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Diurnal anisotropy of polar neutron monitors: Dome C looks poleward

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Abstract

Galactic cosmic rays (GCR) exhibit a small local anisotropy observed as diurnal variability of ground-based neutron monitor (NM) count rates. Since the asymptotic directions of various NMs are different, their ability to observe the GCR diurnal variation also varies. Here we show that the Dome C (DOMC) NM is hardly sensitive to the diurnal variation, with its amplitude being 0.03%, in contrast to other polar NMs whose sensitivity to the diurnal variability ranges from 0.16 to 0.4%. We argue that this is related to the fact that DOMC NM has a narrow asymptotic-direction cone looking nearly to the South pole (geographic latitude above 75°). This makes the DOMC NM a unique detector being the only existing NM accepting cosmic-ray particles originating from the off-equatorial region. This is important for detailed studies of cosmic-ray transport in the vicinity of Earth, specifically for anisotropic solar energetic particle events.

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1. Introduction

The flux of galactic cosmic rays (GCRs) as measured by ground-based detectors is modulated by the Sun and its magnetic field on various time scales, one of which is diurnal variability, caused by the Earth's rotation around its axis (e.g., Ahluwalia and Dessler, 1962). The diurnal cosmic ray (CR) variability has been known since the early years of the CR measurements and reflects the local GCR anisotropy (see Section 2) usually described in terms of the diffusion-convection theory of the GCR interplanetary transport (e.g., Krymsky, 1964; Parker, 1964). The heliospheric transport of GCR particles is structured by expanding solar wind with the frozen-in magnetic field, concerning convection, diffusion, large-scale drifts and adiabatic cooling (Parker, 1965; Potgieter, 2013).

typically studied using data from ground-based neutron monitors (NMs) that, because of the Earth's rotation, scan the GCR flux from different directions in space and depict the anisotropy as the diurnal variability as shown in Fig. 1. Various properties of diurnal variation are broadly discussed in the literature (e.g., Tezari et al., 2016; Modzelewska et al., 2019; Modzelewska and Gil, 2021). For example, differences between epochs of the solaractivity cycle and heliospheric magnetic field (HMF) polarity were extensively studied (e.g., Sabbah, 2013; Tezari and Mavromichalaki, 2016; Thomas et al., 2017). The North-South asymmetry in diurnal amplitudes and phases was shown, e.g., by El-Borie et al. (2016). Relations between the magnitude of Forbush decreases and the amplitude of the diurnal variability have been also discussed (e.g., Belov et al., 2009; Lingri et al., 2019; Okike and Alhassan, 2021; Okike, 2021; Papailiou et al., 2021). Generally, the diurnal anisotropy of cosmic rays allows one to estimate the heliospheric GCR particles transport

The diurnal GCR variability (of low-rigidity GCRs) is

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Fig. 1. Hourly count rate of Oulu NM for the period of 20–31 January (DOY 20–31) of 2021 with a pronounced diurnal-wave 'train'.

parameters (e.g., Bieber and Chen, 1991; Hall et al., 1997; Ahluwalia et al., 2015).

However, not all NMs are sensitive to the local anisotropy. As we show here, the Dome C NM, installed at the Concordia station at the Central Antarctic plateau, does not show the diurnal variability, in contrast to all other NMs. In this paper, we analyze the diurnal GCR variability in the count rates of the Dome C NM and compare it with the data from other polar NMs, and argue that the lack of the diurnal variability of the Dome C NM reflects the fact that it looks poleward.

2. Local CR anisotropy

Most of the time, NMs count rates exhibit diurnal variability in the form of the so-called 'trains' of the diurnal waves, as exemplified in Fig. 1. Typical magnitude of the diurnal variability in NM count rates is a few percent but can be greater or smaller depending on exact conditions (e.g., Potgieter, 2013).

The diurnal variability is mostly related to the small true local anisotropy of GCR (e.g., Grieder, 2001) that is caused (see a schematic view in Fig. 2) by a combination of the radial away-of-the-Sun (from the direction of the local noon on Earth) convection by solar wind with the frozen-in magnetic field on one hand, and the inward diffusion along the HMF line from the direction of about 21 local time (LT), on the other hand. The resulting anisotropy vector is located in the late afternoon LT sector.

Because of the Earth's rotation, a ground-based detector scans the local space in the counter-clockwise directions and thus detects the anisotropy expressed as a nearlysinusoidal wave in the count rate. Because of the shift of the detector's asymptotic acceptance cone eastward (see Section 3), the maximum count rate appears earlier, around the afternoon local time.

On top of these regular mechanisms, the transient interplanetary effect can modify the local GCR anisotropy, viz. interplanetary coronal mass ejections, shocks, merged interaction regions, etc., distorting the regular pattern. The time period studied here corresponds to the late declin-



Fig. 2. Simplified not-to-scale scheme of the GCR anisotropy in the vicinity of Earth (denoted as the grey circle): the plot corresponds to the ecliptic plane as viewed from the north. Two main mechanisms (see text) are: radial outward convection by the solar wind and inward diffusion along the HMF line. The summary anisotropy vector is shown by the thick red arrow. Other mechanisms, e.g., the Earth's movement, are not shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ing and minimum phase of the solar cycle, which was quiet and generally not characterized by strong disturbances.

In addition to the true local CR anisotropy, there are some other effects contributing to the observed diurnal variability, but they are typically small. One is related to the orbital movement of Earth, so that more CRs are expected from the direction where the planet moves to (06 LT). Another type of diurnal variability can be related to the day-night variability of the terrestrial environment (e.g., Dorman, 2009): the difference in the geomagnetic rigidity cutoff and the meteorological conditions in the detector's location. The former is negligible for the polar NMs studied here, while the latter is standardly accounted for by the barometric correction. Thus, in this work, we refer mostly to the true local GCR anisotropy caused by the heliospheric transport of GCR.

3. Neutron monitor data

We consider here 1-h resolution data of efficiency- and pressure-corrected count rates of six NMs with the cutoff rigidity $P_c < 1$ GV, three in each polar region: Dome C, South Pole and Terre Adelie in Antarctica, and Thule, Apatity, and Oulu in Arctic. Details of the NMs, including their standard acronyms, are collected in Table 1. Data were obtained from http://cosmicrays.oulu.fi for DOMC and OULU, and from NMDB (https://www.nmdb.eu) for other NMs. Here we focus on the DOMC NM, which was installed at the Central Antarctic plateau in 2015 (scientific data available since March 2016) as two detectors

Table 1

Neutron monitors used in this study. Columns represent: (1) the NM name and standard acronym; (2) geomagnetic rigidity cutoff P_c in GV; (3) geographical coordinates of the NM location; (4) average diurnal amplitude $\langle A_1 \rangle$ (in %) for the period studied here.

NM	$P_{\rm c}$	Coordinates	$\langle A_1 \rangle$
Dome C (DOMC)	0	75.06° S, 123.20° E	0.03
Thule (THUL)	0	76.50° N, 68.70° W	0.17
South Pole (SOPO)	0.1	90.00° S	0.41
Terre Adelie (TERA)	0	66.65° S, 140.00° E	0.16
Apatity (APTY)	0.5	67.57° N, 33.40° E	0.30
Oulu (OULU)	0.7	65.05° N, 25.47° E	0.20

(see details in Poluianov et al., 2015): a standard mini-NM (an analogue of NM64) and a "bare" (lead-free) NM, called DOMC and DOMB, respectively. Here we focus on DOMC data since the count rate of DOMB NM is lower making the statistical significance of the diurnal variability determination poor.

The time of analysis is restricted by the Dome C NM data coverage, viz. from March 2016 through August 2021 (Similä et al., 2021) which includes about 50,000 hourly values. Fig. 3 displays the NM hourly count rates for each station, detrended using the high-pass FFT filter (cutoff period of 2 years). The data contain some gaps that account for about 2% for Dome C, South Pole and Terre Adelie NMs, $\approx 0.4\%$ for Thule NM, $\approx 0.5\%$ for Apatity, and $\approx 0.008\%$ for Oulu NM.

The Earth's magnetic field governs the propagation of cosmic rays, specifically with low rigidities, in the vicinity of our planet. Therefore, for a realistic study of different CR phenomena and related effects, specifically with ground-based instruments such as NMs, it is necessary to possess a detailed knowledge of their propagation in the geomagnetosphere (e.g. Smart et al., 2000; Bütikofer, 2018, and references therein). The Earth's magnetic field determines, considering the energy and the incidence direction of CR particles, the CR access to a specific point, where the detector is located. The magnetospheric transmissivity and the access of CR to a given location on the Earth are quantified by the cut-off rigidity (P_c) and the concept of asymptotic direction (AD) (for details see Cooke et al., 1991). Here we computed the asymptotic directions of all the NMs considered in our analysis, as shown in Fig. 4. The magnetospheric computations were carried out using the MAGNETOCOSMICS code, explicitly considering the measured K_p index corresponding to the exact period of the NMs records (Desorgher et al., 2005). During the computation, a combination of the IGRF geomagnetic model (epoch 2015) as the internal field model (Thébault et al., 2015) and the Tsyganenko 89 model as the external field (Tsyganenko, 1989) were employed, providing a straightforward depiction of ADs of all NMs used in our analysis (Kudela and Usoskin, 2004; Kudela et al., 2008; Nevalainen et al., 2013). One can see in Fig. 4 that ADs are displaced eastward and equatorward off the real NM location, with the displacement reduced with increasing



Fig. 3. High-pass (2 years) filtered hourly count rates, for the period 16-Mar-2016–31-Aug-2021, for six neutron monitors studied here: DOMC (a), OULU (b), THUL (c), SOPO (d), APTY (e), and TERA (f).



Fig. 4. Asymptotic directions of the polar NMs considered here are represented by colored curves, as denoted on the top. Computations were made using the MAGNETOCOSMICS code for the date of 22-Aug-2016 for GCR particles with rigidity between 1 and 20 GV as denoted by the numbers near each curve. Locations of the geomagnetic poles (IGRF, epoch 2020) are indicated by stars. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

energy/rigidity of CRs (for details see Bieber and Evenson, 1995; Smart et al., 2000; Mishev and Usoskin, 2020, and references therein). Thus, most of the polar NMs actually accept lower-energy CRs from the tropical regions and thus scan the space as Earth rotates. Interestingly, even the SOPO NM, located at the geographical South pole, has AD at mid-latitudes (30–60°S). It is only

DOMC NM whose AD lies in the polar region (above 70° latitude even for low-energy particles).

4. Methods

4.1. Diurnal amplitudes

For the analysis, we used 1-h data $x(t_n)$ from six NMs as described in Section 3. First, the data were de-trended by removing the 25-h running mean. This running mean was used to exclude trends larger than the diurnal wave. The cosmic rays de-trended intensity oscillates around zero, which is crucial for a further analysis. Then, the Fourier analysis method (e.g., Xue and Chen, 2008) was applied to the data:

$$x(t_n) = \frac{a_0}{2} + \sum_{k=1}^{T/2} \left(a_{r_k} \cos \frac{2\pi k t_n}{T} + a_{\phi_k} \sin \frac{2\pi k t_n}{T} \right), \tag{1}$$

For each calendar day, amplitudes of the harmonics were calculated as

$$A_k = \sqrt{a_{r_k}^2 + a_{\phi_k}^2},$$
 (2)

where

$$a_0 = \frac{1}{T/2} \sum_{n=1}^{T} x(t_n), \tag{3}$$

$$a_{r_k} = \frac{1}{T/2} \sum_{n=1}^{T} x(t_n) \cos \frac{\pi k t_n}{T/2},$$
(4)

and

$$a_{\phi_k} = \frac{1}{T/2} \sum_{n=1}^{T} x(t_n) \sin \frac{\pi k t_n}{T/2}$$
(5)

are the coefficients of the Fourier series, T is equal to 24 h. Here we refer only to A_1 as the index of the amplitude of the diurnal variability. Days with data gaps longer than several (>4) hours were excluded from the analysis. Shorter gaps were filled by the Lagrange interpolation (e.g., Ern and Guermond, 2021) and processed as normal. At the following step, days with the A_1 amplitudes greater than 0.7% were excluded from further consideration as generally related to transient interplanetary disturbances rather than to the regular anisotropy (e.g., Modzelewska and Alania, 2018).

4.2. Power spectral density

To study more details of the characteristics of the diurnal variability we used the Lomb–Scargle periodogram (Lomb, 1976; Scargle, 1981), where the power is defined in the following way:

$$P(\omega) = \frac{1}{2} \left\{ \frac{\left[\sum_{j}^{N} x_{j} \cos \omega(t_{j} - \tau)\right]^{2}}{\sum_{j}^{N} \cos^{2} \omega(t_{j} - \tau)} + \frac{\left[\sum_{j}^{N} x_{j} \sin \omega(t_{j} - \tau)\right]^{2}}{\sum_{j}^{N} \sin^{2} \omega(t_{j} - \tau)} \right\}$$
(6)

where x_j is the measured value taken at the times t_j , N is the number of the data set elements, and ω is the angular frequency. The time offset τ is defined as:

$$\tan(2\omega\tau) = \frac{\sum_{j=1}^{N} \sin(2\omega t_j)}{\sum_{j=1}^{N} \cos(2\omega t_j)}.$$
(7)

The power spectral density (PSD) was obtained using the normalised (viz. divided by the average count rate for each NM during the studied period) NM data.

5. Results

Fig. 5 displays the calculated A_1 amplitudes of GCR diurnal variability for the six NMs considered here. The average amplitudes, shown as blue dashed lines, are listed in the last column of Table 1. One can see that the amplitudes of diurnal variation oscillate around the mean values



Fig. 5. Amplitudes of the diurnal variability calculated here (Section 4.1) for the period of 16-Mar-2016–31-Aug-2021 for six NMs: DOMC, OULU, THUL, SOPO, APTY, and TERA (panels a–f, respectively). The blue dashed line denotes the mean amplitude for each NM. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ranging between 0.1% and 0.4% for five NMS, while it is very small, 0.03%, for DOMC. Interestingly, SOPO NM, located at the geographical South Pole, exhibits the greatest mean A_1 value among all the studied stations. The obtained amplitudes are in general agreement with the values characteristic for descending and minimum phases of the solar activity cycle (see Fig. 1 in Tiwari et al., 2012), except for DOMC NM.

In the following, we analyze the diurnal anisotropy measured at DOMC NM with more details. It is interesting that, while the A_1 amplitude is very stable and low for



Fig. 6. Asymptotic directions for DOMC NM for selected periods as denoted in the legend. The notations are as in Fig. 4.



Fig. 7. Power spectral density of the count rates for the six NMs: DOMC, OULU, THUL, SOPO, APTY, and TERA (panels a–f, respectively) for the time interval between 16-Mar-2016–31-Aug-2021 around the 24-h period.

DOMC (Fig. 5a), there are apparent peaks ca. 2017 and early 2019, but it is very stable after March 2019. For each of such periods of the enhanced daily variability, we computed the asymptotic directions of DOMC NM for the day with the highest amplitude, as shown in Fig. 6. By comparing these ADs with those for the quiet period (Fig. 4), one can see that the low-rigidity (≈ 1 GV) tail of AD slightly moves to lower latitudes during the disturbed periods increasing the diurnal-wave amplitude.

To estimate the level and the very existence of the diurnal GCR variability, we used the Lomb-Scargle analysis as described in Section 4.2. The power spectral density is shown in Fig. 7 for the period range 24 ± 0.5 h. While most of the data from other NMs exhibit a sharp peak exactly at 24 h, the PSD estimate for the DOMC NM (Fig. 7a) yields only a broad and very weak increase at around 24 h. This broad peak can be related to a slight dependence of the DOMC efficiency on the temperature inside the station building during the austral summer. Although the data are routinely corrected for the barometric pressure and indoor temperature, the correction could be not perfect, giving rise to the small variability. We note that since March 2019, when the upgraded data acquisition system (Strauss et al., 2020) had been installed at DOMC NM, the A_1 amplitude is very stable and small (Fig. 5a).

6. Discussion and conclusions

We have demonstrated that DOMC is the only NM with nearly absent diurnal variability in its data. This is explained by the fact that this NM looks nearly vertically to the South-pole direction (latitudes above 75° south), as confirmed by the computations of its AD. Other NMs, not explicitly considered here, have acceptance cones in the equatorial region - see, e.g., the results of previous analyses (Mishev et al., 2018; Mishev et al., 2021). Accordingly, DOMC is the only NM which can probe propagation CR perpendicular to the equatorial plane.

The global NM network within the geomagnetic field can serve as a giant spectrometer, using the Earth's rotation to scan the space and evaluate the cosmic-ray anisotropy (see the "Spaceship Earth" concept, Bieber and Evenson, 1995). This is crucially important to study cosmic-ray transport in the heliosphere (e.g., Bieber and Chen, 1991; Ahluwalia et al., 2015). This is also important for the study of low-energy cosmic rays, specifically for strong and hard-spectrum solar energetic particle (SEP) events called ground level enhancements (GLEs) (Shea and Smart, 1982; Bieber and Evenson, 1995; Poluianov et al., 2017; Mishev et al., 2021). Thus, NMs located at different locations with the corresponding rigidity cut-offs are sensitive to different parts of the incoming CR-particle spectrum and arrival direction since the response of each station depends on its location, particle rigidity, altitude and the angle of incidence of the incoming SEPs (e.g. Miroshnichenko, 2018). However, because of the focusing effect of the geomagnetic field, all NMs are sensitive to energetic particles entering the Earth's magnetosphere near the ecliptic plane and are not well-suited to measure the offplane anisotropy, which may be dramatic for some impulsive SEP events (e.g., GLE#69 on 20-Jan-2005, Bütikofer et al., 2009). Because of the specifics of the current NM network, an optimization and a need for a reference detector has been recently discussed (e.g. Mishev and Usoskin, 2020).

Taking into account the very small diurnal variations of DOMC data, its relatively narrow AD cone that provides better angular resolution compared to the bulk of NMs, which is specifically important for GLE analysis (e.g. Bieber and Evenson, 1995), we can consider DOMC as a reference station in the optimized global NM network (e.g. Mishev and Usoskin, 2020), towards providing early space radiation alerts and corresponding analysis of solar proton events (Souvatzoglou et al., 2014; Mishev et al., 2017). Therefore, DOMC is crucially important station for sustainable operation and space weather services of the global NM network (e.g. Mavromichalaki et al., 2004).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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