

# CALET Observations of Cosmic Ray Electrons in the Heliosphere

Yoshiko Komori\*, Shoji Torii†, Tadahisa Tamura‡, Kenji Yoshida§ Toshio Terasawa¶  
and Kazuoki Munakata||

\* Kanagawa University of Human Services, Yokosuka, Kanagawa 238-8522, Japan

† Research Institute for Science and Engineering, Waseda Univ., Tokyo, Japan

‡ Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan

§ Department of EIS, Shibaura Institute of Technology, Saitama, Japan

¶ Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

|| Department of Physics, Shinshu University, Matsumoto, Nagano, Japan

**Abstract.** 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 the development is being carried out successfully. CALET has a large geometric factor that makes it possible to continuously and precisely measure electron intensities, and can provide statistically sufficient data for GeV energies, though the low energy measurements will be performed in a restricted time period and are severely restricted by ISS orbits.

The purpose of the CALET mission pertaining to solar physics is to get new information on the cosmic ray transport in the heliosphere. We estimate the energy dependence of the diffusion of electrons through the solar magnetic field. Further we simultaneously observe electrons and protons in the 1-10 GeV energy range and investigate the charge sign dependence of solar modulation. We also discuss some expectations in different solar polarities, using a correlation between the cosmic-ray intensity and the neutron monitor counting rate. For short-term measurements, we expect to detect several Forbush decreases in electron flux. In such decreases, short-term variations of negative charges might differ from those of positive ones.

**Keywords:** electrons, solar modulation, ISS

## I. 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 CALET instrument has fully capability of the precise measurement of spectral variations as shown in the previous paper [2]. The observation will 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. [3][4]) and balloon experiments (e.g. [5]), showing

large modulations of electron intensity by solar activity. On the other hand, such influences above several GeV have not yet been measured. In the 10–100 GeV energy range, various electron experiments using balloons have been performed for the past forty years and exhibit various differences. The CALET mission will find the cause of these differences.

Prior measurements of the positron/electron ratio [6] suggest a charge sign dependence of solar modulation, and the drift dominated modulation model [7] has been presented to explain the difference in the transport of positively and negatively charged cosmic rays. Drift models also predict different modulation for electrons and protons. The Ulysses mission in 1990's ( $A>0$ ) with the orbit radius of 1-5 AU has given a lot of data and results (e.g. [8]). The precise observations of both 2.5 GV electrons and protons for the long term of 1992-1998 indicates that the electron/proton ratio shows gradually increase to the solar minimum of 1996-1997. That may be explained by the drift being dominant in the minimum period. The observations of nuclear components by IMP satellite series have given the result that during the 1970's solar minimum period ( $A>0$ ), the helium/electron ratio at the same rigidity was higher than that in 1980's solar minimum ( $A<0$ ) [9]. Another significant result about the charge sign dependence is the antiproton/proton ratio for BESS experiments [10], in which the ratio in 2000-2002 ( $A<0$ ) is higher than that in 1997-1999 ( $A>0$ ). It is consistent with the IMP result. The BESS experiments also indicate that the ratio largely change at the solar maximum period and the charge sign dependence of modulation exist not only in the solar minimum but in the maximum period [11].

It is widely recognized that the ratio of negative particles to positive ones in the  $A<0$  period is higher than that in the  $A>0$  period. Whether the higher value is realized in both solar minimum and maximum period, the causes of differences, and the drift effectiveness should be investigated more precisely. We therefore simultaneously observe electrons and protons in the 1-10 GeV range and investigate the charge sign dependence of intensity variations. Forbush decreases will also be measured in the flux of electrons and protons and the difference in those profiles are investigated.

CALET has a large geometric factor for the purpose of TeV electron measurements, and will mainly measure electrons above 10 GeV at the high energy mode. On the other hand, the low energy mode below 10 GeV will be performed in a restricted time period, however, CALET can provide statistically sufficient data for GeV energies. ISS orbits also severely restrict low energy measurements, and it is necessary to estimate the variation of geomagnetic cutoff rigidity.

## II. COSMIC RAY TRANSPORT IN THE HELIOSPHERE

### A. Diffusion process of cosmic rays in the Force-Field Approximation

The simple diffusion-convection model with a spherically symmetric geometry is called the Force-Field (FF) approximation [12] and represents the magnitude of solar modulation by the potential energy  $\Phi$  MeV, which is widely used for interpretation of modulated spectra in primary cosmic ray measurements.

The FF approximation includes the diffusion coefficients of cosmic rays, the solar wind speed and the boundary of the heliosphere as input parameters from solar physics. In the FF approximation the differential intensity  $J(r, E, t)$  of galactic cosmic rays(GCR) with total energy  $E$  and the rest energy  $m$  is given by:

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

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

$$\zeta(E, t) = \int_m^E \frac{D_2(E', t)}{(E'^2 - m^2)^{1/2}} dE'$$

$$\phi(r, t) = \int_r^{r_b} \frac{V(r', t)}{3D_1(r', t)} dr'.$$

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  $D_2(E, t) = (E/1 \text{ GeV})^\alpha$ , and especially its spectral index  $\alpha$  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  $\alpha$  is smaller, the higher energy part of the spectrum is influenced by solar modulation. The previous data below 10 GeV seem to be in good agreement with a curve defined by setting  $\alpha = 1$ , which means the modulation parameter  $\Phi$  is independent of energy.

### B. Models of Solar Modulation and the Charge Sign Dependence

We have shown one method of investigating whether cosmic ray transport in the solar magnetic field has a charge sign dependence [2]. The parameter  $\Phi$  of the

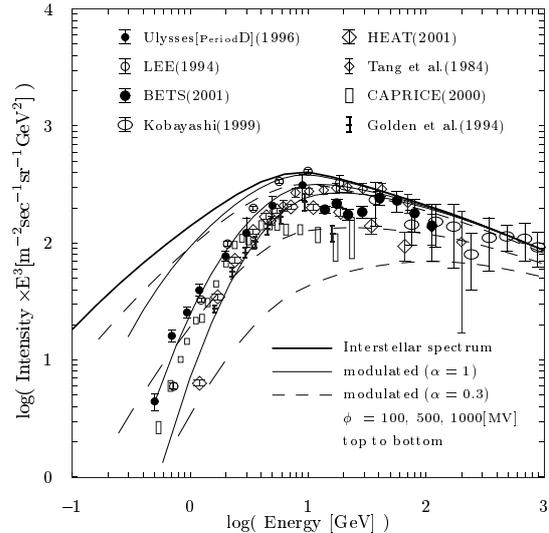


Fig. 1: Modulated electron spectra expected from FF approximation with the modulation parameter 100, 500, 1000 MV, in the case of the energy index of the diffusion coefficient,  $\alpha = 0.3, 1$ . Experimental results [4][5][13][14][15][16][17][18] are shown together.

FF Approximation correlates with the neutron monitor (NM) counting rate  $N$  and has a specific relationship at the response energy  $E_m$  of the neutron monitor [19]. 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:

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

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  $E_m$ .

$$\Phi = E_m \left\{ \sqrt{\left( \frac{N_{max}}{N} \right)^{2/(\gamma+2)} + \left( \frac{0.94}{E_m} \right)^2} - 1 \right\} \quad (2)$$

in which  $N_{max}$  is the counting rate corresponding to the interstellar spectrum of cosmic rays, which receive no influence from solar modulation. It cannot be evaluated exactly and is thus treated as a parameter. We assume  $N_{max} = 5300$  in this paper. The slope of eq. (2) is almost independent of  $N_{max}$ .

As shown in the previous paper [20] and in Fig. 2, the  $\Phi$  values of the ICE 1.2 GeV data are separated into two groups of different solar polarities and the slope of each group generally agrees with the curve of eq. (2) calculated from FF approximation.

On the other hand,  $\Phi - N$  relationship of nuclear components are shown in Fig. 3. The  $\Phi$  values of 70–95 MeV per nucleon cosmic-ray helium observed by IMP-8 for the period of 1973–1980 [21] show the same slope as the calculation curve except the solar maximum period. That consistency might suggest the effectiveness of FF approximation in the wide energy range from very

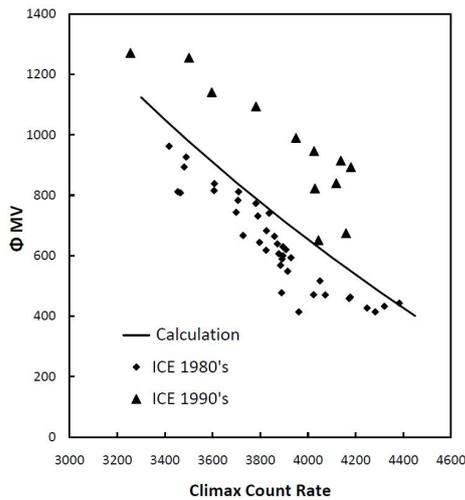


Fig. 2: The correlations between the modulation parameter  $\Phi$  and the Climax neutron monitor counting rate. The  $\Phi$  values of ICE 1.2 GeV electron data [3] are estimated from the local interstellar spectrum shown in Fig. 1. The calculation curve represents the formula of eq. (2) derived from FF approximation with  $N_{max} = 5300$ .

low energy to high energy. The  $\Phi$  values of protons have been obtained from the BESS balloon experiments with the 0.2-20 GeV kinetic energy range [22]. The slope of the protons for the  $A > 0$  period is good agreement with the calculation curve. The  $\Phi$  values obtained for the solar maximum period of 2000-2002 are high and steep, which indicates that the FF approximation does not hold in the solar maximum.

The drift model 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 [7]. 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. The effectiveness of the drift process is also expected the slope of  $\Phi-N$  curves in the solar minimum period [2]. If the drift dominates in the  $A > 0$  period after 2013, the electron flux, namely  $\Phi$ , changes by a large amount while  $N$  changes by a relatively small amount. Given this effect, the slope of the  $\Phi-N$  curve becomes steeper with increasing  $N$ .

Thus we consider that the correlation between the modulation parameter  $\Phi$  of FF approximation and the neutron monitor counting rate is useful for comparison of various cosmic ray species. It may also distinguish between different solar polarities and may have indications of different modulation models. The CALET long-term observation will give a sufficient data of electrons and protons at various energies, and thus, it should become possible to verify modulation models and to confirm the charge sign dependence of solar modulation.

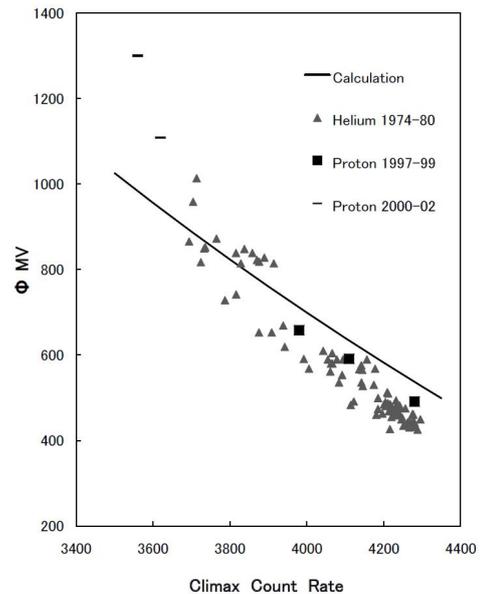


Fig. 3: Helium data of 70-95 MeV in 1973-1980 ( $A > 0$ ) period are adopted from Fig. 4 in the paper of M. Garcia-Munoz et al. [21]. Proton data of the BESS experiments [22] have 0.2-20 GeV kinetic energy range in both 1997-1999 ( $A > 0$ ) and 2000-2002 ( $A < 0$ ) period. The curve is the same as in Fig. 2.

### C. Forbush Decreases

We expect to measure several Forbush decreases (Fds) in the short-term variation events after 2013, especially in the next solar maximum period of 2013-2015. The number of Fds are confirmed by Izmiran NM [23] located at  $55^\circ\text{N}$ , and Climax NM [24] at  $40^\circ\text{N}$ , in the period from 2000 to 2004, which expect  $\sim 5$  events ( $>4\%$ )/year and 7-10 events/year in the solar maximum period. Here, we measure Fd profiles in electron flux, and compare with those in proton flux or neutron monitors. 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. We 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.

### III. ELECTRON MEASUREMENTS BELOW 10 GeV

The ISS orbit with an inclination of  $51.6^\circ$  severely restricts the measurement of electrons below 10 GeV. We will simultaneously measure electrons and protons at the highest latitude of the cutoff energy below 2 GV for five minutes, eight times per day alternately in the northern and the southern hemisphere and accumulate the data. Fig. 4 shows the variation of the geomagnetic cutoff rigidity for measurements at the highest latitude  $50^\circ\text{N}$  and  $50^\circ\text{S}$ . Marked points represent alternately  $50^\circ\text{N}$  and  $50^\circ\text{S}$  measurements every 46 min, where the dipole approximation is used. More precise estimates

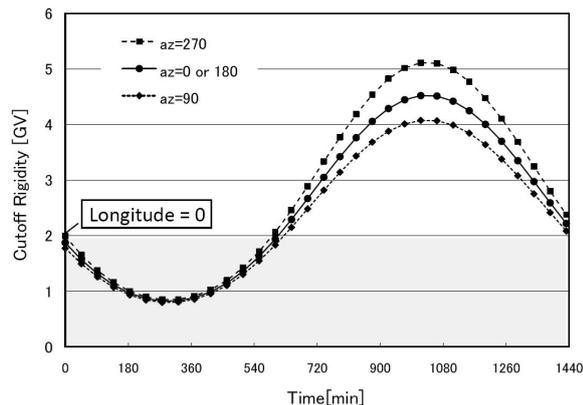


Fig. 4: Time variations of cutoff rigidity when the ISS passes through the highest latitudes of  $50^{\circ}\text{N}$  and  $50^{\circ}\text{S}$  every 46 minutes at the altitude 400 km. "az" means azimuth angle of incoming electrons within the zenith angle of  $30^{\circ}$ . The measurements are performed in the shaded range with the cutoff energy below 2 GV.

and the trigger conditions are presented in the paper of the CALET performance [25]. If the exposure factor is  $40 \text{ m}^2\text{sr}\cdot\text{min}$ , and the modulation parameter is  $\Phi = 500\text{--}1000 \text{ MeV}$ , 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.

#### IV. 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 from the simultaneous observation of electrons and protons, and consider the correlation with the neutron monitor counting rate, which is useful to distinguish between different modulation models. In addition, more than a few Fds are expected in short-term measurements of electron flux and the profiles will be compared with those in proton flux or the neutron monitor flux.

The low energy mode below 10 GeV will be performed in a restricted time period and the almost observation time will be spent at the high energy mode above 10 GeV. However, CALET has a large geometric factor, that is enough to observe electron spectral variation for several years, and can provide statistically sufficient data for GeV energies. We measure electrons in the 1–10 GeV energy range at the highest latitudes of cutoff rigidity below 2 GV. Observation in these energy range over ten minutes will net an intensity measurement of a statistical error no greater than 2%.

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