CALET Mission for the Observation of Cosmic Rays on the International Space Station

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We have proposed CALET (CALorimetric Electron Telescope) mission to make observations of high energy cosmic rays, electrons, gamma-rays, and nuclei, on the International Space Station (ISS). CALET mission has been approved as one of the candidates for the next mission utilizing the Japanese Experiment Module (JEM). The detector of CALET consists of an imaging calorimeter (IMC) and a total absorption calorimeter (TASC). Main objective of cosmic-ray observation with CALET is to determine precise energy spectrum of electrons up to 20 TeV. As the super nova remnants (SNR) are taken to be sources of electrons, some structure caused by nearby electron sources is expected to appear in the energy spectrum over 1 TeV. Gamma-rays from 20 MeV to a few TeV can be also observed by CALET. Because a thick TASC of CALET gives high energy resolution, annihilation line of SUSY particle, which is a candidate of the dark matter, can be detected. Observation of nuclei is also possible up to 1000 TeV owing to the thick TASC. We have been going on conceptual design of CALET to clear a next judgment in one or two years to proceed to practical development for launching in 2013.

Key Words: Cosmic ray, Electron, Gamma-ray, Dark matter, International Space Station

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1. Introduction

The principle to detect high energy electrons and gamma-rays with an imaging calorimeter (IMC) is based on a detector which we developed for the balloon experiments. We have established a technique to detect electrons and gamma-rays with high accuracy by reducing background protons effectively with an IMC. We add a thick total absorption calorimeter (TASC) to the IMC for CALET to extend the energy range up to 20 TeV.

We made several balloon experiments to observe primary electrons and atmospheric gamma-rays with a balloon-borne electron telescope with scintillating fibers, BETS.\(^\text{5}\) We have developed an IMC which consisted of scintillating fibers (SciFi) and lead plates to detect electromagnetic cascade showers induced by incident electrons or gamma-rays with energies from 1 to 100 GeV. In order to reject protons, profile of shower caused by proton is distinguished from that of electromagnetic shower with the IMC. Because the ratio of the flux of proton to that of electron is about 150 in the energy range from 10 to 100 GeV, total rejection power of 2400 against proton backgrounds achieved by the BETS detector was enough to observe electrons.\(^\text{2,3}\)

Electron observations were carried out successfully at Sanriku in 1997 and 1998. Observation time amounted to about 13 hours in total.\(^\text{4}\) We added an anti shield of plastic scintillator to the BETS instrument to observe atmospheric gamma-rays up to a few 10 GeV. We obtained an important result to calibrate simulation code relating to the atmospheric neutrino oscillation and also confirmed the detection capability of the BETS instruments for gamma-ray.\(^\text{5}\)

We developed a new detector, PPB-BETS, to observe electrons over 100 GeV by improving the BETS.\(^\text{6,7}\) An observation was made for about 13 days in the Antarctica with the polar patrol balloon (PPB) in January 2004. We obtained a result on the electron flux up to several hundreds GeV.

The highest energy of electron to be observed at the Earth is estimated to be around 10 TeV. Electron flux is expected to change drastically over 1 TeV. Since such high energy electron loses its energy within 10\(^3\) years and cannot reach to the Earth beyond 1 kpc, contributions from nearby sources should become dominant over 1 TeV. Super nova remnants (SNRs) are supposed to be a candidate of the electron source, and there exist a few SNRs within 1 kpc from the Earth.\(^\text{9}\) That is why the spectrum may break off the power law over 1 TeV. We need the proton rejection power higher than 10\(^5\) to observe high energy electrons because the ratio of proton to electron ranges from 10\(^5\) to 10\(^6\) over 1 TeV. Longer observation period is also necessary to detect the low flux of electron in the high energy region.

The International Space Station (ISS) provides an opportunity to make a long duration observation on the order of year. The Japanese Experimental Module (JEM) on the ISS will have an exposed facility (EF) where several payload modules will be attached to make scientific and technological experiments in the outer space. Two modules, MAXI and SMILES, have been already approved as the scientific experiments in the early phase utilization of the JEM/EF. Most of the attach points can be loaded with standard payload of maximum weight of 500 kg. We need heavier detector than 500 kg to achieve a higher rejection power than 10\(^5\) against proton backgrounds. Two attach points, No.2 and No.9, can be loaded with heavy payload of maximum weight of 2500 kg. Such a heavy payload enables us to make the observation of electron in the high energy region up to 10 TeV.\(^\text{10}\) In order to apply to the middle phase utilization of the JEM/EF, we have been developing a new detector, CALET, to observe high energy cosmic rays. We will request the observation period of three years at least.

2. Scientific Objectives

2.1. Electron

Electron observation in the energy range between 1 GeV and 20 TeV is our main objective. A life time of electron over 1 TeV is shorter than 10\(^5\) years and a distance that the electron diffuses within its life time is less than a few kpc. There exist a limited number of candidates of electron sources within a few kpc from the Earth. Consequently, effects from each nearby source must be identified in the energy spectrum over 1 TeV. The Vela is one of the most likely sources which are expected to originate prominent excess over 1 TeV.\(^\text{5}\) CALET will be able to determine a shape of electron spectrum originated by the Vela. It will give a direct evidence of acceleration of high energy electrons in the SNR and will bring important information on release timing of electrons from the SNR, energy amount of electrons ejected from the SNR, maximum energy of electrons, and so forth.

Figure 1 shows an electron spectrum expected to be obtained with CALET. We estimate to detect 3.0 \times 10\(^3\) electrons over 1 TeV for 3 years by assuming a power law index of -3.26.

The energy spectrum of electron from 10 GeV to 1 TeV is supposed to be integration of contributions from all sources. In order to study distribution of SNRs, birth rate of SNRs, amount of energy flow from SNRs to electrons, the diffusion coefficient and so on, it is crucial to...
Fig. 2. All sky map of exposure time for gamma-rays over 100 MeV with CALET. The brightest region reaches to 52 days for one year and the darkest region corresponds to 43 days.

determine the precise flux of electron in this energy range. The number of electrons detected for 3 years with CALET is expected to be $9.8 \times 10^7$ over 10 GeV and $5.4 \times 10^5$ over 100 GeV. We will be able to obtain the energy spectrum with sufficient statistics.

Electrons less than 10 GeV is strongly affected by the solar modulation. Cosmic-ray flux changes in a long time due to 11-year cycle of solar activity. To inspect the force field model which is a standard and simple model of the solar modulation or the drift model in which an effect of drift of cosmic rays moving in the solar magnetic field is taken into account, a long term observation of electrons is important. On the other hand, quick decrease of cosmic-ray flux, which is called forbush decrease, will be observed about 30 times for 3 years with CALET. The flux of cosmic ray decreases by a few percent in a few hours, and it takes between 3 and 10 days for the flux to recover. The mechanism of the forbush decrease has not been comprehended yet. It is supposed to be caused by coronal mass ejection from the sun, therefore observation of the forbush decrease will become a good probe to investigate the solar activity in a short period.

2.2. Gamma-ray

We can make observations of electrons and gamma-rays simultaneously with CALET. Figure 2 shows all sky map indicating exposure time of CALET for gamma-rays over 100 MeV. The brightest region reaches to the exposure time of 52 days for 1 year and the darkest region corresponds to that of 43 days. We can carry out an observation of 48 days in average for one year on one point. CALET makes us enable to observe many point sources and diffuse components of inner and outer galaxy in the energy range from 20 MeV to a few TeV.

Diffuse gamma-ray component estimated from electron and proton origin shows some inconsistency with the result obtained by EGRET over 10 GeV. CALET will be able to survey diffuse gamma-rays up to higher energy region with better sensitivity than EGRET. It will be possible for us to study the origin of diffuse component in detail.

As for point sources of gamma-ray, we have pulsars in our galaxy and active galactic nuclei (AGNs) in outer galaxy. Several pulsars have been found to emit pulsed gamma-rays up to a few GeV by EGRET. According to outer gap model of the pulsed emission, the pulsed component might deviate and decrease from a power law curve over several GeV. CALET will be able to detect gamma-rays up to over 10 GeV with a sufficient statistics to study mechanisms of the pulsed emission. As for AGNs, energy spectrum of gamma-ray are expected to have break due to the absorption by the interaction of gamma-rays with infrared background photons. Strength of absorption depends on a distance to each AGN, amount of infrared background photons, and cosmological parameters. Figure 3 shows examples of expected energy spectrum of gamma-rays from typical AGNs observed by CALET for 3 years. The strength of absorption will be completely determined with CALET.

As regards gamma-ray bursts, we estimate that a few 10 gamma-ray bursts of the order of $10^{-5}$ erg/cm$^2$ and a few bursts of the order of $10^{-4}$ erg/cm$^2$ will be detected with CALET in the observation period of 3 years. Number of photons to be detected with CALET in a gamma-ray burst of $10^{-5}$ erg/cm$^2$ is estimated to be 600 over 100 MeV, where the power law index of -2 is assumed for the energy spectrum. We will be able to study high energy gamma-ray bursts event by event. We can also study low energy gamma-ray burst in the energy range from 7 keV to 20 MeV with a gamma-ray burst monitor (GBM). The GBM consists of hard x-ray monitor (HXM) which covers energy range from 7 keV to 600 keV and soft gamma-ray monitor (SGM) which covers higher energies from 100 keV to 20 MeV. The GBM is set beside the main detector of CALET. We will expect to detect 150 gamma-ray bursts in a year.

Fig. 4. A Gamma-ray line spectra to be produced by annihilation of neutralino. Expected result to be obtained from 3-year observation with CALET.
2.3. Proton and nucleus

Direct observation of protons and heavy nucleus up to iron will provide a conclusive result to the shock acceleration of cosmic rays in SNRs. Spectral break of cosmic ray around $3 \times 10^{15}$ eV, called 'Knee', is thought to indicate a limit of the shock acceleration in SNRs. CALET can observe protons and nuclei up to $10^{15}$ eV and investigation of them just below the limit will be possible. Should the break point of the Knee correspond to the nuclei like iron, protons might show spectral break around $10^{14}$ eV.

2.4. Dark matter

Neutralino is a candidate of dark matter and its mass is predicted to be more than a few 10 GeV. Two gamma-rays generated by annihilation of the neutralinos should be detected as gamma-ray line of neutralino mass. By assuming that the mass of the neutralino is 690 GeV and it distributes along the galactic disk,\(^{11}\) we will obtain a sharp peak with CALET in the energy spectrum of gamma-ray as shown in Figure 4. Such a clear peak will be obtained by CALET with an excellent energy resolution in higher energies owing to its thick TASC.

Super-symmetric particles or Kaluza-Klein dark matters should produce a pair of electron and positron when they annihilate.\(^{12}\) Consequently a ratio of positron to sum of positron and electron might show a prominent bump around a few 100 GeV. Although CALET will not be able to distinguish positron from electron, electron spectrum including both electron and positron obtained with CALET will show an obvious bump as shown in Figure 5.

3. Instrumentation

The detector of CALET is composed of two instruments as shown in Figure 6. The IMC is upper part of them to determine shower axis, incident charge, and starting point of shower precisely by taking shower image with scintillating fibers. It is also useful to reject proton backgrounds below 100 GeV. The anti-coincidence detector of plastic scintillator (ACD) covers the IMC to reject charged cosmic rays for the observation of gamma-rays below 10 GeV. The silicon array (SIA) is arranged on the top of the IMC to detect high Z particles and to identify incident particles. The TASC is lower part of the detector to achieve high rejection power against proton backgrounds in the high energy electron observation. The background reduction is essential to detect electrons up to 20 TeV with high accuracy. The thick calorimeter will also bring an advantage of high energy resolution. We carried out several beam experiments to test performance of the IMC and the TASC with a prototype detector.

3.1. IMC

The IMC consists of scintillating fiber (SciFi) belts and tungsten (W) plates. The area of IMC is $896 \times 896$ mm\(^2\). The SciFi belt of 896 mm square is assembled with 896 SciFi’s of 1 mm square. Two SciFi belts at right angles to each other form one SciFi layer. Ten tungsten plates of 0.1 radiation length (r.l.), five tungsten plates of 0.2 r.l., and two tungsten plates of 1 r.l. are inserted between 17 SciFi layers. Incident charge will be determined with the SIA set at the top of the IMC. Total thickness of the tungsten plates is 4 r.l. or 0.13 mean free path. We need 30464 SciFi’s in total. An estimated maximum number of minimum ionizing particle (MIP) in one SciFi is to be 3000.

Scintillation light from the SciFi is to be detected by a multi-anodes photo multiplier tube (MAPMT) which has anode outputs of 64 channels.\(^{13}, 14\) Each anode output corresponds to each SciFi. Therefore 476 MAPMTs are needed to read out all SciFi’s. In order to read out signals of 30464 channels from the MAPMTs, VLSI chip in

![Fig. 6. Schematic drawing of the CALET detector. It is composed of the IMC, the TASC, the SIA, and the ACD.][1]

![Fig. 7. Front end circuit developed to read out MAPMT. Two VLSI (Viking) chips are used for one MAPMT.][2]
which a lot of channels of amplifier and signal holding function are contained is indispensable as front end circuits to reduce the power consumption and the size of electronics. We have developed a VLSI chip, VA32HDR14, which is based on a Viking chip produced by IDEAS in Norway. It includes 32 sets of pre-amplifier, shaping amplifier, and sample hold circuit in one chip. Analog signals held in each channel are to be read out through one multiplexer.

Figure 7 shows a front end circuit which we have developed with the VA32HDR14 chips. Two VLSI chips are used to read out 64 channels of one MAPMT. We measured power consumption and it turned out to be 420 mW for 64 channels. Then, total power consumption of the front end circuits for MAPMTs becomes 200 W for 30464 channels. We have already confirmed that the VA32HDR14 has high dynamic range reaching to 3000 and input range of the VLSI matches to the output charge from the MAPMT.

3.2. TASC
The TASC has an area of $60 \times 30$ cm$^2$ and a thickness of 30 cm. It is composed of 576 BGO logs of $2.5 \times 2.5 \times 30$ cm$^3$. We need a set of two BGO logs arranged lengthwise for the side length of 60 cm. In one layer, 24 such sets are laid in a same direction. The TASC consists of stacks of 12 layers. Directions of BGO logs in alternate layers cross at right angles. Total thickness of the TASC corresponds to 27 r.l. or 1.4 mean free path. Such thick calorimeter achieves rejection power of more than $10^5$ against proton backgrounds. Showers induced by electrons cannot survive through the thick calorimeter while those induced by protons go on developing at the bottom of the TASC. Protons are to be distinguished from electrons with such different behavior in thick calorimeter.

In order to obtain such high rejection power, it is essential to detect the energy deposition more than 0.5 MIPs in one BGO log. On the other hand, maximum energy deposition reaches to $10^8$ MIPs for protons with energy of $10^{15}$ eV. Thus the dynamic range required for a readout of the BGO extends through about $10^8$. We have chosen photo diodes (PDs) for the readout and it is considered to use two or three sets of PDs and readout circuits for one BGO log to achieve such high dynamic range.\(^{(16)}\)

4. Event Trigger
We can make simultaneous observation of electrons, gamma-rays, and nuclei. Three types of trigger mode are to be provided with CALET according to each incident particle and its energy.

First, a trigger mode for low energy gamma-ray is used to detect gamma-rays with energies from 20 MeV to 10 GeV. The trigger mode requires that energy deposition in anti shield should be less than 0.5 MIPs and tracks in the IMC should be detected in more than three layers. We estimate the trigger rate of gamma-rays which mostly come from the galactic plane to be 14 Hz and that of albedo background to be 37 Hz. Hadron background is negligibly small.

Second, a trigger mode for high energy electrons and gamma-rays is to operate in the energy range between 10 GeV and 10 TeV. The trigger is generated by detecting shower developments in the IMC, which is the shower trigger. The anti shield is not used for the gamma-rays because it is not valid due to backscattered particles over 10 GeV. The shower trigger can reduce the backgrounds to less than 1 %. As a consequence, the trigger rate is estimated to be around 40 Hz. Proton backgrounds to electrons and gamma-rays can be reduced to less than $10^5$ after analysis of shower development and shower profile in the TASC, that is, the rejection power exceeds $10^5$. Electron backgrounds to gamma-rays can be smaller to less than $2 \times 10^3$ by detailed image analysis to check charged tracks around incident position.

Third, a trigger mode for protons and heavy ions with energies from 10 GeV to 1000 TeV is also set up. The trigger will be created by detecting shower developments in the TASC. The trigger rate is expected to be around 0.1 Hz. Charge of incident particles can be identified with incident signal in the SIA and with incident tracks in the IMC by image analysis.

5. Proto-type Test

5.1. Balloon experiment
We made a 1/64 scale model of CALET as a proto-type detector to carry out a balloon experiment in 2006. Figure 8 shows a picture of the proto-type detector under preparation for a balloon flight in Sanriku.

The IMC had 4 layers each of which consisted of two SciFi belts in X and Y direction. The width of the SciFi belt was 128 mm. We assembled 1024 SciFi in total for this proto-type IMC. The scintillation light from the SciFi was read with 16 MAPMTs, and two front end circuit units each of which contained 16 chips of the VA32HDR14 were used to read signals of 1024 channels out of the MAPMTs.

The TASC had 6 layers, and 4 BGO logs were laid in one layer. The scintillation light from the BGO was read with a PD. Four BGOs in the top layers were also read with PMTs to detect shower energy deposited in the

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**Fig. 8.** CALET 1/64 scale model for balloon experiment.
TASC and to generate a trigger signal.

We obtained energy spectrum of electrons from about 0.6 GeV to 15 GeV. It was consistent with the previous result obtained with BETS over 10 GeV, and simulated result below 10 GeV.

5.2. Gamma-ray beam experiment

We made a test to confirm the performance of the IMC to detect low energy gamma-rays with another proto-type detector. The IMC was composed of 8 SciFi belts of 32 mm in width and 4 SciFi belts of 64 mm in width. The SciFi belts were arranged in one direction. The lead plates were inserted between the SciFi belts. Figure 9 shows examples of pair creation trucks of electron and positron obtained with the proto-type IMC by irradiating 0.8 GeV gamma-ray beams at the Laboratory of Nuclear Science (LNS) in Tohoku University.

Fig. 9. Examples of pair creation trucks by 0.8 GeV gamma-rays obtained with the proto-type detector. Gamma-ray beams were irradiated from left. There was no lead plate between left 4 SciFi belts of 32 mm shown with white bars. Although 4 SciFi belts of 64 mm were set in right, two of them are not shown due to low gain. Electron and positron pair trucks are indicated by red squares.

6. Summary and Conclusions

The JEM/EF facility of the ISS is very suitable to cosmic-ray observation at very high energies with a heavy payload. We have successfully been developing the CALET instrument for the JEM/EF facility from the experience of balloon experiments. CALET has capabilities to observe the electrons up to 20 TeV, gamma-rays from 20 MeV to a few TeV, protons and heavy ions from 10 GeV to 1000 TeV for investigation of high energy phenomena in the universe. CALET has been selected as one of candidates for the next mission utilizing the JEM/EF. We have been going on conceptual design of CALET to clear a next judgment in one or two years to proceed to practical development for launching in 2013.

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