IINVESTIGATION OF ENERGY SPECTRUM OF SEMIDIURNAL VARIATIONS OF COSMIC RAYS

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Abstract

The data of registration of cosmic rays by the ground and underground multidirectional muon telescopes (stations Yakutsk, Nagoya, Hobart, Kuwait, São Martinho da Serra, Misato, Sakashita, Matsushiro), which covers the time period from 1971 to 2018 and median energy range from 55 to 686 GeV, are used. Average annual values of semidiurnal variations of cosmic rays observed by the mentioned stations and free from atmospheric and geomagnetic effects are obtained. Based on the analysis of the obtained data, a form and temporal dynamics of their energy spectrum are investigated. It is established that the energy spectrum reveals dependence on the solar activity cycle.

1. INTRODUCTION

Modulation of galactic cosmic rays (CR) in the heliosphere leads to a formation of their anisotropic distribution in the near-Earth space that is registered by ground-based detectors as periodical diurnal and semidiurnal oscillations of secondary CR intensity. Amplitudes of these oscillations, as a rule, are equal to hundredths of the total flow of CR, however, CR anisotropy is an important source of information on modulation processes in the heliosphere. Wherein, usually, more attention is attracted to the diurnal variations than to the semidiurnal one. Meanwhile, the semidiurnal variations are also very important for having a full picture of CR modulation in the heliosphere [1].

The current work continues our early investigations of the second spherical harmonics of CR angular distribution [23-27] and sets a goal to define an energetic spectrum of semidiurnal variations of CR and its dependence with SA and GMFS in a huge energy range. Particularly, the data of 11 multidirectional muon detectors of the northern and southern station that are placed on the ground and deep underground were used. The stations worked continuously for the last four SA cycles and register particles with median energy range from 55 to 686 GeV.

2. METHOD

In order to define an energy spectrum of semidiurnal variation of CR intensity we have used the data of 11 stations of muon telescopes. The list of stations, their abbreviations, depths underground, median energies of registration and operation period are presented in the table. Further, in the work, the stations are marked by their abbreviations.

An accurate treatment of the experimental data of hourly registration of the above-mentioned devices was carried out. Those events or “jumps” in data are able to introduce “spurious” semidiurnal variations of CR intensity were excluded from the analysis.

On the basis of the method described in the works [2,28], we calculate so-called receiving vectors for each station channels (directions). The introduction of the receiving vectors allows excluding influences of atmospheric and magnetospheric factors on CR and thus defining their angular distribution in free space.

No.	Direction	Abbreviation	E_{med}, GeV	No.	Direction	Abbreviation	E_{med}, GeV	No.	Direction	Abbreviation	E_{med}, GeV
Nagoya (1971- 2018)				Yakutsk 0 m w.e. (1972- 2018)				Hobart (2006-2018)			
1	V	NAGV	59.6	13	V	Y00V	60	25	V	HOBV	54.6
2	N	NAGN	64.5	14	N30	Y00N	63	26	N	HOBN	59.0
3	S	NAGS	62.7	15	S30	Y00S	63	27	S	HOBS	59.0
4	N2	NAGN2	83.1	Yakutsk 7 m w.e. (1972-2018)				Kuwait (2006-2018)			
5	S2	NAGS2	80.6	16	V	Y07V	77	28	V	KUWV	62.4
Misato (1974-2014)				17	N30	Y07N	82	29	N	KUWN	67.7
6	V	MISV	145.0	18	S30	Y07S	82	30	S	KUWS	69.3
7	N	MISN	155.0	Yakutsk 20 m w.e. (1972- 2018)				Sao-Martinho (2006-2018)			
8	S	MISS	155.0	19	V	Y20V	110	31	V	SAOV	55.6
9	N2	MISN2	187.0	20	N30	Y20N	115	32	N	SAON	59.9
10	S2	MISS2	194.0	21	S30	Y20S	115	33	S	SAOS	59.1
Sakashita (1977-1999)				Yakutsk 60 m w.e. (1972-2003)							
11	V1	SAKV	331	22	V	Y60V	260				
Matsushiro (1985-2014)				23	N30	Y60N	263				
12	V	MATV	686	24	S30	Y60S	263				

Table. List of used directions (channels) of muon telescopes with the indication of operation periods (in parentheses), abbreviations and estimated median energies of registered CR (according to [29, 30]).

3. OBTAINED RESULTS

Using the above-mentioned method by the data of measurements of the 11 muon telescopes from 33 directions (channels) (see table) we have calculated parameters of semidiurnal variations of CR during 1971-2018. In figure 1 amplitudes A_2^2 are presented. The panels of the figure are ordered so that median energies of registration of the directions (channels) growing from top to bottom. As seen, the behavior of A_2^2 reveals dependence to SA cycle, during SA minima A_2^2 decreases and during SA maxima – increases. Wherein it is observed an interesting feature, during SA declination and inclination, especially in the positive polarity of the GMFS, A_2^2 reaches its maximum values while during SA A_2^2 maxima and minima reveals decreases (figure 1i). Decrease of A_2^2 during SA minima in the positive polarity is deeper than in the negative one. During SA maxima A_2^2 also falls down. However, it is necessary to admit that the mentioned features weaken with detection depth, i.e. growth of particle energies.

In figure 2 there are shown temporal change of the phase T_2^2, i.e. maxima time of semidiurnal variations of CR. The order of presentation is analogous to figure 1. In general, it is seen that T_2^2 at all levels is close to 3 (15) hour of LT which in good agreement with the theory. However, there is some dependence on SA and GMFS polarity. It is seen that T_2^2 shifts to the early time in 1975, 1996 and 2018, i.e. during SA minima. These periods tmatch with maxima of the intensity of magnetic fields in the northern polar cap, i.e. 22-year oscillation of phase is observed. Moreover, 22-year phase changes are better revealed by the detectors directed to the north (NAGN, NAGN2, MISN, MISN2) and lesser phase change is observed by the detectors directed to the south (NAGS, NAGS2, MISS, MISS2). In addition, it seems that 22-year change is absent at higher energies (figure 2g).

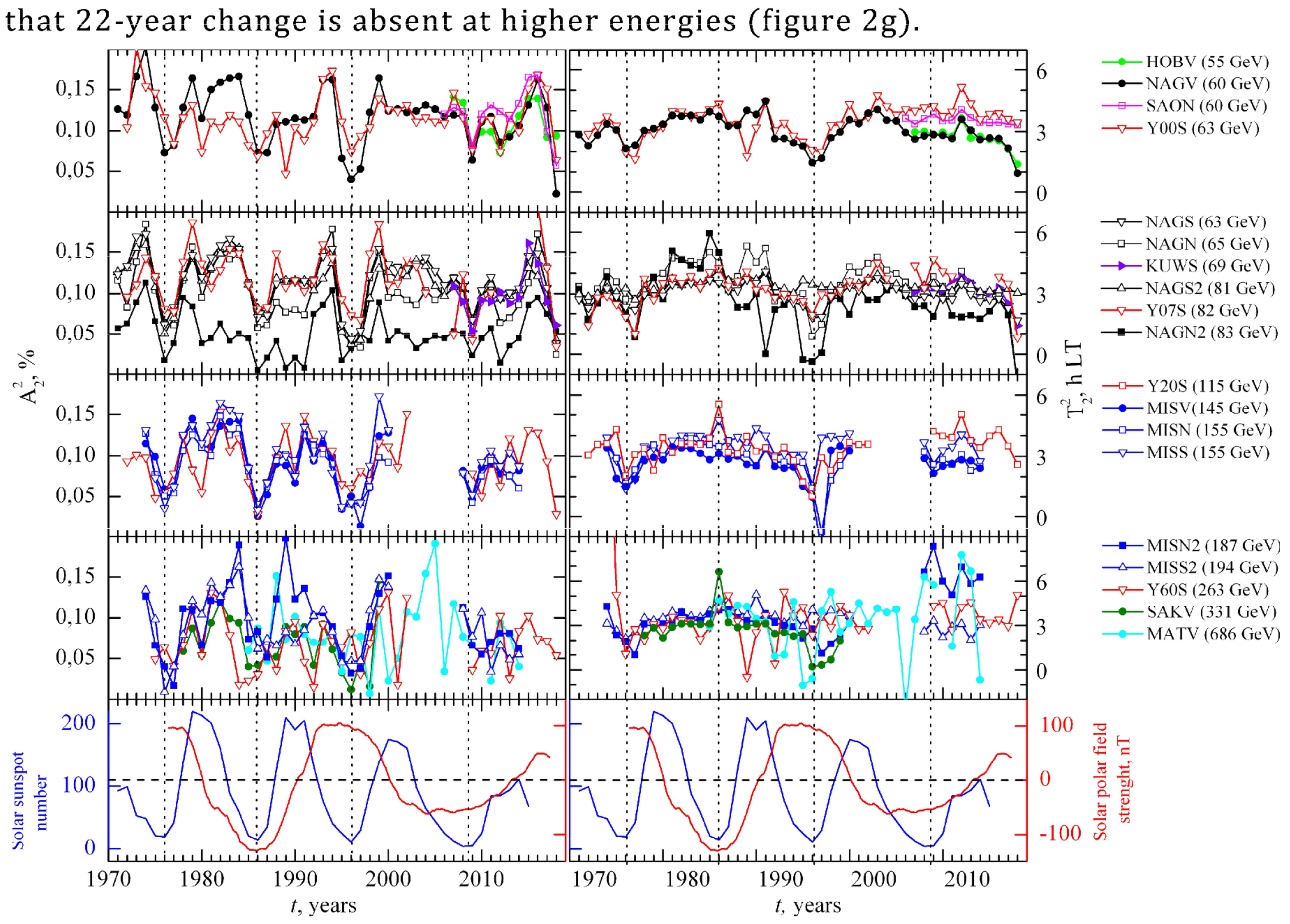

Figure 1. Average annual values of the amplitude (left panel) and phase (right panel) of semidiurnal variations of CR in free space during 1971-2018 observed by ground and underground muon telescopes. At the bottom panel – number of solar sunspots (blue curve) and solar polar field strength (right curve) according to http://wso.stanford.edu.

In order to define the dependence of the energetic spectrum of A_2^2 from SA and polarity of the GMFS, we have selected periods of SA minima (1975-77, 1985-87, 2008-2010) and maxima (1979-1981, 1989-1990, 1999-2001, 2012-2014) and used all the directions (channels) presented in table. The obtained average energetic spectra during 1971-2018, minima and maxima of SA are presented in figure 3a-c. As seen from the figures on average during 1971-2018 the energy spectrum has a power-law type with the index $\gamma = -0.29\pm0.13$. But during SA minima, the spectrum softens till $\gamma = -0.52\pm0.13$ and during SA maxima, vice versa, hardens to almost a flat form with $\gamma = -0.15\pm0.10$. However, the points with great deviations from the average spectrum in the figure are observed by NAGN, NAGN2, HOBS, SAOS, Y00N, Y07N, Y20N, Y60N, MISN and MISN2, i.e. those ones that are directed to high latitudes and have less sensitivity to CR semidiurnal variations.

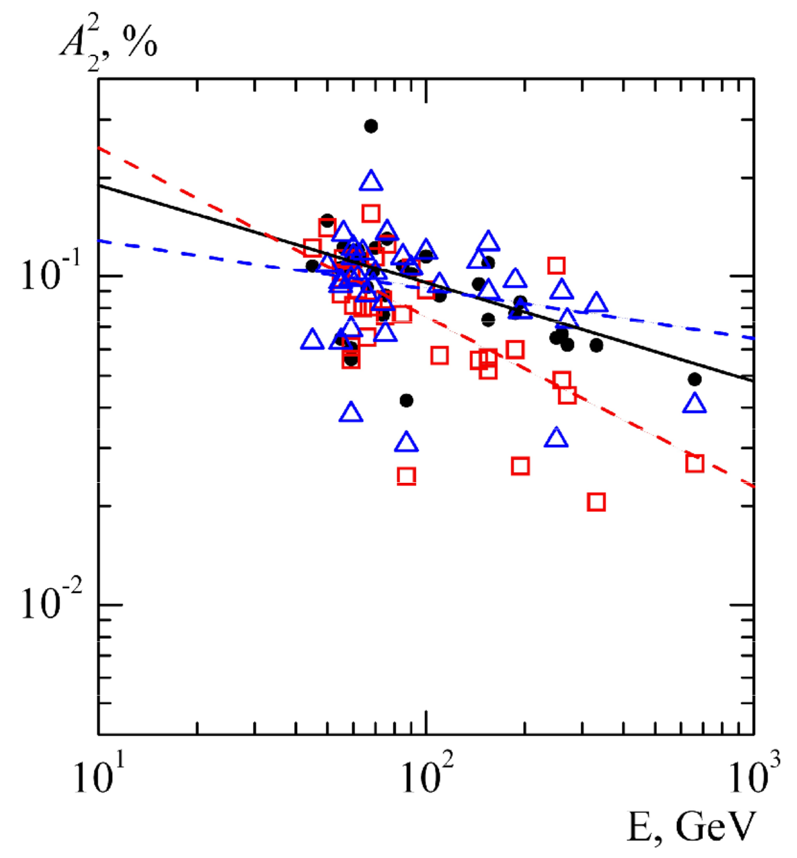

Figure 2. Energy spectra of semidiurnal variations of CR during the periods: (black circles) – 1971-2018; (red rectangles) – SA minima; (blue triangles) – SA maxima. The solid curves indicate power law approximation.

Using the method of receiving vectors on the basis of treatment of the data of 11 stations of muon telescopes on the surface and underground, the parameters of semidiurnal variations of CR intensity during 1971-2018 in the median energy range from 55 to 686 GeV were obtained. It is established that both the amplitude A_2^2 and phase T_2^2 of semidiurnal variations of CR intensity reveal dependence to SA cycle and polarity of GMFS. Wherein, behavior of A_2^2 is defined predominantly by SA, while T_2^2 - by the polarity of GMFS. The energy spectrum of semidiurnal variation of CR is close to the power law form with the index $\gamma = -0.29\pm0.13$. One can conclude that the mentioned above factors are a call for the theory of the formation of CR.

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