Investigation of mechanisms of formation of the second spherical harmonics of the galactic cosmic ray angular distribution

To cite this article: P. Yu. Gololobov et al 2019 J. Phys.: Conf. Ser. 1181 012012

View the article online for updates and enhancements.

You may also like

- Special issue on applied neurodynamics: from neural dynamics to neural engineering
  Hillel J Chiel and Peter J Thomas

- Electron acceleration in the aurora and beyond
  K.G. McClements

- Modeling the Galactic Magnetic Field and its Application in verifying a Pulsar Origin of Very High Energy Cosmic Rays
  Pantera Davoudifar and Keihanak Rowshan Tabari
Investigation of mechanisms of formation of the second spherical harmonics of the galactic cosmic ray angular distribution

P. Yu. Gololobov, P. A. Krivoshapkin and G. F. Krymsky
Yu. G. Shafer Institute of Cosmophysical Research and Aeronomy of the Siberian Branch of the RAS (ShICRA), 31 Lenin ave., Yakutsk, Russia, 677980
E-mail: gpeter@ikfia.ysn.ru

Abstract. Mechanisms of formation of a second spherical harmonic of an angular distribution of galactic cosmic rays in the heliosphere are investigated. On the basis of data of Nagoya multidirectional muon telescope using a method of tensor anisotropy of cosmic rays time courses of symmetric diurnal, antisymmetric diurnal and semidiurnal variations of cosmic rays were obtained for the period 1971-2017. An abrupt offset of a phase of the semidiurnal variation to the earlier time during a positive polarity of the general magnetic field of the Sun, which closely correlates with the temporal change of a phase of the symmetric diurnal variations. It was shown the existence of annual variations of the tensor anisotropy components, which can be satisfactorily described by a single modulation factor - a screening of cosmic rays by the sector-structured interplanetary magnetic field. Moreover, the theory indicates on the existence of a stable north-south asymmetry of the interplanetary magnetic field - shift of the neutral current sheet to the south of solar equator.

1. Introduction
The heliospheric modulation of cosmic rays (CR) leads to the occurrence of the specific spatial angular distribution of CR which has an anisotropic character. This anisotropic flow existing in the interplanetary space reveals itself in data of ground-based CR detectors as diurnal and semidiurnal oscillations due to the rotation of the Earth around its own axis. At the same time, registration of the mentioned oscillations by a single CR detector reflects only small part of the full CR angular distribution. In order to obtain the full distribution it is necessary to use a huge number of differently directed CR detectors which could cover a sufficient area of the celestial sphere. Wherein, the number of detectors depends on how much detailed CR distribution is needed to be determined.

Our earlier calculations of the CR distribution using data of muon telescopes of Nagoya and Yakutsk stations and a world-wide network of neutron monitors allow us to obtain average parameters of the second spherical harmonic of the CR distribution, the so-called CR tensor anisotropy, which have been observed for the last 4 solar activity cycles [1, 2, 3]. As a theoretical interpretation of the obtained results it was suggested a model that consists of two CR modulation mechanisms which were able to create the necessary CR distribution: mechanisms of CR screening by the sector-structured interplanetary magnetic field (IMF) [4] and shear flow of solar wind [5]. Furthermore, juxtaposition of the model calculations and the experimental data
allow us to reveal an important phenomenon - the north-south asymmetry of the IMF, which is today considered as a basic property of the heliosphere [6, 7]. Nevertheless, an approach to calculation of the tensor anisotropy and the theory itself had a number of shortcomings. Firstly, the influence of a temperature effect on muons was ignored. Secondly, the theoretical model based on two different mechanisms and this fact complicates the interpretation process. In the current work the further investigation of the temporal dynamic of the CR tensor anisotropy for the long time period 1971-2017 is carried out taking into account the mentioned backgrounds.

2. Investigation method
The angular distribution of CR is determined by processing of data of measurements of 17 independent directions of registration of the Nagoya multidirectional muon telescope [http://www.stelab.nagoya-u.ac.jp/stewww1/div3/muon/muon3.html] using a method of receiving vectors [8, 9]. The method allows us to take into account influences of the atmospheric and magnetospheric factors, except the temperature effect, on the registered CR intensity. The detailed description of the method is presented in [1, 10].

The angular distribution of CR in space \( I(\theta, \varphi) \) is presented as series of spherical harmonics

\[
I(\theta, \varphi) = \sum_{n=0}^{\infty} \left( a_n^m \cos(m\varphi) + b_n^m \sin(m\varphi) \right) P_n^m \left( \sin\theta \right)
\]

, where \( \theta \) and \( \varphi \) are latitude and longitude in a corresponding coordinate system, \( P_n^m \left( \sin\theta \right) \) is the associated Legendre’s polynomials. If to represent the distribution \( I(\theta, \varphi) \) as a multidimensional vector \( \vec{A} = (a_n^m, b_n^m) \) then for each device (channel) one can define such a multidimensional vector \( \vec{Z} = (x_n^m, y_n^m) \) that the CR intensity \( J \) registered by a device would be equal to a scalar product \( J = \vec{A} \cdot \vec{Z} \). In the current work we use the receiving vectors which are presented in [11] with an assumption that spectra of vector \( f_1 \) and tensor \( f_2 \) anisotropies of CR have the next forms:

\[
f_1 = \begin{cases} 
E^1, & \text{if } E \leq E_1 \\
0, & \text{if } E > E_1 
\end{cases}
\]

\[
f_2 = \begin{cases} 
E^2, & \text{if } E \leq E_2 \\
E^{-1}, & \text{if } E > E_2 
\end{cases}
\]

where \( E_1 = 100 \text{ GeV} \) and \( E_2 = 70 \text{ GeV} \), according to [11] [10].

If the number of devices (channels) are sufficient then the vector \( \vec{A} \) can be defined by a solution of a system of linear equations which number is equals to the number of devices (channels). For example, the CR vector anisotropy requires at least 4 channels, while the tensor anisotropy - 9 channels.

3. Model of CR tensor anisotropy
Earlier in the works [3, 11] we developed the theory which can describe the experimental data on tensor anisotropy of CR. The theory was based on mechanism of CR screening by the sector-structure IMF which successfully explains an excess of CR in direction perpendicular to the IMF direction. Hence, the observed temporal dynamic of the tensor anisotropy appeared to be slightly complicated and the explanation required an additional mechanism. It was suggested that the second mechanism is the shear flow of solar wind which manifests itself during large scale disturbances of solar wind. On the other hand, we used average monthly data, so the model need to be stationary. Therefore, below is presented the new model which is based only on the CR screening mechanism.

According to [10, 3] in the solar equatorial coordinate system, which polar axis is directed to the Sun’s north pole and the zero longitude matches to the position of the Sun, the CR screening mechanism will have the tensor anisotropy with the next components:

\[
\vec{A}_{Scr} = \left( 1/2, 0, 0, \sqrt{3}/2 \cos 2\varphi, \sqrt{3}/2 \sin 2\varphi \right)
\]
where ϕ is an angle between the archimedian spiral and the Earth-Sun line, which in the model is equals to 45°.

Let us suggest that the amplitude of tensor anisotropy, that is due to the CR screening mechanism, depends on the heliolatitudinal position of the Earth (coefficient k) relatively to the plane of symmetry of the neutral of current sheet, which is deflected to the south or north from the solar equatorial plane on the angle α. Moreover, it is necessary to take into account the course of the heliolatitudinal position of the Earth over a year from -7.25° to -7.25°.

So, the vector \( \vec{A}_{Sc}\) will have the next form:

\[
\vec{A} = \vec{A}_{Sc} (1 - \kappa \cos^4 (30(\sin \frac{t}{25})))
\]

where \(-14.5° \leq \alpha \leq 14.5°\) and \(t\) is a time of year which is counted from the day of the solstice - 21st June.

Transition from the solar heliographic coordinate system to solar geographical one, taking into account the possible north-south displacement of the plane of symmetry of the neutral current sheet, is carried out by the next transformations: \(M^{long}(-t) \cdot M^{lat}(7.25°) \cdot M^{long}(t) \cdot M^{lat}(\alpha) \cdot \vec{A}\), where the rotation matrixes are presented in [9] and have the next forms:

\[
M^{long}(\chi) = \begin{pmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & \cos \chi & \sin \chi & 0 & 0 \\
0 & -\sin \chi & \cos \chi & 0 & 0 \\
0 & 0 & 0 & \cos 2\chi & \sin 2\chi \\
0 & 0 & 0 & -\sin 2\chi & \cos 2\chi
\end{pmatrix},
\]

\[
M^{lat}(\xi) = \begin{pmatrix}
1 - \frac{3}{2} \sin^2 \xi & 0 & \frac{3}{2} \sin 2\xi & 0 & -\sin \xi \\
0 & \cos \xi & 0 & 0 & 0 \\
\frac{2}{\sin \xi} \sin 2\xi & 0 & \cos 2\xi & \sin 2\xi & 0 \\
\frac{-2}{\sin \xi} \sin^2 \xi & 0 & -\frac{1}{2} \sin 2\xi & (1 + \cos^2 \xi) & 0 \\
0 & \sin \xi & 0 & 0 & \cos \xi
\end{pmatrix}.
\]

The results of modeling of annual oscillations of the antisymmetric diurnal \(R_{1,exp}^{−}\) and semidiurnal \(R_{2,exp}^{−}\) components of the CR tensor anisotropy in the solar geographical coordinate system for \(k = 0.00, 0.15, 0.30\) and \(\alpha = -10°, 0°, 10°\) are presented in figure [1]. It is seen that during a year the component \(R_{1,exp}^{−}\) reveals oscillations strictly toward 9-21 h of LT and the vector skews to 9 h when the neutral sheet is tilted to the south from the solar equator, and vice versa, to 21 h when the sheet is tilted to the north. The effect rises with the value \(\kappa\). The expected annual change of \(R_{2,exp}^{−}\) also depends on the value \(\alpha\). When the \(\alpha\) increases, the semianual oscillations of \(R_{2,exp}^{−}\) becomes complemented by annual oscillations, depending on \(\kappa\). In the case when the neutral current sheet is shifted to the south (north) from the solar equator, the minimal values of the vector \(R_{2,exp}^{−}\) are expected in August-September (February-March) and the maximum values - in April-May (October-November).

4. Results and discussions

By the data of 17 directions of the multidirectional muon telescope Nagoya the decomposition of CR distribution into the vector \(\vec{R}_1 = (a_1, b_1)\) and the tensor \(\vec{R}_2 = (a_2, b_2)\) anisotropy components is carried out for the period 1971-2017. The obtained values of the mentioned components are presented in figure [2]. A detailed analysis of the components shows an occurrence of annual and semianual periodic oscillation of the components \(a_1, b_1, a_2\) and \(b_2\). In calculations we have used the data are uncorrected for the temperature effect. On the other hand, using the method described in [12, 13] we have taken into account the temperature
Figure 1. The vector diagram of annual variations of the antisymmetric diurnal $R_1^i$ and semidiurnal $R_2^i$ components of the CR tensor anisotropy that are expected by the model for different values of $k$ and $\alpha$. The numbers around the points denote months.

for the period 2006-2015. It is shown that for the selected period the average value of the vector anisotropy $|R_1^i|$ corrected for the temperature effect is equals to 0.29 % and time of maxima $T_{1,\text{max}}^i$ - 16.6 h LT while the values without corrections are 0.28 % and 15.3 h LT, respectively. It means that the temperature effect for the mentioned time period created a diurnal variation with an amplitude 0.1 % and phase 9.5 h LT. The temperature effect almost did not affect the anisymmetric diurnal and semidiurnal components of tensor anisotropy.

The obtained average yearly amplitudes and phases of vector and tensor anisotropies of CR for 1971-2017 are presented in figure 3. It is shown that the amplitudes $|R_1^i|$ and $|R_2^i|$ during the investigated period have changed synchronously respectively to the sunspot number - during the periods of solar activity minima the amplitudes decreases. The phases $T_{1,\text{max}}^i$ and $T_{2,\text{max}}^i$ have changed depending on a polarity of the general magnetic field of the Sun (GMFS) - during solar activity minima of positive polarity the phases shift to earlier time.

It is well known that during a 11-year solar activity cycle the geometry of solar wind in the Sun's meridional plane changes, the solar wind at solar activity minima becomes "flattened" and the level of regularity of the IMF increases. During the periods of positive GMFS the CR are mainly carried away from the Sun through its equatorial plane. All this physical processes are well reflected in the observed amplitude-phase oscillations of the vector anisotropy [14, 15].

The phase $T_{2,\text{max}}^i$ in average is equals to 3 h of LT as it is expected by the CR screening mechanism, but during solar activity minima the phases shift to the earlier time up to 1 h. Moreover, $T_{1,\text{max}}^i$ and $T_{2,\text{max}}^i$ are suspiciously well correlates to each other. The reason of this phenomenon is unknown.

It is necessary to note that the amplitude $|R_2^1|$ during the whole investigated period has low value and does not change with solar activity.

In figure 4 the average annual change of the components of the CR tensor anisotropy $R_{1,\text{obs}}^i$ and $R_{2,\text{obs}}^i$, which were observed during the investigated period, are shown. Also, in the figure there are presented $R_{2,\text{exp}}^i$ and $R_{2,\text{exp}}^i$ which are expected from the mechanism of CR screening by
Figure 2. The observed average monthly values of the components of the vector \((a_1, b_1)\) and the tensor \((a_2, b_2, a_3, b_3)\) anisotropies of CR which are obtained by the above mentioned method using the data of muon telescopes Nagoya for the period 1971-2017.

Figure 3. Average annual amplitudes of the vector \(|\mathbf{R}_{1}\)| and the tensor \((|\mathbf{R}_{1}|, |\mathbf{R}_{2}|)\) anisotropies of CR and the maxima times \(T_{1,\text{max}}\) and \(T_{2,\text{max}}\), respectively, and also the sunspot number. The regions with positive and negative signs in the bottom of the figure reflect the GMFS polarity changes.

Figure 4. The vector diagrams of the average annual change of the antisymmetric diurnal \(R_{2,\text{obs}}\) and semidiurnal \(R_{2,\text{obs}}\) components of the CR tensor anisotropy that were observed by the Nagoya muon telescope during 1971-2017. And the same components expected by the model \(R_{1,\text{exp}}, R_{2,\text{exp}}\) for \(k = 0.3\) and \(\alpha = -10^\circ\).
the IMF for $\alpha = -10^\circ$ and $\kappa = 0.3$. Comparison between the experimental data and the model calculations have shown that the suggested mechanism sufficiently describes the observed annual change of the tensor anisotropy. Moreover, the model indicates on the north-south asymmetric structure of the heliosphere - shift of the neutral sheet to the south from the solar equatorial plane.

It should be noted that another theoretical mechanisms (for example [16] [17] [18] [19]) which are able to create the same excess of particles in direction perpendicular to the IMF, can produce the same oscillations of CR tensor anisotropy.

5. Conclusions

Using the data of the multidirectional muon telescope Nagoya the vector and tensor anisotropies of CR for 1971-2017 were obtained. The components of the CR tensor anisotropy $(a_1^2, b_1^2, a_2^2, b_2^2)$ experiences annual and semiannual oscillations which are not due to the temperature effect. On the basis of the CR screening mechanism it was created the model which explains the observed oscillations of the CR tensor anisotropy. It is shown that the neutral current sheet is shifted to the south of the solar equator on $\sim 10^\circ$.

5.1. Acknowledgments

The work has been carried out under the support of RFBR grants Nos. 18-32-00064-mol-a and 18-02-00451-a. We acknowledge the Cosmic Ray Section, Solar-Terrestrial Environment Laboratory, Nagoya University for providing the data.

References

[1] Gololobov P, Krymsky G and Krivoshapkin P 2017 Proceedings of Science PoS(ICRC2017) 021
[2] Gololobov P Y, Krymsky G F, Krivoshapkin P A, Gerasimova S K and Grigoryev V G 2015 J. Phys.: Conf. Ser. 632 012056
[3] Krymsky G F, Krivoshapkin P A, Gerasimova S K and Gololobov P 2014 Astron. Lett. 40 230–233
[4] Krivoshapkin P A, Krymsky G F, Kuzmin A I, Skripin G V and Metlyaeva E A 1970 Acta Physics Academiae Scientiarum Hungaricae 29(2) 147–151
[5] Berezhko E G 1981 JETP Letters 33 399–401
[6] Simpson J A, Zhang M and Bame S 1996 The Astrophysical Journal 465 L69–L72
[7] Krymsky G F, Krivoshapkin P A, Mamrukova V P and Gerasimova S K 2009 Astronomy Letters 35 333–337
[8] Chirkov N P, Altukhov A M, Krymsky G F, Kuzmin A I and Skripin G V 1967 Geomagnetism and aeronomiya 7 620–631
[9] Krymsky G F, Krivoshapkin P A and Kuzmin A I 1968 Canadian Journal of Physics 46 S959–S961
[10] Krymsky G F, Kuzmin A I, Krivoshapkin P A and et al 1981 Cosmic rays and solar wind (Novosibirsk, Russia: Nauka)
[11] Fujimoto K, Inoue A, Murakami K and et al 1984 Coupling coefficients of cosmic ray daily variations for meson telescopes (Nagoya, Japan: Rep. 9, Cosmic Ray Res. Lab., Nagoya University)
[12] Kostyuk M G, Petkov V B, Novoseltseva R V and et al 2013 Bull. of. RAS: Phys. 77 569–571
[13] Ospenko A, Abunin A A, Berkova M D, Titova M A, Belov A V, Eroshenko E A, Yanke V G, Barabashina N S, Grigoryev V G, Starodubtsev S A, Kuzmenko V S and Yanchukovsky V L 2015 Bull. of the RAS: Phys. 75 662–666
[14] Krymsky G F 1964 Geomag. Aer. 4 763–769
[15] Munalata K, Kozai M, Kato C and Kota J 2014 The Astrophysical Journal 791:22 16
[16] Quenby J J and Lietti B 1968 Planet. Space Sci. 16 1209–1219
[17] Sarabhai V, Pai G L and Wada M 1965 Nature 206 703–704
[18] Nagashima K, Ueno H, Fujimoto K, Fujii Z and Kondo I 1972 Rep. Ionos. Space Res. Japan 26 1–30
[19] Nagashima K, Fujimoto K, Fujii Z, Ueno H and Kondo I 1972 Rep. Ionos. Space Res. Japan 26 31–68