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STUDYING DYNAMICS OF ENERGY SPECTRUM OF SOLAR DIURNAL VARIATIONS IN COSMIC RAYS DURING SOLAR ACTIVITY CYCLES 20–25, USING METHOD OF CROSSED MUON TELESCOPES

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Abstract. The cosmic ray (CR) intensity recorded by ground-based detectors experiences solar diurnal variations (SDVs) associated with the existence of anisotropic angular distribution of CRs in near-Earth space. Long-term observations show that SDVs exhibit a dependence on the solar activity cycle, experiencing periodic 11- and 22-year variations. Such behavior of SDVs is linked to a change in the nature of galactic CR propagation in the heliosphere when it changes during a solar activity cycle. On the other hand, this phenomenon can be partially due to a change in the magnitude of CR drift by the geomagnetic field associated with changes in the SDV energy spectrum.

In this work, we determine the dynamics of the SDV energy spectrum in solar activity cycles. The solution to this problem presents certain difficulties associated with peculiarities of ground-based CR recording and with the sensitivity of CR detectors to changes in the state of environment. Therefore, we employ an approach using crossed muon telescopes to estimate it, which allows us to bypass the above difficulties. We analyze data from Yakutsk, Nagoya, Sao Martinho, and Hobart muon telescopes for 1972–2022. It is shown that at solar minima during periods of positive polarity of the Sun's general magnetic field, a significant softening of the spectrum is observed. The results are discussed.

Keywords: cosmic rays, solar diurnal variation, energy spectrum, muon telescope.

INTRODUCTION

Galactic cosmic rays (GCRs), which propagate in the heliosphere, are continuously exposed to the interplanetary magnetic field (IMF) and the solar wind. The result of this interaction is the anisotropy of angular distribution of GCRs, which is observed in near-Earth space. This distribution is manifested in measurement data from ground-based cosmic ray (CR) detectors as periodic 24-hr variations in recorded intensity, called solar-diurnal variations (SDVs). It is known that amplitudes of these variations are, on average, tenths of the total intensity, and the maximum of the diurnal wave occurs at 18 LT. Nevertheless, in the solar cycle SDV parameters undergo significant changes due to changes in the state of the Sun and hence in the entire heliosphere.

Since the beginning of SDV research by ground-based detectors, the main problem has been to determine the anisotropy of primary CRs in interplanetary space. It is complicated by the fact that the approach to determining the CR anisotropy is based on the need to cover a sufficiently large area of the celestial sphere by using a large number of detectors located in different parts of the planet, often heterogeneous. In addition, the sensitivity of secondary CRs to changes in atmospheric parameters is also a serious obstacle. Furthermore, ground-based CR detectors as integrated devices that detect all particles regardless of their energy have limitations in studying the energy spectrum of anisotropy. Since GCRs are charged particles, the geomagnetic field has a significant effect on them: it changes the trajectory of the particles, and for some of them it becomes an insurmountable obstacle and leads to the formation of directions unavailable for propagation. Therefore, the use of observational data by ground-based instruments requires an understanding of the interaction of CRs with the geomagnetic field and Earth's atmosphere.

One of the most developed methods for determining the spatial-angular distribution of CRs in the interplanetary medium from ground-based measurements is the so-called method of receiving vectors (also referred to as coupling coefficients) [Krymsky et al., 1966, 1967; Fujimoto et al., 1984], which is based on general ideas about the interaction of CRs with the atmosphere and the geomagnetic field. The method allows us to take into account the individual receiving characteristics of a detector and to estimate all possible distorting factors to define the CR distribution. The only free parameter for this method is the energy spectrum of variations, which is found by analyzing a large amount of data over a long period of time.

It is also important for ground detectors to take into account the so-called temperature effect — the effect of the atmospheric temperature regime on generation and propagation of secondary CRs to the observation point. This is most evident in the muon component of CRs. Accounting for this phenomenon requires knowledge of densities of temperature coefficients [Dorman, 1957] and the atmospheric temperature profile. Densities of temperature coefficients are calculated theoretically, and the altitude variation of temperature requires constant measurements with balloon probes over the observation point. Such measurements are currently performed only twice a day, which does not allow us to consider the temperature effect with sufficient accuracy. Despite the development of modern remote sensing methods [Berkova et al., 2018] and ground-based indirect measurements of atmospheric parameters [Nikolashkin et al., 2020], it is still urgent to solve this problem. An original and reliable way to circumvent this problem is to apply the method of crossed telescopes proposed at SHICRA SB RAS sixty years ago [Skripin et al., 1965; Skripin, 1965].

Traditionally, measurements with high-, mid-, and low-latitude neutron monitors, as well as ground and underground muon telescopes, are employed to determine the SDV energy spectrum [Rao et al., 1983; Riker et al., 1989; Ahluwalia, Sabbah, 1993; Pomerantz, Duggal, 1971]. Implementation of this approach made it possible to identify both the type of spectrum and its dynamics in the solar activity cycle. SDVs were demonstrated to weakly depend on CR energy and to remain constant up to a certain energy (upper cutoff) that averages ~100 GeV and varies in a cycle. The amplitude of these variations varies according to different estimates: for example, Hall et et al. [1997] have shown that the upper cutoff is 100±25 GeV; Ahluwalia [1992] has indicated that it varies between 50 and 200 GeV depending on IMF strength. Presumably, the difference in estimates lies in the fact that different time intervals with arrays of stations scattered around the planet and equipped with CR detectors of different types are studied. This approach has some disadvantages: insufficiently accurate consideration of atmospheric factors and individual characteristics of detectors of different types inevitably causes considerable uncertainties. In this work, the method of crossed muon telescopes is adopted which allows us to take this disadvantage into account and estimate the SDV energy spectrum most reliably.

DATA AND METHOD

We have used data from the Nagoya, Hobart, and Sao Martinho muon telescopes of the global network GMDN [Okazaki et al., 2008; https://cosray.shinshu-u.ac.jp/crest/DB/Public/main.php], as well as the muon telescope of the Yakutsk CR spectrograph located on the Earth surface [Chuprova et al., 2009; https://ysn.ru/ipm /]. The main characteristics of the detectors are shown in Table.

Basic characteristics of the muon telescopes used in this work

Station	Direction	Geographic location	Period of recording	Count rate, imp/hr (on Jan. 01, 2018)	Statistical accuracy of 1-hr recording, %
Yakutsk	N30	62° N, 129° E	1972–2023	321000	0.17
	S30			322000	0.17
Nagoya	N2	35° N, 137° E	1971–2023	1356000	0.09
	S2			1340000	0.09
Hobart	N2	43° S, 147° E	2006–2023	620000	0.12
	S2			583000	0.12
Sao Martinho	N2	29° S, 306° E	2006–2023	891000	0.11
	S2			916000	0.10

In this work, the original method of crossed telescopes was employed to determine the SDV energy spectrum [Skripin et al., 1965]. It is based on the fact that the contribution of atmospheric factors to data from a pair of telescope directions having identical directional diagrams, but spaced in azimuth, proves to be the same. Therefore, the difference between intensities recorded by a pair of crossed telescope directions contains variations exclusively of extra-atmospheric origin due to the difference in sensitivity to primary CR anisotropy.

In this paper, we propose an approach that differs somewhat from the original method of crossed telescopes, but allows us to indirectly estimate the energy spectra of CR variations. Figure 1 exemplifies asymptotic angles of particle arrival from the north and south directions, calculated using the method of inverse trajectory calculations [Dorman et al., 1971]. It is evident that in general CRs experience a drift toward the equator by the geomagnetic field, which depends both on the detector energy and geographic location. In this case, the relationship between the asymptotic angles of particle arrival and observed SDVs is as follows: the latitude of the angle of particle arrival Φ defines the amplitude of variations as $\cos\Phi$; and the longitude Ψ, the SDV phase.

Accordingly, the phase difference $\Delta\Psi(E)=\Psi_N(E)-\Psi_S(E)$ between the north and south detection directions depend on CR energy, as well as the ratio of their amplitudes $\alpha(E)=\cos\Phi_N/\cos\Phi_S$. Thus, the use of crossed telescopes makes it possible to estimate energy spectra of CR variations without employing a large number of different detectors.

To accurately estimate the energy spectrum, we take into account the individual characteristics of the detectors with the receiving vector method [Krymsky et al., 1966, 1967], using the expression

$$z_n^m = x_n^m + iy_n^m = \frac{\int_{R_c}^{\infty}\int_0^{2\pi}\int_0^{\frac{\pi}{2}} W(E,\theta) f_n(E) N(\theta,\varphi) e^{im\Psi(E,\theta,\varphi)} P_n^m(\sin\Phi(E,\theta,\varphi))\, dE d\varphi d\theta}{\int_{R_c}^{\infty}\int_0^{2\pi}\int_0^{\frac{\pi}{2}} W(E,\theta) f_n(E) N(\theta,\varphi)\, dE d\varphi d\theta},$$

where θ, φ are zenith and azimuth angles; E is the particle energy; $N(\theta, \varphi)$ are the detector's directional diagrams; $W(E, \theta)$ are coupling coefficients; $f_n(E)$ is the energy spectrum of the nth harmonics of CR variations.

Thus, by comparing pairs of crossed (north and south) directions of muon telescopes, we can calculate the expected values of the phase difference ΔΨ and the phase ratios α: $\alpha = \left|z_1^1\right|_{\rm S} / \left|z_1^1\right|_{\rm N}$, $\Delta\Psi = \Psi_{\rm N} - \Psi_{\rm S}$, where $\Psi = \arctan\left(y_1^1 / x_1^1\right)$.

When calculating ΔΨ and α, we assume that the energy spectrum has the form $f_1(E \le E_0) = const$ and $f_1(E > E_0) = 0$, where E_0 is the upper cutoff we set. The results are presented in Figure 2.

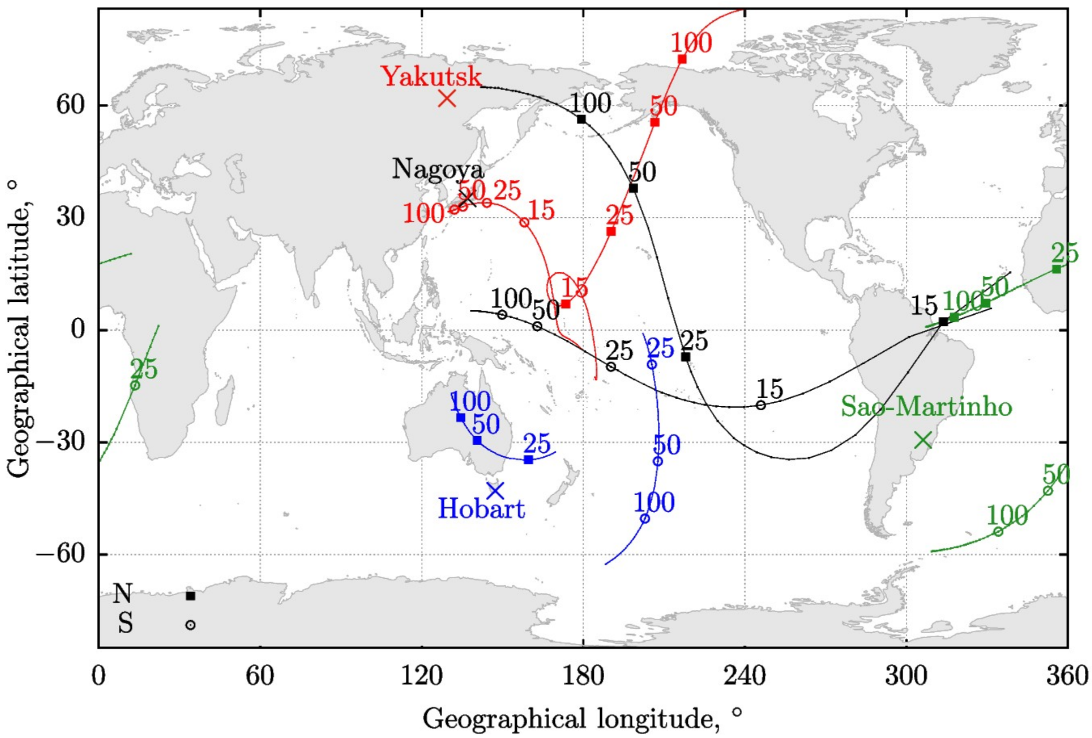

Figure 1. Asymptotic angles of particle arrival in the north and south directions at zenith angles of 30° of the muon telescopes Yakutsk, Sao Martinho, Nagoya, and Hobart. Numbers near dots denote energy (GV). Station locations are marked with crosses

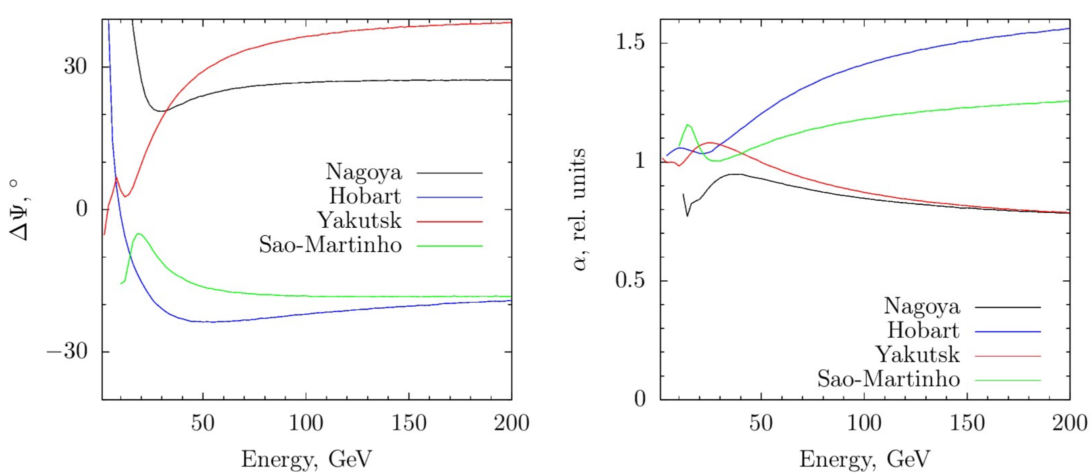

Figure 2. Results of calculation of ΔΨ and α at different E_0 values

The parameters ΔΨ and α for all stations are seen to be ambiguous in the energy range $E_0 \lesssim 50$ GeV. The north-south asymmetry of ΔΨ and α for $E_0 \gtrsim 50$ GeV is expected and determined by the geomagnetic field structure. At energies above 150 GeV, the E_0 dependence of the parameters disappears due to an increase in the transparency of the geomagnetic field for CRs of such energies. Below, we estimate E_0 by comparing the ΔΨ and α values we calculated with those observed using the least square method.

RESULTS AND DISCUSSION

The results of calculations of ΔΨ and α are compared with observations by crossed muon telescopes in Figure 3. You can see that E_0 experiences 22-year variations, averaging 80 GeV and undergoing a short-term decrease to 20 GeV at solar minima during epochs of positive polarity of the Sun's general magnetic field. This behavior of E_0 is consistent with the muon telescope measurements, satisfactorily describing the ΔΨ and α variations. High E_0 in 1980–1991 as compared to the rest of the period was obviously caused by the following reasons: when estimating E_0 before 2005, only two stations, Yakutsk and Nagoya, participated in the analysis; before 1990, the Yakutsk muon telescope had a relatively low statistical accuracy; at energies >100 GeV, the dependences of ΔΨ and α on E_0 began to weaken, so the ambiguity in estimating E_0 increased. It is therefore fair to assume that such high E_0 values during these years are determined by these factors. Nevertheless, the same data allows us to argue that the given period was characterized by relatively high E_0.

Such a dramatic decrease in E_0 to 20 GeV is unexpectedly low, although it is consistent with the results received in [Ahluwalia, Sabbah, 1993]. With such a soft spectrum, SDVs should not be observed by CR detectors insensitive to such energies. Indeed, low-latitude neutron monitors with large geomagnetic cutoffs detect a relatively larger amplitude decrease and phase shift during these periods than high-latitude ones [Sabbah, 2013]. Moreover, underground muon telescopes should not detect SDVs during these periods. However, as shown in [Munakata et al., 2010], the muon telescope at Matsushiro station with a median energy of 0.6 TeV recorded statistically significant SDVs with ~0.04 % amplitudes, which though are associated with the generation of anisotropy by the interaction of GCRs with the heliospheric neutral sheet forming SDVs in the energy range >100 GeV [Kóta et al., 2008].

Particular attention should be given to the shape of the SDV energy spectrum. The spectrum with the upper cutoff considered in this work has no theoretical basis, yet, as shown in [Rao et al., 1983; Riker et al., 1989; Ahluwalia, Sabbah, 1993; Pomerantz, Duggal, 1971; Hall et al., 1997; Ahluwalia, 1992], it most closely corresponds to measurement data. Indeed, our calculations we carried out outside the scope of this work, using the SDV spectrum described by the power-law function, show a lower degree of agreement with observations. Nonetheless, it is impossible to exclude the possibility that the spectrum may have a different shape and change during a solar cycle.

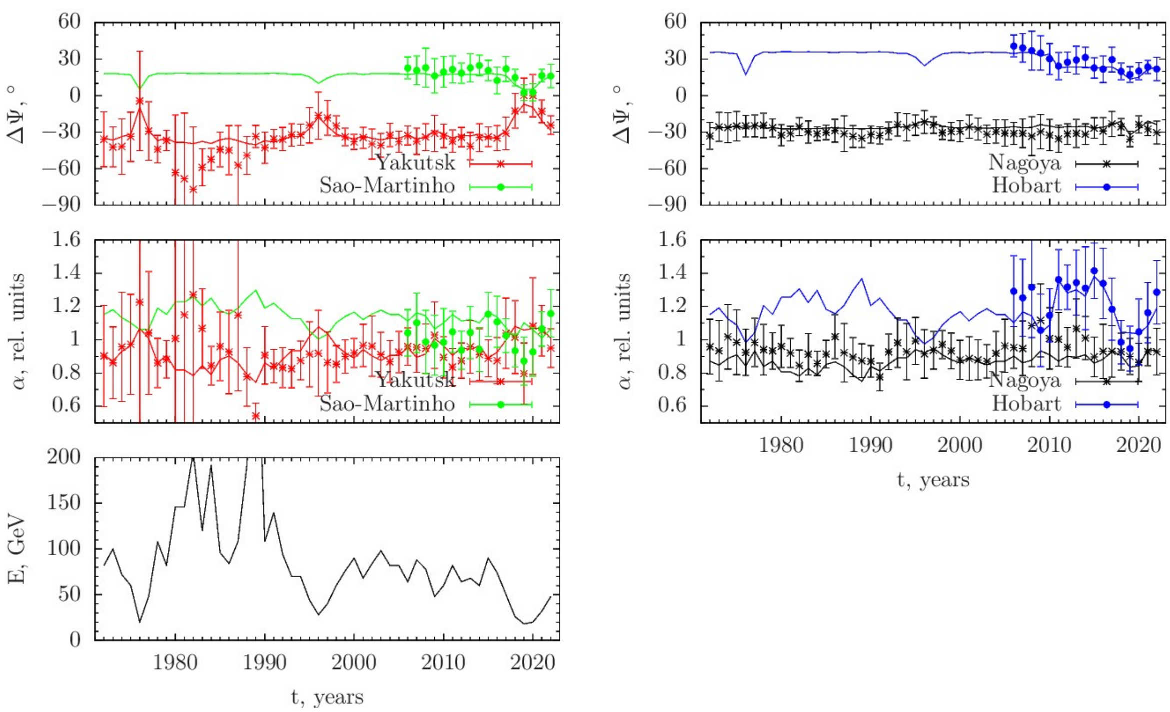

Figure 3. Comparison of calculated ΔΨ and α with those observed by the crossed muon telescopes Yakutsk, Sao Martinho, Nagoya, and Hobart, as well as the results of estimates of the upper cutoff of E_0 for 1972–2022

As is known, the dependence of the heliospheric modulation of GCRs on the sign of the Sun's general magnetic field is due to their drift. In the epochs of positive polarity, the drift is directed from high to low solar latitudes [Gerasimova et al., 2017], and in the epochs of negative polarity; vice versa. This behavior is quite well manifested in the data on 11-year CR intensity variations [Gololobov et al., 2020]. The detected SDV energy spectrum softening during these periods may be linked to this phenomenon.

CONCLUSIONS

Using the method of crossed telescopes, we have estimated the dynamics of the SDV energy spectrum during solar cycles 20–25. It has been established that during solar minima with a positive polarity of the Sun's general magnetic field there is a significant SDV energy spectrum softening. Taking into account the sign dependence of the spectrum, we can conclude that the nature of its softening is related to the GCR drift in the heliosphere. The results can serve as an additional source of information when developing the theory of heliospheric GCR modulation.

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