PROCEEDINGS OF SCIENCE

The CALorimetric Electron Telescope (CALET): High Energy Astroparticle Physics Observatory on the International Space Station

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The CALorimetric Electron Telescope (CALET) space experiment, which has been developed by Japan in collaboration with Italy and the United States, is a high-energy astroparticle physics mission to be installed on the International Space Station (ISS). The primary goals of the CALET mission include investigating possible nearby sources of high energy electrons, studying the details of galactic particle propagation and searching for dark matter signatures. During a two-year mission, extendable to five years, the CALET experiment 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 several 100 TeV. The instrument consists of two layers of segmented plastic scintillators for the cosmic-ray charge identification (CHD), a 3 radiation length thick tungsten-scintillating fiber imaging calorimeter (IMC) and a 27 radiation length thick lead-tungstate calorimeter (TASC). CALET has sufficient depth, imaging capabilities and excellent energy resolution to allow for a clear separation between hadrons and electrons and between charged particles and gamma rays. The instrument is currently being prepared for launch on August 16, 2015 to the ISS with HTV-5 (H-II Transfer Vehicle 5) and installed on the Japanese Experiment Module- Exposed Facility (JEM-EF)

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1. Introduction

CALorimetric Electron Telescope (CALET) is a Japan-led international mission funded by the Japanese Space Agency (JAXA), the Italian Space Agency (ASI) and NASA. The instrument was designed and built in Japan, with hardware contribution from Italy and assistance from collaborators in Italy and the United States. The instrument is currently being prepared for launch on August 16, 2015 by a Japanese carrier, H-II Transfer Vehicle (HTV), and robotically installed on the Japanese Experiment Module-Exposed Facility (JEM-EF) on the International Space Station (ISS) for a two-year mission, extendable to five years, collecting new data on high-energy cosmic and gamma-rays.

The primary science goal of CALET is to perform high-precision measurement of the electron spectrum from 1 GeV to 20 TeV to observe discrete sources of high energy particle acceleration in our local region of the Galaxy. Thanks to its observations of cosmic-ray electrons and gamma-rays from a few GeV up to the TeV and nuclei from a few 10 GeV up to the several 100 TeV, the CALET mission will address many outstanding questions of High-Energy Astroparticle Physics, such as the origin of cosmic rays (CRs), the mechanism of CR acceleration and galactic propagation, the existence of nearby CR sources and dark matter. It will also monitor gamma ray transients with a dedicated gamma-ray burst detector and solar modulation. Figure 1 shows CALET attach point #9 on the JEM-EF. A schematic overview of the CALET instrument is presented in Fig. 2 . The instrument pallet includes a Gamma-ray Burst Monitor (CGBM), composed of a hard X-ray monitor (HXM) and a soft gamma-ray monitor (SGM), an Advanced Sky Camera (ASC) for attitude determination, a Mission Data Controller (MDC) to manage the individual detector systems and handle the accumulated data, as well as the CALET instrument itself.

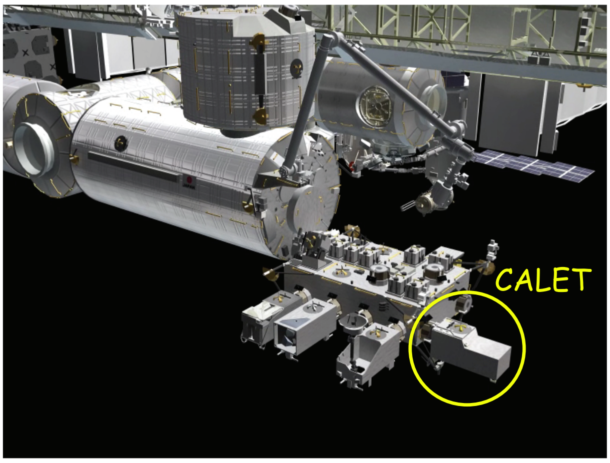

Figure 1: Japanese Experiment Module-Exposed Facility and CALET attached at the #9 port (as of 2015).

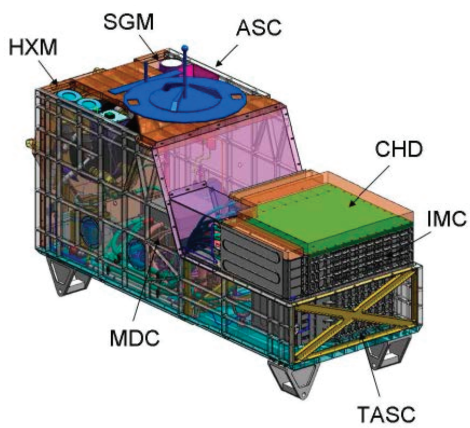

Figure 2: CALET instrument package showing the main calorimeter composed of CHD, IMC and TASC (see §2 for the details), and CGBM subsystems.

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. These features are essential to search for possible nearby astrophysical sources of high energy electrons and search for dark matter signatures in both the electron and gamma-ray spectra up to the TeV region. The hadronic data provide another channel through which the details of particle acceleration in supernova remnants or other sources will be investigated. Equipped with a charge

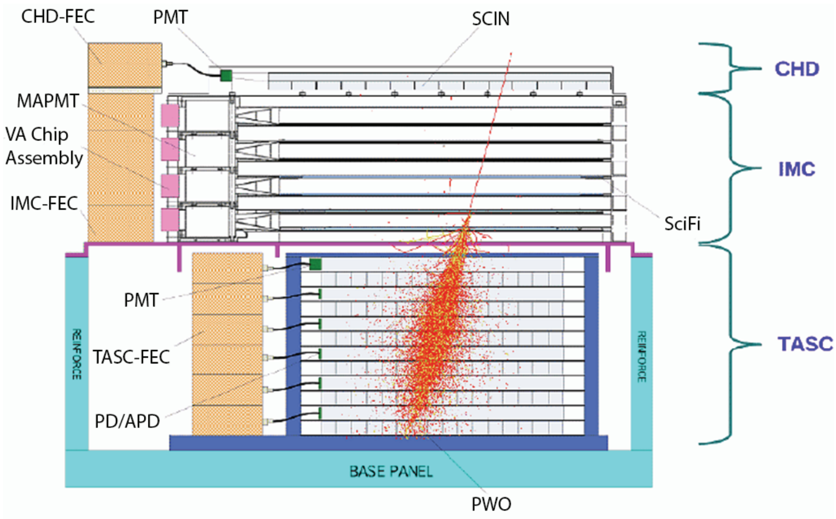

Figure 3: A schematic side view of the main calorimeter. An example of a simulation event for a 1 TeV electron is over-written to illustrate the shower development in the calorimeter.

identifier module, placed at the top of the apparatus and capable to identify the atomic number, Z, of the incoming cosmic rays, CALET will perform long-exposure observations of cosmic nuclei from proton to iron and will detect trans-iron elements with a dynamic range up to Z=40 [1].

2. The CALET Instrument and its performance

The main instrument of the mission is the calorimeter, shown in detail in Fig. 3 with a simulated shower profile produced by a 1TeV electron, which has a field of view of $\sim$ 45 degrees from the zenith. CALET is an all-calorimetric instrument, with a total thickness equivalent to 30 radiation lengths (X_0) and 1.3 proton interaction lengths (λ_I), preceded by a particle identification system. The energy measurement relies on two kinds of calorimeters: a fine granulated pre-shower IMaging Calorimeter (IMC), followed by a Total AbSorption Calorimeter (TASC). In order to identify the individual chemical elements in the cosmic-ray flux, a Charge Detector (CHD) is placed at the top of the instrument. The effective geometrical factor for CALET for high-energy electrons is $\simeq$1200 cm^{2}sr and the total weight is 613 kg.

The CHD has been designed to measure the charge of incoming particles via the Z^2 dependence of the specific ionization loss in double layered, segmented, plastic scintillator array placed above the IMC. Each layer consists of 14 plastic scintillator paddles, with dimensions 450 mm(L) $\times$ 32 mm(W) $\times$10 mm(H). This segmented configuration has been optimized to reduce multi-hits on each paddle caused by backscattering particles. The two layers of paddles are orthogonally arranged to determine the incident position of cosmic-rays. The generated scintillation light is collected and read out by a photomultiplier tube (PMT). The CHD and related front-end electronics have been designed to provide incident particle identification over a large dynamic range for charges in Z =1$\sim$40. Charge identification capabilities of CHD have been measured by exposing it on an ion beam at GSI facility [2] and CERN-SPS [3], giving a charge resolution ranging from 0.15 electron charge units (e) for B to $\simeq$0.30-0.35 e in the Fe region.

The IMC will image the early shower profile with a fine granularity by using 1 mm square cross section scintillating fibers (SciFi) individually read out by Multi-Anode Photomultiplier Tubes (64-anode Hamamatsu R7600-M64). The imaging pre-shower consists of 7 layers of tungsten plates each separated by 2 layers of SciFi belts arranged in the X and Y direction and capped by an additional X,Y SciFi layer pair. Each SciFi belt is assembled with 448 fibers and the dimensions of the SciFi layers are 448 mm (L) $\times$ 448 mm (W). The total thickness of the IMC is equivalent to 3 X_0. The first 5 tungsten-SciFi layers sample the shower every 0.2 X_0 and the last 2 layers provide 1.0 X_0 sampling. The IMC fine granularity allows to : (i) reconstruct the incident particle trajectory; (ii) determine the starting point of the shower; (iii) separate the incident particles from backscattered particles. Above several tens of GeV, the expected angular resolution for gamma-rays is $\sim 0.24^\circ$, while the angular resolution for electrons is $\sim$0.16 $^\circ$, which is better than that of gamma-rays.

The homogeneous calorimeter is designed to measure the total energy of the incident particle and discriminate the electromagnetic from hadronic showers. TASC is composed of 12 layers, each consists of 16 lead tungstate (PWO) logs. Each log has dimensions of 326 mm (L)$\times$19 mm (W)$\times$20 mm (H) . Layers are alternately arranged with the logs oriented along orthogonal directions to provide a 3D reconstruction of the showers. Six layers image the XZ view and the other six the YZ view. The total area of the TASC is 326 $\times$ 326 mm^2 and the total thickness corresponds to about 27 X_0 and 1.2 λ_I in normal incidence. Each PWO log at the top layer is readout by the PMT to generate a trigger signal. Hybrid packages of silicon Avalanche PhotoDiode and silicon PhotoDiode (Dual APD/PD) are used to detect photons from all of the remaining PWO bars in the eleven layers. The readout front end system of each pair of the APD/PD sensors is configured with Charge Sensitive Amplifier (CSA) and pulse shaping amplifier with dual gain. Such a readout system provides a dynamic range covering 6 orders of magnitudes and allows to measure in each bar signal spanning from 0.5 MIPs (Minimum Ionizing Particles) to 10^6 MIPs, which is the energy deposit expected from a proton-induced 1000 TeV shower.

The main scientific objective of CALET is the measurement of the electron spectrum over the range from 1 GeV to 20 TeV. For this purpose, TASC is required to have a linear energy response from GeV up to the TeV region and an excellent resolution to resolve possible spectral features as expected in case of the presence of nearby CR sources or dark matter. According to Monte Carlo simulations and CERN-SPS beam test data, TASC can measure the energy of the incident electrons and gamma rays with resolution $\leq$2 % above 100 GeV [4]. Another necessary requirement is to efficiently identify high-energy electrons among the overwhelming background of CR protons. Particle identification information from both IMC and TASC is used to achieve an electron detection efficiency above 80 % and a proton rejection power $\sim 10^5$ [5].

In the region above 10 GeV, electrons and gamma rays are separated by the IMC, as gamma rays have no tracks in the IMC, except for backscattered particles. Furthermore, the charge measurements of the CHD can be used to reject photons. At energies less than 1 TeV, a gamma-ray rejection power (for electron observations) is expected to be $\sim$500, while the electron rejection power (for gamma-ray observations) is better than 10^4 [6].

Charged particles and gamma rays with energy larger than 10 GeV will be triggered above a 15 MIP threshold from the sum of the signals from the last two IMC SciFi belts and a 55 MIP threshold from the signal of the top layer in the TASC. Electrons in the energy range between 1 GeV and 10 GeV will be observed only for a limited exposure by reducing the IMC trigger thresold. The trigger rate above 10 GeV is estimated around 13 Hz [7].

3. CALET Science Goals

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

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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 Search for nearby sources of high-energy electrons

It is generally accepted that CRs are accelerated in shock waves of supernova remnants (SNRs), which are the only galactic candidates known with sufficient energy output to sustain the CR flux. Evidence that particle acceleration to multi-TeV energy is taking place in 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. Unlike the hadronic component of CRs, the electrons, during their diffusion in the Galaxy, lose their energy in proportion to their squared energy by synchrotron radiation and inverse Compton scattering. Thus TeV electrons observed at Earth likely originated in sources younger than $\sim 10^5$ years and less than 1 kpc far from the Solar System. Since the number of such nearby SNRs is limited (e.g.: Vela, Monogem and Cygnus Loop remnants and few others), the electron energy spectrum around 1 TeV could exhibit spectral features and, at very high energies, a significant anisotropy in the electron arrival directions is expected. Thanks to its excellent energy resolution and capability to discriminate electrons from hadrons, CALET will be able to investigate possible spectral structures by detecting very high-energy electrons and possibly provide the first experimental evidence of the presence of a nearby CR source.

For a given choice of assumed model parameters as calculated by [8], Fig. 4 shows the simulated electron spectrum (dotted line) and the anticipated data points from a five year CALET mission compared to a compilation of previous electron measurements. Moreover, a significant anisotropy ~ 10 % in the electron arrival directions is expected for Vela as also presented in Fig. 4. The investigation of possible spectral features in the electron (and positron) spectrum and the observation of a possible anisotropy in the direction of the Vela SNR are one of the main goals of CALET.

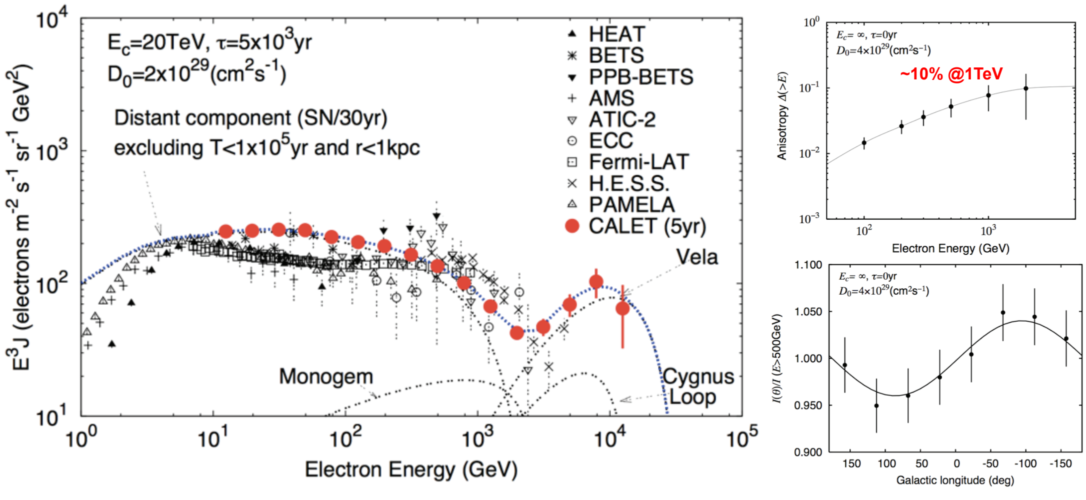

Figure 4: Expected observation by CALET with measured and expected data compared with calculations as described in text. The figure at the bottom right presents the expected anisotropy from Vela and at the top right the energy dependence of the amplitude of anisotropy.

3.2 Measurements of primary and secondary nuclei

A direct measurement of the high-energy spectra of individual cosmic-ray nuclei up to the PeV scale provide important complementary information to the one derived from electron observations. Possible charge-dependent high-energy spectral cutoffs, hypothesized to explain the CR "knee" , or spectral hardening due to non-linear acceleration mechanisms, could only be investigated by a space experiment with long enough exposure to extend the direct measurement of CR nuclei spectra to unprecedented energies.

CALET will be able to identify CR nuclei with individual element resolution and measure their energies in the range from a few tens of GeV to several hundreds of TeV. In five years of data taking on the ISS, it is expected to extend the proton energy spectrum up to $\sim$900 TeV, the He spectrum up to 400 TeV/n (Fig. 5) and measure the energy spectra of the most abundant heavy primary nuclei C, O, Ne, Mg, Si and Fe with sufficient statistical precision up to$\sim$ 20 TeV/n. It will also investigate precisely possible spectral features or deviations from a pure power-law spectrum, as observed by PAMELA [9] and AMS-02 [10] for proton and helium spectra.

Additional information on the CR propagation might be obtained by directly measuring, besides proton and helium energy spectra, the secondary-to-primary flux ratios, most notably Boron/Carbon - can discriminate, via its energy dependence, among different propagation models. This observable is less prone to systematic errors than absolute flux measurements. The relative abundances of CR secondary-to-primary elements (like B/C or sub-Fe/Fe) are known to decrease, following a power law in energy $E^{-\delta}$, where δ is a key parameter in the description of the CR diffusion in the Galaxy at high energies. Unfortunately, the available measurements, pushed to the highest energies with Long Duration Balloon experiments, suffer from statistical limitations and large systematic errors at several TeV/n, due to the residual atmospheric overburden at balloon altitude. This sets an effective limit to the highest energy points of the secondary-to-primary ratios obtainable with measurements on balloons and has not allowed so far to place a stringent experimental constraint on the value of δ. On the other hand, experiments in space are free from this limitation. Taking advantage of its long exposure in space and the absence of atmosphere, the CALET mission will provide, as well as AMS-02, new data to improve the accuracy of the present measurements and extend them above 1TeV/n, as illustrated in Fig. 6.

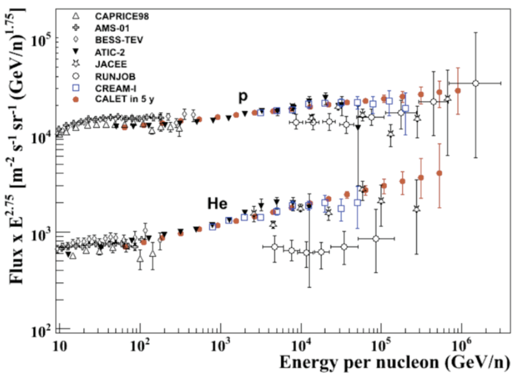

Figure 5: Expected p and He spectrum by CALET five-year observation comparing with present data.

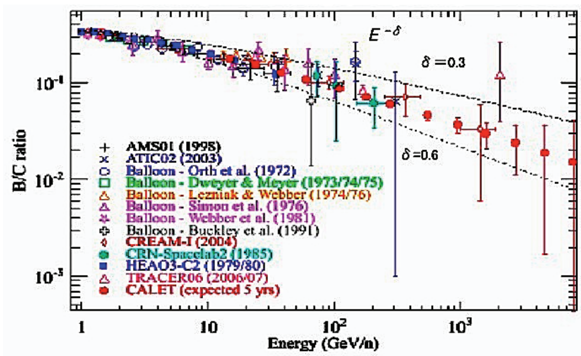

Figure 6: Expected B/C ratio by CALET comparing with present data, which is capable of defining the power index, δ, up to a few TeV.

3.3 Indirect dark matter search

Besides studying the CR sources and diffusion, CALET will also conduct a sensitive search for signatures of dark matter candidates in both the electron plus positron (1 GeV - 20 TeV) and gamma-ray (10 GeV - 10 TeV) spectra. Surviving dark matter candidates (i.e. not yet excluded by the available experimental findings and current theoretical work) include Weakly Interacting Massive Particles (WIMPs) .

The prominent increase of the positron fraction over 10 GeV, reported by PAMELA [11], Fermi-LAT [12] and AMS-02 [13], has fueled an intense debate whether this observation is related to dark matter or it is the result of an astrophysical effect. With its excellent energy resolution, hadron rejection power and long exposure in space, CALET will shed new light on this open question. On the assumption that the positron excess is caused by a single nearby pulsar, CALET will be able to set significantly more stringent limits on Dark Matter annihilation compared to current experimental data, especially for annihilation to pure e^+e^- and Lightest Kaluza-Klein Particle case [14]. Should CALET results not be compatible with the assumed single pulsar case in the TeV region, it may hint at Dark Matter partially contributing to the positron excess or even causing it completely, for example, in the form of decaying Dark Matter [15]. CALET has a potential to detect the distinctive features from dark matter annihilation/decay in the electron and positron energy spectrum in the TeV region while it cannot separate the sign of charge.

Since CALET has an outstanding energy resolution ($\sim$2 % over 100 GeV), it is an ideal detector to observe monochromatic gamma rays from dark matter annihilations from several tens of GeV up to several tens of TeV.

4. Current status of the CALET mission

4.1 Status of the CALET flight model

The final review for the CALET flight model production has successfully been done after the functional and environmental tests (EMC, Acoustic, Thermal vacuum, muon runs, etc.), Prior to the assembling of each component (CHD, IMC and TASC), ground tests for calibrations were carried out: (i) UV laser irradiation to each PWO log to get a correlation data between APD and PD with dual gain (i.e: APD-high, APD-low, PD-high, PD-low). (ii) Trigger function test by using pulses simulated by actual trigger signals. (iii) Muon runs including thermal-vacuum test of each component. The payload assembled in the JEM-EF standard package presented in Fig. 7, was transferred in the beginning of April, 2015 to the launch site at the Tanegashima Space Center (TNSC), and was mounted on the HTV exposed facility pallet as shown in Fig. 8.

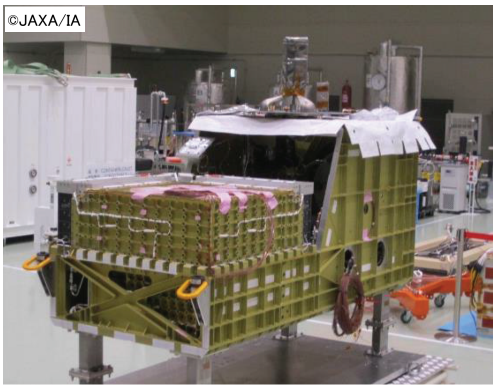

Figure 7: CALET flight model viewed from the calorimeter side.

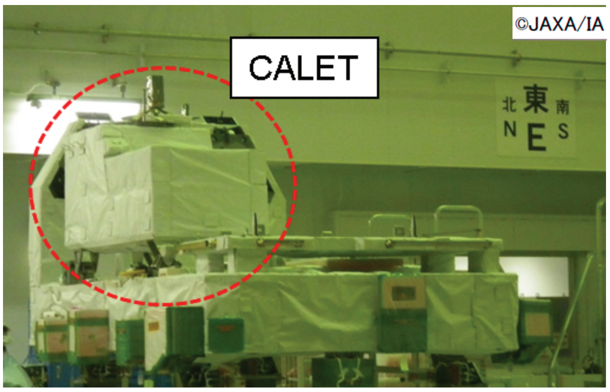

Figure 8: CALET flight model assembled on the HTV palette.

4.2 Ground Support Equipment

The data down link will be done by two telemetry channels: One is the Ethernet channel which is operated at a medium rate of 600 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 50 kbps. In the medium rate mode, an event observed by CALET on the ISS will be transferred to the Tsukuba Space Center (TKSC) of JAXA a few seconds following the event. The data that are not available via the real time link are recorded on-board the ISS 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 cosmic-ray events.. A Japanese link will be prepared in addition to the NASA link mentioned above. The CALET data will be transmitted to TKSC via MSFC in the United State, and are sent to the Waseda CALET Operations Center (WCOC) in real time for monitoring the events [7]. The off-line data analysis is performed by the international CALET team based on the data delivered from the WCOC.

5. Summary and Future Prospects

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 August, 2015 with a mission life of 5 years.

Acknowledgments

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