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Sidereal-diurnal galactic cosmic ray variation originating in the solar system

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Abstract: A cosmic ray anisotropy manifesting in diurnal variations is homogeneous in space and changes within a year near the Earth. As a result, diurnal variations appear by sidereal and anti-sidereal time. In the work the anisotropy of both vector and tensor types is taken into consideration

Keywords: cosmic ray, sidereal diurnal variations

1 Introduction

Variations of cosmic ray intensity originating in sidereal time is of the great interest to study the heliosphere structure and to determine real galactic anisotropy which creates these variations.

In [1, 2, 3] significant results on a study of sidereal-diurnal cosmic ray variations were obtained. Variations of cosmic ray intensity observed in a wide energy range $< 10^4$ GeV the authors explains as a following complex of 3 types of anisotropy: from the galaxy center, tail and nose part of the heliosphere. This types of anisotropy are differently manifested in sidereal time depending on the particle energy and general solar magnetic field polarity.

In [4] the study of this variation using the ionization chamber ASK-1 data was started. In [5] the data of muon telescopes located at different underground levels were added to the ASK-1 data. Later the study was continued in [6, 7]. However, a statistical accuracy of registration of muon intensity with the Yakutsk spectrograph at that time were insufficient for the detailed study of sidereal-diurnal variation property.

Since the amplitude of sidereal-diurnal variations in muon component is less than 0.03 % an extraction of oscillations of such type requires the extended set of qualitative data. In the present work we use the data of long-standing registration of muon intensity with the Nagoya (35°10' N, 136°58' E) multidirectional muon telescope for 1972-2011 registering the particles with median energies 60-110 GeV `http://www.stelab.nagoya-u.ac.jp` and with the Yakutsk (62°01′ N, 129°43′ E) complex of underground muon telescopes for 1971 to 2012 `http://www.ysn.ru/ipm`. The Yakutsk station consists of muon telescopes on the ground and underground at levels 7, 20, 60 m w. e. and registers the particles with median energies 67-263 GV. Both stations have continuous data for long period of time and high count rate.

2 Acceptance vectors and their using

An angular distribution of observed cosmic rays can be presented as series of spherical harmonics ($a_0^0, a_1^0, a_1^1, b_1^1, a_2^0$, a_2^1, b_2^1, a_2^2, b_2^2). The first spherical harmonic is described by a zonal component a_1^0 and azimuthal a_1^1, b_1^1 one. The second spherical harmonic is by the following 5 components: $a_2^0, a_2^1, b_2^1, a_2^2, b_2^2$, where a_2^1, b_2^1 are components of antisymmetric diurnal variations, and a_2^2, b_2^2 are components of semidiurnal variations.

Since the particles registered by the detectors are carried away in the heomagnetic field, an amplitude and phase of primary anisotropy will be changed. This change depends on an angular characteristics of differential coupling coefficients of detector. The multidimensional acceptance vector z_n^m takes into account all these parameters and recovers different types of unchanged anisotropies which are outside of magnetosphere.

Vectors $\vec{r}_n^m$ and $\vec{z}_n^m$ could be presented as complex components:r_n^m=a_n^m+ib_n^m; z_n^m=x_n^m+iy_n^m.

The acceptance vector has the form:

$$z_n^m = \frac{\int_{\varepsilon_{min}}^{8} \int_0^{2\pi} \int_0^{\pi/2} W(\varepsilon,\beta) \frac{\partial D(\varepsilon)}{D(\varepsilon)} N(\alpha,\beta) sin\beta z_n^m(\varepsilon,\alpha,\beta) d\varepsilon d\alpha d\beta}{\int_{\varepsilon_{min}}^{8} \int_0^{2\pi} \int_0^{\pi/2} W(\varepsilon,\beta) \frac{\partial D(\varepsilon)}{D(\varepsilon)} N(\alpha,\beta) sin\beta d\varepsilon d\alpha d\beta},$$

where $W(\varepsilon,\beta)$ is differential coupling coefficients of the instrument, $\frac{\partial D(\varepsilon)}{D(\varepsilon)}$ is an anisotropy spectrum, $N(\alpha,\beta)$ is a directional diagram of the instrument, α, β are azimuthal and zenithal arrival angles of particles, respectively, $\varepsilon_m in$ is a primary particle energy, $z_n^m(\varepsilon,\alpha,\beta)$ are the acceptance vector components at different angles α, β.

We have calculated the acceptance vectors taking into account expected energy spectra of anisotropy for Nagoya and Yakutsk In the case of symmetric diurnal anisotropy the spectrum has the form:

$$r_1^1 = \frac{b_0}{\varepsilon + b_0}, \tag{1}$$

where b_0 is a value that changes in the range 30-60 GeV [8] and for antisymmetric diurnal and semidiurnal variations we have used the energy spectrum:

$$\sim \begin{cases} \varepsilon^1 & ,if \quad \varepsilon \le \varepsilon_0 \\ \varepsilon^{-2} & ,if \quad \varepsilon > \varepsilon_0. \end{cases} \tag{2}$$

3 Separation of symmetric and antisymmetric diurnal variations

A separation of diurnal variations into symmetric component and antisymmetric one is carried out by a tensor method, for example for the Nagoya station, in the following way:

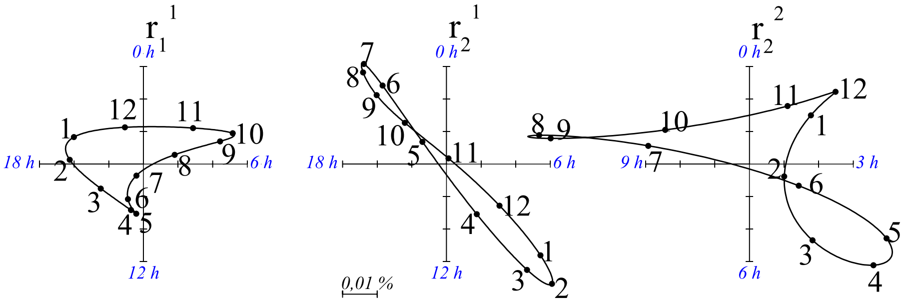

Fig. 2: The observed annual variations of symmetric $\vec{r}\,^1_1$, antisymmetric $\vec{r}\,^1_2$ and semidiurnal $\vec{r}\,^2_2$ variations of cosmic rays.

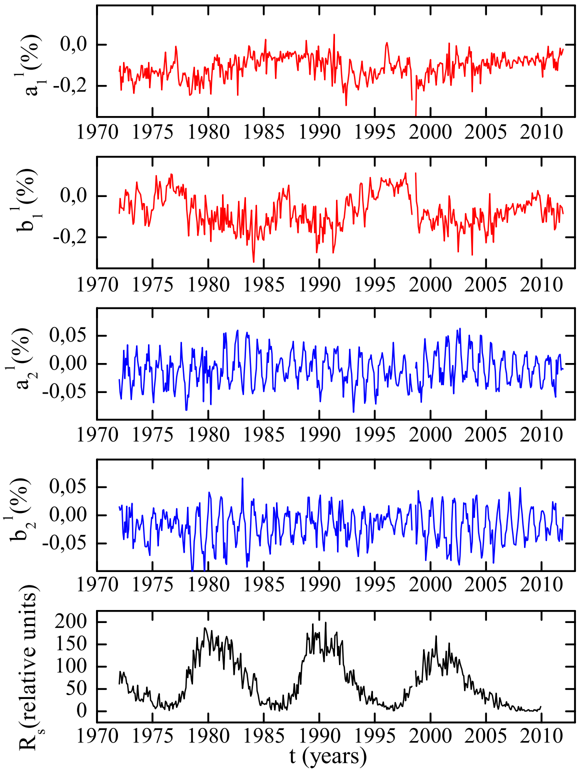

Fig. 1: The observed change of components of symmetric a^1_1, b^1_1 and antisymmetric a^1_2, b^1_2 diurnal variations obtained with the help of the tensor method by data of the Nagoya station and the number of sunspots R_s during 1972-2011.

$$M \cdot A_{exp} = A_{obs} \tag{3}$$

where the observed diurnal variation A_{obs}, the acceptance vector matrix M and the expected components of diurnal anisotropy A_{exp} are equal, respectively:

$$A_{obs} = \begin{pmatrix} a_{1,obs} \\ b_{1,obs} \\ \dots \\ a_{17,obs} \\ b_{17,obs} \end{pmatrix}, A_{exp} = \begin{pmatrix} a^1_{1,exp} \\ b^1_{1,exp} \\ a^1_{2,exp} \\ b^1_{2,exp} \end{pmatrix},$$

$$M = \begin{pmatrix} x^1_{1,1} & -y^1_{1,1} & x^1_{2,1} & -y^1_{2,1} \\ y^1_{1,1} & x^1_{1,1} & y^1_{2,1} & x^1_{2,1} \\ \dots & \dots & \dots & \dots \\ x^1_{1,17} & -y^1_{1,17} & x^1_{2,17} & -y^1_{2,17} \\ y^1_{1,17} & x^1_{1,17} & y^1_{2,17} & x^1_{2,17} \end{pmatrix}$$

values i=1,17 of tensor components $x^1_{1,i}, y^1_{1,i}, x^1_{2,i}, y^1_{2,i}, a_{i,obs}, b_{i,obs}$ correspond to the Nagoya telescope registration directions presented in Table 1.

The matrix equations (3) can be solved as follows:

$$M^T M \cdot A_{exp} = M^T \cdot A_{obs} \tag{4}$$

$$A_{exp} = (M^T M)^{-1} M^T A_{obs}, \tag{5}$$

where M^T is a transposed matrix.

Substituting the values of observed diurnal variation and calculated acceptance vectors into (5) we obtain the components of symmetric a^1_1, b^1_1 and antisymmetric a^1_2, b^1_2 diurnal variations. Their accuracies are determined with the equation $\frac{\triangle^T \triangle}{N-n}$, where N is the number of registration directions and n is the number of expected diurnal components. And they do not exceed 0.0015 % for 40 years.

N	Nagoya station		Yakutsk station	
	Index	Direction	Index	Direction
1	V	Vertical	0V	Vertical, 0 m w. e.
2	N30	North 30°	0N30	North 30° 0 m w.e.
3	E30	East 30°	0S30	South 30° 0 m w.e.
4	S30	South 30°	7V	Vertical, 7 m w.e.
5	W30	North 30°	7N30	North 30° 7 m w.e.
6	NE39	North-East 39°	7S30	South 30° 7 m w.e.
7	SE39	South-East 39°	20V	Vertical, 20 m w. e.
8	SW39	South-West 39°	20N30	North 30° 20 m w.e.
9	NW39	Norh-West 39°	20S30	South 30° 20 m w.e.
10	N49	North 49°	60V	Vertical, 60 m w. e.
11	E49	East 49°	60N30	North 30° 60 m w.e.
12	S49	South 49°	60S30	South 30° 60 m w.e.
13	W49	West 64°		
14	N64	Norh 64°		
15	E64	East 64°		
16	S64	South 64°		
17	W64	West 64°		

Table 1: Indexes and corresponding registration directions at the Yakutsk and Nagoya stations.

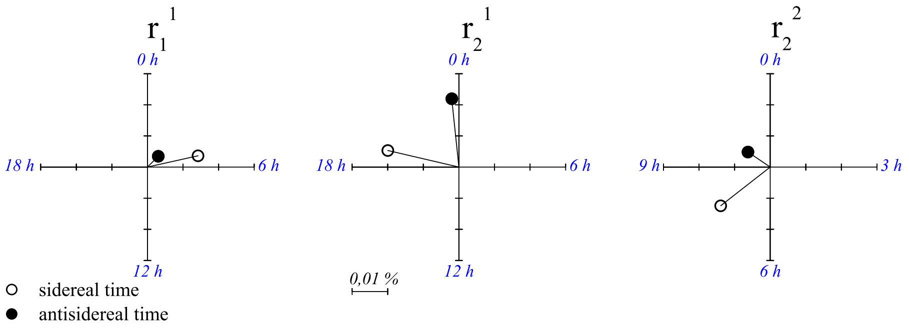

Fig. 3: The observed symmetric $\vec{r}_1^{\,1}$, antisymmetric $\vec{r}_2^{\,1}$ diurnal and semidiurnal $\vec{r}_2^{\,2}$ variations which appear in sidereal and antisidereal time.

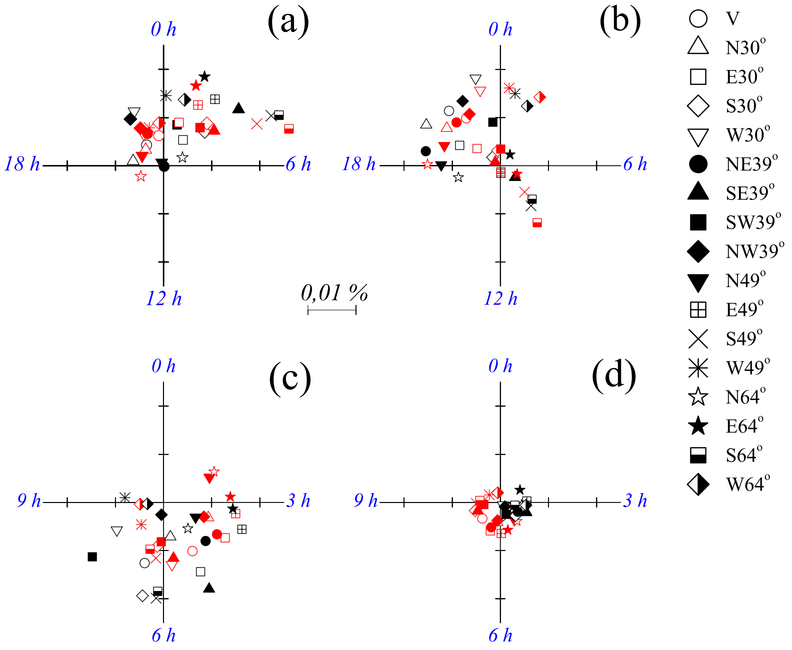

Fig. 4: The observed and expected at the Nagoya station the sidereal (a) and antisidereal (b) diurnal variations of cosmic rays and also sidereal (c) and antisidereal (d) semidiurnal variations. The red symbols are correspond to the expected sidereal diurnal vectors and black symbols are observed vectors.

4 Calculation results and discussion

Fig. 1 presents the annual change of components of the symmetric a_1^1, b_1^1 and antisymmetric a_2^1, b_2^1 diurnal variations and solar activity index during the period 1972-2011. It is seen that the component b_1^1 of symmetric diurnal variation undergoes annual variations in comparison with a_1^1 and depends on the solar magnetic field polarity. The systematical annual change of antisymmetric diurnal variation is found. The same annual oscillations of semidiurnal variations are observed [9]. The averaged for the period of 40 years the symmetric $\vec{r}_1^{\,1}$, antisymmetric $\vec{r}_2^{\,1}$ and semidiurnal $\vec{r}_2^{\,2}$ variations are shown on the hour dial in Figure 2. The numbers indicate months and a curve corresponds to the movement of the end of anisotropy vector during a year. The annual change of vectors $\vec{r}_2^{\,1}$ and $\vec{r}_2^{\,2}$ has the same origin: they are caused by the constant presence of the second spherical harmonic in the angular distribution of galactic cosmic rays in the heliosphere. The mechanisms of this distribution are a cosmic ray screening [8] and solar wind shear flow [10]. As for the symmetric diurnal variation $\vec{r}_1^{\,1}$, it could be caused by a latitudinal gradient of cosmic rays. The annual and semiannual changes of indicated variations could lead to the corresponding sidereal diurnal and sidereal semidiurnal variations. The parameters of variations obtained from the mentioned above data are shown in Table 2.

From Table 2 it is seen that the antisymmetric sidereal and antisymmetric antisidereal variations are equal and have the highest amplitude. Their vectors are arranged

	Sidereal time		Antisidereal time	
	Amplitude, $10^{-3}\%$	Phase, h	Amplitude, $10^{-3}\%$	Phase, h
$\vec{r}_1^{\,1}$	14.6 ± 1.5	5.05 ± 0.39	4.6 ± 1.5	2.75 ± 1.20
$\vec{r}_2^{\,1}$	20.7 ± 1.5	19.00 ± 0.27	22.0 ± 1.5	23.65 ± 0.26
$\vec{r}_2^{\,2}$	18.6 ± 0.3	15.22 ± 0.03	7.9 ± 0.3	20.52 ± 0.07

Table 2: Amplitude and phase of the observed sidereal and antisidereal symmetric $\vec{r}_1^{\,1}$, antisymmetric $\vec{r}_2^{\,1}$ diurnal and semidiurnal $\vec{r}_2^{\,2}$ variations.

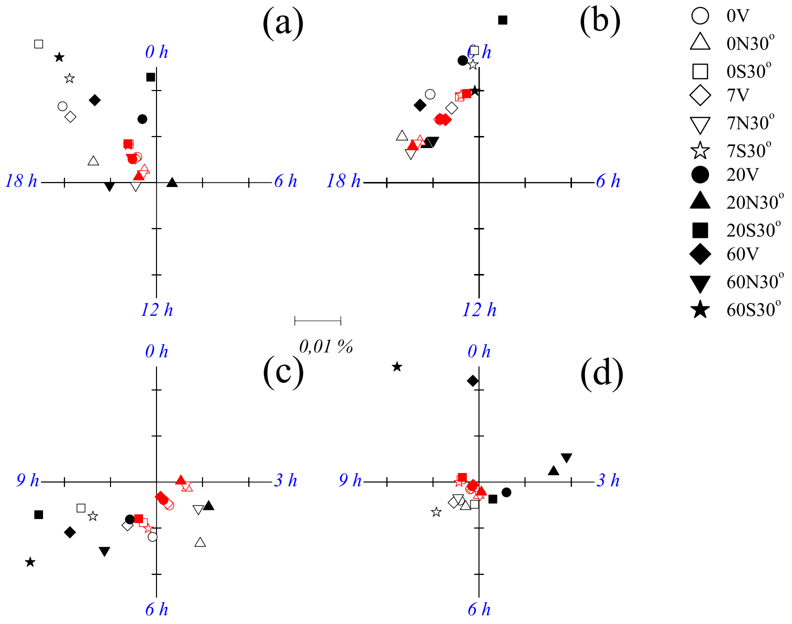

Fig. 5: The observed and expected at the Yakutsk station the sidereal (a) and antisidereal (b) diurnal variations of cosmic rays and also sidereal (c) and antisidereal (d) semidiurnal variations. The red symbols are correspond to the expected sidereal diurnal vectors and black symbols are observed vectors.

specularly relatively to the hour line of 9h - 21h. The amplitudes of antisidereal symmetric diurnal and antisidereal semidiurnal variations are negligible.

The symmetric diurnal variation in sidereal time can appear if in the solar system there is an anisotropy directed parallel to the axis of rotation of the Sun. In this case the time of maximum of the variation should be equal to 7h and 19h of sidereal time. The antisidereal variation should be absent. As is seen from Figure 3, the symmetric diurnal variation has these properties.

Using the obtained real $\vec{r}^{\,1}_{1(Sid)}, \vec{r}^{\,1}_{2(Sid)}$ and corresponding components of antisidereal $\vec{r}^{\,1}_{1(ASid)}, \vec{r}^{\,1}_{2(ASid)}$ variations we have solved the inverse problem of finding the expected variations with the account of the geomagnetic field influence. In Figure 4 the expected vectors which are presented as a sum of vectors $\vec{r}^{\,1}_{1(Sid)} + \vec{r}^{\,1}_{2(Sid)}$ and $\vec{r}^{\,1}_{1(ASid)} + \vec{r}^{\,1}_{2(ASid)}$ are compared with the corresponding observed vectors obtained for each direction of muon telescope of the Nagoya station. The accuracy of observed vector is not more than 0.007 %. The above-mentioned vectors have been determined for the spectrum (1) at b_0=40 GeV and spectrum (2) at ε_0=70 GeV. As is seen from Figure 4 the difference between the observed and expected vectors is negligible.

On the basis of above spectra the expected vectors for the Yakutsk station have been calculated (Fig. 5). In this case an agrement between the expected variations and observation is somewhat worse because the statistical accuracy of registration at the Yakutsk station is significantly lower than at the Nagoya station and when selecting the energy spectra a wide energy range of the Yakutsk spectrograph registration have not been taken into account.

5 Conclusions

To study the sidereal diurnal variations of galactic cosmic rays the tensor method of separation of symmetric and antisymmetric diurnal variations were used. It is shown that the sidereal variations are caused mainly by the second spherical harmonic of angular distribution of galactic cosmic rays in the heliosphere. The presence of antisymmetric sidereal-diurnal and semidiurnal variations whose mechanisms are given in [9] indicates to this fact.

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References

[1] K. Nagashima, K. Fujimoto and R. M. Jacklyn , Journal of Geophysical Research 103 (1998) A817429-A817440 doi:10.1029/98JA01105.
[2] K. Munakata, T. Kitawada, S Yasue et al., Journal of Geophysical Research 104 (1999) 2511-2519 doi:10.1029/1998JA900057.
[3] K. Nagashima, K. Fujimoto, R. M. Jacklyn, Earth Planet Space 58 (2006) 1487-1498.
[4] G. V. Skripin, Scientific reports of Yakut branch of the USSR Academy of Sciences 1 (1958) 160 (in Russian).
[5] G. V. Skripin, Heo- and heliophysical effects in cosmic rays and aurorae (2006) 42-47 (in Russian).
[6] G. F. Krymsky, A. M. Altukhov, P.A. Krivoshapkin, A. I. Kuzmin, N. P. Chirkov, Bulletin of the Russian Academy of Sciences. Physics 31 (1967) 1360 (in Russian).
[7] A. I. Gavrilyev, P. A. Krivoshapkin, A. I. Kuzmin, G. V. Skripin, V. A. Filippov, Geomagnetism and Aeronomy 17 (1977) 377-380 (in Russian).
[8] G. F. Krymsky, A. I. Kuzmin, P. A. Krivoshapkin et al., Cosmic Rays and Solar Wind, Novosibirsk:Nauka, (1981) 224 (in Russian).
[9] S. K. Gerasimova, P. Yu. Gololobov, P. A. Krivoshapkin et al., Bulletin of the Russian Academy of Sciences. Physics 77 (2013) 526-528 doi:10.3103/S1062873813050195.
[10] E. G. Berezhko, G. F. Krymsky, Soviet Astronomy Letters 7 (1981) 352-354.