray spectrum in 1- several tens of GeV at an altitude of $\sim$ 35 km.

2.3 Subsystems

The CALET Gamma ray Burst Monitor, CGBM, composed of the Hard X ray Monitor, HXM, and the Soft Gamma ray Monitor, SGM [3], a support sensor composed of the Advanced Sky Camera (ASC) and the GPS receiver, GPSR, will be arranged on the pallet. The mission data processor, MDP, for data acquisition will be allocated with the high voltage system provided by Italy. CALET will use the Active Thermal Control System, ATCS, by the fluid interface, which is adopted in ISS as standard equipment to control the temperature difference in one orbit within a few degrees.

2.4 CALET on Orbit

CALET will be launched by a Japanese carrier, H-II Transfer Vehicle, HTV, launched by the H-IIB rocket, and attached to the Exposed Facility Unit, EFU ♯ 9, which has a wide field of view, 45 degrees. CALET is designed to utilize the standard JEM-EF hardware, and therefore includes a standard pallet to support the sub-systems and attach to the EFU.

The data down link will be done by two telemetry channels: One is the Ethernet channel which is operated at a medium rate of 300 kilobits per second (kbps) functions in real time mode for, on average, approximately 70 % of each day, and the other is a MIL-STD-1553B channel which provides low rate data at 20 kbps. In the medium rate mode, an event observed by CALET on the ISS will be transferred to the Tsukuba Space Center a few seconds following the event. The data that are not available via the real time link are recorded on-board the ISS in the High rate Communication Outage Recorder (HCOR) for later replay. The low rate mode is used as a redundant channel for telemetering the CALET house keeping data plus a sample of the highest priority events. A Japanese link will be prepared in addition to the NASA link mentioned above. The CALET data are transferred to the JAXA Tsukuba Space Center (TKSC) via MSFC in US, and are sent to the Waseda CALET Operation Center, WCOC, in real time for monitoring the events. The off-line data analysis is performed by the international CALET team based on the data derivered from the WCOC.

3 Science Objectives

It has become increasingly clear in recent years that major changes in, and the evolution of, our own and other galaxies are intrinsically linked to high energy phenomena - e.g., Supernova explosions, Black Hole accretion, Active Galactic Nuclei (AGN) jets, etc. - and that these involve the acceleration of charged particles, often to extreme energies. The release of these high energy particles fuels the galactic cosmic radiation, while the interactions of the energetic particles produce X ray and gamma radiation through synchrotron, inverse Compton, and pion decay processes. CALET will provide another important window on the High Energy Universe by observing high energy electrons, hadrons, diffuse gamma rays up to the highest energies observed in space.

3.1 Nearby Sources: Electrons

Evidence that particle acceleration to multi-TeV energy is taking place in supernova remnants, SNR, is provided by electron synchrotron and gamma ray emission measurements. Although the photon evidence for particle acceleration in SNR is clear, there is no direct evidence that the accelerated particles escape the source region. CALET is uniquely able to address this question by investigating nearby SNR sources via very high energy electrons.

Electrons provide a singularly sensitive probe of nearby high-energy cosmic accelerators. High-energy electrons lose their energy in proportion to the square of the energy, by synchrotron radiation and inverse Compton scattering. As a result, the highest energy electrons (in the TeV region) that we see very likely originate from sources at a distance less than $\sim$1 kpc from the Solar System and younger than $^{\sim}10^5$ years. Prime candidates are the Vela, Monogem and Cygnus Loop remnants, but other possible SNR include G65.3, HB21, Geminga, S147, Loop1, SN185, and of course unidentified sources. Thus, the high energy electron spectrum should exhibit structure [4] and very likely anisotropy. This, plus the certainty that electrons are accelerated to multi-TeV energies, provides the possibility of identifying individual cosmic accelerators and determining the diffusion coefficient.

For a particular choice of assumed model parameters, Fig. 5 shows the calculated electron spectrum compared to a compilation of previous electron measurements. Investigating such structure in detail and directly observing, for the first time, a source of electron acceleration at very high energies is only possible with CALET. At very high energies, significant anisotropy in the electron arrival directions is expected due to local sources. Since the anisotropy is expected to be nearly 10% for Vela, CALET is capable of observing both the structure in the spectrum and the anisotropy to bring us clear evidence of the electron acceleration and escape from the Vela remnant.

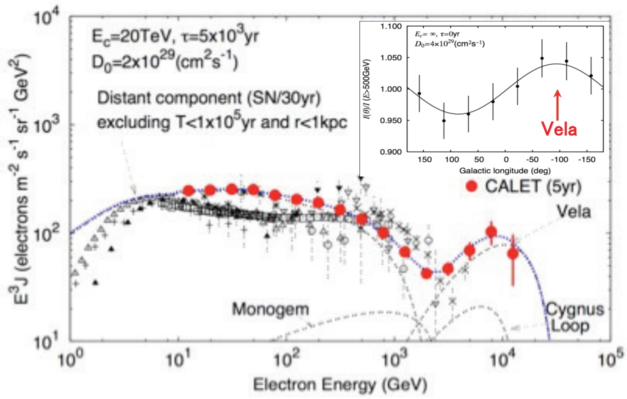

Figure 5: Expected observation by CALET with measured and expected data compared with calculations as described in text. The figure at the top right corner presents the expected anisotropy from Vela.

3.2 Acceleration and Propagation: Hadrons

High energy hadron spectra provide an important complement to the information derived from electron observations. Measurements of the cosmic ray H, He and higher Z energy spectra, including important secondary elecments (e.g. B), have been pushed to ever higher energy through Long Duration Balloon experiments, but these are reaching a practical limit in energy. While particle acceleration associated with supernova remnant shocks appears to be the best explanation for how galactic cosmic rays below the "knee" achieve their high energies, the energy spectrum signatures that would provide strong support for this SNR model (i.e. charge dependent high energy spectral cutoffs) have yet to be observed. Extending direct measurements is only possible with the long exposure of a space experiment. CALET can provide new data to extend the H, He and heavy ion spectra and the B/C ratio to an unprecedented region [5] and to measure the fluxes of Ultra-heavy particles with a better sensitivity than balloon experiments.

3.3 Gamma Ray Sources

As a high resolution electromagnetic calorimeter, CALET will be able to perform energy-resolved measurements of the diffuse gamma-ray emission. Current state-of-the-art direct measurements from the Fermi space telescope [6] benefit from a large effective area; CALET will complement these high-statistics observations by providing data in an energy range extending from some GeV to beyond the current upper limit of 100 GeV with an energy resolution varying from 7 % at 10 GeV to 2 % at highest energies. The energy resolution will, moreover, make CALET uniquely capable of searching for sharp lines in the high energy diffuse spectrum.

Observation of sources will not be a primary objective for CALET. However, data on strong sources (in particular, transients) will be available for analysis. CALET will follow Fermi into space by 5 years. If one or more sources has a major outburst, CALET will measure variability and energy spectrum changes as a function of time.

3.4 Dark Matter

Over the last several decades, experimental and theoretical work has essentially eliminated all known particles as dark matter candidates leaving only a few exotic species as possible candidates. Such candidates include Weakly Interacting Massive Particles, WIMPs, such as neutralinos, which annihilate and produce gamma rays and positrons as a signature. Another possibility is the Kaluza-Klein (KK) particles resulting from theories involving compactified extra dimensions. CALET will conduct a sensitive search for signatures of these dark matter candidates in both the electron (including positron) and gamma ray spectra. The predicted signatures are dependent on models with many parameters and even a non-observation by CALET will effectively constrain these parameters or eliminate some theories.

A prominent increase of the positron fraction over 10 GeV up to 350 GeV, as reported by PAMELA [7], Fermi/LAT [8] and AMS-02 [9], is discussed as a possible signature of dark matter. Moreover, the electron (including positron) excess in 300-800 GeV range observed by ATIC might consistently be understood as a result of KK particles with a mass of 620 GeV [10]. The observation by Fermi/LAT presents a hump around the same region with much less significance, and gives a harder energy spectrum with a power index of -3.04 in the 20-1000 GeV range [11]. Such a feature could be the result of a nearby source or could be a signature of dark matter annihilation. Higher precision and higher statistics measurements are required to understand this intriguing energy range. CALET, with its excellent energy resolution and hadron rejection power, will be able to investigate this feature in detail [12].

If neutralinos are the dark matter particles, they are most readily seen as a line in the high energy gamma ray spectrum. Since Fermi/LAT did not clearly detect such a line shape, the neutralino mass should be over several hundreds of GeV if neutralinos do exist. CALET is capable of searching for such a line in the higher energy region with superior energy resolution.

3.5 Gamma Ray Transients

CALET will extend the GRB studies being performed by other experiments (e.g. Swift and Fermi/LAT) and will provide added exposure when other detectors are not available or are viewing in other directions. Moreover, the CALET main telescope has limited sensitivity - with low resolution- down to 1 GeV, so that higher energy photons associated with a burst event can be recorded over the entire CALET energy range.

3.6 Solar Modulation

The effects of solar modulation extend up to 10-20 GeV for electrons. With the high statistics data from CALET, including measurements below 10 GeV, the evolution of the electron spectrum as a function of time can be recorded in detail. These data can be used to validate models for the transport of electrons into and within the Heliosphere.

4 Summary and Future Prospects

The CALET mission is proposed to perform observations of electrons, gamma rays, and H, He and heavy ions at the high energy frontier. Nearby sources of electrons will be directly identified by observing the energy spectrum and the anisotropy in the TeV region. Signatures of dark matter candidates will be searched with a sensitivity expected by theory in both the electron and gamma ray spectra. The hadron observation has the potential to reveal the origin of the "knee" and the mechanism of transport in the Galaxy. CALET will be useful for monitoring gamma ray transients and solar modulation. CALET is anticipated to begin operations on the ISS-JEM in 2014 with a mission life of 5 years.

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