

Charge-Sign Dependent Cosmic-Ray Modulation Observed with the Calorimetric Electron Telescope on the International Space Station

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We present the observation of a charge-sign dependent solar modulation of galactic cosmic rays (GCRs) with the Calorimetric Electron Telescope onboard the International Space Station over 6 yr, corresponding to the positive polarity of the solar magnetic field. The observed variation of proton count rate is consistent with the neutron monitor count rate, validating our methods for determining the proton count rate. It is observed by the Calorimetric Electron Telescope that both GCR electron and proton count rates at the same average rigidity vary in anticorrelation with the tilt angle of the heliospheric current sheet, while the amplitude of the variation is significantly larger in the electron count rate than in the proton count rate. We show that this observed charge-sign dependence is reproduced by a numerical “drift model” of the GCR transport in the heliosphere. This is a clear signature of the drift effect on the long-term solar modulation observed with a single detector.

DOI: [10.1103/PhysRevLett.130.211001](https://doi.org/10.1103/PhysRevLett.130.211001)

Introduction.—The galactic cosmic ray (GCR) intensity observed at Earth shows a clear ~ 11 -yr cycle variation in anticorrelation with the solar activity. This well-known phenomenon known as the heliospheric modulation of GCRs has been interpreted as a result of the large-scale GCR transport in the heliosphere. The potential importance of the gradient and curvature drift in the GCR transport was addressed theoretically by Jokipii *et al.* [1]. Numerical calculations by Jokipii and Thomas [2] and Kóta and Jokipii [3] showed that the drift effect results in an anticorrelation between the GCR intensity at Earth and the tilt angle of the heliospheric current sheet (HCS), which increases with the solar activity and the waviness of the HCS. Since the orientation of the guiding center drift velocity reverses according to the alteration of the sign (q) of the particle’s charge and the sign (A) of the solar magnetic field polarity, the drift effect is predicted to have different anticorrelations between the GCR intensity and the HCS tilt angle when $qA > 0$ or $qA < 0$. During periods with $A > 0$ the solar polar magnetic field is directed away from (toward) the Sun in the northern (southern)

hemisphere, and the drift leads electrons ($q < 0$) inward toward the Earth along the HCS while the distance along the access route becomes longer as HCS waviness increases. The drift, on the other hand, leads protons ($q > 0$) to arrive at Earth from the heliospheric polar region, reaching the HCS less often. This results in a larger modulation of the electron flux than that of the proton flux at Earth given the HCS tilt angle increase during periods with $A > 0$. The same effect is also seen in “peaked” and “flat” maxima of ~ 11 -yr GCR variations when $qA < 0$ or $qA > 0$, respectively [3].

So far, the drift effect has been explored by analyzing GCR data in several ways. By examining the anticorrelation between the HCS tilt angle and the neutron monitor count rates corresponding to GCR protons and helium with $q > 0$, Cane *et al.* [4] found no clear difference in the anticorrelations when $A > 0$ or $A < 0$ except for short periods around the solar activity minima. They attributed the majority of the observed modulation to the change of the Sun’s magnetic field strength instead of the change of the HCS tilt angle. In such an analysis with data taken at different time periods, however, it is difficult to distinguish the difference due to the drift effect from other modulation parameters. For example, other parameters include the solar wind velocity and the magnetic field strength, which are generally not the same in different time periods [5]. Bieber *et al.* [6], on the other hand, suggested that a notable change in the flux ratio of GCRs with $q < 0$ or $q > 0$ is expected

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from the drift model and would provide a good test of the magnitude of the effect. This change is actually observed in the flux ratio (\bar{p}/p) of GCR antiprotons (\bar{p}) and protons (p) from the BESS balloon-borne experiment [7]. The observed change of \bar{p}/p is also quantitatively reproduced by the numerical calculation of the drift model. Recently, Adriani *et al.* [8] and Aguilar *et al.* [9] also reported similar results from analyzing the flux ratio (e^+/e^-) of GCR positrons (e^+) and electrons (e^-) observed by several space experiments. However, the qA dependence of the anticorrelation between the GCR intensity and the HCS tilt angle over the solar activity cycle has not been reported yet. In this Letter, we report for the first time the anticorrelations with the HCS tilt angle of the electron and proton count rates simultaneously observed by the Calorimetric Electron Telescope (CALET) [10–19] onboard the International Space Station over nearly 6 yr between 2015 and 2021.

CALET instrument and data analysis.—Figure 1 shows a schematic side view of CALET consisting of a charge detector (CHD) for identifying the charge of the incident particle, an imaging calorimeter (IMC) for track reconstruction and for fine-spatial resolution imaging of the early stage shower development, and a total absorption calorimeter (TASC) for measuring the energy of the electromagnetic shower [13]. The CHD is composed of a pair of x - y layers each consisting of 14 plastic scintillator paddles with dimensions of 450 mm long \times 32 mm wide \times 10 mm thick. The IMC is composed of eight x - y layers of 448 mm long \times 1 mm square cross-section scintillating fibers interleaved with tungsten plates. The first five tungsten plates have 0.2 radiation length (X_0) thickness and the last two plates each have 1.0 X_0 thickness. The total thickness of the IMC is equivalent to 3 X_0 . The TASC consists of 12 crossed layers of 16 lead tungstate logs, each with dimensions of 326 mm long \times 19 mm wide \times 20 mm thick, for a total thickness of 27 X_0 . The total thickness of the calorimeter is 30 X_0 , equivalent to ~ 1.3 proton interaction lengths, allowing CALET to obtain near total absorption of electron showers even up to about 20 TeV.

The normal event trigger of CALET is provided by the high-energy trigger with an energy threshold of ~ 10 GeV. In addition to the high-energy trigger, in order to collect the low-energy ($\gtrsim 1$ GeV) particle events efficiently, a low-energy electron (LEE) trigger is useful at high geographical latitudes where the geomagnetic cutoff rigidity (COR) is below 5.0 GV. This LEE shower trigger mode is operated for 90 s twice per International Space Station orbital period (~ 91 m), at a 51.6° orbital inclination, in each of the north and south regions. In this Letter, we analyze the flight data collected in the LEE trigger mode during 2058 d from October 13, 2015, to May 31, 2021. We have collected about 91×10^6 low-energy GCR candidates in a total observational live time of approximately 766 h. From this

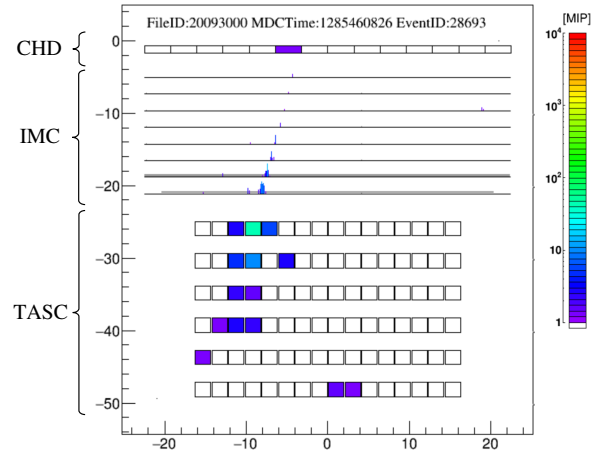


FIG. 1. Schematic cross-sectional view of CALET with an electron LE event candidate with energy of ~ 3.9 GeV.

dataset, we select electrons and protons and deduce their count rates for the same average rigidity.

For the event selection and energy reconstruction, we adopt a Monte Carlo (MC) simulation developed to simulate physical processes and detector response based on the simulation package EPICS [20] (EPICS 9.20 and COSMOS 8.00) and the DPMJET-III model for hadron interactions. The MC event samples consist of the response to downward propagating electron and proton events generated isotropically on a spherical surface with a radius of 78 cm surrounding the instrument. We apply the following event-selection criteria: (a) off-line trigger condition requiring energy deposits in the bottom two layers of the IMC and the top layer of the TASC to exceed a given set of thresholds, (b) quality cut on the reconstructed track of the incident particle by the Kalman filter method, (c) geometrical condition requiring the reconstructed track to traverse the CHD top layer and the TASC bottom layer, (d) cut on the CHD output to select incident particles with single charge, (e) cut on an energy deposit in all layers of the IMC and the TASC to exclude events passing through the layer without energy deposit, (f) additional cut on the spatial concentration of hit signals in the IMC bottom layer to reduce the proton contamination for the analysis of electron count rates, and (g) cut on the lateral shower development in the TASC top layer for electron and proton discrimination [see the Supplemental Material [21] about the detail of criteria (f) and (g)]. Details of these criteria are provided in [11,14] for the analysis of high-energy electrons, with the important distinction that the analysis here imposes selections on the IMC bottom layer and TASC top layer for electron and proton discrimination given that the low-energy electrons do not penetrate all layers of the TASC.

In order to minimize the count rate variation due to the COR, we choose periods in which the COR is below 0.8 GV and select events recorded with a deposited energy

exceeding 1.0 GeV. The COR is calculated by back-tracing the particle trajectory in the magnetosphere defined by the IGRF-13 [31] and TS05 [32] empirical models [33] for every incident direction. Orbit calculations are repeated by decreasing the particle's rigidity and the COR is defined as the lowest rigidity before the appearance of the penumbra.

For the analysis of the charge-sign dependent solar modulation in this Letter, we derive the count rates of electrons and protons at the same average rigidity. The average rigidity of electrons that passed the above selection criteria is estimated to be ~ 3.8 GV from MC simulations. The average rigidity of protons is adjusted to ~ 3.8 GV by selecting the events for which the energy deposit in all layers of the IMC and the TASC is between 1 and 3 GeV, which is verified from MC simulations. We analyze about 0.77×10^6 electron and 1.26×10^6 proton candidates collected in a total observational live time of about 196 and 197 h, respectively.

Results and discussion.—Figure 2(b) shows the electron and proton count rates at an average rigidity of 3.8 GV (blue and red symbols), C_{e^-} and C_p , respectively, observed by CALET for the 6-yr period corresponding to $A > 0$ [34]. Shown in the figure are only statistical uncertainties given that the systematic uncertainties do not vary appreciably over the period under consideration. For reference, Fig. 2(a) displays the sunspot number (SSN) [35] and the HCS tilt angle based on the radial model at the Wilcox Solar Observatory [36] (courtesy of Hoeksema [37]) representing the solar activity in the same period. The error on the HCS tilt angle is deduced from the difference between the values in the northern and southern hemispheres. In Fig. 2(b), the average count rate over the entire period is normalized to 100 and each symbol shows an average within each solar rotation (Carrington rotation) period. Since CALET is incapable of discriminating positrons from electrons, it is necessary to correct the temporal variation of the observed electron flux for the contribution from the positron flux, which has been found to be below 10% of the electron flux at 3.8 GV [8,9]. We correct C_{e^-} for this positron contamination by assuming that the positron contamination is 7% on October 2015 [9] and that the variation of the normalized positron count rate is identical to C_p in Fig. 2(b) (see the Supplemental Material [21] for more detail). We find that the amplitude of the C_{e^-} variation increases by about 3.1% by taking this correction into account.

The electron count rate measured by CALET reached its maximum about 6 months after the beginning of solar cycle 25 in December 2019 [see SSN and HCS tilt angle in Fig. 2(a)]. Also shown in Fig. 2(b) is the Oulu neutron monitor count rate (C_{NM}) [38,39], which is sensitive to high-energy (~ 10 GV) GCR protons (black solid curve). A good correlation is seen between C_p and C_{NM} with a correlation coefficient of 0.98 (see Fig. S2 of the Supplemental Material [21]). The ratio of C_p to C_{NM} with average rigidity of ~ 10 GV is about 3.32, indicating

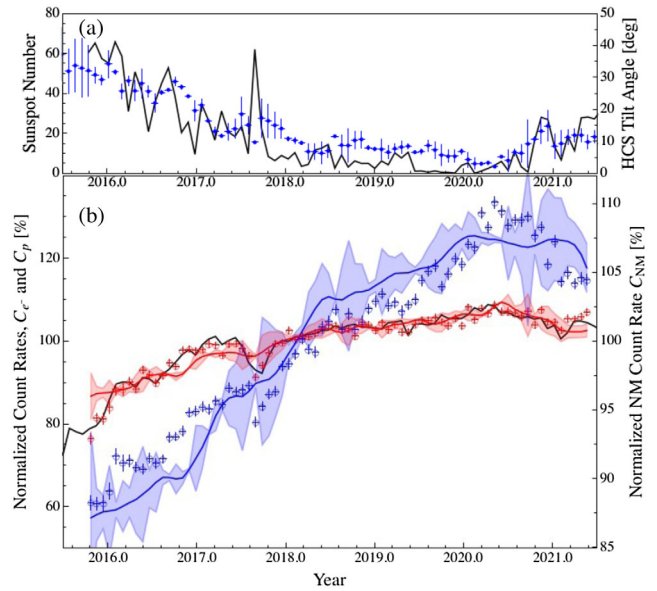


FIG. 2. (a) Time profiles of the sunspot number (solid line) and the HCS tilt angles (blue solid circles) as a function of the central time of each Carrington rotation. (b) Time profiles of the normalized count rates of electrons C_{e^-} (blue open circles) and protons C_p (red open circles) for each Carrington rotation (left vertical axis), where statistical uncertainties are shown. The black curve shows the count rate of a neutron monitor at the Oulu station on the right vertical axis, while the blue and red curves show the electron and proton count rates reproduced by the numerical model, respectively. Each shaded area around the reproduced curve indicates the error deduced from the error of the HCS tilt angle and the regression coefficient between the tilt angle and the reproduced curve (see text).

the rigidity spectral index of the proton count rates is about -1.24 . This result is consistent with the spectrum known for the long-term solar modulation in this rigidity region (e.g., Munakata *et al.* [40]), providing further support that our determination of the proton count rate is handled correctly.

From Fig. 2(b), we see that both C_{e^-} and C_p increase with decreasing solar activity toward the solar minimum in 2019, as indicated by the SSN and HCS tilt angle in Fig. 2(a). The most striking feature in Fig. 2(b) is that the variation of C_{e^-} is clearly larger than that of C_p at the same average rigidity. As mentioned in the introduction, this is consistent with the drift effect in which a stronger anti-correlation between the GCR intensity and the HCS tilt angle results for $qA < 0$ than for $qA > 0$. The blue (red) solid curve displays C_{e^-} (C_p) calculated by a numerical drift model [33,41] (see the Supplemental Material [21] for details), with an average uncertainty of 5.9 ± 4.3 (%) (1.6 ± 1.2 (%)) mainly due to the error in the HCS tilt angle. The model simultaneously reproduces the observed variations in both C_{e^-} and C_p , with some departures in the predictions of C_{e^-} , most notably before 2018.

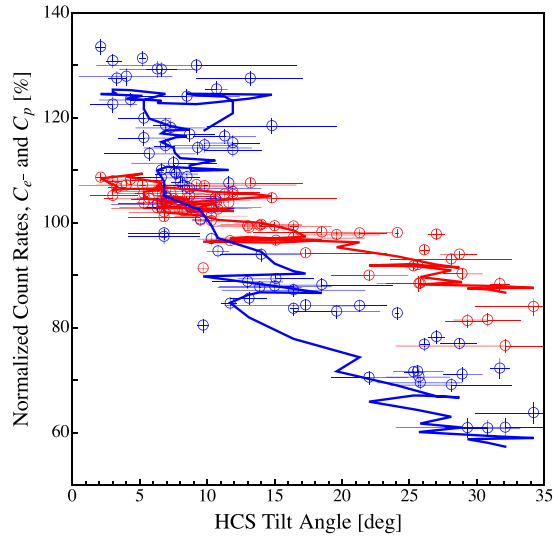


FIG. 3. Correlation plot between the normalized count rate and the HCS tilt angle. Blue (red) open circles show the correlation of the observed electron (proton) count rate, respectively, while blue and red solid curves display correlations reproduced by the numerical model (see text).

Figure 3 shows the observed C_{e^-} (blue symbols) and C_p (red symbols) as a function of the HCS tilt angle on the horizontal axis together with the model prediction displayed by the blue (red) solid curve. The regression coefficient of the observed C_{e^-} as a function of the HCS tilt angle is -2.12 ± 0.17 ($\%/^\circ$) and is significantly larger than -0.72 ± 0.06 ($\%/^\circ$) for C_p . The regression coefficients of the reproduced C_{e^-} and C_p are -2.57 ± 0.19 ($\%/^\circ$) and -0.69 ± 0.05 ($\%/^\circ$), respectively, roughly consistent with our observations. Differences between the observed and modeled correlation with the HCS tilt angle can be attributed to model-dependent assumptions that can be further refined in the future. For instance, the model could better represent distortions in the HCS introduced by solar wind disturbances, including coronal interaction regions [42]. It is also known that the GCR variation at Earth lags several Carrington rotations behind the HCS tilt angle, as seen in Fig. 2 by the fact that the maxima of C_{e^-} and C_p are delayed with respect to the minimum value of the HCS tilt angle. This hysteresis effect is shown in Fig. 3 with clockwise rotations of C_{e^-} and C_p that are also reproduced by the numerical model (solid curves in Fig. 3).

In summary, we have determined the solar rotation averages of electron ($q < 0$) and proton ($q > 0$) count rates, C_{e^-} and C_p , measured by CALET at the same average rigidity for approximately 6 yr from 2015 to 2020 corresponding to $A > 0$ of the solar magnetic field polarity. A good correlation between C_p and C_{NM} with a correlation coefficient of 0.98 validates the determination of the CALET proton count rate. It is found that the modulation amplitude of the average C_{e^-} is clearly larger than that of

C_p , consistent with the drift model predictions of a larger anticorrelation between the GCR intensity and the HCS tilt angle when $qA < 0$ than that with $qA > 0$. It is also shown that the observed modulations of C_{e^-} and C_p are simultaneously reproduced by a numerical model that accounts for the drift effect in the GCR transport in the heliosphere. This is the first clear evidence of the drift effect playing a major role in the long-term modulation of GCRs.

We used JAXA Supercomputer System generation 3 (JSS3) with business name: “Numerical study on the solar modulation of low-energy cosmic rays measured with CALET” (business code: ACA51). We gratefully acknowledge JAXA’s contributions to the development of CALET and to the operations onboard the International Space Station. We also express our sincere gratitude to ASI and NASA for their support of the CALET project. This work was supported in part by JSPS Grant-in-Aid for Scientific Research (S) Grant No. 19H05608, JSPS Grant-in-Aid for Scientific Research (C) Grant No. 20K03956, JSPS Grant-in-Aid for Scientific Research (C) Grant No. 21K03592, and by the MEXT-Supported Program for the Strategic Research Foundation at Private Universities (2011-2015) (Grant No. S1101021) at Waseda University. The CALET effort in Italy is supported by ASI under Agreement No. 2013-018-R.0 and its amendments. The CALET effort in the U.S. is supported by NASA through Grants No. 80NSSC20K0397, No. 80NSSC20K0399, No. NNH18ZDA001N-APRA18-004, and under Award No. 80GSFC21M0002.

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