Dynamics of energetic spectrum of solar-diurnal variations of cosmic rays in 19-24 solar activity cycles

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Abstract

The anisotropic angular distribution of cosmic rays (CR) in the interplanetary medium manifests itself on Earth as periodic diurnal intensity variations. Ground-based detectors of CRs have different energy sensitivity to the primary CR radiation and, therefore, the amplitude and phase recorded by them are also different. This fact makes it possible to study the energy spectrum of the variations when using a sufficient number of detectors. In this work, the results of the investigation of the energy spectrum of solar-diurnal variations of CRs obtained by a network of neutron monitors and muon telescopes are presented. The network allows measuring CRs with median energies from units to hundreds of GeV. The expected values of the amplitude and phase of the daily CR variations at the selected ground-based stations for different types of the energy spectrum are shown. The calculated data are compared with experimental data for 19-24 solar activity cycles.

1. Introduction

The flux of galactic cosmic rays (CR) observed in near-Earth space is anisotropic. CR detectors located on Earth register such anisotropy as a periodic 24-hour variation of intensity, which is commonly called solar-diurnal variations (SDV). It is known that SDV reaches a maximum at 18:00 of local time and has an amplitude of about 0.5 % of the total CR intensity. SDVs are observed in a wide range of energies and are found in the data of CR detectors located both high in the mountains and deep underground. At the same time, the SDV amplitude decreases with increasing energy and, according to neutron monitors (NM) data, is about $\sim$ 0.5 % (Munakata et al. 2014), and according to the underground muon telescope Matsushiro at a depth of 220 m w.e. (meters of water equivalent) - only $\sim$ 0.05 % (Munakata et al. 2010). At the same time, the exact form of the SDV energy spectrum remains insufficiently studied so far. In Ahluwalia & Ericksen (1971), Ahluwalia & Riker (1987), Jacklyn et al. (1969) and Pomerantz & Duggal (1971) an SDV rigidity spectrum was studied. For simplicity, we assume that CRs consist exclusively of protons. Then the rigidity spectra proposed in the above works can ber converted to the following form of the SDV energy spectrum

$$f_{SDV}(E) = \begin{cases} E^{\beta}, & if \ E \le E_u, \\ 0, & if \ E > E_u \end{cases}$$

(1)

where the parameters E_u and β could be found by comparing the experimental data with theoretical calculations. The above studies showed that the spectrum most likely has the parameters β = 0 and E_u = 100 GeV, where the latter can vary depending on the solar activity cycle, reaching 50 GeV at the minimum and 150 GeV at the maximum. A later attempt (Hall et al. 1997) showed that β also ranges from -0.3 to +0.5. Also, Ahluwalia (1992) showed that E_u has a functional relationship with the strength of the interplanetary magnetic field.

This work aims to study the SDV energy spectrum (1) using measurements of ground-based and underground CR detectors based on general ideas about the interaction of CRs with the geomagnetic field and the Earth's atmosphere. At the same time, the dynamics of the spectrum with the solar activity cycle is also considered.

2. Determination of the SDV energy spectrum

2.1. Data and methods

The list of ground-based CR detectors used in this work is presented in the table 1. It includes 7 NMs located in high-, mid- and low-latitude regions of the Earth, as well as 7 ground-based and underground muon telescopes (MT). Such a set of detectors makes it possible to cover the region of median energies Emed from a few to hundreds of GeV.

The CR intensity recorded by the i-th ground-based detector can be expressed as a series of spherical harmonics as follows:

$$I^i = \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(a_n^m x_n^{m,i} + b_n^m y_n^{m,i} \right),$$

(2)

where $x_n^{m,i}$, $y_n^{m,i}$ are components of the so-called receiving vector $\boldsymbol{R}_n^{m,i}$, a_n^m and b_n^m are the components of the multidimensional distribution vector of the CR $\boldsymbol{A}_n^m$ (Krymsky et al. 1966, 1967). In the framework of this work, we will limit ourselves to considering the equatorial components of the diurnal anisotropy, namely a_1^1 and b_1^1, since they are easiest to observe in an experiment.

№	Station name, detector type	Abbreviation	Geographical coordinates	Altitude, m / depth, m w.e. (water equivalent)	Cutoff rigidity, GV	Emed, GeV
1	Apatity NM	APTY	67.55N 33.33E	177	0.57	15
2	Climax NM	CLMX	39.37N 106.18W	3400	2.99	11
3	Lomnicky stit NM	LMNC	49.20N 20.22E	2634	3.98	13
4	Yakutsk NM	YKTK	62.01N 129.43E	105	1.65	16
5	Thule NM	THUL	76.50N 68.7W	26	0.00	16
6	Rome NM	ROME	41.90N 12.52E	60	6.32	24
7	Haleakala NM	HALE	20.72N 156.27W	3030	12.91	29
8	Nagoya MT	NAGO	35.15N 136.97E	77 / 0 m w.e.	11.50	52
9	Yakutsk MT	Y00V	62.01N129.43E	105 / 0 m w.e.	1.65	51
10		Y07V		105 / 7 m w.e.		69
11		Y20V		105 / 20 m w.e.		104

12	Misato MT	MISA	36.12N 137.50E	735 / 30 m w.e.	11.39	131
13	Sakashita MT	SAKA	35.58N 137.53E	334 / 80 m w.e.	11.50	270
14	Matsushiro MT	MATS	35.15N 136.97E	408 / 220 m w.e.	11.50	672

Table 1: Information about the NM stations and MT used in this work. Emed for MTs and NMs are determined based on response functions presented by Fujimoto et al. (1984) and Aleksan'yan et al. (1982).

As can be seen from equation (2), the amplitude and phase of the SDV observed by ground-based detectors will be determined by the vector $\boldsymbol{R}_n^{m,i}$. The calculation of the parameters $x_n^{m,i}$ and $y_n^{m,i}$ is carried out with some adaptation of the method of receiving vectors (Grigoryev et al. 2011, Yanchukovsky et al. 2016), in which the calculation results become similar to the coupling coefficients (Yasue et al. 1982; Fujimoto et al. 1984):

$$x_n^m + iy_n^m = \frac{\int_{Rc}^{\infty}\int_{0}^{\frac{\pi}{2}}\int_{0}^{2\pi}W(E,\theta)f_{SDV}(E)N(\theta,\varphi)sin\theta e^{im\Psi}P_n^m(sin\Phi)dEd\theta d\varphi}{\int_{Rc}^{\infty}\int_{0}^{\frac{\pi}{2}}\int_{0}^{2\pi}W(E,\theta)N(\theta,\varphi)sin\theta dEd\theta d\varphi}, \qquad (3)$$
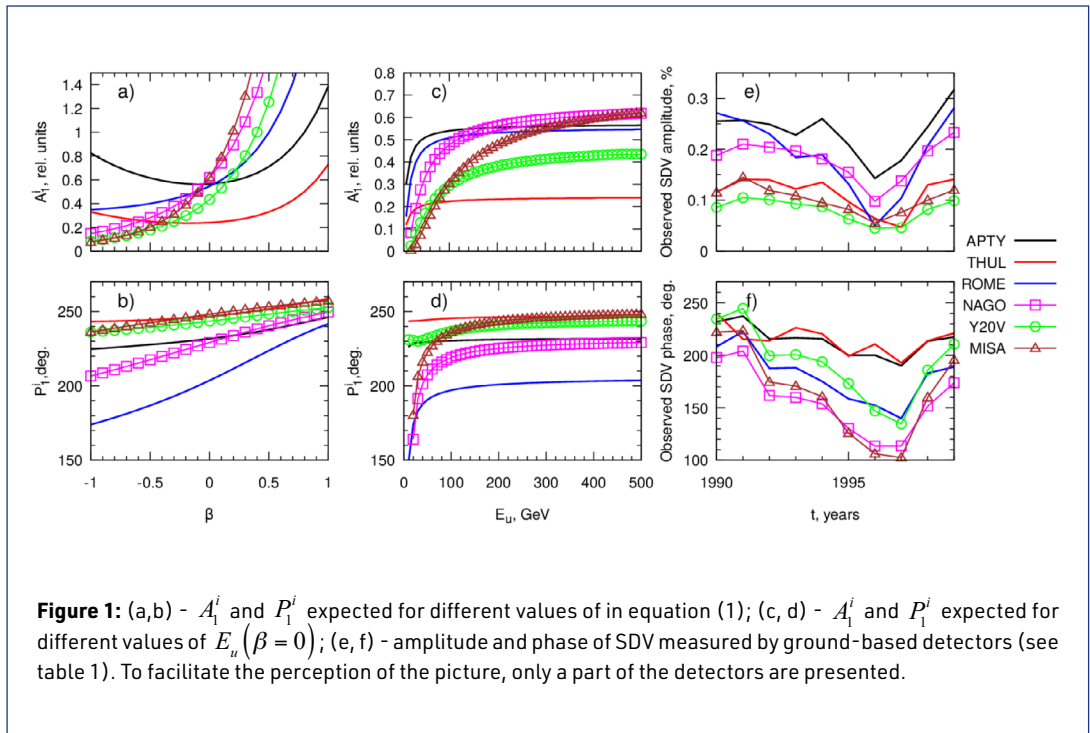
where $W(E,\theta)$ are the response functions, $N(\theta,\varphi)$ is the directional diagram of the device, θ, φ are latitude and longitude, Ψ and Φ are the asymptotic angles of arrival of particles. Here, the integral in the denominator is equal to the total CR intensity, and in the numerator - the intensity due to the SDV. Therefore, the amplitudes and phases of diurnal variations observed by ground-based detectors will be determined by the expressions

$$A_1^i = \sqrt{(a_1^1)^2 + (b_1^1)^2} \cdot \sqrt{(x_1^{1,i})^2 + (y_1^{1,i})^2} \quad \text{and} \quad P_1^i = atan(a_1^1 / b_1^1) - atan(x_1^{1,i} / y_1^{1,i}),$$ respectively.

2.2. Analysis of the obtained results and discussion

Assuming an 18-hour maximum anisotropy and specifying the distribution components as $a_1^1 = 1$ and $b_1^1 = 0$, we investigate the dependence of A_1^i and P_1^i on the spectrum parameters β and E_u in (1). Considering $-1.0 \le \beta \le 1.0$ we get the picture shown in figure 1 a, b. As you can see, with negative values of β, the amplitudes of daily variations observed by NMs significantly exceed MT, but with an increase of β the situation changes in the opposite direction. Only when β is close to 0 the expected amplitudes for NM and MT are mutually comparable. The difference between phases P_1^i of MTs and NMs is practically leveled when $\beta > 0$, and, on the contrary, it grows when $\beta < 0$. Comparing this picture with the SDV parameters measured experimentally in 1990-1998 (figure 1 e, f), we can conclude that β should vary near 0.

Based on the foregoing, consider the dependence of the same parameters A_1^i and P_1^i on E_u at β = 0 (figure 1c, d). It is seen that, as a result of the influence of the geomagnetic field and the Earth›s atmosphere, the primary SDVs are suppressed and phase is shifted at an early time. Moreover, A_1^i observed for MT is always lower than for NM. On the other hand, the P_1^i phase is higher for mid- and low-latitude stations than for high-latitude stations, regardless of the type of detector. It is noteworthy that the A_1^i and P_1^i of NMs strongly depend to E_u only within ∼ 100 GeV, while A_1^i and P_1^i of MTs - within ∼ 400 GeV.

Figure 1: (a,b) - A_1^i and P_1^i expected for different values of in equation (1); (c, d) - A_1^i and P_1^i expected for different values of $E_u(\beta = 0)$; (e, f) - amplitude and phase of SDV measured by ground-based detectors (see table 1). To facilitate the perception of the picture, only a part of the detectors are presented.

The shown above result qualitatively demonstrates the applicability of the theoretical spectrum in describing experimental data. For a quantitative assessment of the effect, we consider the ratios: A_1^i / A_1^0 and $P^i = P_1^i - P_1^0$, where we will take APTY as the 0th device, due to its stability and continuity. These relationships, expected theoretically and obtained experimentally, are presented in figure 2. The figure demonstrates the relationship between E_u and the level of solar activity. At the same time, the E_u values are quite consistent with the previously obtained results of other 50 authors ($GeV \le E_u \le 150V$). However, E_u cannot be determined unambiguously.

Figure 2: (a, b) - calculated values of A_1^i / A_1^0 and ΔP^i expected for different values of $E_u(\beta = 0)$. (c,d) - the same parameters obtained experimentally for the period 1971-2017.
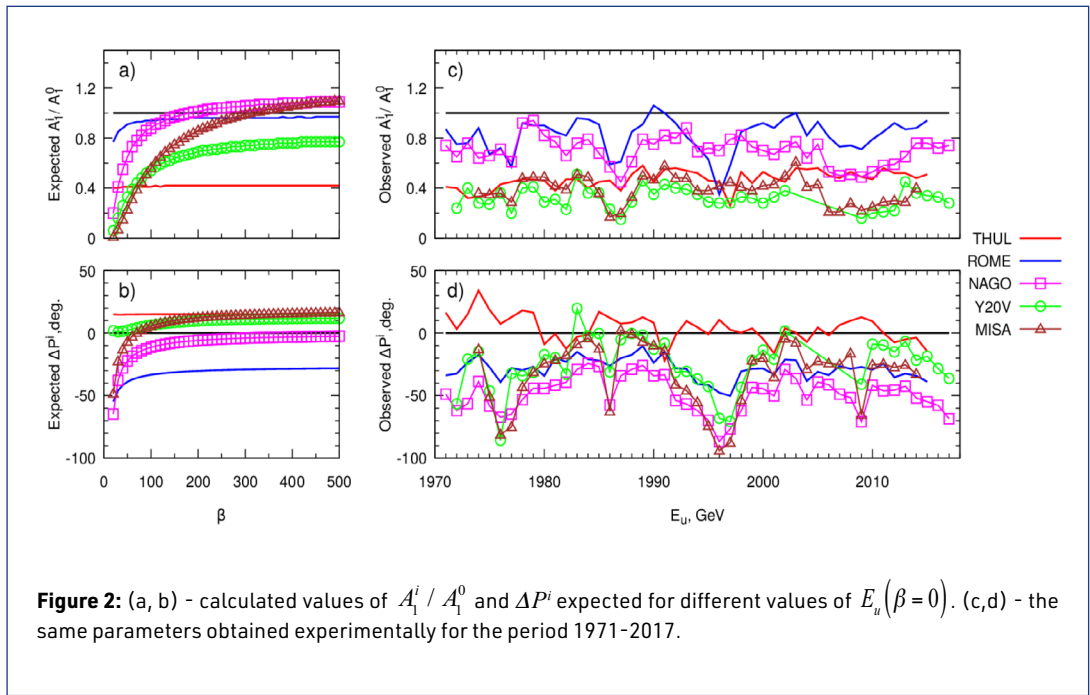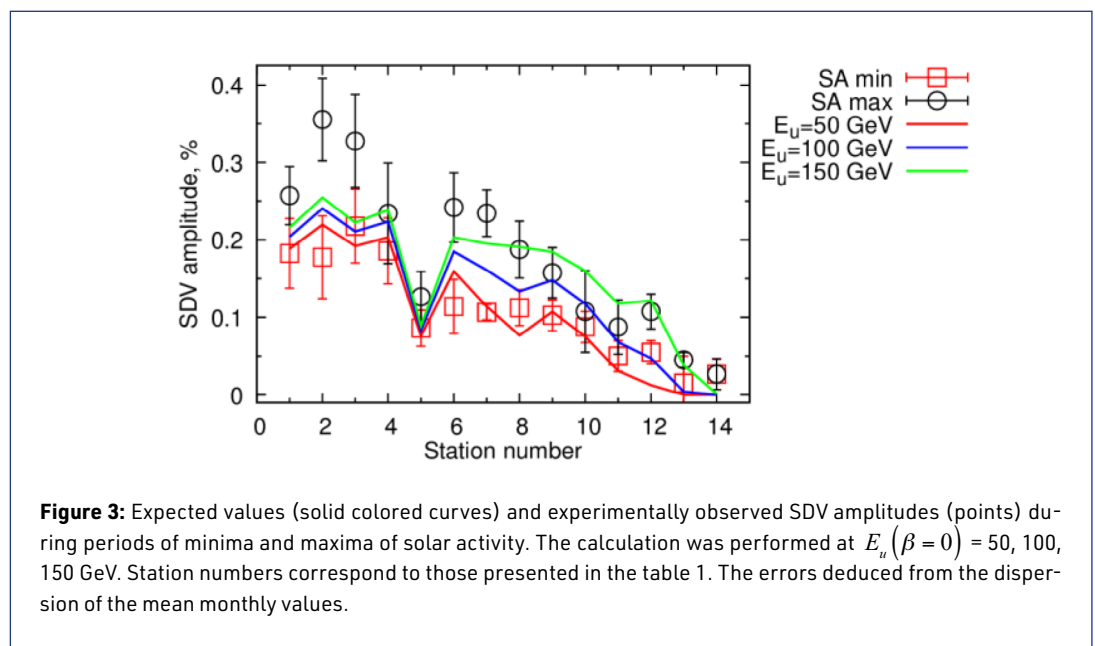
Figure 3 shows the values of the amplitude of the SDV according to the measurements of CR detectors presented in table 1, as well as, for comparison, the same parameters expected from theory. The experimental SDV was obtained separately for periods of maximum and minimum solar activity through averaging of the SDV amplitudes observed in 1980, 1990, 2000, 2013 and 1976, 1986, 1996, 2008, respectively. It can be seen that there is a mutual agreement between the experiment and theory. A closer look shows that there are some disagreements. The probable reason is the greatly simplified form of the SDV spectrum, as well as the lack of accounting of the temperature effect (for MT) and the orbital motion of the Earth (Compton-Getting effect). Also, from the figure, it is seen that the SDV amplitudes observed by LMNC and CLMX during solar activity maximum greatly differ from the estimated values. These stations are high-altitude stations and, probably, the response functions need to be estimated more precisely.

Figure 3: Expected values (solid colored curves) and experimentally observed SDV amplitudes (points) during periods of minima and maxima of solar activity. The calculation was performed at $E_u \left(\beta = 0 \right)$ = 50, 100, 150 GeV. Station numbers correspond to those presented in the table 1. The errors deduced from the dispersion of the mean monthly values.

3. Conclusion

Based on NM data and ground and underground MT data, the energy spectrum of SDV was studied. The measured SDV values were compared with those theoretically expected on the selected CR detectors for the period 1971-2017. It is shown that the spectrum of a flat form with an upper cutoff ~ 100 GeV is qualitatively describing the experimental data. More research is needed to determine the exact shape of the energy spectrum.

Acknowledgments

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