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CALET Measurements of Cosmic Ray Electrons in the Heliosphere

Yoshiko KOMORI[1]*, Shoji TORII[2], Yuki SHIMIZU[2] Tadahisa TAMURA[3], Kenji YOSHIDA[4], Toshio TERASAWA[5], and Kazuoki MUNAKATA[6]

[1]*Kanagawa University of Human Services, Yokosuka, Kanagawa 238-8522, Japan*
[2]*Research Institute for Science and Engineering, Waseda Univ., Tokyo, Japan*
[3]*Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan*
[4]*Department of EIS, Shibaura Institute of Technology, Saitama, Japan*
[5]*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
[6]*Department of Physics, Shinshu University, Matsumoto, Nagano, Japan*

The CALorimetric Electron Telescope (CALET) mission has been proposed to measure electrons and gamma rays in a wide energy range on the Japanese Experiment Module (JEM) /International Space Station (ISS) and approved for the phase A study by the Japan Aerospace Exploration Agency (JAXA). In this paper we present the purposes of the CALET mission pertaining to solar physics and expected results from measurements of electrons in the 1–100GeV energy range. Cosmic rays in this energy region are largely modulated by solar activity and their intensity has both long-term and short-term variations. Measuring such variations precisely will give new information about the transport of cosmic rays in the heliosphere. We estimate the energy dependence of the diffusion of cosmic rays through the solar magnetic field and verify some transport models. Electrons in this energy range are mostly negative though CALET does not distinguish the sign of charges directly. We therefore investigate the charge sign dependence of variations using a correlation between the electron intensity and the neutron monitor counting rate, which indicates the variation of proton intensity. We also expect to detect Forbush decreases in the electron flux. In such decreases, short-term variations of negative charges might differ from those of positive ones.

KEYWORDS: cosmic ray, electron, solar modulation, Forbush decrease, ISS, JEM

1. Introduction

The scientific objectives for the CALET mission above 100 GeV are to explore electron sources near the solar system and to search for dark matter signatures through electron and gamma-ray measurements.[1)] In the lower energy region, below 100 GeV, we measure both the long-term and short-term variations of electron intensity caused by solar activity. The intensity variations of Galactic cosmic rays (GCR) in the heliosphere give information about the solar magnetic field, shocks, coronal mass ejections, etc.

Long-term measurements of electron intensity below several GeV have been performed in both spacecraft (e.g.[2)3)]) and balloon experiments (e.g.[4)]), showing large modulations of electron intensity by solar activity. However, such influences above several GeV have not yet been measured, and we have proposed long-term measurements of this in the CALET mission. For the past forty years, various electron experiments in the 10–100 GeV energy range have been performed using balloons. However, the spectra observed from such experiments exhibit various differences. One purpose of the CALET mission will be to estimate the influence of solar modulation in this energy region, and to find the cause of these differences.

Prior measurements of the positron/electron ratio[5)] suggest a charge sign dependence of solar modulation, and the drift dominated modulation model[6)] has been presented to explain the difference in the transport of positively and negatively charged cosmic rays. Although CALET does not distinguish the charges, we can confirm the charge sign dependence of solar modulation using a correlation between the electron intensity and neutron monitor data. In addition, we expect to be able to measure the Forbush decreases in the short-term variation events, which may show evidence of a charge sign dependence.

CALET will also have a large geometric factor that makes it possible to continuously and precisely measure electron intensities. On the other hand, it is necessary to estimate the variation of geomagnetic cutoff rigidity, as ISS orbits severely restrict low energy measurements.

2. GCR Electron Transport in the Heliosphere

2.1 Diffusion Process of GCR Electrons

Galactic electrons diffuse in the solar magnetic field, and are convected by the solar wind in the heliosphere. The diffusion coefficient is considered to be smaller than that in the interstellar space by several orders of magnitude, so that the latter can be neglected in solar physics. The simple diffusion-convection model with a spherically symmetric geometry is called the Force-Field (FF) approximation[7)] and represents the magnitude of solar modulation by the potential energy Φ MeV, which is widely used for interpretation of modulated spectra in primary cosmic ray measurements.

In the FF approximation the differential intensity $J(r, E, t)$ of GCR with total energy E and the rest energy

*E-mail: komori-y@kuhs.ac.jp

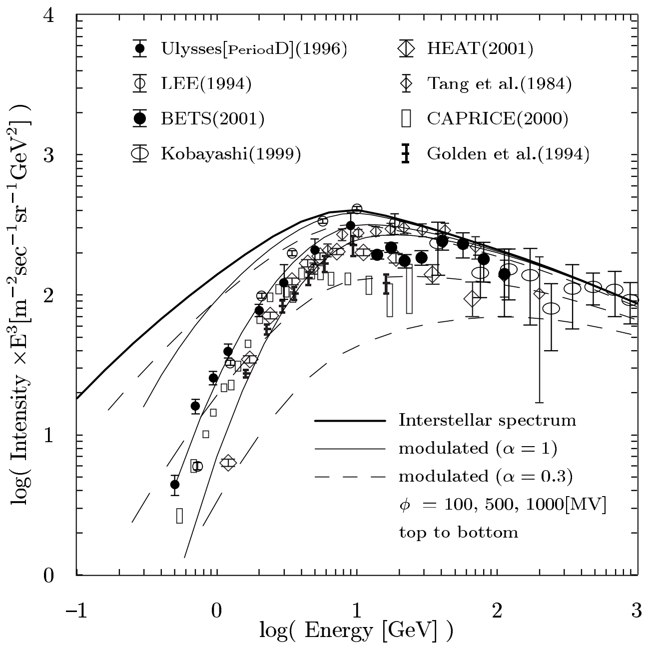

Fig. 1. Modulated electron spectra expected from FF approximation with the modulation parameter 100, 500, 1000 MV, in the case of the energy index of the diffusion coefficient, α = 0.3, 1. Experimental results[3)4)8)9)10)11)12)13)] are shown together.

m is given by:

$$\frac{J(r,E,t)}{E^2-m^2} = \frac{J(\infty,E+\Phi)}{(E+\Phi)^2-m^2}\ , \qquad (1)$$

at the distance r from the sun, and at the time t. $J(\infty, E)$ represents the interstellar spectrum and the modulation function Φ is calculated from the definition $\Phi(r,E,t) = \psi(\zeta+\phi,t) - \psi(\zeta,t)$: ψ is the inverse function of ζ, in which the functions ζ and ϕ are given by:

$$\begin{aligned}\zeta(E,t) &= \int_m^E \frac{D_2(E',t)}{(E'^2-m^2)^{1/2}}dE' \\ \phi(r,t) &= \int_r^{r_b} \frac{V(r',t)}{3D_1(r',t)}dr'\ .\end{aligned}$$

These formulas include the solar wind velocity V, the boundary of the heliosphere r_b and the diffusion coefficient $D = D_1(r,t)D_2(E,t)$ of GCR.

In the CALET observations the energy dependent term $D_2(E,t) = (E/1\ \mathrm{GeV})^\alpha$, and especially its spectral index α will be estimated from precise measurements of variations of spectral shapes in the 1–100 GeV energy range. The modulated electron spectrum is calculated and shown in Fig. 1 with $\alpha = 0.3,\ 1.0$. Fig. 1 shows that if the value of α is smaller, the higher energy part of the spectrum is influenced by solar modulation . The previous data below 10 GeV seem to be good agreement with a curve defined by setting $\alpha = 1$.

2.2 *Models of Solar Modulation and Charge Sign Dependence*

By the following method, we investigate whether cosmic ray transport in the solar magnetic field has a charge sign dependence.

Though the FF Approximation does not distinguish between charge signs of cosmic rays, the parameter Φ correlates with the neutron monitor (NM) counting rate N and has a specific relationship at the response energy E_m of the neutron monitor.[14)] If the interstellar spectrum of protons with rest energy m is expressed as a power law of momentum-energy p, $J(\infty,E) = J_0 p^{-\gamma}$, Eq. (1) yields the expression represented by:

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

In the above expression, the counting ratio N_{max}/N is substituted for $J(\infty,E_m)/J(r,E_m,t)$ of protons at the energy E_m.

$$\begin{aligned}\Phi &= E_m\{\sqrt{(\frac{N_{max}}{N})^{2/(\gamma+2)} + (\frac{0.94}{E_m})^2} - 1\} \qquad (2) \\ &\sim \frac{E_m}{\gamma+2}\cdot \ln(\frac{N_{max}}{N}), \qquad (3)\end{aligned}$$

in which N_{max} is the counting rate corresponding to the interstellar spectrum of cosmic rays, which receive no influence from solar modulation. It should exceed the observed maximum value of ∼4400(Climax): however, it cannot be evaluated exactly and is thus treated as a parameter. The approximate expression Eq. (3) shows good agreement with Eq. (2) as shown in Fig. 2. Note that the slope is independent of N_{max}. If the proton spectral index of $\gamma = 2.70 \pm 0.05$ and $E_m = 11$ GeV (Climax NM) are given, the slope becomes

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

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

Using the above relationship, we will confirm the effectiveness of the FF approximation and the charge sign dependence of cosmic ray transport. If the FF approximation is effective in all periods, the values of the parameter Φ obtained from GCR measurements will always satisfy the Φ–N relationship. Secondly, Electrons in the 1–100 GeV energy range are mostly negative, while the NM rate is approximately proportional to the proton flux at the response energy E_m. Thus, it is expected that the Φ–N relationship, and especially its slope, will shows the difference between the charge-dependent model (the drift model) and the charge-independent model (the FF Approximation).

The model considering drift effects in the heliosphere is widely accepted because it can reproduce the flat shape (A>0) and the peak shape (A<0) in the neutron monitor profiles during the solar minimum period.[6)] As the solar magnetic field reverses polarity every 11 years, the drift will also vary with this period, and differently influence the cosmic rays with differing charge sign. This has also been used for explaining the charge sign dependence of modulation. Fig. 2 shows the Φ–N curve expected from drift model.[15)] If the drift dominates in the A>0 period after 2010, the electron flux, namely Φ, changes by a large

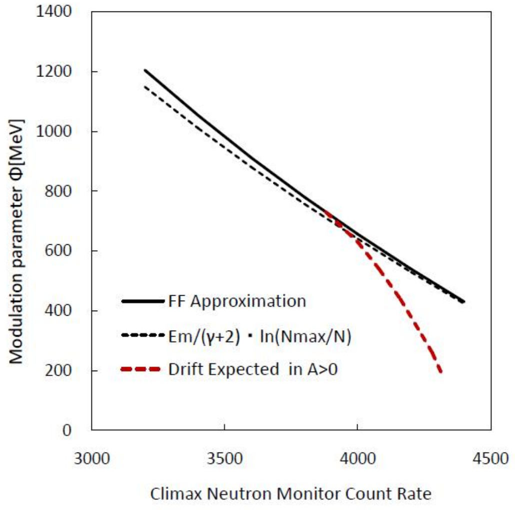

Fig. 2. Relationship between the modulation parameter Φ MeV and the Climax NM counting rate N. The solid line is estimated by the FF approximation at the response energy 11 GeV (Eq. (2)), while the dashed line is the expected curve, determined by the drift model, for negative particles in the solar quiet period of A>0, which is just estimated qualitatively. (The dotted line is an approximate expression of Eq. (3) and is good agreement with the solid line.)

amount while N changes by a relatively small amount. Given this effect, the slope of the Φ–N curve becomes steeper with increasing N as shown in Fig. 2. We will confirm this steepness at various energies using neutron monitor data and indicate the drift effects quantitatively.

The CALET long-term observation will give quite a bit of (N, Φ) data at various energies, and thus, it should become possible to verify modulation models and to confirm the charge sign dependence of modulation.

2.3 Forbush Decreases

There are periods during which cosmic ray flux decreases abruptly, called Forbush decreases (Fds), which follow a coronal mass ejection and generally have a two-step decrease through the passage of the forward shock and the ejecta.[16] These Fds, however, are sometimes not accompanied by the shock or ejecta, and so are varied and complex events. On general grounds, we expect Fd events in electron flux. The number of Fds, confirmed by Izmiran NM, located at 55°N and Climax NM at 40°N, in the period from 2000 to 2004 is ~5 events(>4%)/year (7–10 events in the solar maximum period)[17],[18] so that more than a few Fds are expected during the CALET measurements.

The charge sign dependence of Fds is presently quite controversial. Fd analysis from the IMP spacecraft and the neutron monitors over the period 1972–1984 have shown that the Fd recovery profile hardly depends on the solar polarity.[19] On the other hand, other neutron monitor results during the period 1959–1980 have shown a recovery in the A>0 period that is more rapid than that in A<0 period, as expected from the drift effect.[20] Here, we measure Fd profiles in electron flux and compare with those in neutron monitors. We expect that Fds

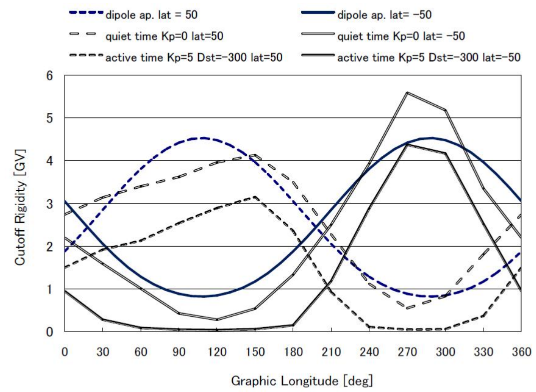

Fig. 3. Longitudinal variations of vertical cutoff rigidity in the case of the latitude, 50°N and 50°S, and the altitude, 400 km. The employed models are the Dipole approximation and the Tsyganenko model with International Geomagnetic Reference Field for 1995.[22]

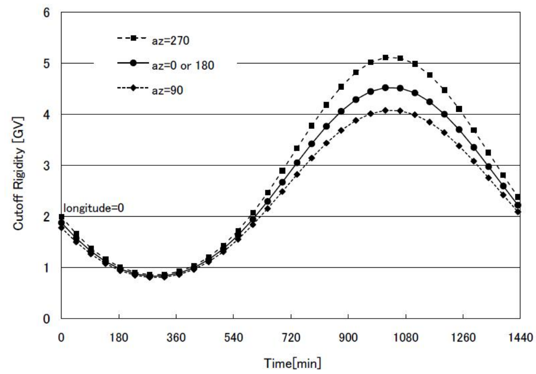

Fig. 4. Time variations of cutoff rigidity when the ISS passes through the highest latitudes of 50°N and 50°S every 46 minutes at the altitude 400 km. "az" means azimuth angle of incoming electrons within the zenith angle of 30°. The electron cutoff is higher from the west direction, 270°.

in electron flux might be different from neutron monitor Fds. The profile of Fds in the recovery period may play an important role here because the solar magnetic field is known to largely influence that period. Given this, we certainly plan to investigate the difference in these profiles. Precise measurements of Fds are also useful to estimate the background intensity for measurements of Galactic primary cosmic rays at low energy.

The intensity of GCR electrons is very low and is also limited by the geomagnetic rigidity cutoff determined from the ISS orbit. However, the CALET has a large geometric factor and an exposure time large enough to measure Fds, as shown in the next section.

3. Electron Measurements Below 10 GeV

The ISS orbit with an inclination of 51.6° severely restricts the measurement of electrons below 10 GeV. We will thus measure electrons in the highest latitudes for several minutes. Fig. 3 shows the variation of vertical geomagnetic cutoff rigidity with geographic longitude at the latitude ± 50°. In Fig. 3 two kinds of geomagnetic field models are shown: the central dipole approximation[21] and the more realistic Tsyganenko model with the International Geomagnetic Reference Field for 1995 calculated at both quiet and active times.[22] Fig. 3 shows that the curves in quiet times roughly agree with the dipole approximation. We consider, therefore, that the dipole approximation gives an upper limit, and a cutoff energy remains below 6 GeV.

Fig. 4 shows the variation of the geomagnetic cutoff rigidity for measurements performed every 46 minutes at the latitude 50°N and 50°S. Marked points represent alternately 50°N and 50°S measurements, where the dipole approximation is used. If we observe GeV electrons within the zenith angle of 30°, the cutoff energy continuously ranges between 1 and 5 GeV.

The geomagnetic cutoff on electron measurements causes a decrease in observed electron flux. Even if the measurement is performed at the highest latitudes, we can only obtain a few 10% electrons in the range of 2–4 GeV while all events are obtained above 6 GeV. However, we will be able to get sufficient data in the accumulated observation time. If the exposure factor is 40 m^2sr·min and the modulation parameter is Φ =500–1000 MeV, the observed number of electrons is estimated as $\sim$ 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 at a statistical error of 1–2% per day. On the other hand, for Fd observations, continuous measurements are required. Five minutes of measurement of 2–12 GeV electrons will be performed alternately at 50°N and 50°S. We will observe about 2000 events in each measurement, and the total number of electrons observed in the northern and the southern hemisphere will be enough to obtain a statistical error within 2%.

4. Summary

CALET has the capability to make precise measurements of the GCR electron energy spectrum over a wide range of energies. With sufficient data about variations of spectral shapes, we estimate the energy dependence of diffusion coefficients of electrons and expect new information regarding GCR transport in the heliosphere. We may also confirm the charge sign dependence of solar modulation by considering the correlation between electron intensity variation and the NM counting rate, which is useful to distinguish between different modulation models. In addition, more than a few Fds are expected in continuous measurements of electron flux and will be compared with those in the NM flux.

The CALET measurements of low energy electrons (<10 GeV) will be performed in a restricted time period as numerous background protons in this energy range have to be eliminated. However, CALET has a large geometric factor to observe electrons, and can provide statistically sufficient data for GeV energies. Cosmic ray measurements in this energy range are severely restricted by the geomagnetic cutoff rigidity. We will measure electrons at the highest latitudes for several minutes. In highest latitudes of the ISS orbit, the cutoff energy changes in the range of 1–5 GeV. Observation in the 1–10 GeV energy range over ten minutes will net an intensity measurement of a statistical error no greater than 2%.

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