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The science objectives for CALET

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Abstract: The CALorimetric Electron Telescope, CALET, is a new all-sky electron and gamma ray observatory to be installed on the standard external payload port of the Japanese Experiment Module Exposure Facility (JEM-EF) of the International Space Station (ISS). The high precision measurements of the electron energy spectrum and the particle arrival directions (10 GeV – 20 TeV) enable CALET to detect distinctive features from nearby cosmic-ray electron sources and WIMP dark matter annihilation or decay. The electron observations in the 1 GeV – 10 GeV region also allow solar modulation investigations. The outstanding energy resolution, better than $\sim$2 % above 100 GeV, is ideal to detect gamma-ray lines and/or spectral signatures from WIMP dark matter through galactic and extra-galactic diffuse gamma-ray observations in the 10 GeV – 10 TeV region. Gamma-ray sources such as SNRs, AGNs, GRBs, and so on are also objectives for CALET to investigate high-energy phenomena. The cosmic-ray spectra of proton, helium, and heavier nuclei up to iron can be measured in the energy range from several 10 GeV to 1000 TeV. In particular, the measurements of the B/C-ratio above 100 GeV will enable CALET to limit cosmic-ray propagation mechanisms. In this paper, we present the scientific prospects of CALET to investigate the origin, acceleration and propagation mechanisms of cosmic rays and conduct a dark matter search.

Keywords: Cosmic-ray electrons, Gamma rays, Nuclei, Cosmic-ray origin, Dark matter

1 Introduction

The most important scientific objectives in cosmic-ray physics are to make clear the origin, the acceleration mechanisms, and the propagation properties of cosmic rays. The nature and origin of the dark matter is also one of the most important unresolved problems in astrophysics. Although we have many observational evidences for the existence of the dark matter, we do not know what the dark matter is made of. In order to investigate these objectives, 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].

2 Electron observations

Electrons in cosmic rays have unique features, complementary to the nuclear components, because of their low mass and leptonic nature. High-energy electrons lose energy via synchrotron and inverse Compton processes during propagation in the Galaxy. Since the energy loss rates almost increase directly with the square of the electron energy, higher energy electrons lose their energy more rapidly. These radiative processes, combined with the absence of hadronic interactions, simplify modeling of the propagation of electrons compared to the other cosmic-ray components such as nucleons.

2.1 Identification of cosmic-ray sources

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. The current observed electron spectra can be explained by the SNRs scenario with an output energy of electrons of $\sim 1\times 10^{48}$ erg and a supernova rate of $\sim 1/30$ yr^{-1} in our Galaxy (e.g. [2]). These results suggest that SNRs are the most likely primary sources of cosmic-ray electrons.

Because of the electron energy losses as described above, TeV electrons lose most of their energy on a time scale of 10^5 yr, and their propagation distances are therefore limited to $\sim$1 kpc. Since the number of such candidates of the astrophysical sources is very limited, the TeV electrons should exhibit spectral structures and very likely anisotropy. Kobayashi et al. (2004) pointed out that some nearby SNRs, such as Vela, Cygnus Loop, or Monogem, could leave unique signatures in the form of the identifiable structure in the energy spectrum and show anisotropies toward the nearby SNRs [2].

In the case of one of their calculations, a diffusion coefficient of $D_0 = 2 \times 10^{29}$cm^2/s at 1 TeV, a cut-off energy of E_c=20 TeV for the electron source spectrum, and the burst-like release at $\tau = 5\times10^3$ yr after the supernova explosion, we calculated the simulated electron energy spectrum with CALET, as shown in Fig. 1. Figure 1 presents that CALET has a capability to identify the unique signature from nearby SNRs, especially originating from the Vela SNR, in the energy spectrum with high statistical precision. Table 1 shows the expected number of electrons for the 5 years observations.

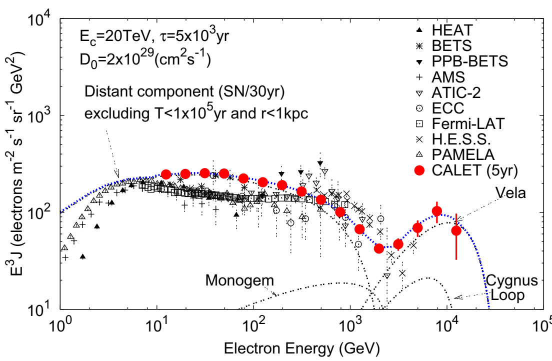

Figure 1: Simulated electron energy spectrum of the CALET for 5 years observations from a SNR scenario model [2], compared to the previous electron (+ positron) spectra [4, 5, 6, 7, 8, and references therein].

Table 1: The expected number of electrons (5yr).

Energy	>10 GeV	>100 GeV	>1 TeV
The number of electrons	$\sim2.5\times10^7$	$\sim2.0\times10^5$	$\sim1.0\times10^3$

In addition to the electron spectrum, we calculated the expected electron intensity distribution along the Galactic longitude by using the calculated results by Kobayashi *et al.* (2004) [2]. Figure 2 shows the electron intensity distribution along the Galactic longitude in the case of a diffusion coefficient of $D_0 = 4\times10^{29}$cm^2/s at 1 TeV and a cut-off energy of $E_c = \infty$ for the prompt release after the explosion ($\tau = 0$). The maximum intensity is in the direction of the Vela SNR at $(\ell, b) = (263^\circ.9, -3^\circ.3)$. As shown in Fig. 2, CALET has a capability to detect the anisotropy toward the Vela SNR.

2.2 Dark matter search

Recent electron and positron observations by PAMELA [3, 4], ATIC [5], PPB-BETS [6], H.E.S.S. [7], and Fermi-LAT [8] have indicated electron and positron excesses in their spectra. In order to explain the excesses, the natures of possible sources have been widely discussed (e.g. [9, 10]). Figure 3 presents a simulated electron + positron spectrum by CALET observations for 2 years with Kaluza-Klein dark matter annihilations [9] for 620GeV mass and the boost factor of 40, which is much lower than the estimation of the ATIC. As shown in Fig. 3, the CALET has a potential to detect the excess from dark matter annihilation in the energy spectrum.

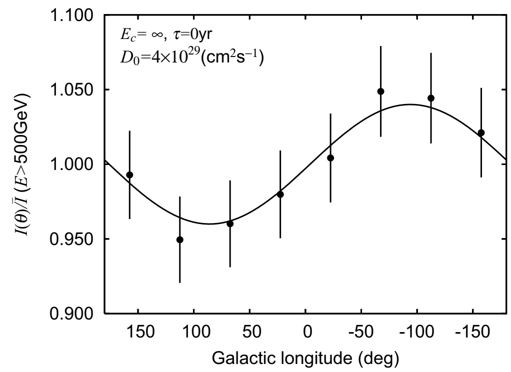

Figure 2: Electron intensity distribution along the Galactic longitude with the simulated distribution of CALET for 5 years observations.

Dark matter particles might be unstable and decay with a lifetime much longer than the age of the universe (e.g. [10]). The observed excesses in electron and positron spectra can be explained by electrons and positrons which are produced from decaying dark matter particles with the life time of $O(10^{26})$ s. Figure 4 presents the expected energy spectrum of electrons + positrons from the decaying dark matter [10].

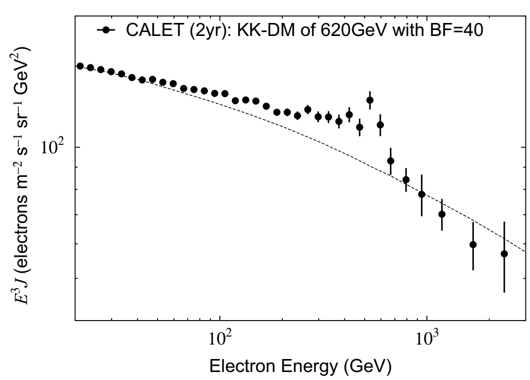

Figure 3: Simulated energy spectrum of $e^- + e^+$ from Kaluza-Klein dark matter annihilation with a 620 GeV mass and a boost factor of 40 for 2 years observations with CALET [9].

3 Gamma ray observations

3.1 All-sky gamma ray survey

The ISS is in orbit of an inclination angle of 51.6°, changing longitudes of ascending node at the rate of -5.0° per day by the precession. The line of sight of the CALET detector is in the opposite direction of the earth. In the

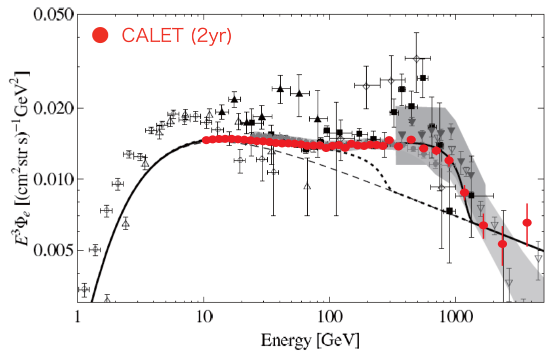

Figure 4: Simulated energy spectrum of $e^- + e^+$ from decaying dark matter for a decay channel of $D.M. \rightarrow \ell^+\ell^-\nu$ with the mass of 2.5 TeV and the decay time of 2.1×10^{26} s for 2 years observations with CALET [10].

ISS orbit, the CALET can survey the sky almost uniformly without attitude control of the instrument. The survey of the variable gamma-ray sky with CALET enables us to study the high-energy universe up to higher energies and with a better energy resolution than Fermi-LAT [11]. Figure 5 shows the simplified sky map simulation of gamma rays above 10 GeV with CALET for 3 years observations. In addition to the diffuse gamma rays, one can see some gamma-ray point sources detectable with CALET.

The CALET can observe gamma-ray energy spectra in the TeV region for the Galactic and extra-galactic diffuse components. Although Fermi-LAT reports the gamma-ray spectra up to 300 GeV, CALET has a capability to observe extra-galactic gamma rays up to several TeV, as shown in Fig. 6.

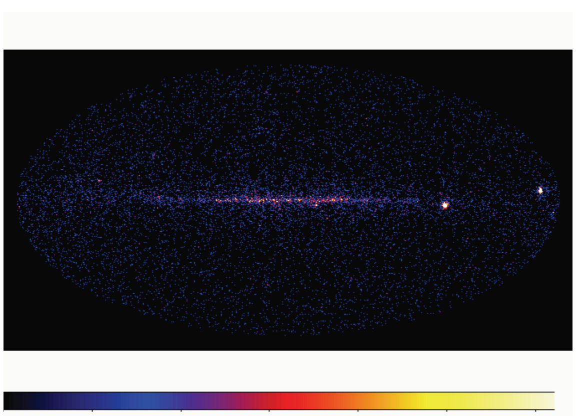

Figure 5: Simulated sky map of gamma rays above 10 GeV with CALET for 3 years observations.

3.2 Dark matter search

There are many calculations of gamma-ray signals from WIMP dark matter annihilations or decays. In addition to the gamma rays produced directly from dark matter, there are gamma rays from inverse Compton scattering of $e^- + e^+$ from dark matter with inter-stellar and inter-galactic photons. Figure 6 presents the expected extra-galactic gamma ray spectrum from decaying dark matter, including inverse Compton scattering gamma rays (lower-energy components) and an isotropic extra-galactic background (a power-law spectrum), with the same parameters as Fig. 4 [10].

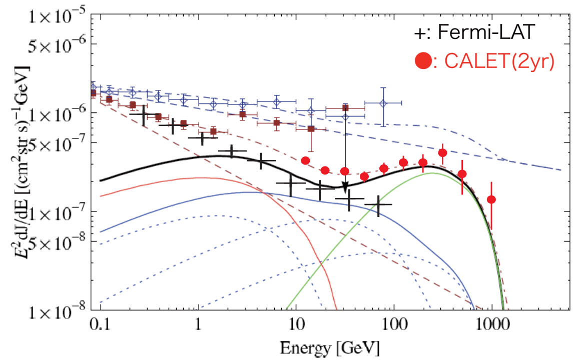

Figure 6: Simulated energy spectrum of the extra-galactic diffuse gamma rays from decaying dark matter, including inverse Compton scattering gamma-ray spectra and an isotropic extra-galactic background, with the same parameters as Fig. 4 [10].

Figure 7 shows an example of the simulated energy spectrum of monochromatic gamma rays of 820 GeV from neutralino annihilation, assuming a Moore halo profile with a boost factor of 5 [12]. Since CALET has the outstanding energy resolution of ~2 %, CALET is an ideal detector to observe monochromatic gamma rays from dark matter annihilations in the several 10GeV - several TeV region, as shown in Fig. 7.

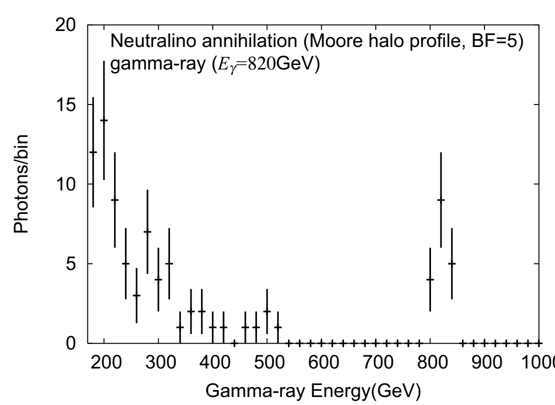

Figure 7: Simulated energy spectrum of a gamma-ray line at 820 GeV from neutralino annihilation toward the Galactic center including the Galactic diffuse background for 2 years observations with CALET, assuming a Moore halo profile with a boost factor of 5.

4 Nuclear components observations

4.1 Energy spectra of nuclear components

The energy spectra of nuclear components in proximity of the knee region is very important to resolve the problems of the acceleration limit and the propagation of cosmic rays (e.g. [13, 14]). In contrast with the RUNJOB data [13], the CREAM data [15] indicate hardening of the nuclear spectra above ∼200 GeV/nucleon and a spectral difference between protons and helium nuclei, in which the helium spectrum agrees well with the spectra of heavier nuclei from carbon to iron. Their data indicate a contradict of the traditional view that a simple power law can represent cosmic rays without deviations below the knee at $\sim 10^{15}$ eV.

The energy spectra of protons and helium, which are expected to be observed with CALET, are shown in Fig. 8. A single power law is assumed for the estimation with a power-law index of -2.70 for both protons and helium. This result suggests that we can confirm the spectral hardening of the energy spectra for nuclear components above ∼200 GeV/nucleon and the spectrum changing due to the acceleration limit predicted around the knee region.

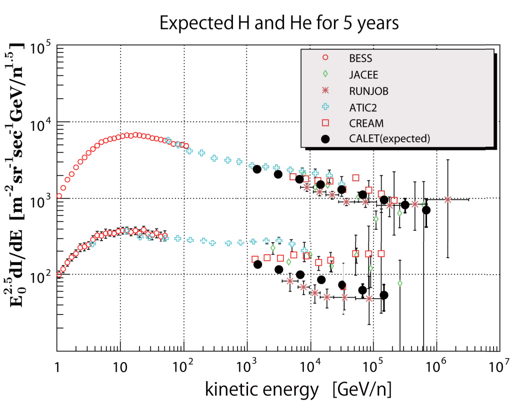

Figure 8: Expected proton and helium spectra for 5 years observations with CALET, compared to the observed data [13, 14, and references therein].

4.2 Secondary/primary ratio

The energy dependence of the ratio of secondary nuclei relative to primaries is important for understanding the propagation mechanism of cosmic rays. In particular, although observations in the high-energy region above 100 GeV/nucleon are important to check the difference between some propagation models, there are scarcely data with enough statistics [15]. We estimated the expected ratio of boron to carbon (B/C) with CALET, assuming a diffusion coefficient with an energy dependence of E^{δ}, where $\delta = 0.45$. This result suggests that we can put severe restriction on the current propagation models.

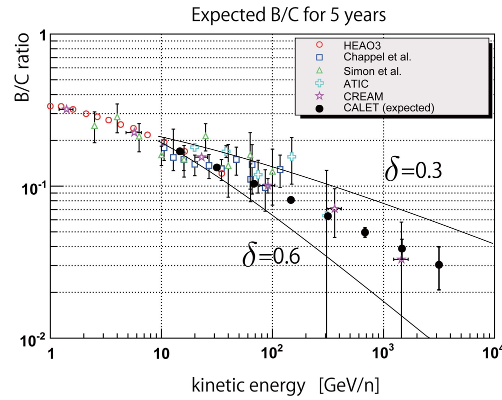

Figure 9: Expected B/C ratio for 5 years observations with CALET, compared to the observed data [13, 15, and references therein].

5 Summary

In this paper, we provided an overview of the CALET's capabilities to investigate the origin, acceleration mechanisms and propagation properties, and conduct a dark matter search by the observations of electrons, gamma rays, and nuclear components. In addition, solar modulation investigations are allowed by the 1 GeV – 10 GeV electron observations, and GRBs are also an interesting objective for the CALET gamma-ray observations. CALET will be installed on the JEM-EF of the ISS in 2013 and open a new phase in the study of high-energy astrophysics and cosmic ray physics.

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