Scientific Prospects of Electron and Gamma-Ray Observations with the CALET Instrument on-board ISS

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***Abstract*. The CALorimetric Electron Telescope, CALET, is a new all-sky gamma-ray and electron observatory being developed for the Exposure Facility of Japanese Experiment Module (JEM-EF) on the International Space Station (ISS). The mission goal is to investigate high-energy universe by observing cosmic-ray electrons in 1 GeV – 20 TeV, gamma rays in 20 MeV – 10 TeV, and protons, heavier nuclei in several 10 GeV – 1 PeV. The main instrument consists of an imaging calorimeter of scintillating fibers, IMC, and a total absorption calorimeter of BGO, TASC. CALET has a unique capability to observe high-energy electrons and gamma rays with an energy resolution better than a few % above 100 GeV, an angular resolution of 0.1 deg above 100 GeV, a wide field of view of around 1.8 sr, and a hadron rejection power larger than 10^5. This capability enables us to search for nearby cosmic-ray sources, dark matter, and survey the variable gamma-ray sky.**

***Keywords*: Cosmic-Ray Electron, Gamma Ray, Dark Matter**

I. Introduction

We are developing CALorimetric Electron Telescope (CALET) for all-sky electron and gamma-ray observations on the Japanese Experiment Module Exposure Facility (JEM-EF) of the International Space Station (ISS) [1]. The JEM-EF on the ISS gives us an excellent opportunity to carry out the high-energy electron and gamma-ray observation for a long exposure. The CALET can perform all sky electron and gamma-ray survey without attitude control of the instrument by using the ISS orbit [2].

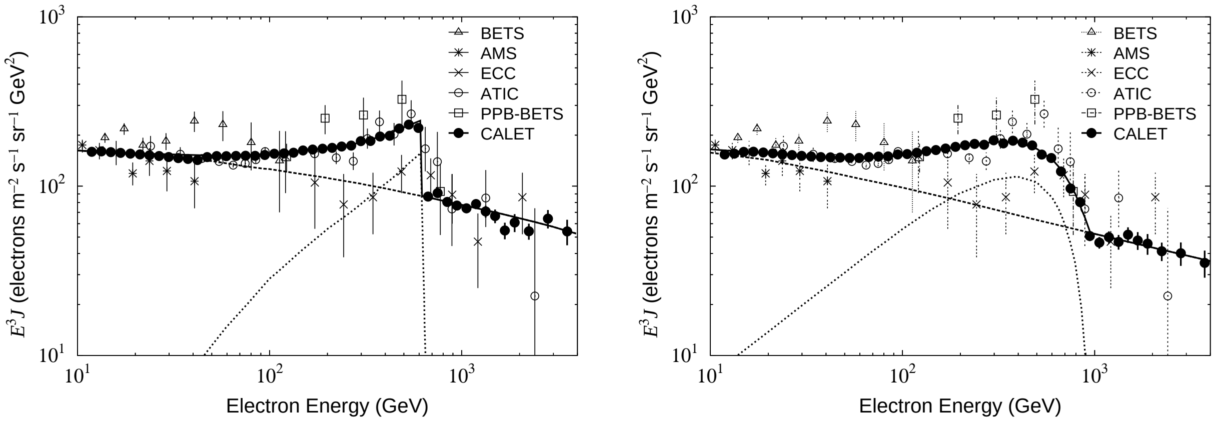
In this paper, we present scientific prospects of high-energy electron and gamma-ray observations with the CALET.

II. Electron Observations

Electrons in cosmic rays have unique features, complementary to all other cosmic-ray nucleonic components, because of their low mass and leptonic nature. High-energy electrons lose energy by synchrotron radiation in the Galactic magnetic field and inverse Compton scattering with the interstellar photons in the Galaxy. These processes, combined with the absence of hadronic interactions, simplify modeling of the propagation of electrons compared with other cosmic-ray components such as nucleons.

There are two possible sources of electrons and/or positrons in cosmic rays. One is primary sources of cosmic rays, and the other is the decay product of nuclear reactions of cosmic rays in the interstellar medium. Evidences for non-thermal X-ray emission from supernova remnants (SNRs) have indicated that high-energy electrons in the TeV region are accelerated in the remnants (e.g. [3]). These observations strongly suggest that cosmic-ray electrons are accelerated in SNRs and that SNRs are the most likely primary sources of cosmic-ray electrons. Kobayashi *et al.* [4] found that the observed electron spectra are understood by the SNRs scenario with an output energy of electrons of $1{\times}10^{48}$ erg and a supernova rate of $1/30$ yr in our Galaxy. They also predicted that nearby SNRs such as Vela could leave unique signatures in the form of identifiable structure in the energy spectrum of TeV region and show anisotropies toward the nearby SNRs. These scientific prospects with CALET are described in [5] in detail.

Besides such primary electrons, high-energy electrons and positrons are produced in the decay processes $\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$ of pions resulting from nuclear interactions of cosmic-ray nuclei with the interstellar medium. Although in such processes the number of positrons is almost equal to the electrons, the fraction of positrons is approximately 5 % of the electrons at energies of $1 - 10$ GeV region (e.g. [7]). Therefore, it has been believed that most electrons are originated from primary sources, in which they are accelerated, and that approximately 5 % of the electrons and possibly all positrons in cosmic rays are from nuclear interactions in the interstellar medium. The spectral power-law index of -2.7 for secondary electrons is the same as the index of the parent cosmic-ray protons and nuclei. The magnitude of this index is larger than that of primary electrons at the sources, that is $-2.1{\sim}-2.4$ (e.g. [4]). Hence, the positron fraction of $e^+/(e^- + e^+)$ should decrease with increasing energy as approximately $E^{2.4-2.7} = E^{-0.3}$.



(a) Annihilation into e^+e^- (b) Annihilation into $\mu^+\mu^- \rightarrow e^+e^-$

Fig. 1. Simulated $e^+ + e^-$ energy spectra with dark matter annihilations (dot line) and ordinary electron sources (dash line) for three years observation with CALET. (a) Dark matter annihilations into e^+e^- for a mass of 620 GeV and a boost factor of $2{\times}10^2$, which can reproduce the ATIC excess in the $e^+ + e^-$ spectrum [6]. (b) Dark matter annihilations into $\mu^+\mu^- \rightarrow e^+e^-$ for a mass of 1 TeV [11].

On the contrary, PAMELA [8] observed an increase in the positron fraction at energies above $\sim$10 GeV, which cannot be understood by standard models describing the secondary production of cosmic rays. The PAMELA positron data indicate the existence of primary positron sources such as the annihilation of dark matter particles in vicinity of our Galaxy, nearby pulsars, and nearby micro-quasars. ATIC also observed an excess of cosmic ray electrons (including positrons) at energies of 300 – 800 GeV [6]. The "bump" of the ATIC electron + positron spectrum indicates a nearby source of high-energy electrons and/or positrons such as dark matter, a nearby pulsar, and so on.

In order to explain the PAMELA and ATIC anomalies, the natures of possible sources have been widely discussed. The major candidates of these excesses are annihilating dark matter, decaying dark matter, and nearby pulsars.

A. Annihilating Dark Matter

Although the nature and origin of the dark matter are one of the most important unresolved problem in astrophysics, we do not know what the dark matter is made of. The most predominant candidates of dark matter are some weekly interacting massive particles (WIMPs). Among WIMPs, neutralino, χ, of the lightest stable supersymmetric (SUSY) particle and the lightest Kaluza-Klein particle (LKP) in models of universal extra dimensions are the most well motivated.

Although the direct annihilation to e^+e^- is suppressed for neutralino in supersymmetric theory, W^+W^- and $\mu^+\mu^-$ produced by the annihilation of neutralinos decay into e^+e^- [9]. As for the Kaluza-Klein dark matter in universal extra-dimensions, the direct annihilation of Kaluza-Klein gauge bosons into e^+e^- produces mono-energetic electrons and positrons [10] . In order to explain the observed excess flux by ATIC, dark matter annihilation scenarios require an annihilation cross section rate of $1{\times}10^{-23}$ cm^{3}s^{-1}, which corresponds to a boost factor of $2{\times}10^2$.

While propagating through the Galaxy, these annihilated electrons and positrons lose their energy, E, mainly via the synchrotron and inverse Compton processes. The energy-loss rate, dE/dt, is given by

$$\frac{dE}{dt} = -bE^2,\ b{\simeq}(1-2){\times}10^{-16}\mathrm{GeV}^{-1}\mathrm{s}^{-1}. \quad (1)$$

Therefore, the propagation of the mono-energetic electrons and positrons through the Galaxy modify their energy spectra to be a power-law with an index of -2.0 and a cut-off of the WIMP mass.

Figure 1 presents simulated $e^+ + e^-$ energy spectra with dark matter annihilations for 3 years observation with CALET. Figure 1a shows dark matter annihilations into e^+e^- for a mass of 620 GeV and a boost factor of $2{\times}10^2$, which can reproduce the ATIC excess in the $e^+ + e^-$ spectrum [6]. Figure 1b shows dark matter annihilations into $\mu^+\mu^- \rightarrow e^+e^-$ for a mass of 1 TeV [11]. As shown in Fig. 1, CALET has a capability to distinguish between the direct annihilation into $e^+ + e^-$ and decay of the annihilation products such as $\mu^+\mu^- \rightarrow e^+e^-$.

B. Decaying Dark Matter

In addition to the annihilation of WIMP dark matter, there are another scenario that a hidden gauge boson constitutes dark matter of the Universe and decays into the standard model particles [12]. Chen *et al.* (2008) [12] introduce an extra dimension with two branes at the boundaries. Suppose that the hidden gauge sector is on one brane and the standard model particles are on the other brane, which are well separated from each other so that direct interactions between the two sectors are exponentially suppressed. In their scenario, although antiprotons are suppressed, being consistent with the BESS experiments, e^+e^- are directly produced by the decay of dark matter with the life time of $O(10^{26})$ sec, in which the energies of e^+e^- are a half of the WIMP mass. In particular, the decaying dark matter scenario can easily explain the observed excesses regardless of boost factors, adjusting the life time of dark matter. Since these e^+e^-'s from decaying dark matter show the same spectral feature as the direct annihilation, CALET also has a capability to detect these electrons from decaying dark matter.

C. Nearby Pulsar

In addition to scenarios of annihilating dark matter and decaying dark matter, nearby pulsars are also discussed to explain the excess in the positron fraction with PAMELA and the bump in the electron + positron spectrum with ATIC. In order to explain these excesses, nearby pulsars such as B0355+54 (1.1 kpc, 5.6×10^5 yr) [13] and B0656+14 (0.29 kpc, 1.1×10^5 yr) [14] are suggested as the candidates. Since these nearby pulsars are expected to show electron anisotropy of

$$\delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \simeq 1\%$$

above 100 GeV, CALET has a capability to detect these anisotropies with 3σ levels for three year observations. Thus, CALET can make a discrimination of the origin of the electron excess between WIMP dark matter and nearby pulsars.

III. Gamma-Ray Observations

The survey of the variable gamma-ray sky with CALET enable us to study the high-energy universe up to higher energies and with a better energy resolution than Fermi Large Area Telescope (LAT) [15]. Figure 2 presents the expected point source sensitivity of CALET, compared to the other experiments. For air Cherenkov telescopes on the ground, the sensitivities are derived for a 50 hour exposure on a single source. For CALET, EGRET, AGILE, and Fermi, the sensitivities are shown for one year of all sky survey. It is possible for the CALET to observe time variability of gamma-ray sources with the intensity of a few Crab on a time scale of about one hour.

The scenarios of annihilating dark matter, decaying dark matter and nearby pulsars, which are described in the previous section, are predicted to produce the different Galactic diffuse gamma-ray spectra due to the inverse Compton radiation by the electrons and/or positrons. For the Galactic diffuse gamma rays, the annihilating dark matter shows obvious excess beyond the ordinary background radiation above $\sim$10 GeV, the decaying dark matter shows the intermediate excess, and nearby pulsars show the little excess [16]. In addition to electron observations, since CALET can also observe gamma rays, CALET has a possibility to make a discrimination between these scenarios. Figure 3 presents

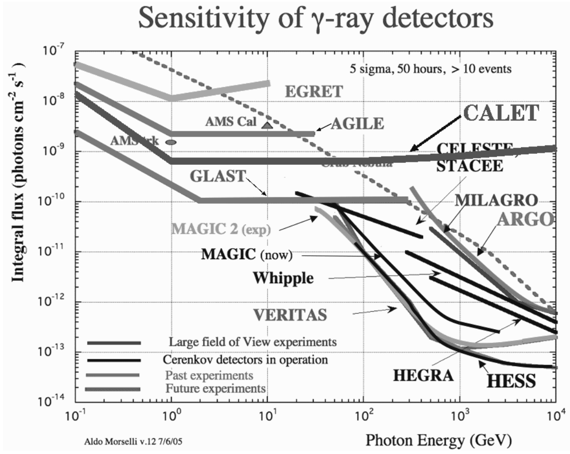


Fig. 2. Gamma-ray point source sensitivity of CALET, compared to the other instruments.

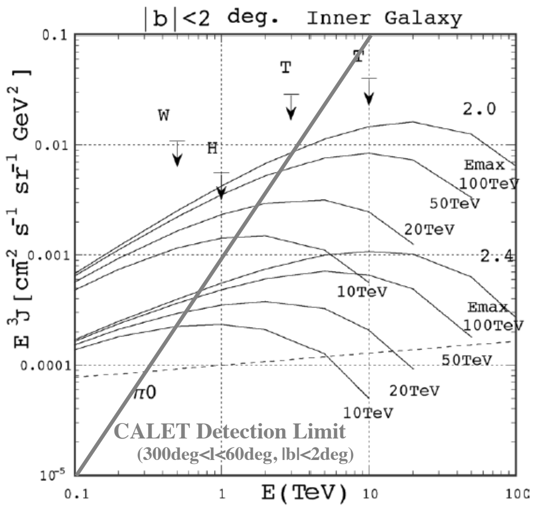


Fig. 3. The CALET detection limit of Galactic diffuse gamma rays above 0.1 TeV for 4 years, compared with the calculated energy spectra [17].

the CALET detection limit of Galactic diffuse gamma rays for 4 years.

There are many calculations of gamma-ray signals from WIMP dark matter annihilations. Figure 4 shows an example of the simulated energy spectrum of a gamma-ray line at 820 GeV from neutralino annihilation [18] for the three years observation, assuming Moore halo profile [19] without clumpy structures, that is a boost factor of 1. As shown in Fig. 4, CALET has a capability to detect a monochromatic gamma-ray signal from dark matter annihilations in the several 10 GeV – 1 TeV region with an excellent energy resolution better than 2 – 3 % above 100 GeV.

The decaying dark matter will also produce continuous gamma rays, which are mainly produced by neutral pions generated in the QCD hadronization process and the decay of τ. Figure 5 shows the simulated energy spectrum of the extra-galactic diffuse gamma rays from decaying dark matter with a mass of 1.2 TeV and a

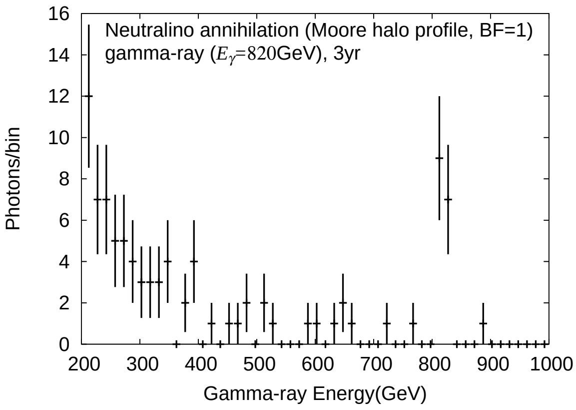


Fig. 4. Simulated energy spectrum of a gamma-ray line at 820 GeV from neutralino annihilation toward the Galactic center including the Galactic diffuse background for 3 years observation with CALET, assuming Moore halo profile with a boost factor of 1.

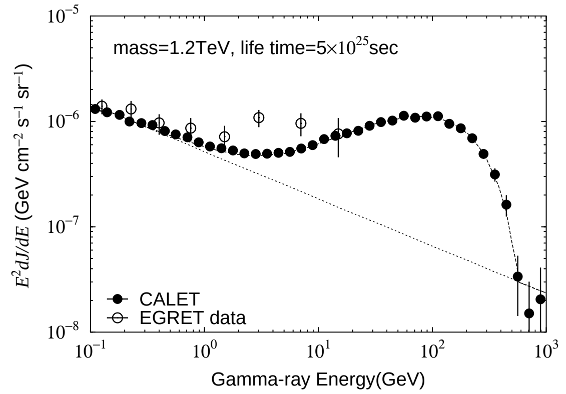


Fig. 5. Simulated energy spectrum of the extra-galactic diffuse gamma rays from decaying dark matter with a mass of 1.2 TeV and a life time of 5×10^{25} sec for 3 years observation with CALET [12]. The power-law line shows an ordinary background spectrum.

life time of 5×10^{25} sec. Since CALET has a capability of observing up to higher energy than Fermi LAT, it is possible to determine a mass of dark matter as shown in Fig. 5.

IV. SUMMARY AND DISCUSSION

Recent high energy positron observations up to 100 GeV by the PAMELA satellite experiment clearly show the significant deviation from predictions of secondary production models [8]. As for the electron observations, the observations with ATIC indicate a spectral structure in the several 100 GeV region. The excess in the electron + positron flux as well as the PAMELA anomaly in the positron fraction may be simultaneously explained by some WIMP dark matter scenarios.

Following PAMELA [8], ATIC [6], and PPB-BETS [20], Fermi LAT observed cosmic-ray electrons + positrons from 20 GeV to 1 TeV [21], and H.E.S.S. also observed cosmic-ray electrons + positrons from 340 GeV to 5 TeV [22]. The electron spectrum observed with Fermi LAT does not exhibit prominent spectral features, and seems to be inconsistent with the ATIC electron spectrum. In order to verify the electron spectrum, we need an instrument with a large hadron rejection power of 10^5, accurate measurements of electron energies, and accurate determination of the geometrical factor. CALET is suitable for the above requirements: a large hadron rejection power of $> 1\times10^5$, an excellent energy resolution of a few % above 100 GeV with a wide energy range of 1 GeV to 20 TeV for electrons and 20 MeV to 10 TeV for gamma rays, and a simple detector configuration. In the near future, CALET will open a new phase in the study of high-energy cosmic ray electrons and variable gamma-ray sky.

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