Cosmic-Ray Modulation during Solar Cycles 24-25 Transition Observed with CALET on the International Space Station

Shoko Miyake[1], Kazuoki Munakata[2], Yosui Akaike[3,4], for the CALET Collaboration

1. National Institute of Technology (KOSEN), Ibaraki College, 2. Shinshu University, 3. Waseda University, 4. Japan Aerospace Exploration Agency

Abstract: We present the solar modulation of electrons and protons observed by the CALorimetric Electron Telescope onboard the International Space Station for about 7 years since October 2015, during the transition phase from the descending phase of the 24th solar cycle to the ascending phase of the 25th solar cycle. The observed variations of electron and proton count rates at an identical average rigidity of 3.8 GV show a clear charge-sign dependence of the solar modulation of galactic cosmic rays (GCRs), which is reproduced by a numerical drift model of the GCR transport in the heliosphere. It is also found that the ratio of 3.8 GV proton count rate to the neutron monitor count rate in the ascending phase of the 25th solar cycle is clearly different from that in the descending phase of the 24th solar cycle. Correlations between the electron (proton) count rate and the heliospheric environmental parameters, such as the current sheet tilt angle, obtained in this study would be useful for developing an appropriate numerical model of solar modulation for reproducing the observation.

CALET - CALorimetric Electron Telescope

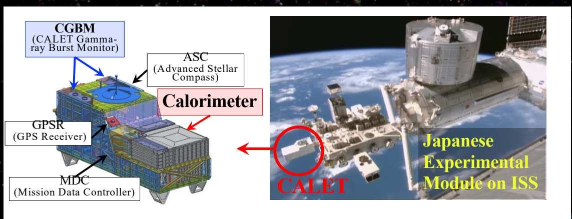

Figure 1: CALET instrument package showing the calorimeter, the CALET gamma-ray burst monitor (CGBM), the mission data controller (MDC), the GPS receiver (GPSR), and the advanced stellar compass (ASC).

Launch: Aug. 19, 2015
Observations: Oct. 13, 2015
Observation Targets:

- Electron (e- + e+): 1GeV – 20 TeV
- p--Fe: 10 GeV – 1000 TeV
- Ultra heavy ions (26<Z<=40): > 600 MeV/n
- Gamma-rays (Diffuse + Point sources): 1 GeV – 1 TeV

Data Analysis

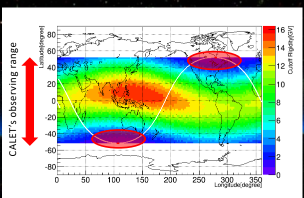

Figure 2: Cutoff rigidity map and ISS orbit

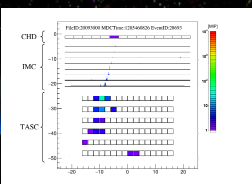

Figure 3: Schematic cross-sectional view of the CALET with an electron LE event candidate with energy of ~3.9 GeV.

- We have analyzed the flight data collected in a low-energy electron (LEE) trigger mode that works at high geomagnetic latitudes from October 13 in 2015 to April 30 in 2023.
- 124 million low-energy GCR candidates in a total observational live time of ~1044 hours have been collected.
- In order to minimize the count rate variation due to the cutoff rigidity (COR), we have chosen periods in which the COR is below 0.8 GV and have selected events recorded with rigidity much higher than the COR.

- We have applied the following event-selection criteria:
  - (a) Off-line trigger condition: IMC7-8 and TASC top layer
    - Trigger GeV-energy events
  - (b) Tracking condition: IMC
    - Kalman filter track reconstruction with IMC
  - (c) Geometrical condition: IMC
    - Entire trajectory is inside IMC and TASC
  - (d) Charge determination: CHD
    - CHD energy deposit to remove Z>=2
  - (e) Energy deposit condition: IMC and TASC
    - Exclude events passing through the layer without energy deposit
  - (f) e/p separation with a spatial concentration of hit signals applied only for electron event selection: IMC bottom
    - Energy deposit and Shower concentration of IMC bottom layer
  - (g) e/p separation with a lateral shower development: TASC top layer
    - lateral spread parameter R_E in TASC top layer

Results

- We see a clear charge-sign dependence of the solar modulation of GCRs, showing the variation amplitude of the electron count rate C_{e^-} is much larger than that of the proton count rate C_p at the same average rigidity [1].
- We have succeeded in reproducing variations of C_{e^-} and C_p simultaneously with a numerical drift model of the solar modulation (see Supplemental Material of [1] for detail), which implies the drift effect plays a major role in the long-term modulation of GCRs.
- We also find a clear difference between ratios, C_p/C_{NM}, during the descending phase of the 24th solar cycle and the ascending phase of the 25th solar cycle.
- Correlations between C_{e^-} (C_p) and the heliospheric environmental parameters, such as the HCS tilt angle, would help developing the numerical model of solar modulation that can reproduce the observation.

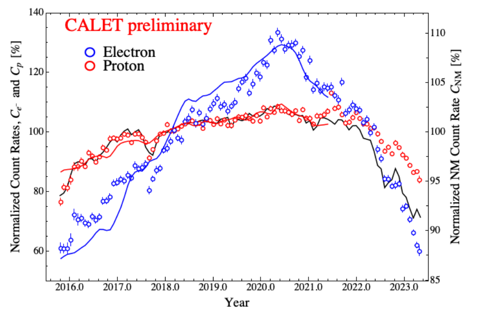

Figure 4: Time profiles of the normalized count rates of electrons C_{e^-} (blue open circles) and protons C_p (red open circles) for each Carrington rotation (left vertical axis), compared with the count rate of a neutron monitor at the Oulu station (black curve) [2] on the right vertical axis and the electron (blue curve) and proton (red curve) count rates reproduced by the numerical drift model.

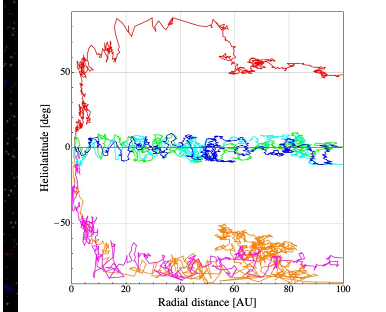

Figure 5: Sample trajectories of protons (red, orange, and magenta lines) and electrons (blue, cyan, and green lines) in the heliosphere in October 2019, in which the polarity of the solar magnetic field is positive (A>0). These sample trajectories are calculated by the numerical drift model.

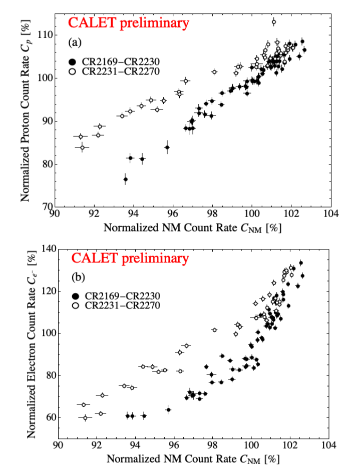

Figure 6: CALET proton (a) and electron (b) count rates at the average rigidity of 3.8 GV as a function of neutron monitor count rates at the Oulu station during the descending phase in the 24th solar cycle (closed circles) and the ascending phase in the 25th solar cycle (open circles).

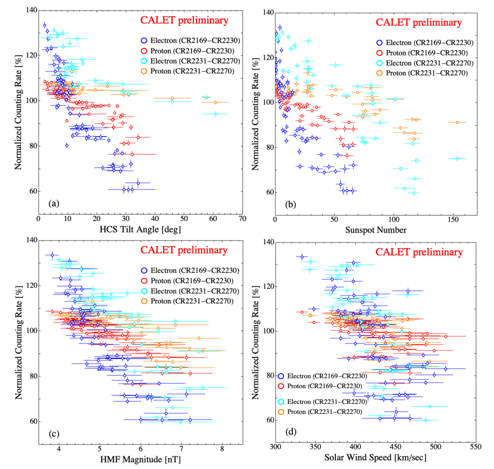

Figure 7: Electron and proton normalized count rates, C_{e^-} and C_p, as a function of the HCS tilt angle (a) [3], the sunspot number (b) [4], the HMF magnitude (c) [4], and the solar wind speed (d) [4]. Blue and red open circles show the electron and proton count rates during the descending phase in the 24th solar cycle (CR2169 ~ CR2230) respectively, while cyan and orange open circles show the electron and proton count rates during the ascending phase in the 25th solar cycle (CR2231 ~ CR2270) respectively.

Acknowledgments: We gratefully acknowledge JAXA's contributions to the development of CALET and to the operations onboard the International Space Station. The CALET effort in Italy is supported by ASI under Agreement No. 2013-018-R.0 and its amendments. The CALET effort in the United States is supported by NASA through Grants No. 80NSSC20K0397, No. 80NSSC20K0399, and No. NNH18ZDA001N-APRA18-0004. This work is 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, and JSPS Grant-in-Aid for Scientific Research (C) Grant No. 21K03592 in Japan.

References:

[1] O. Adriani et al. (CALET Collaboration), Phys. Rev. Lett., 130, 211001 (2023).
[2] Sodankyla Geophysical Observatory, Oulu Cosmic Ray Station, https://cosmicrays.oulu.fi/
[3] The Wilcox Solar Observatory, HCS tilt angle, http://wso.stanford.edu/Tilts.html
[4] NASA/Goddard Space Flight Center, OMNIweb, https://omniweb.gsfc.nasa.gov/form/dxl.html