Behavior of the cosmic ray vector anisotropy near interplanetary shocks

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Abstract—**The behavior of the galactic cosmic ray density and vector anisotropy during geomagnetic storms with sudden storm commencements are being investigated using the Global Survey Method (GSM) and the results derived from neutron monitor (NM) network data over the time period 1964 - 2006. It is shown that in average the anisotropy directly before the sudden storm commencement (SSC) has a perceptible increase which is proportional to the magnitude of the following Forbush decrease (FD). The approach of a shock wave begins to affect the cosmic ray anisotropy and density about five hours prior to the shock's arrival at the Earth. Changes of the anisotropy direction, especially for western sources of Forbush effects (FEs), may be revealed significantly earlier.**

1. Introduction

The fact that cosmic rays, observable at the Earth, react to a shock wave approach, prior to its arrival [1], [2] is a subject already known but more actively investigated during the last 15 years [3], [4], [5], [6], [7], [8], [9]. As it was emphasized in [6], the effect of the arriving shock (precursor) is a complicated combination of the pre-increase and pre-decrease in the cosmic ray (CR) variations. This presupposes unusual pitch-angle distribution of the CR intensity which cannot be described by the sum of some first spherical harmonics. Nevertheless, this effect may be revealed in variations of the zero (CR density) and first (anisotropy) cosmic ray spherical harmonics.

In the present work the CR density and the first harmonic of CR anisotropy before the shock arrival are investigated on the big statistical material

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2. Data and methods

In the present analysis the CR density and anisotropy were calculated using the GSM [6] on an hourly basis covering 48 years (1957-1962 and 1964-2006). One of the main tools of this analysis was the new database, created in IZMIRAN and recently presented in the Internet (http://cr20.izmiran.rssi.ru/AnisotropyCR/Index.php), which combines the results derived by the GSM for CRs of 10 GV with the parameters of solar wind and other interplanetary characteristics acquired from OMNI database (http://omniweb.gsfc.nasa.gov/ow.html). Data concerning the interplanetary disturbances and FEs were derived from another database, also created in IZMIRAN. From 5800 FEs in total, 1529 FEs begin simultaneously with the SSC of the magnetic storm and 1317 of them refer to the time period 1964 - 2006, which is mainly studied in this paper.

Furthermore, the component A_{xy} (the projection vector of anisotropy on the Earth equatorial plane) of the first harmonic of anisotropy is mainly used for analysis. This component is responsible for the creation of solar diurnal variations and diurnal waves, both of which are known to all dealing with NM data. The advantages of A_{xy} component are that it is derived separately for each hour and it does not depend, in any way, on the procedure of combining the results obtained by the GSM for different time intervals. It is also important that we can define an absolute value of A_{xy} which is difficult to calculate for another component of the full vector of anisotropy A, e.g. the north-south component A_z directed along the Earth's axis [10].

3. Results - discussion

Firstly, CR anisotropy (A_{xy}) is considered to vary directly before the shock arrival, at the hour preceded the SSC registration. For the 1529 FEs, beginning simultaneously with the SSC, the value of the averaged anisotropy (A_{xyb}) was calculated and the same value of A_{xyb} was also found for the 1317 FEs, within the time period 1964 - 2006. For comparison, the mean value of A_{xy} for all 376402 hours over the time period 1964 - 2006 (only the periods of ground level enhancements of solar cosmic rays are excluded) was calculated. All these results are shown in Table I. As it is seen the anisotropy before the SSC is perceptibly higher than the mean value. However this increase of anisotropy can not be immediately attributed to the approaching shock. It must be taken under consideration that FEs are often developing by series and a significant amount of FEs begin on a disturbed background. If retain only those FEs started not earlier than in 72 hours (t_A>72) then averaged A_{xyb}=0.70±0.02 (525 events), and for the period 1964-2006 A_{xyb}=0.70±0.02 (471 events). It is obvious that under such a selection the magnitude of anisotropy before the shock decreases a little, but it still exceeds the mean values.

In order to be certain that disturbed periods before the shock are excluded we selected only those events when the interplanetary conditions near Earth were sufficiently quite at the hour preceded the SSC: solar wind velocity <550 km/s and interplanetary magnetic field (IMF) intensity <9 nT. Under these conditions (t_A>48 hrs), 368 events were registered and the averaged anisotropy was calculated (Table I). For those quiescent interplanetary conditions (131316 hours in total) the mean value of anisotropy was A_{xy} =0.574±0.001 %, i.e. it is perceptibly lower than that calculated for all hours of the time period 1964 - 2006. Thus, the difference between the mean A_{xy} and the anisotropy before the SSC is more than 6 standard statistical errors and it may be considered as meaningful. This confirms the fact that the obtained distinction appears to be due to the approaching shock and the interplanetary disturbance following it, and not due to earlier disturbances.

TABLE I
THE AVERAGED ANISOTROPY BEFORE THE SHOCK ARRIVAL A_{XYB} AND THE MEAN VALUE OF ANISOTROPY A_{xy} FOR THE EVENTS UNDER CONSIDERATION

	Averaged anisotropy (before the shock arrival)	**Mean value of anisotropy**
1529 FEs (onset simultaneously with the SSC)	A_{xyb}=0.77±0.01 %	
1317 FEs (1964 – 2006)	A_{xyb}=0.77±0.01 %	A_{xy}=0.6165±0.0007 %
525 FEs (t_A>72 hrs)	A_{xyb}=0.70±0.02	
471 FEs (t_A>72 hrs) (1964 – 2006)	A_{xyb}=0.70±0.02	
368 FEs (t_A>48 hrs) (1964 – 2006)	A_{xyb}=0.73±0.02 %	A_{xy} =0.574±0.001 %

The radial A_x and azimuthally A_y components of the equatorial anisotropy ($A_{xy}=\sqrt{A_x^2+A_y^2}$) were calculated and compared for different conditions. For the quiescent solar wind (131316 hours) A_x = 0.070±0.001 % and A_y = 0.370±0.001 %. For the same quiescent but pre - shock conditions (368 hours) A_x = 0.05±0.02 % and A_y = 0.47±0.03 %. The differences concern mainly the A_y component and they are less than in A_{xy}, which means that before the SSC the anisotropy not only increases but it becomes more variable due to the strengthening of Ay directed from east to west.

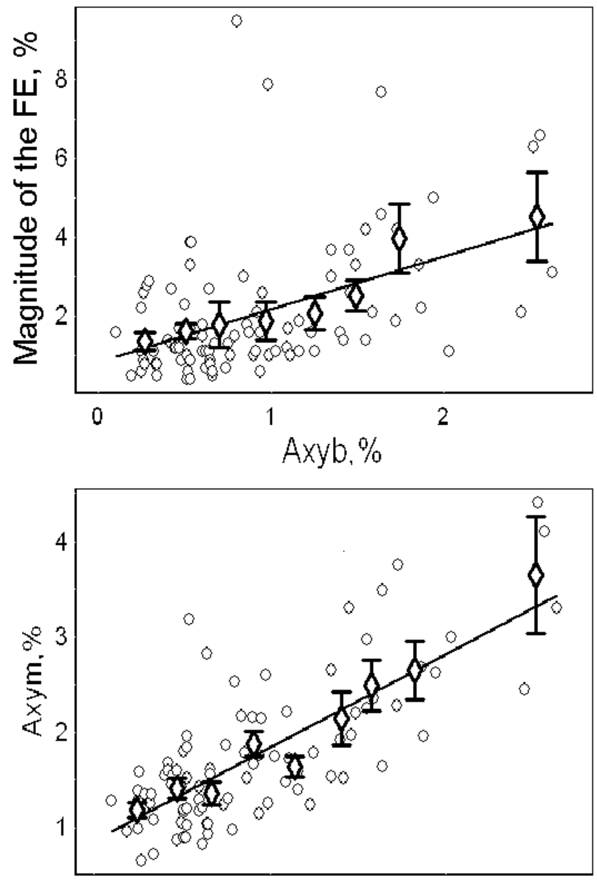

Fig. 1. Correlation of the FE magnitude (A_F) and maximum amplitude of the first harmonic of CR anisotropy (A_{xy}) during the FEs with the magnitude of the first harmonic (A_{xyb}) directly before the shock.

In order to find out if the anisotropy (A_{xyb}) before the onset of event is connected to the magnitude of the following FE (A_F) and to the anisotropy inside the FE, only the events which began in the quiescent conditions (as they were defined above) have been considered. The decreases with the minimum CR density, which are less than one day apart from the events' onset, are considered, in order to reduce the possible number of events caused by the high speed solar wind streams from coronal holes or by complicated FEs due to several sources. In Fig. 1 the magnitudes of FEs and maximum values of the equatorial component of anisotropy A_{xym} are depicted upon the anisotropy before the shock (A_{xyb}). It is obvious that the magnitude of the FE (A_F) increases with the increase of the A_{xyb} and the correlation coefficient of these two parameters is 0.46. Stronger correlation is observed between A_{xyb} and A_{xym} (correlation coefficient equal 0.74). One can see that the magnitude of CR anisotropy, as it is observed before the shock, is statistically connected both with the magnitude of the evolving FE and the anisotropy inside this FE and is determined by them in some way.

The CR anisotropy changes may be seen not only directly before the shock but earlier as well, as it is indicated in Fig. 2, where the variations of CR density and A_{xy} component of anisotropy, averaged by the superposed epoch method, are depicted relatively the SSC moment.

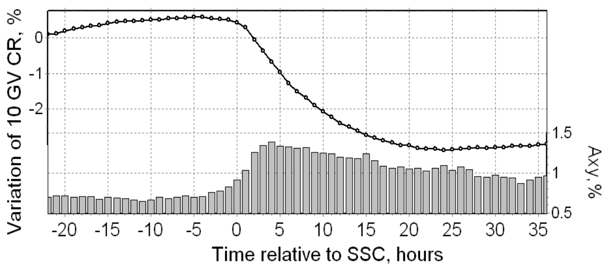

Fig. 2. Variations of CR density (points) and amplitude of the first harmonic of anisotropy (columns) for the periods before and after the SSC obtained from 332 FEs.

One day before the occurrence of the SSC, a gradual increase of the CR density is noticed. This is the recovery phase after the preceded FDs. During the last 12 hours the rate of this increase slows down. This increase is followed by a decrease which started to be clearly observed at least 5 hours prior to the SSC. The A_{xy} is close to the mean value during this day. In the last 5 - 7 hours a gradual increase of A_{xy} is observed which becomes larger near the SSC moment and continues after the SSC. Note, that CR anisotropy reaches its maximum in 3 - 4 hours after the SSC for this kind of FEs.

The effect of the shock on the greatest part of CR is likely to be detectable at a distance of one larmor radii ρ from the front. In the used set of 332 events started on the quiet background the mean IMF intensity before the SSC was 5.1±0.1 nT. For the protons of 10 GV rigidity in such field the Larmor radii $\rho \approx 0.043$ au and the shock with velocity 500 km/s covers this distance in 3.6 hours.

A distribution of A_{xyb} by the magnitude is considered as compared to the distribution for all A_{xy} over the time period 1964 - 2006 (Fig. 3). As it is seen small magnitudes of A_{xy} (<0.6%) before the shock are observed more rarely than at other times, whereas magnitudes higher than 0.6% are observed more often. This difference is especially noticeable for A_{xyb}>1.1%. Hereby the strengthened CR flux is directed from east to the Sun that apparently points out on the perceptible increase of CR gradient along the IMF. Besides, as the analysis has shown, the events with A_{xyb}>1.1% are distinguished by the more deep FD and higher values of anisotropy. All these peculiarities more clearly manifest for the FEs associated to the remote western sources, while the region of the strongest modulation is located to the west of Earth.

The averaged behavior of the anisotropy succeeded in picking up the effect of approaching shock, but this effect is relatively small. It is obviously decreased while averaging. The point is that in FEs two types of precursors occurring by a different way (pre-increase and pre-decrease) are combined, and they create almost opposite anisotropy.

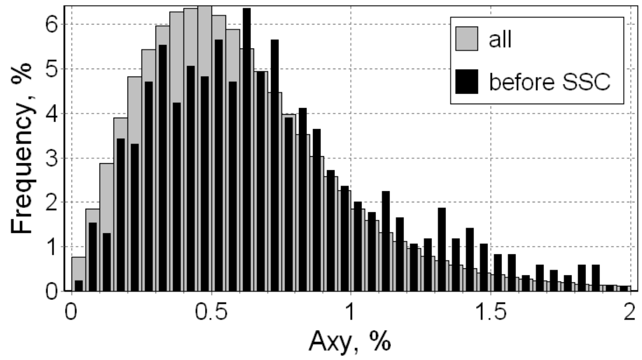

Fig. 3. A frequency distribution of the amplitude of the first harmonic of CR anisotropy at the last hour before the SSC.

There is also a big variety of interplanetary conditions before the shock. It is clear that for separate events and FE groups more considerable effect should be pronounced.

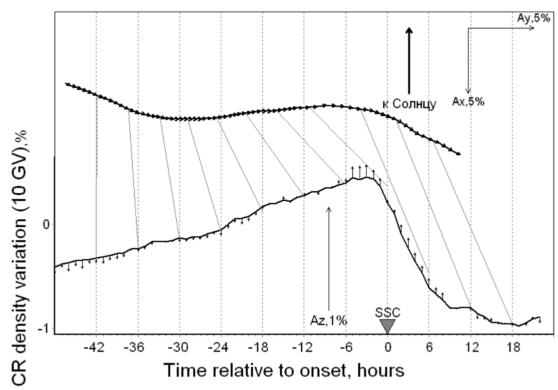

Fig. 4. Averaged variations of the CR density and anisotropy before the Forbush effects caused by the western sources.

In Fig. 4 the variations of CR density and equatorial component of the first harmonic of anisotropy (A_{xy}) are shown before and just after the SSC, averaged for 15 events which begun with quiet interplanetary and geomagnetic conditions and followed at least by a moderate magnetic storm (K_p-index ¿ 6). These events were associated to western sources (associated flares were located to the west of 30°W). One can see that in such events the anisotropy vector starts its turning to the Sun approximately 30 hours prior to the shock arrival.

4. CONCLUSIONS

The analysis of the CR vector anisotropy derived from the data of the world wide NM network during the FEs is able to provide the information about approaching shock waves. For different groups of such events the precursors are big enough and become detectable more than a day prior to the geomagnetic storm onset. The most interesting results of this analysis are:

- The values of the equatorial CR anisotropy before the shock arrival (A_{xyb}) averaged separately:
- by all 1529 FEs,
- by the 1317 FEs through the time period 1964 – 2006,
- by those FEs which started not earlier than in 72 hours one after another
- and by the 368 FEs, which were registered during quiescent interplanetary conditions, - is higher than the mean value of anisotropy (A_{xy}) as it was calculated for the FEs mentioned above (see section 3)

- The values of the two components A_x and A_y of equatorial anisotropy were calculated for both quiescent solar wind and the same quiescent but pre - shock conditions. The difference is more significant for component A_y.

- CR anisotropy before the shock is statistically connected to the magnitude of the evolving FEs and especially to the anisotropy inside these FEs.

- CR anisotropy changes may be seen not only directly before the shock but earlier as well.

- Small magnitudes of A_{xyb} before the shock are observed more rarely than at other times, whereas magnitudes higher than 0.6% are observed more often. This difference is especially noticeable for A_{xyb}>1.1%.

It is important to complete the analysis of CR vector anisotropy and density by studying the CR pitch - angle distribution, which can be found without the benefit of the spherical harmonics.

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