

## Dependence of solar diurnal variation on solar wind speed

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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 (Kojima et al., 2018). In the present study, we used the same dataset for the years 2000-2015, covering about 5000 days and divided into 25 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 a positive correlation between the amplitude and phase of the flow of galactic cosmic rays perpendicular to the ecliptic plane, depending on the polarity of the IMF and the solar wind speed. 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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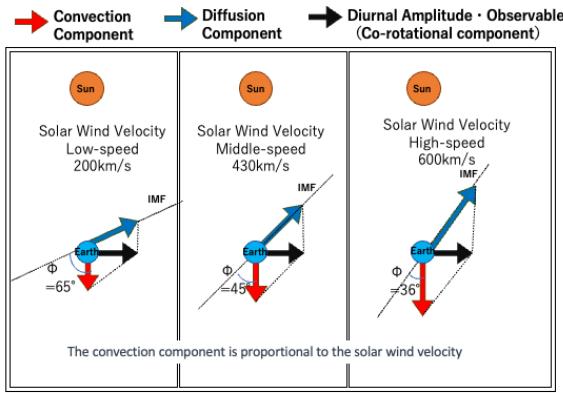


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## 1. Introduction

The anisotropy of cosmic rays near the Earth is explained based on Parker's cosmic ray transport theory called the diffusison-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 influence of the solar wind, this is the convection component, and the convection makes radial gradient of global cosmic ray density in heliosphere and This density gradient leads cosmic rays diffusely 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. Figure 1 presents an overview of the transport components, including convection, diffusion, and co-rotating components, in cosmic ray transport.

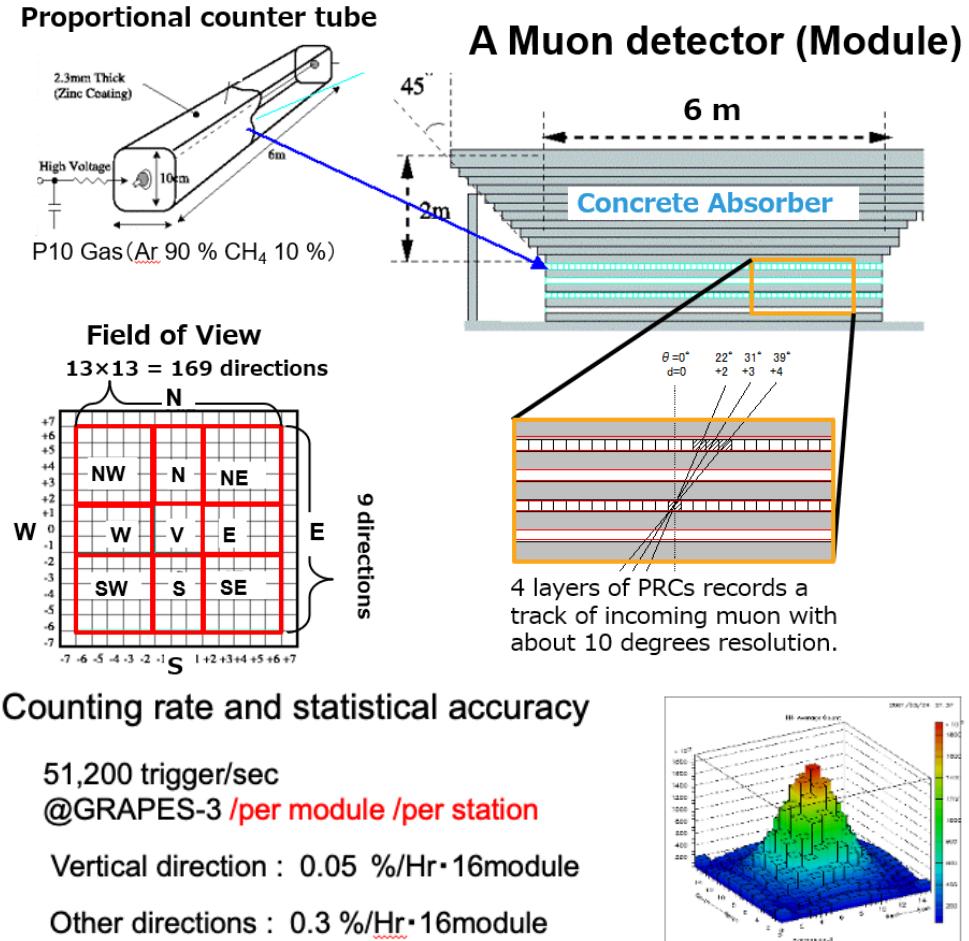


**Figure 1:** A schematic diagram illustrating the relationship between solar wind velocity, interplanetary magnetic field in the vicinity of Earth, and the transport components of cosmic ray transport including convection, diffusion, and co-rotating components.

## 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  $10\text{cm} \times 10\text{cm} \times 600\text{cm}$ . Within each module, there are 4 layers of 58 proportional counter tubes, arranged orthogonally along the main proportional counter tube. 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  $15 \times 15 = 169$  subdivisions and coarse directions of  $3 \times 3 = 9$  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 area of  $560 \text{ m}^2$  and this large surface area, facilitates high statistical observation capabilities. Typical counting rate of muon is 51,200 Hz. 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 multi-directional muon telescope of GRAPES-3 for the years 2000 to 2021 to investigate the solar diurnal variation of cosmic rays. We conducted an analysis 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 intervals to 1-hour intervals on a yearly basis, resulting in a set of 22 years of hourly data. From this, we calculated the annual average value and standard deviation ( $\sigma$ ) for the 1-hour data. If any hourly values deviated more than  $10\sigma$  from the average, they were marked as abnormal and

excluded from the analysis. After removing these abnormal data points based on the  $10\sigma$  criteria, we recalculated the annual average and standard deviation ( $\sigma$ ). If any hourly values still deviated more than  $5\sigma$  from the average, they were similarly removed. 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  $-0.12\%/\text{(hPa)}$  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.

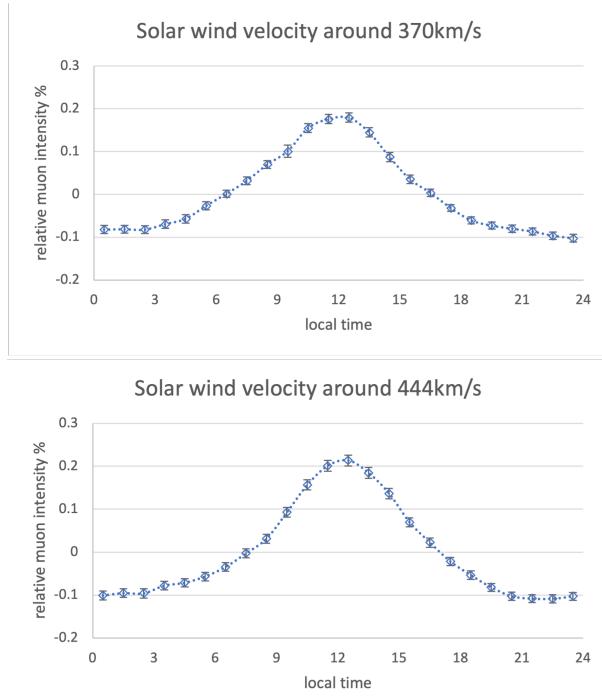
The data from the entire period was divided into 26 categories based on the daily average magnitude of solar wind velocity to ensure statistical equivalence across the categories. From the data of each category, we derived the solar diurnal variations of the relative muon intensity. The amplitude of 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. The median rigidity of primary cosmic rays that generate the vertical component of muons has been estimated to be 66 GV through simulations.

#### 4. Results

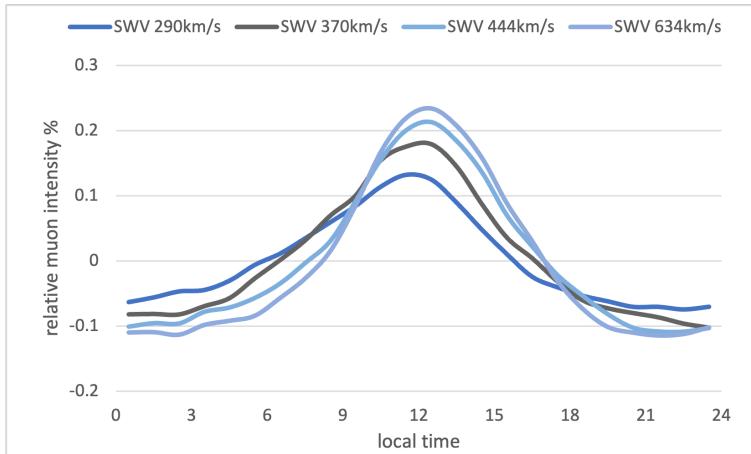
If we assume a balance between the advection and diffusion components and consider that the direction of the interplanetary magnetic field is determined by the velocity of the solar wind, fundamentally, the anisotropy of cosmic ray intensity is expected to primarily manifest as a co-rotating component oriented towards 18:00 (local solar time), and its amplitude and phase are believed to remain unchanged based on the solar wind velocity. 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, and 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 90 degrees 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 40 degrees 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 is capable of observing muons from various directions, and 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 in this field.



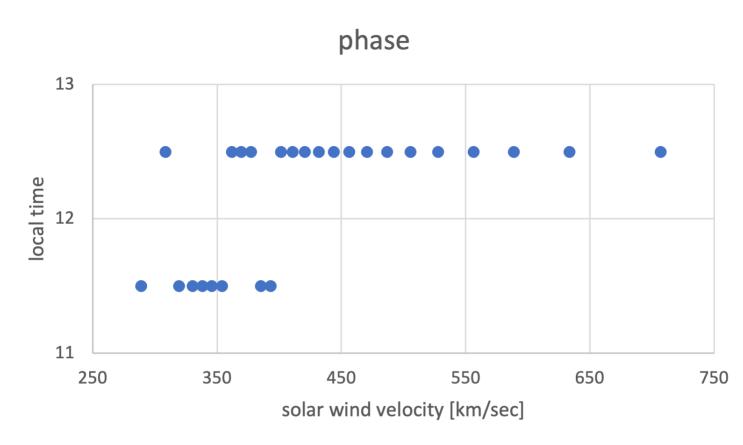
**Figure 3:** Cosmic ray intensity variation in local time categorized into the solar wind velocity of 370 km/s, 444 km/s with vertical error-bar



**Figure 4:** Cosmic ray intensity variation in local sidereal 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

## 5. Acknowledgement

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

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