Phase distribution of the first harmonic of the cosmic ray anisotropy during the initial phase of Forbush effects

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Abstract. Phase distribution and amplitude-phase dependence of the first harmonic of the cosmic ray anisotropy in the initial phase of Forbush decreases are studied in the events during the time period 1957-2013. Statistical analysis of all Forbush decreases with a sudden onset for this period showed that the specific features of the phase distribution of the first harmonic of the cosmic ray anisotropy exist throughout the initial phase of the Forbush decreases, starting one hour before the shock, and ending at the time of maximum amplitude of anisotropy. Amplitude of the cosmic ray vector anisotropy is higher than in quiet periods already before the shock arrival, and it gradually increases as Earth enters deeper into the interplanetary disturbance, which creates the Forbush decrease.

1. Introduction

Numerical experimental data and convective-diffusive model [1, 2, 3] tell about advantageous directions of cosmic rays (CR) vector anisotropy. The specific directions in the interplanetary space are determined by the solar wind velocity and field line configuration of the interplanetary magnetic field (IMF). In addition, the observed radial gradient of CR intensity near the Earth is almost continually positive in sign and moderate in size. A consequence of these circumstances is the non-uniform phase distribution of vector anisotropy [4, 5].

Long-term changes of phase distribution and amplitude-phase interrelation of the first harmonic of galactic CR have been studied in [6]. It was shown that these changes mainly follow 11- and 22-year solar cycles, and that non-uniform phase distribution and considerable amplitude-phase dependence are almost continual. The aim of this work is to study phase distribution of the first harmonic of CR anisotropy not only during the quiet but in disturbed periods as well, at the beginning of a Forbush effect – 1 hour prior to the shock arrival and in the first couple (or several) hours after its arrival. Forbush effects are the results of two types of interplanetary disturbances: recurrent and sporadic [10, 11, 12]. The first group of FEs arises from the impact of high speed plasma streams from coronal holes; the second one are caused by coronal mass ejections (CMEs) from the Sun. We use a large statistical sample (the events during 1957-2013) collected in IZMIRAN databases, the description of which is given in the next section.

2. Data and Method

In this work we use IZMIRAN databases, created by the Cosmic Ray Department under the management of A. Belov. The databases provide a selection of CR events with a number of parameters. After processing hourly data from world wide neutron monitor network (www.nmdb.eu; http://cr0.izmiran.ru/mosc) by the Global Survey Method (GSM) [9] we obtain hourly values of the CR density and anisotropy above the Earth atmosphere and magnetosphere, specially calculated for 10GV rigidity. These data are supplemented by corresponding solar, interplanetary and geomagnetic characteristics taken from http://omniweb.gsfc.nasa.gov/ow.html, ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap/wdc, and http://www.swpc.noaa.gov/ to form the first database "on the CR variations", containing data in the time period covering more than 50 years of observations (1957-2013) [7, 15]. The second database "on interplanetary disturbances and Forbush effects (FE)" contains characteristics of FEs (see figure 1 and description) on more than 6000 events and corresponding solar wind disturbance parameters, indices of geomagnetic activity and information on solar sources [8, 12]. The information on solar wind is taken from the OMNI database (http://omniweb.gsfc.nasa.gov).

For the analysis the FEs were selected from the FE database using following criteria: (1) the onset of FE is simultaneous with the shock arrival, which was determined using Sudden Storm Commencement (SSC); (2) The FE onset is separated from the following event (onset) at least for 36 hours, and from the beginning of the previous one – for 60 hours and more when the previous event was larger than 1,4%; (3) We also didn't use the hours with observed ground level enhancement (GLE) – all such hours were removed from the analysis. The selection resulted in a total of 817 events.

To understand better which parameters and characteristics of the FEs we use for analysis, below in figure 1 a typical behavior of CR density in the main phase of shock-associated FE is presented. We consider FEs, caused by sporadic interplanetary disturbances accompanied by the interplanetary shock arrival. These FEs are characterized by a sudden decrease followed by the gradual recovery of the CR density that usually lasts for several days [13]. In the text below one can find a description of each parameter which is easy to get from the database.

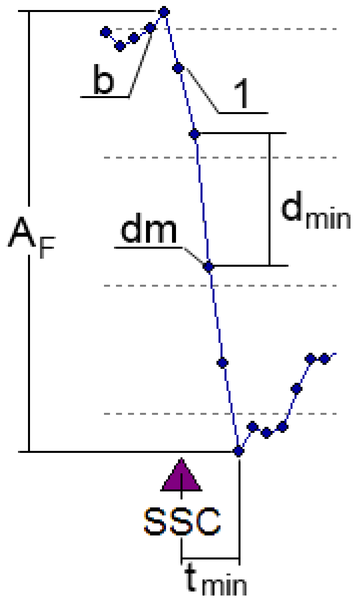

Figure 1. Behavior of the CR density in time at the beginning of FE. For explanation see text below.

In figure 1, obtained by GSM, FE characteristics are shown: A_F – magnitude of FE (the maximum variation of CR density for 10 GV rigidity); d_{min} – maximum one-hour decrease in CR density (maximum decrement, which is always negative); t_{min} – full time of the main phase of FE (time from the onset of event – SSC to the maximum decrease of CR density). The measured timings of the investigated FE time period are: zero hour (shock arrival, *i.e.* SSC), hour preceding the zero hour, denoted "b", and the hour following the zero hour, denoted "1". In addition, the timing of the maximum one-hour decrease in CR density, t_{dm}, and the timing of the maximum amplitude of the equatorial component of CR anisotropy ($A_{xymax}(p)$), t_{max} (not shown in the figure) with respect to zero epoch are considered. Correspondingly, we also consider phase dependence of $A_{xymax}(p)$ where p is the phase of anisotropy, and the phase distribution of the number of hours with maximum amplitude of CR anisotropy, $N_{max}(p)$. All of these parameters are found in the second IZMIRAN database for each FE. The time period between timing "b" and "1" is 2 hours for each of the events in the sample, whereas t_{dm} and t_{max} differ from one event to another. On the average for all of the chosen events, t_{dm} and t_{max} are 10.8 and 14.2 hours, respectively.

3. Results and discussion

Amplitude-phase dependence $A_{xyb}(p)$ and phase distribution $N_b(p)$ before the shock arrival, averaged for each phase by the 817 events, are shown in figure 2 in comparison with respective distributions during the quiet periods $A_{xyq}(p)$ and $N_q(p)$ (averaged for 158140 hours).

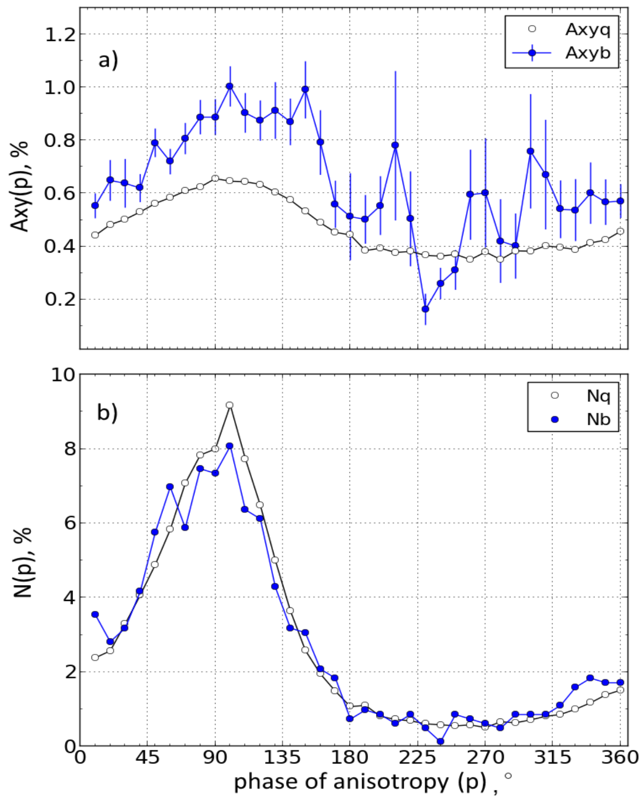

Figure 2. Amplitude-phase dependence (a) and phase distribution (b) one hour before the shock arrival (A_{xyb}, N_b) and during the quiet periods (A_{xyq}, N_q)

The hours of quiet periods were chosen from the first (CR variations) database by the following criteria: IMF intensity B<10 nT, geomagnetic activity index Ap<20 (2nT) and solar wind velocity

V<450 km/s. After excluding GLE effects from our sample 158140 quiet hours remained. One can see that number of hours for quiet parameters is much more than the number of the studied FEs, therefore errors in determination of q parameters are much less. This allows us to use more fine scale for plotting.

One can see that one hour before the shock arrival the amplitude of CR anisotropy (A_{xyb}(p)) substantially increased as compared with the usual quiet periods, and this increasing is observed at almost all longitudes (figure 2a). Therefore, it is reasonable to conclude that the interplanetary environment before FE is more disturbed, than during the quiet periods. Given the criteria for selection of quiet time periods, it is reasonable to assume a dependence of amplitude of CR anisotropy on intensity of IMF (B), solar wind velocity (V) and geomagnetic indices (e.g., Ap).

We aim to answer a question: Is the interplanetary medium more disturbed before the FEs than in the quiet periods? Thus, we calculated mean values of space parameters before (b) the FEs (see the table) and compared them to quiet (q) period values. It seems that conditions before the FE are somewhat more disturbed than in quiet periods. Although there seems to be connection between the change in the interplanetary conditions and A_{xy}, this should be further tested.

Table. Mean values of space parameters before the FEs and at quiet period.

	b	q	q_2
Ap_mean	9.3	5.6	
V_mean, km/s	410	370	
B_mean, nT	8.9	5.3	
A_{xy}, %	0.77	0.56	0.63

Will the anisotropy be the same amplitude if we select from quiet hours only the hours with characteristics close to those in the period "before" FEs? To answer this question we selected only quiet hours with parameters close to average values of parameters before the FEs, *i.e.* with a speed of solar wind V_{q2} = 400 - 420km/s, IMF intensity B_{q2} = 7 - 9 nT, and Ap_{q2} = 8 – 10 (2nT). A selection resulted in 629 hours. For this new sample the average value of amplitude of CR anisotropy is A_{xyq2}= 0.63% which is a little higher than A_{xyq} but substantially less than A_{xyb}. Thus, it is obviously, that revealed distinctions in interplanetary conditions are not enough to explain a difference in A_{xy} amplitudes.

Thus, only some part of a difference (A_{xyb}–A_{xyq}) can be explained with the change in the interplanetary conditions. The bigger part of increase in anisotropy just before the FE is most likely the precursor of arrival of interplanetary disturbance. This result confirms and completes the conclusions from [12]. If the disturbances are the same and interplanetary conditions before their arrival were constant, then we would see an increase of CR anisotropy in specific directions only. Rather large anisotropy at all phases indicates a variety of disturbances and situations before the interplanetary shock arrival. It characterizes pre-shock time period and results in a variety of precursors seen in CR measurements [e.g., 14].

In figure 2a we observe an increase in the amplitude of anisotropy corresponding to large phases. This implies the appearance of Sun-directed CR flows towards the disturbed region where the Forbush decrease occurs before the arrival of interplanetary disturbance. Nevertheless, in figure 2b it can be seen that phase distributions for quiet hours and the hour preceding the shock arrival are very similar. The behavior of the phase distribution, N(p) and amplitude-phase dependence, A_{xy}(p) during the passage of the disturbance over the Earth was also investigated.

We compare the two for several different timings before and within the FE main phase: one hour before the shock arrival (A_{xyb} and N_b), one hour after the shock arrival (A_{xy1} and N_1), at the hour of the maximum one-hour decrease in CR density within the FE (A_{xydm} and N_{dm}) and at the hour of the maximum value of the CR anisotropy (A_{xymax} and N_{max}). We remind the reader that the hour of shock arrival is considered as zero hour. The results are presented in figure 3 (a, b).

One can see (figure 3a) that the maximum amplitude of the anisotropy (A_{xymax}(p)) is higher than all the others for all of the phases (2-3 times). It is high even in comparison with A_{xydm}(p) value, which is observed already deeply in interplanetary disturbance. A_{xymax}(p) has a large value in all directions, even in unusual anisotropy directions..

To explain such anisotropy within the simplified version of the convective-diffusive model a large negative radial gradient of CR density would be necessary [2; 3]. However in reality such anisotropy results from contribution of all components of the CR gradient in the IMF which can strongly differ from a quasispiral field of a quiet solar wind.

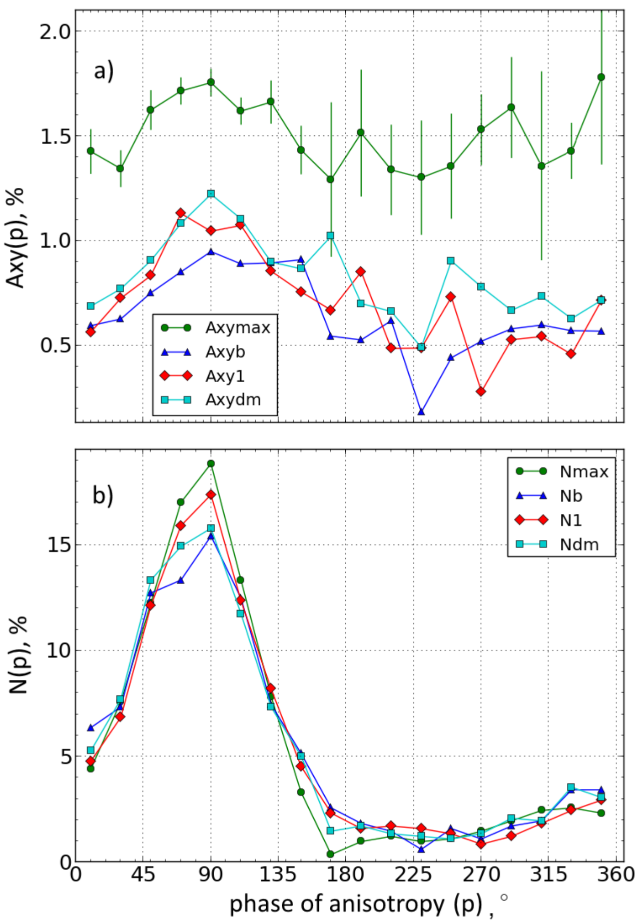

Figure 3 (a, b). Amplitude-phase dependence (a) and phase distribution (b) one hour before the shock arrival (A_{xyb}, N_b), one hour after the shock arrival (A_{xy1} and N_1), at the hour of maximum one-hour change in CR density (A_{xydm} and N_{dm}) and at the hour of maximum value of the anisotropy (A_{xymax} and N_{max}).

For phases up to 130° the anisotropy amplitudes are more or less consecutively increased as the interplanetary disturbance passes over the Earth ($A_{xyb}<A_{xy1}<A_{xydm}<A_{xymax}$). We note that the maximum of A_{xy} is considerably late with respect to the timing of the fastest fall of CR density (on average for 3.4 hours, see Section 2), which in turn has to be close in time with the maximum radial component of the CR gradient. Although it would be interesting to investigate this phenomenon, as well as the behavior of the latitudinal and azimuth components of the CR gradient and the role of the IMF

changes in the increase of the A_{xy}, this would require further analysis which is beyond the scope of this paper.

It can be seen in figure 3b that the phase distributions for all selected FE timings differ very little, however, we see that $N_b(p)$ is somewhat flatter than others, whereas $N_{max}(p)$ is the least flat distribution. We note that decreases in amplitude of anisotropy (figure 3a) and in number of events (figure 3b) around 165° occur not only due to FEs with amplitude $A_F<2\%$, but also due to large FEs.

The majority of distributed number of hours of the phase distributions are found within the phase range 45° - 135° (figure 3b): 69.3% for N_{max}, 61.4% for N_b, 63.2% for N_{dm}, and 66% for N_1. Similar calculations were carried out in [6] for phase distributions over the time period 1957 – 2010, where the majority of distributed number of hours (60.4%) were found within the phase range 40° - 130°. In general, the main features of the distribution remain the same at the entrance into the disturbance, as well as in the continuing hours throughout the main phase, even at the maximum amplitude of anisotropy, i.e. the preferred directions of anisotropy exist almost continually, even during the passage of the disturbance.

4. Conclusions

In the hours preceding an arrival of a shock wave, the amplitude of the CR anisotropy considerably increases compared to quiet periods, and this increase occurs in almost all of the phases of anisotropy.

The maximum amplitude of anisotropy (A_{xymax}) in a Forbush decrease is substantially higher than the anisotropy in an hour before the shock arrival, in an hour after the shock arrival and in an hour of maximum one-hour decrease of CR density.

For phases up to 130° the amplitude of anisotropy increases with time as the interplanetary disturbance passes over the Earth (Axyb<Axy1<Axydm<Axymax). In general, the main features of phase distribution are the same just before the FE and throughout its main phase, i.e. the preferred directions of the anisotropy exist even inside of interplanetary disturbances.

5. References

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