PROCEEDINGS OF SCIENCE

Dependence of solar diurnal variation on solar wind speed

T. Koi,[a,*] H. Kojima,[b] S. Shibata,[c] H. Takamaru,[a] A. Oshima,[a] K. Yamazaki,[a] T. Tabata,[a] S. Kawakami,[d] Y. Hayashi,[d] K. Tanaka,[e] T. Nakamura,[f] T. Nonaka,[g] S.K. Gupta,[h] P.K. Mohty,[h] K.P. Arunbabu,[i] M. Chakraborty,[h] S.R. Dugad,[h] B. Hariharan,[h] P. Jagadeesan,[h] A. Jain,[h] S. Mahapatra,[h] P.K. Nayak,[h] D. Pattanaik,[h] M. Rameez,[h] K. Ramesh,[h] L.V. Reddy,[h] P. Subramanian[j] and M. Zuberi[h]

[a] *Faculty of Science and Engineering, Chubu University, Kasugai-shi, Aichi, Japan*
[b] *Chubu Astronomical Observatory, Kasugai-shi, Aichi, Japan*
[c] *Center for Muon Science and Technology, Chubu University, Kasugai-shi, Aichi, Japan*
[d] *Graduate school of science, Osaka City University, Sugimoto-cho, Osaka, Japan*
[e] *Hiroshima City University, Hiroshima, Japan*
[f] *Faculty of Science, Kochi University, Kochi, Japan*
[g] *Institute for Cosmic Ray Research, Tokyo University, Kashiwa, Chiba, Japan*
[h] *Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai, India*
[i] *St. Albert's College, Ernakulam, India*
[j] *Indian Institute of Science Education and Research, Pune, India*

E-mail: tkoi@isc.chubu.ac.jp

We have continuously observed muon intensities from 2000 to the present using the GRAPES-3 multi-directional muon telescope in Ooty, South India. The radial diffusion coefficient and mean free path of the propagation of Galactic cosmic rays (GCR) in the heliosphere have been derived from the regression coefficients of cosmic-ray intensity and solar wind velocity variations [6]. In the present study, we used the same dataset for the years 2000-2021, covering about 5000 days and divided into 26 groups by the solar wind speed to examine the relationship of the amplitude and phase of solar diurnal variation of each group with the average solar wind speed on the corresponding group. This analysis shows that (1) there is a positive correlation between the amplitude and phase of the solar diurnal variation and the solar wind speed, and (2) in particular, the slope of the regression line between the amplitude of the solar diurnal variation and the solar wind speed becomes slower on the high-speed side than around 450 km/s.

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*Speaker

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1. Introduction

The anisotropy of cosmic rays near the Earth is explained based on Parker's cosmic ray transport theory called the diffusion-convection model. This theory assumes a steady-state density of cosmic rays near the Earth and a balance between the inflow and outflow of cosmic rays in the cosmic-ray propagation structure from the outer heliosphere to the vicinity of the Earth. In essence, the theory suggests that cosmic rays near Earth are transported from the Sun-centric direction due to the solar wind's influence, this is the convection component, and the convection makes the radial gradient of global cosmic ray density in the heliosphere. This density gradient diffuses cosmic rays into the heliosphere along the Interplanetary Magnetic Field (IMF). This is the diffusion component. Assuming the steady-state condition for the density of cosmic rays near Earth, it is expected that the transport components of convection and diffusion are balanced radially. Therefore, the anisotropy of cosmic rays would predominantly manifest as the co-rotating component aligned with the Sun. The angle between the interplanetary magnetic field in near Earth and the radial direction from the Sun is determined by the velocity of the solar wind[4, 5]. Figure 1 presents an overview of the transport components, including convection, diffusion, and co-rotating components, in cosmic ray transport.

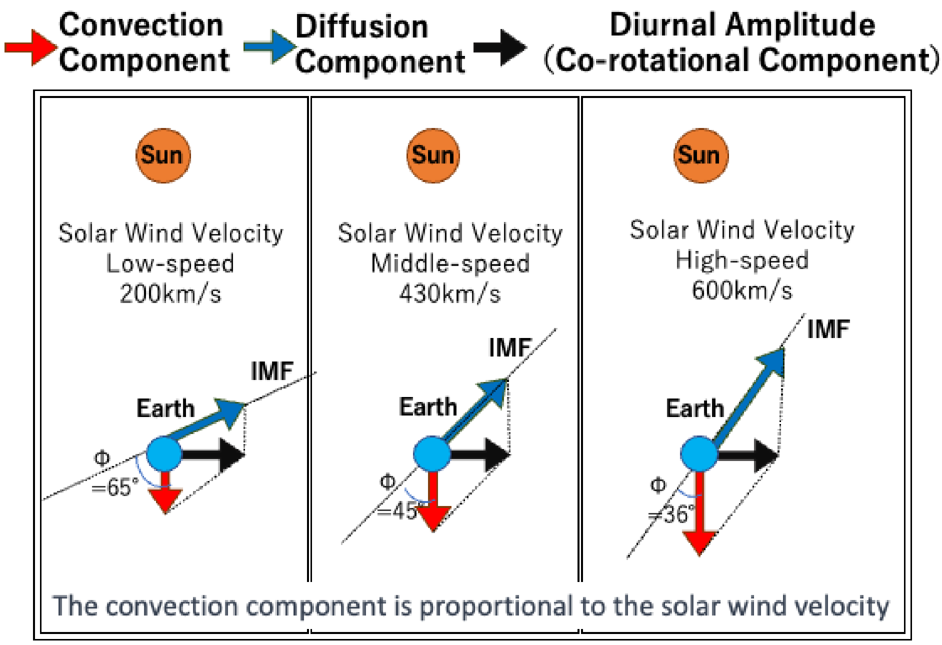

Figure 1: A schematic diagram illustrating the relationship between solar wind velocity, interplanetary magnetic field in the vicinity of Earth, and the transport components of cosmic ray transport including convection, diffusion, and co-rotating components.

2. Instrument

The GRAPES-3 multi-directional muon telescope consists of 16 detector modules, each comprising 232 proportional counter tubes. These detector units are constructed using steel and have dimensions of $10cm \times 10cm \times 600cm$. Within each module, there are four layers, each consisting of 58 proportional counter tubes.These layers are arranged in such a way that the tubes within each layer are orthogonal to each other. This configuration allows for the measurement of the arrival direction of atmospheric muons with an angular resolution of approximately 6 degrees. To establish a threshold energy for vertical muons, absorber layers with a total thickness of 2.5 m, made of concrete blocks, are employed. This configuration sets the threshold energy for vertical muons to be around 1 GeV. The muon counting is conducted on penetrating muons, which are then categorized into fine directions of 15×15 = 169 subdivisions and coarse directions of 3×3 = 9 subdivisions, utilizing the hit pattern marked by the muon. The GRAPES-3 muon telescope, composed of 16 modules each having four layers of proportional counter tubes, has an effective area of 560 m^2, and this large surface area facilitates high statistical observation capabilities[1]. The typical counting rate of the muon is about 60 kHz in whole telescope. Figure 1 presents a schematic view of the muon module.

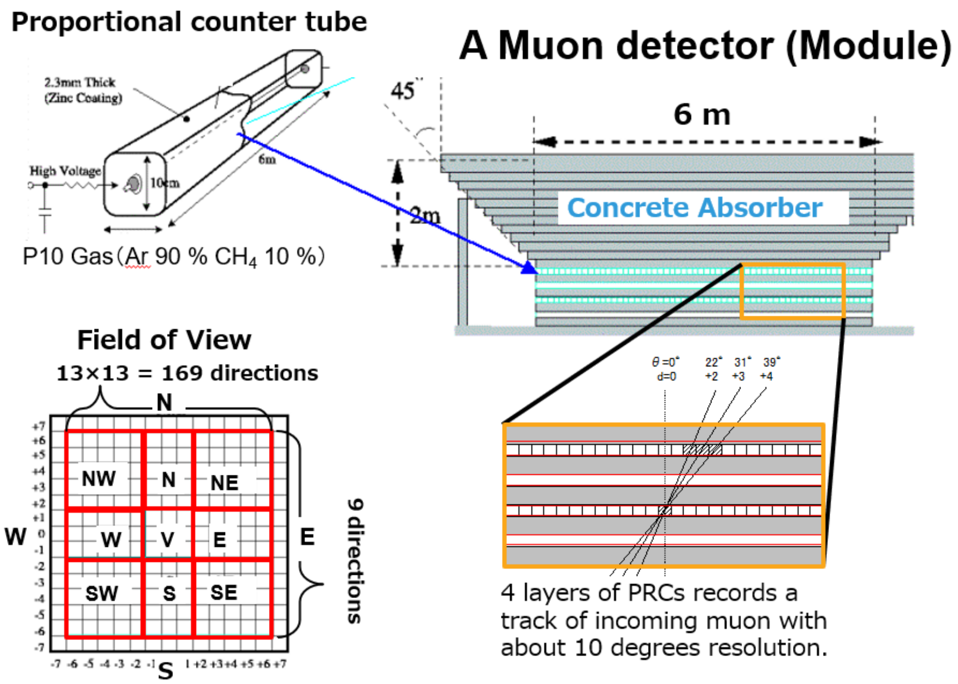

Figure 2: GRAPES-3 muon telescope consists of 16 muon tracking detectors which is called module.

3. Analysis

We analyzed the data from the multi-directional muon telescope of GRAPES-3 for the years 2000 to 2021 to investigate the solar diurnal variation of cosmic rays. We analysed on the daily variation of cosmic rays using the following procedure. Firstly, we removed any abnormal values from the original data for each module. This involved aggregating the data from 10-second to 1-hour intervals on every year, resulting in a set of 22 years of hourly data. We calculated the annual average value and standard deviation (σ) for the 1-hour data. If any hourly values deviated more than 10 σ from the average, they were marked as abnormal and excluded from the analysis. After removing these abnormal data points based on the 10 σ criteria, we recalculated the annual average and standard deviation (σ). Any hourly values were similarly removed if they still deviated more than 5 σ from the average. Once this process was completed, we calculated the percentage hourly values of variation throughout the year. We then performed atmospheric pressure correction on these percentage hourly values (using -0.12 %/(hPa) for the V component). Following the atmospheric pressure correction, a 647-hour moving average was calculated and subtracted from the percentage hourly data, effectively applying a high-pass filter. This filtered data was further processed using a 24-hour high-pass filter, providing the foundational data for the analysis of daily variation.

The data from the entire period was divided into 26 categories based on the daily average magnitude of solar wind velocity [3] to ensure statistical equivalence across the categories. From the data of each category, we derived the solar diurnal variations of the relative muon intensity. The amplitude of the daily variation in solar diurnal anisotropy was calculated by dividing the difference between the highest and lowest relative normalized muon intensities by 2. The time corresponding to the highest intensity was considered as the phase of the solar-time anisotropy. Our detector measures muons in a direction-specific manner, but in this analysis, we utilized the results solely from muons that were detected perpendicular to the most statistically abundant detector. Through simulations, the median rigidity of primary cosmic rays that generate the vertical component of muons has been estimated to be 66 GV[2].

4. Results

Suppose we assume a balance between the advection and diffusion components and consider that the velocity of the solar wind determines the direction of the interplanetary magnetic field. In the case, fundamentally, the anisotropy of cosmic ray intensity is expected to primarily manifest as a co-rotating component oriented towards 18:00 (local solar time). Based on the solar wind velocity its amplitude and phase are believed to remain unchanged. The amplitude of cosmic ray muon intensity showed an increasing trend as the average velocity of the solar wind increased in the low to moderate velocity range. However, in the moderate to high-velocity range, it was found that the amplitude remained almost unchanged despite an increase in the average velocity. Furthermore, the phase of the cosmic ray muon intensity was observed to be aligned with local solar noon. As the average velocity of the solar wind decreased, it indicated a shift towards earlier phases.

The fact that the phase is shifted by approximately 6 hours from the position expected by the Parker model can be partly explained by the deflection of cosmic rays due to the Earth's magnetic field. In our simulations, the median rigidity of primary cosmic rays that generate muons entering the detector is estimated to be around 66 GV, and it is calculated that cosmic rays with this energy are deflected by approximately 3hours by the Earth's magnetic field.

In this analysis, the observation period of 22 years was treated as a single dataset. However, in future studies, we plan to perform data analysis in intervals of 11 years to coincide with the solar activity cycle. Alternatively, our detector can observe muons from various directions. Since the median energy of primary cosmic rays varies for each direction, we plan to utilize this capability to analyze the results by rigidity. This will allow us to gain further insights into cosmic ray anisotropy and expand our understanding of this field.

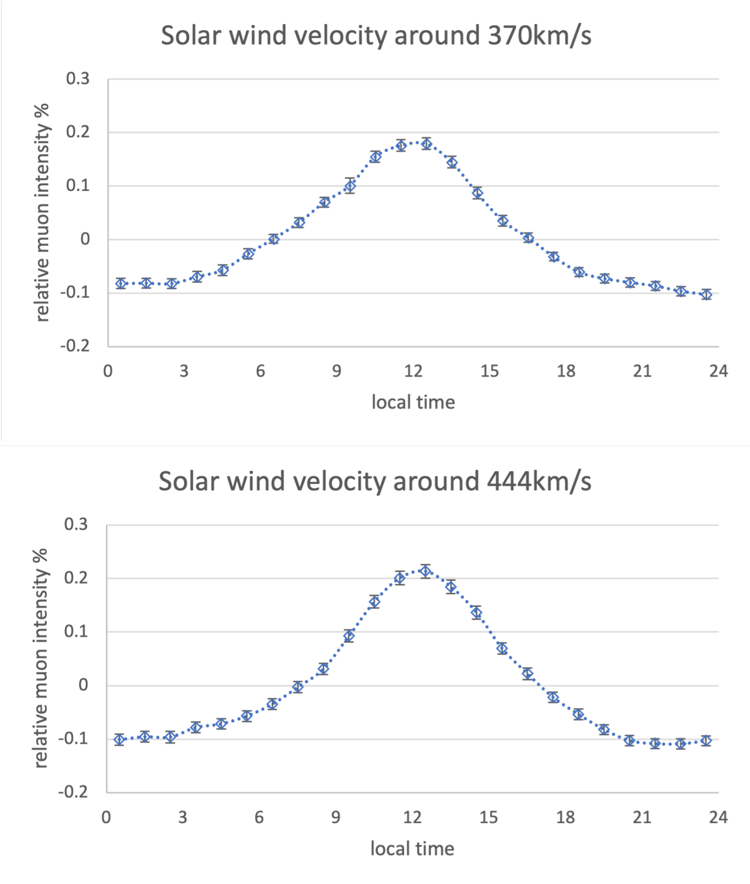

Figure 3: Cosmic ray intensity variation in local time categorized into the solar wind velocity of 370 km/s, 444 km/s with vertical error-bar

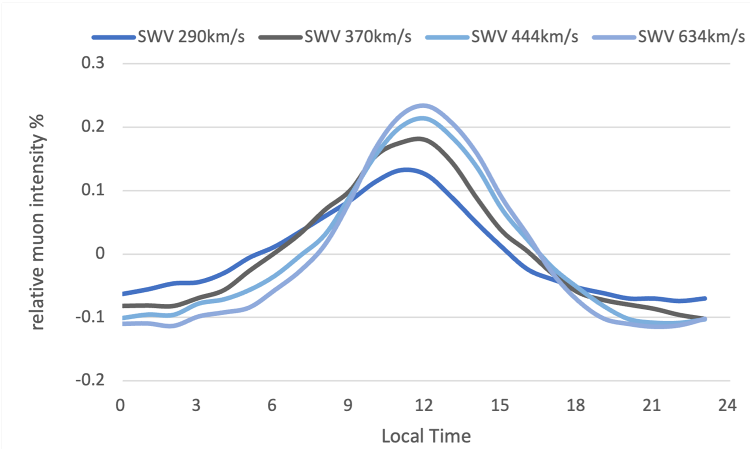

Figure 4: Cosmic ray intensity variation in local time categorized into the solar wind velocity of 290 km/s, 370 km/s, 444 km/s and 634 km/s without vertical error-bar

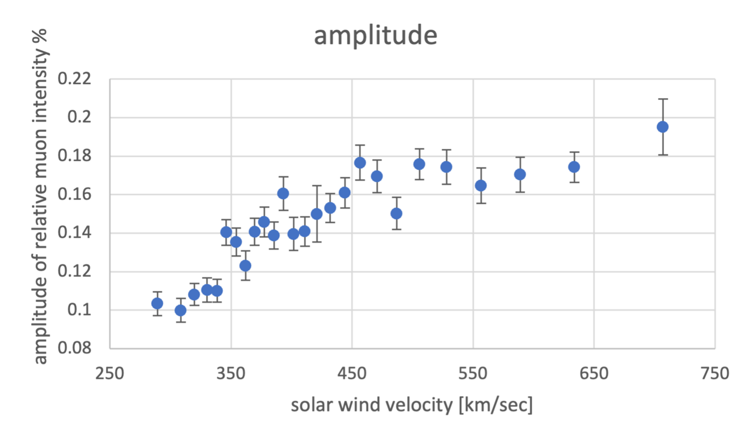

Figure 5: Dependency of the amplitude of cosmic ray variation in local time on the solar wind velocity.

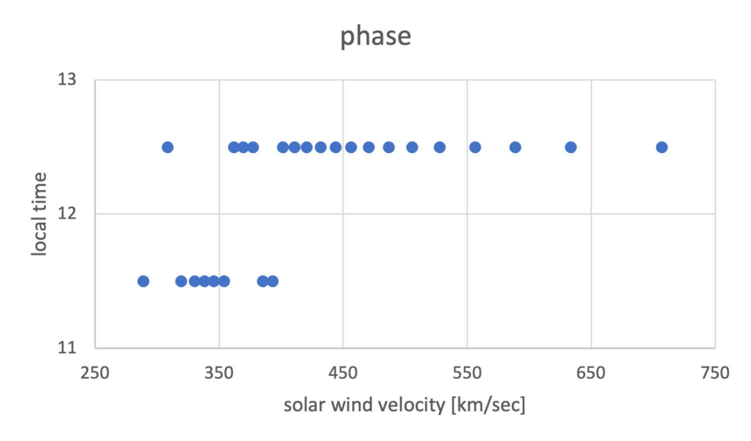

Figure 6: Dependency of the phase of cosmic ray variation in local time on the solar wind velocity.

Acknowledgments

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References

[1] Y. Hayashi et al.: A large area muon tracking detector for ultra-high energy cosmic ray astrophysics - the GRAPES-3 experiment. Nucl. Instrum. Methods A 545, 643 (2005)

[2] T. Nonaka: A study of loss-cone precursor decrease with grapes-3 muon telescopes (in japanese). PhD thesis, Osaka City University (2006)

[3] OMNI 2 Preparation. http://omniweb.gsfc.nasa.gov/html/omni2doc.html

[4] H. Kojima et al., Dependence of cosmic ray intensity on variation of solar wind velocity measured by the GRAPES-3 experiment for space weather studies , Phys. Rev. D 91 (2015) 121303(R)

[5] H. Kojima et al., Measurement of the radial density gradient of cosmic ray in the heliosphere by the GRAPES-3 experiment , Astropart. Phys. 62 (2015) 21.

[6] H. Kojima et al., Measurement of the radial diffusion coefficient of galactic cosmic rays near the Earth by the GRAPES-3 experiment, Phys. Rev. D 98, 022004 (2018)