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CALET measurements of cosmic ray electrons in the heliosphere

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Abstract: We have proposed the CALET(CALorimetric Electron Telescope) mission to observe galactic electrons and gamma rays at the Japanese Experiment Module(JEM) on ISS, and CALET has been approved for the phase A/B studies by JAXA. In this paper we present the measurements of long-term and short-term variations of electron intensities in the heliosphere. Galactic electrons of 1-100 GeV energy range mostly have negative charges and the spectrum largely varies with solar activities. Thus we expect the knowledge of the diffusion coefficient of electrons, especially its energy dependence, and of the effectiveness of propagation models or the charge sign dependence of modulation. We also expect Forbush decreases in electron flux, since the large geometric factor for CALET can compensate for the low intensity of electrons. The ISS orbit severely restricts lower energy measurements, and we have to estimate in detail the variation of geomagnetic cutoff rigidity.

Introduction

Scientific objectives for CALET mission above 100 GeV are to explore the electron sources near the solar system and to search for dark matter signatures through electron and gamma-ray measurements[1][2]. On the other hand, in the lower energy below 100 GeV, we investigate the propagation of charged particles in the heliosphere and will study interplanetary shocks and coronal mass ejections responsible for Forbush decreases.

The long-term measurements of electrons to date have been limited below several GeV and have shown largely modulated intensities of electrons by solar activity. Meanwhile, the influences above several GeV have not yet been measured. For these investigations, we have proposed the electron long-term observation for several years using the CALET instrument, which has a large geometric factor and makes it possible to measure the electron intensity over a wide range of 1-100 GeV energies. In this paper, we discuss predictions of propagation models for electrons and Forbush decrease events for the CALET measurements.

Electron propagation in the heliosphere

Cosmic rays diffuse in the solar magnetic field and are convected by solar wind in the heliosphere. The results of electron experiments on ISEE3/ICE spacecraft[3] and on Ulysses[4] have shown that the intensity of a few GeV electrons varies largely between solar maximum and minimum period.

The simple diffusion-convection model with a spherical symmetric geometry, called the Force-Field(FF) approximation[5], has been widely used for interpretation of modulated spectra $J(r, E)$ with energy E and the distance r from the sun. FF approximation represents the magnitude of solar modulation by potential energy Φ MeV, which is generally used for estimate of the interstellar spec-

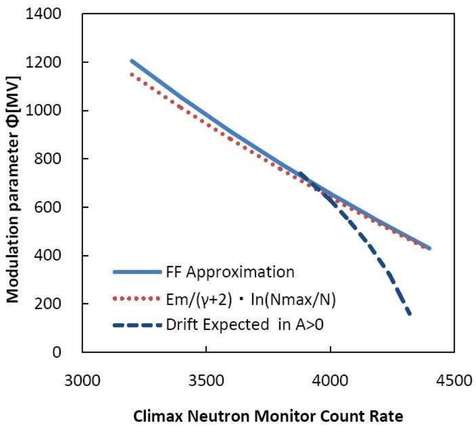

Figure 1: Relationship between modulation parameter Φ and Climax neutron monitor count rate N. FF approximation curve and a curve expected from drift model are shown.

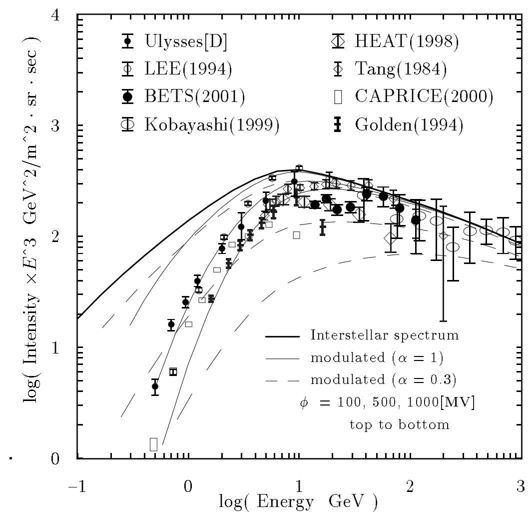

Figure 2: Modulated electron spectrum expected from FF approximation with modulation parameter 100, 500, 1000 MV, if the diffusion coefficient has the energy dependence with $\alpha = 0.3$, 1.

trum $J(\infty, E)$ from data of primary cosmic-ray experiments.

We investigated the relationship between the parameter Φ and the neutron monitor(NM) count rate N, and found a specific relationship between them at a response energy E_m[6]. If the local interstellar spectrum of protons with rest energy m is expressed as a power law of momentum energy p, $J(\infty, E) = J_0 p^{-\gamma}$, the relationship is represented by

$$\Phi = \{p^2 \cdot (\frac{J(\infty, E)}{J(r, E)})^{2/(\gamma+2)} + m^2\}^{1/2} - E \quad (1)$$

$$\sim \frac{E_m}{\gamma + 2} \cdot \ln(\frac{N_{max}}{N}), \quad E > \Phi \,, \quad (2)$$

in which the count rate ratio N_{max}/N is substituted for $J(\infty, E)/J(r, E)$ at the energy $p = E_m$. N_{max} is the count rate parameter corresponding to the interstellar spectrum, that is not affected by solar activity. Approximate expression eq.(2) is shown in Figure 1 and in good agreement with a curve of eq.(1). If the proton spectral index is $\gamma = 2.70 \pm 0.05$ and $E_m = 11$ GeV (Climax NM), the slope becomes

$$-E_m/(\gamma + 2)/N \sim -2300/N,$$

and has the value of $-(0.5 \sim 0.7)$ in the range of $N = 4400 \sim 3500$. The slope has an error of several percent caused by E_m variation and uncertainty. It is important to realize that the slope of Φ–N curve does not include an ambiguous parameter, N_{max}.

CALET does not distinguish the charges of electrons, however electrons are mostly negative, while NM rate is approximately proportional to the proton flux at the response energy E_m. Thus we consider Φ–N relationship, especially its slope, which shows the difference between the charge dependent model(drift model) and the independent model(FF Approximation). Figure 1 shows the Φ–N curves expected from both cases: FF Approximation and drift model[7]. If the drift dominates in the 2010s A>0 period, electron flux, namely Φ, changes largely and N little changes, so that the slope of Φ–N curve becomes steeper with increasing N as shown in Figure 1. The CALET long-term observation will give a lot of (N, Φ) data at various energies, and the obtained slope of Φ–N curve will give verification of propagation models.

Galactic electrons diffuse in the solar magnetic field, and the diffusion coefficient is considered to be smaller than that in the interstellar space by several orders of magnitude. In the FF approximation the diffusion coefficient is separated into two parts as $D \propto D_1(r,t)D_2(E,t)$. We will investigate the energy dependent term $D_2(E,t) = (E/1\ \mathrm{GeV})^\alpha$, namely its spectral index α. The modulated electron spectrum is calculated and shown in Figure 2 with $\alpha = 0.3,\ 1.0$. Figure 2 shows that if the value of α is smaller, the spectrum is more influenced in higher energy region. The observed data below 10 GeV seem to be good agreement with a curve having the index of $\alpha = 1$.

Forbush decreases

Galactic cosmic ray decreases following a coronal mass ejection(CME), called Forbush decreases(Fds), generally have a two-step decrease through the passage of forward shock and ejecta[8]. Some Fds, however, are not accompanied by the shock or ejecta, therefore Fds are various and complex events.

The number of Fds confirmed by both Izmiran NM located at 55°N and Climax NM at 40°N in the period of 2000 to 2004 is ∼5 events(>4%)/year (7–10 events in the solar maximum period)[9][10], so that more than several Fds are expected in the CALET experiment. Fds in negative particle flux might be different from Fds observed by neutron monitors. We will investigate the difference between them. It also seems to be valuable for estimation of the background intensity of anti-proton measurements below 10 GeV.

Galactic electron intensity is very low and, in addition, is limited by the geomagnetic rigidity cutoff determined from the ISS orbit. However, the CALET has a large geometric factor and a part of whole exposure time is enough to measure Fds as shown in the next section.

Measurement of electron intensity below 10 GeV

The ISS orbit with an inclination of 51.6° severely restrict low energy measurements of electrons below 10 GeV. However, we can measure them at the highest latitude for several minutes. Figure 3 shows the variation of vertical geomagnetic cutoff rigidity with geographic longitude at the latitude ± 50°. In Figure 3 two kinds of geomagnetic field model are shown: the central dipole approximation[13] and more realistic Tsyganenko model with International Geomagnetic Reference Field for 1995 calculated in both quiet and active times[11][12]. Figure 3 shows that curves in quiet times roughly agree with the dipole approximation. We consider, therefore, dipole approximation gives the upper limit, and a cutoff energy remains below 6 GeV.

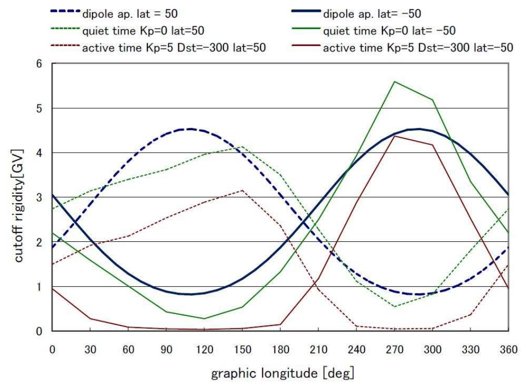

Figure 3: Longitudinal variation of vertical cutoff rigidity. Latitude: 50°N and 50°S; altitude: 400 km; Employed models are Dipole approximation and Tsyganenko model with International Geomagnetic Reference Field for 1995[11][12].

Figure 4 shows variation of the geomagnetic cutoff rigidity every 46 min measurement at latitude 50°N and 50°S. Marked points represent alternately 50°N and 50°S measurement, where we use the dipole approximation of geomagnetic field. If we observe GeV electrons within the zenith angle 30°, the cutoff energy successively changes between 1 and 5 GeV.

The influence of geomagnetic cutoff to electron measurement causes the decrease of observed electron flux. Even if the measurement is performed at highest latitude for several minutes, we can only obtain several 10% electrons in the range of 2–4 GeV and all events are obtained above 6 GeV. However, we get sufficient data in the accumulated observation time. If the exposure factor is 40 $\mathrm{m^2 sr \cdot min}$ and the modulation parameter is $\Phi = 500 - 1000$ MV, the observed number of electrons is estimated as ~ 17000 in the energy range of 2–12 GeV. We divide this region into three energy ranges, and can obtain the intensity at three energies with a statistical error of 1–2% per day.

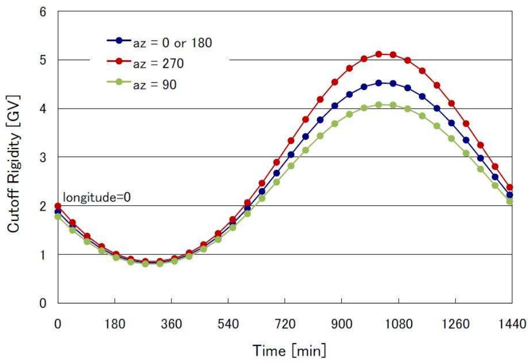

Figure 4: Time variation of cutoff rigidity when the ISS passes through the highest latitude 50°N and 50°S every 46 minutes at the altitude 400 km. ”az” means azimuth angle of incoming electrons within the zenith angle, 30°. The cutoff is higher from the west direction, 270°, for electrons.

On the other hand, for Fd observation, successive measurements are required. Five minutes measurement of 2–12 GeV electrons will be performed alternately at 50°N and 50°S. We will get 2000 events in each measurement, and the total number of electrons observed in the northern and the southern hemisphere will be enough to get a statistical error within 2%.

Summary

The CALET measurements of lower energy electrons($<$10 GeV) will be performed in a restricted time period, because numerous background protons in this energy range have to be eliminated. CALET, however, has a large geometric factor to observe electrons, and can give sufficient statistical data in GeV energies. As a result, we expect new information of electron propagation in the heliosphere. We consider the correlation between electron intensity variation and neutron monitor count rate is useful to distinguish differences of the propagation models.

The Forbush decreases are also expected in successive measurements of electron flux , though it is severely restricted by geomagnetic cutoff rigidity. At the highest altitude of the ISS orbit, the cutoff energy changes in the range of 1–5 GeV. We will measure the flux at this altitude. Ten minutes observation will results in the intensity with a statistical error within 2%.

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