Phase distribution variations of the first harmonic of the cosmic ray anisotropy in 1957-2011 years

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Abstract: The asymmetry of the interplanetary space, caused by the radial velocity of the solar wind and the quasi spiral position of the interplanetary magnetic field, leads to non-uniform distribution of the phases and the amplitude-phase interrelation of the first harmonic of cosmic ray anisotropy. To study the long term variations of cosmic ray anisotropy the characteristics of its first harmonic defined at each hour by global survey method have been used over the period 1957-2011. For each year of this period longitudinal distributions of the cosmic ray vector anisotropy and its amplitude-phase relation were obtained. The results clearly demonstrate the variations of anisotropy due to the solar activity and solar magnetic cycles. It is shown that the degree of inhomogeneity of the phase distribution remains on high level almost all the time (except for the anomalous 1996). Evaluations of the cosmic ray gradient components during disturbed and quiet periods at different polarities of the solar magnetic field were derived. The results of this study are consistent with the convection-diffusion model of the anisotropy.

Keywords: cosmic ray anisotropy, cosmic ray gradient, solar activity cycle, solar magnetic cycle.

1 Introduction

The anisotropy of galactic cosmic rays (GCR) is constantly observed in the solar wind near the Earth, and can be represented as a vector. The magnitude and direction of its vector (the first spherical harmonic of the anisotropy) is well described by the convection-diffusion model [1, 2, 3]. One of consequences of convection-diffusion model is the amplitude-phase interrelation of the first harmonic of anisotropy, which was predicted theoretically [4], and later confirmed experimentally [5, 6].

Long-term variations of the cosmic ray anisotropy have been studied in many papers [7, 8, 9, 10, 11]. Already in the early 50's, it became known that the average characteristics of the GCR anisotropy vector changes with 11- and 22-year periodicity [12]. Later, Scott Forbush [13] found that the long-term variations of the CR anisotropy display the main solar cycles.

In this paper, the first systematic study of long-term variations of amplitude-phase interdependence and phase distribution of the CR anisotropy was performed in the quiet and disturbed periods during the different polarities of the Sun total magnetic field (from July 1957 to January 1958, from August 1971 to November 1979 and from August 1991 to November 1999 – periods with positive polarity, from January 1960 to August 1969, from July 1981 to December 1989 and from January 2001 to December 2011 – periods with negative polarity). Data for 55 years (1957 – 2011) were used - over the five solar cycles. For each year the longitude distribution of the CR anisotropy vector and the interrelation of its amplitude and phase were obtained.

2 Data and methods

We used a database on cosmic ray variations, which was created in IZMIRAN. Density and anisotropy for the CR of 10 GV rigidity were calculated by the global survey method (GSM) [2, 14] by the hourly data from neutron monitor network. This database contains also various parameters of the interplanetary medium (the characteristics of the solar wind, interplanetary magnetic field, etc.), as well as indexes of geomagnetic activity and solar parameters. At our study we did not use the hours when the ground level enhancements (GLE) were observed.

In this paper, we analyze the vector component of CR anisotropy in the plane of the Earth's equator (x-axis is directed outward the Sun), with the amplitude A_{xy} and phase ϕ (the angle of the anisotropy vector with the x-axis, measured counterclockwise). The solar ecliptic system of coordinates is more preferable to comparison to theoretical models. However, for transition to this system it is required to know precisely an A_z-component of anisotropy, and the real A_z value not simply to obtain [15].

3 Discussion of results

3.1 Mean distributions

In figure 1, the phase (longitude) distribution of the first harmonic of the CR anisotropy and its amplitude-phase dependence are presented over the period 1957-2011. To get plotted points, the longitudes were divided into intervals in 10°, and considered values were obtained as averaged within each interval. Maximum of the phase distribution (distribution of the number of hours with a fixed phase of the observable CR anisotropy over the whole period, N_{max}) is about 95°, i.e., in the direction from the east. Maximum of the anisotropy amplitude (A_{xymax}) is very close to the phase distribution maximum.

These smooth dependences are the result of averaging for a long period. In this figure, data on 477226 hours are combined, what explains the small statistical errors, shown in the figure.

The resulting overall distribution is significantly inhomogeneous, which corresponds to the predictions of the simplified version of the convection-diffusion model of the anisotropy [4]. This coincidence first of all means that quasi spiral structure of the interplanetary magnetic field remain-

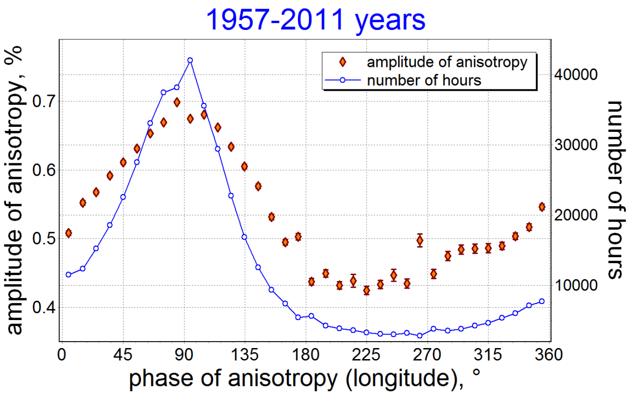

Fig. 1: Amplitude-phase interrelation of solar-diurnal anisotropy and its phase distribution for 1957-2011 years.

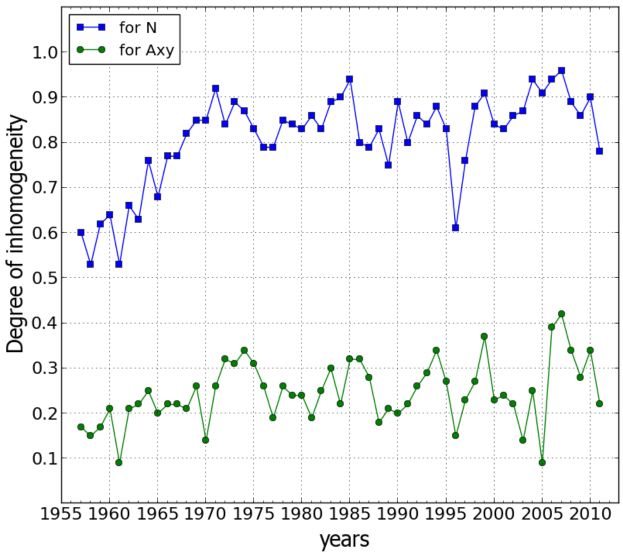

Fig. 2: The time dependence of the degree of inhomogeneity of the anisotropy phases and amplitudes distribution.

s during the main part of the time, and the solar wind velocity is relatively stable. Of course, these facts are well known and need not be further confirmed by CR. However, the following consequence of the obtained nonuniform distribution concerns only CR. This distribution testifies to essential prevalence of a positive gradient of CR density, and that this gradient, as a rule, has small size. Maximum phase distribution (8.79%) in Figure 1 turned out to be in the sector of $90-100°$. One can select the area between 40° and 130°, in which the majority of the points (60.4% of all hours), and the greatest amplitudes are. Area of the minimum values of the number of hours is between 210° and 300° (6.4% of all points) and the smallest amplitude anisotropy are between 180° and 270°.

We define the degree of inhomogeneity of the phase and amplitude-phase distribution as follows:

$$\delta_N = \frac{N90_{max} - N90_{min}}{N90_{max} + N90_{min}}; \delta_A = \frac{A90_{max} - A90_{min}}{A90_{max} + A90_{min}} \qquad (1)$$

where $N90_{max}$ is the largest number of hours in the sector width of 90°, $N90_{min}$, respectively, is the least number of hours in the sector width of 90°; $A90_{max}$ and $A90_{min}$ - the largest and the smallest sum of the values of the anisotropy in sector width of 90°. The values δ_N and δ_A can vary from 0 (completely homogeneous distribution) to 1. For the entire period (Fig. 1) there was obtained: $\delta_N = 0.81$, $\delta_A = 0.19$. These values (especially δ_N) show a substantially inhomogeneous distribution.

3.2 Time dependences

We studied how degree of inhomogeneity of phase distribution changes over the time. It was found that the value of δ_N (Fig. 2), calculated for each year by the formulas (1), varies from 0.53 (for 1958) to 0.96 (for 2007), which indicates the high inhomogeneity of distribution in all years. Sector of maximum density (N90max) located in different years in longitudinal zone from 0° to 150°, and with a minimum density - in the range from 180° to 320°. Sector with a minimum value of anisotropy ($A90_{min}$) located between 130° and 350° and the sector with the maximum value of the anisotropy ($A90_{max}$) – in longitudinal zone from 10° to 150°. The only exception is 2003, when the distribution has two peaks: normal (30° to 120°) and unusual (220° to 310°), and they are almost the same magnitude. Most likely, this feature is due to exceptionally large and effective coronal holes in 2003, and the related large azimuthal gradient of CR.

In the sector width of 90° with the maximum number of points by phase distribution in different years, from 42.4% of points (in 1958) to 77.5% (in 2007) are located. And only 8 years (1957-1963 and 1996) have less than 50% of the points in the maximum sector. Even in these years, the degree of inhomogeneity is high (> 0.5), but it may be considered as abnormally low on the background of majority years when it was > 0.8. It should be noted that in the anomalous period the years of 19^{th} cycle with especially high solar activity and quiet 1996 were combined; this anomaly for 1996 has been seen previously [16]. It is natural to assume that the more active period, the lower the degree of inhomogeneity. Just remember that the gradient of the CR at active periods greater in magnitude and significantly more changeable than in the quiet periods.

Partially, the anomaly of 19^{th} cycle may be associated with this fact, however, the main reason of this is probably methodical. The use in the 19^{th} cycle IGY-type neutron monitors of the small area provided their statistical accuracy much lower than the current neutron monitors. It not so strongly affects the variations of density determined by a global survey method, but the error of definition of a phase of anisotropy strongly depends on the statistical accuracy of separate detectors. Prior to 1963, the neutron monitor global network was equipped with standard IGY detectors of small area, and since 1963 until the end of the 60's old monitors were replaced by a new type of monitors (NM64). This reorganization of the global network is reflected in the variations of parameters in Figure 2.

3.3 Distributions under different conditions

Let's try to understand how solar basic characteristics and conditions in interplanetary space influence on the received distribution. To do this, we have made calculations for quiet periods with different polarities of the sun total magnetic field and disturbed periods at relatively active Sun.

The dependence of the phase of the anisotropy on the magnetic cycle reveals well near the minimum of solar activity that can be clearly seen in figures 3a and 3b. To obtain these figures, we chose the hours in which the Ap-index was less than 10, the sunspots number (SSN) was <50, in the periods of negative ($qA<0$) and positive ($qA>0$) polarity of the general solar magnetic field, respectively.

During the negative polarity of the general solar magnetic field (figure 3a) the maximum of phase distribution is about 95°, the maximum of the anisotropy amplitude is at about 105°. For positive polarity (figure 3b) the maximum of phase distribution and the maximum of the anisotropy amplitude are shifted to about 50°-70°. However, in figure 3b for the positive polarity the second peak (much less) in the amplitude of the anisotropy is seen - around 200°-260°. This may be due to the anomalous 1996 year and some similar periods when the amplitude of the anisotropy did not have a pronounced maximum because of very small magnitude [Belov, 1999].

To study the active periods we selected hours with Ap-index >20, independently of the number of sunspots and polarity. For active periods (figure 3c) the maximum of phase distribution is about 95°, the maximum of the anisotropy amplitude is at about 85°. But about 260°-270° there is another increase of the anisotropy amplitude. This feature can be explained by the fact that the CR gradient during the disturbed periods is not only higher, but more variable. If the radial component of the gradient (as well as the component along the field) is always positive during the quiet periods, then it sometimes becomes negative inside of the interplanetary disturbances sometimes. This combination can create a large anisotropy in the direction opposite to normal. At the same time, the latitudinal and azimuthal components of the gradient also increase significantly and contribute to the anisotropy.

3.4 Estimation of cosmic ray gradient

To obtain estimates of the radial (G_x) and latitude (G_z) components of the CR gradient from the found distributions (Fig. 3a, 3b, 3c), let us assume that the anisotropy vector ($\vec{A_{xy}}$) (with the components A_x, A_y) and the interplanetary magnetic field vector located in the one plane and use the following equations [4, 17]:

$$G_x = \frac{\sqrt{k}}{\rho}\left((A_c - A_x) - A_y \tan\psi\right)$$

$$G_z = \frac{\sin\psi}{\rho}(\sqrt{1-k})\left(A_x - A_c - \frac{\frac{1}{\tan\psi} + k\tan\psi}{1-k} A_y\right)$$

where k is the ratio of the coefficients of longitudinal and transverse diffusion; ρ - gyroradius of protons with 10 GV rigidity; $A_c = (\gamma+2)\frac{u}{c}$ – the convective component of the anisotropy, γ – index of the energy spectrum of primary CR (for these estimates was adopted $\gamma = 2.6$); u – the solar wind velocity, A_x and A_y – radial and azimuthal components of the anisotropy, $\psi = \arctan(\frac{B_y}{B_x})$ – the angle between the IMF and the x axis, B_y and B_x – the components of the IMF vector.

We used the anisotropy amplitude, which corresponded to the maximum in the phase distribution (i.e., the most common value of the amplitude). For those hours which are in the desired phase interval (e.g., $90° < \phi < 100°$, with the maximum phase around 95°), and are consistent with the parameters for the selected period (for quiet periods – $Ap < 10$, $SSN < 50$; for active – $Ap > 20$), the mean

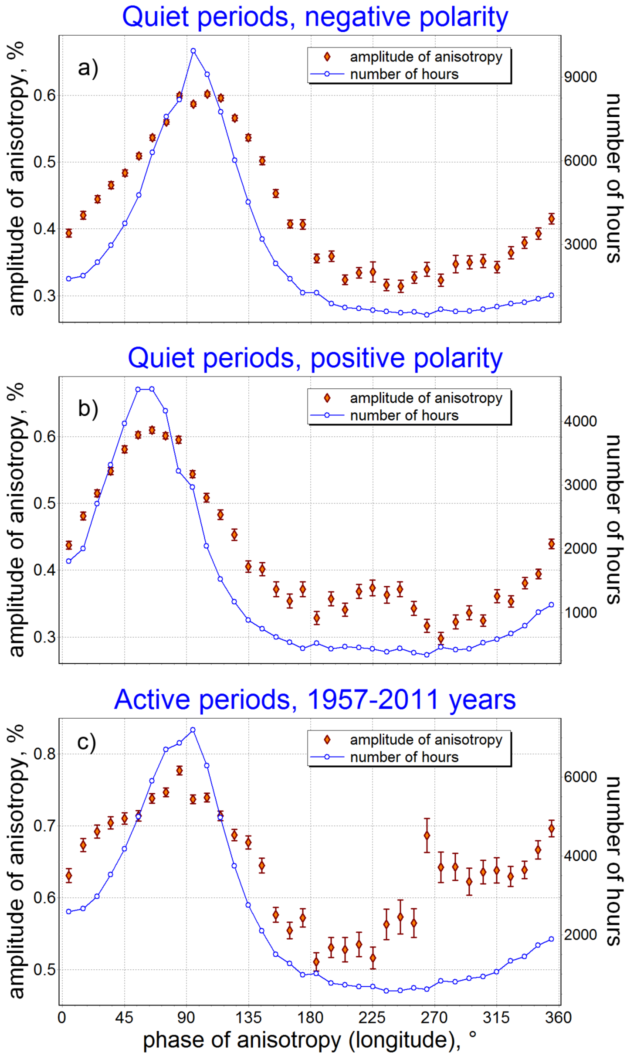

Fig. 3: Amplitude-phase interrelation of solar-diurnal anisotropy and its phase distribution: a) in the quiet periods at the negative polarity of the general solar magnetic field (1960-1969, 1982-1989, 2001-2011 years); b) in the quiet periods at the positive polarity of the general solar magnetic field (1971-1978, 1992-1999 years); c) in the active periods during the 1957-2011.

values of the solar wind velocity, the values of B_x and B_y components of the interplanetary magnetic field and the angle ψ were calculated. Using the above model and the data, we calculated the values of the CR gradient components (G_x and G_z) and other parameters (see table 1). The calculations were performed separately for the different polarity of IMF (i.e., $B_x > 0$ and $B_x < 0$), with $k = 0.01$.

Analyzing the results, we can draw several conclusions: 1) the gradients increased several times in the disturbed periods relatively quiet periods; 2) In the periods of positive and negative polarity of the general solar magnetic field, at the changes of the sign of IMF sector (changing ψ), the sign of G_z component of the CR gradient also changes, so G_z sign always coincides with the sign of IMF sector; 3) when compared the quiet periods with different polarities, we can see that the absolute value of G_z component is less for negative polarity than for positive.

These results are consistent with the conclusions by

	Number of hours	u, km/s	B, nT	A_c, %	ψ,°	G_x, $\%/AU$	G_z, $\%/AU$	ρ, AU	A_{xy}, %	ϕ,°
Quiet periods, $qA < 0$	8024	403	4.5	0.62	148	2.09	-2.87	0.049	0.58	95
					327	2.11	2.56			
Quiet periods, $qA > 0$	4053	402	5.1	0.62	147	1.65	-6.27	0.043	0.61	65
					331	1.53	7.21			
Active periods 1957-2011	5013	556	8.9	0.85	139	6.2	1.71	0.025	0.73	95
					322	5.95	0.72			

Table 1: Characteristics of CR anisotropy and relevant parameters in different periods. Gradients are calculated for different polarity of IMF, and accordingly, for the different mean values of ψ.

[18] that the latitudinal distribution of cosmic rays has a local minimum near the heliospheric current sheet. This is manifested during the positive polarity of the Sun. The situation is more complicated during of negative polarity. At this time drift effects change the sign and we can expect a local maximum near the heliospheric current sheet. However, the structure of the gelio magnetosphere is that galactic cosmic ray is easier penetrate into the polar regions than the equatorial at either polarity of the field. Therefore, at the negative polarity of the Sun drift and structural factors counteract each other and this may explain the decrease of the absolute values of G_z in such periods.

Most likely, the values of gradients are too high in the table. As used herein the assumptions (neglect the latitudinal component of the IMF and the azimuthal component of the gradient of CR, the use of components of the CR anisotropy in the plane of the earth's equator, etc.) does not allow for a detailed quantitative analysis, and we plan to perform a more complete and accurate calculation of gradients in the future, but here give only preliminary, mostly qualitative evaluations.

4 Conclusions

The change of the phase distribution and the amplitude-phase dependences of the solar-diurnal anisotropy, considered for a long time interval (1957-2011), obey in the main features to the 11- and 22 years solar cycles.

Essentially inhomogeneous phase distribution and a significant the amplitude-phase dependence exist almost permanently, but in some periods the inhomogeneous greatly reduce. It occurs in disturbed periods and in certain periods of low solar activity during the positive polarity of the general solar magnetic field.

Estimates of a gradient of CR for various conditions showed that radial and latitudinal components of the gradient during the disturbed periods much more, than in quiet, the sign of the latitudinal component, as a rule, coincides with a sign of sector of the interplanetary magnetic field irrespective of a phase of magnetic cycle of the Sun, and the absolute value of the latitudinal component of a gradient at positive polarity of the general magnetic field on the Sun is higher, than at the negative polarity.

Acknowledgment: This work is partly supported by Russian FBR grants 11-02-01478, Program 22 BR of the Presidium RAS "Fundamental processes of research and development of the Solar System" and Program 10 BR of the Presidium RAS "The fundamental properties of matter and Astrophysics". Authors are thankful to all collaborators provided continue monitoring of the CR neutron component: http://cr0.izmiran.ru/ThankYou, http://www.nmdb.eu/.

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