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Pitch-angle features in cosmic rays in advance of severe magnetic storms: Neutron monitor observations

A. V. Belov[1], **J. W. Bieber**[1], **E. A. Eroshenko**[1], **P. Evenson**[2], **R. Pyle**[2], **and V. G. Yanke**[1]

[1]Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation Russian Academy of Sciences (IZMIRAN), 142190 Troitsk, Moscow region, Russia.
[1]Bartol Research Institute, University of Delaware, Newark, DE 19716, U.S.A.

Abstract. The behavior of cosmic rays in advance of the severe geomagnetic storms of 1978-1982 (from the Gosling list of severe storms) is analyzed on the basis of the cosmic ray anisotropy and pitch angle distribution derived from neutron monitor observations. This analysis aims to reveal cosmic ray predictive effects (loss cone and pre-increase) before arrival of the shock and solar wind disturbed region. Essentially in all cases the changes in cosmic rays, in particular their anisotropy, start well before the beginning of major magnetic storms, which do not always coincide with the time of shock arrival; the severe magnetic storm may start later (up to 20 hours after), depending on the structure, orientation and magnetic topology of solar ejecta. We show examples for which the characteristic changes in CR anisotropy and pitch angle distribution (as a narrow decrease oriented along the magnetic force line) are revealed. These loss cone effects are predictors of strong geomagnetic disturbances.

1 Introduction

The angular distribution of high-energy cosmic rays (CR) is usually well described by the sum of the first and second spherical harmonics, with rare exception. Such exceptions ("nonharmonical" distribution) appear sometimes before the great interplanetary disturbances arrive at Earth, when a combination of CR reflection and acceleration at the shock and "loss cone" effect resulting from magnetic connection with the cosmic ray depleted region behind the shock is usually observed. In this case the CR intensity from nearby directions may increase and decrease simultaneously. Examples of such behavior may be found in a set of experimental papers (e.g. Nagashima et al; 1994; Belov et al., 1995; Morishita et. al., 1997; Ruffolo et al., 1999; Bieber et al., 1999). In the recent numerical model by Ruffolo (1999) the complex pitch angle distribution of charged particles upstream of a shock is obtained theoretically. A combination of CR narrow predecrease (or loss cone) along the interplanetary magnetic field line and wider preincrease is sometimes observed just in the last hours before the shock, and other times for a long time ahead of the shock. Such an effect lasting more than a day in September 1992 was studied by Munakata et al. (2000) and Belov et al. (2001). Peculiar behavior of high energy CR appears to be a precursor of strong geomagnetic disturbances, and becomes more and more a subject of interest.

In the present report we try to identify similar features in CR pitch-angle distributions measured by neutron monitors (NM). The set of severe magnetic storms over the period 1978-1982, collected by Gosling et al. (1990) has been used for this analysis. The same set of 14 events was used already in a similar study of muon telescope data (Munakata et al., 2000).

Correspondence to: E. Eroshenko (erosh@izmiran.rssi.ru)

2 Data and methods

Data on the interplanetary magnetic field (IMF) and solar wind (SW) (OMNI Data) as well as geomagnetic (Kp, Ap and Dst indices) and solar data have been used in our studies. The main analysis employed cosmic ray data including hourly CR intensities from the world wide neutron monitor network and hourly values of density and anisotropy of 10 GV cosmic rays derived from the network (about 40 stations) by the global survey method. All these data are collected into a special database oriented towards analysis of complex CR events. It allows selection of desired events, picking out and visible presentation of all relevant data, calculation of the CR pitch angle and time-longitudinal distribution, and other parameters needed for the analysis. For each event we studied 2 days before and 5 days after a storm sudden commencement (SSC). A CR pitch-angle distribution has been found using CR variations from every station, and the locations of each station at every hour. In results presented further pitch angle is the angle between the real local field measured near Earth and the asymptotic direction for vertically incident 5 GV particles at each station. Pitch angle was measured from the sunward force line independent of field polarity. Asymptotic directions were calculated using the Tsyganenko (1989) model with due regard for diurnal and seasonal changes of the magnetosphere and geomagnetic activity level at every hour (Lin et al. 1995). The results, derived from the worldwide network by the global survey method, were used to subtract the isotropic part of variations. It allowed detectors with different response functions to be used to analyze anisotropy. Usually we used all NMs with cutoff rigidity <4 GV and low enough altitude (standard pressure>900 mb) to obtain the pitch-angle distribution.

Since a convective component of anisotropy is not related to the IMF direction and pitch-angle, a contribution of this component was subtracted from all station data using the real solar wind velocities.

3 Results and Discussion

We first consider events in September 1978 (Fig. 1).

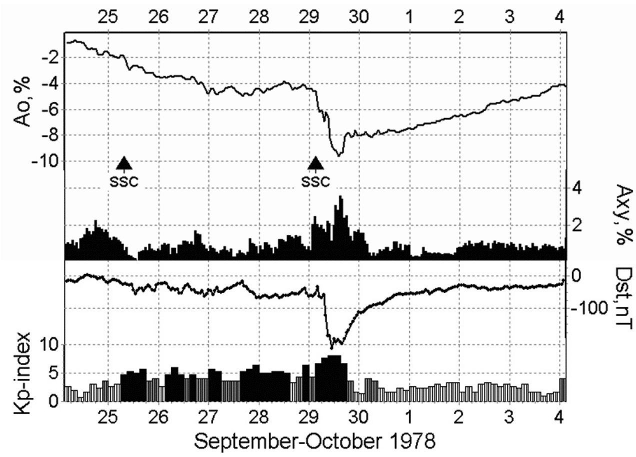

Fig. 1. Variations of cosmic rays together with Kp- and Dst indices of geomagnetic activity during 24 September – 3 October 1978. Ao – density variation of 10 GV cosmic rays, Axy – equatorial component of the CR first harmonic anisotropy.

A severe magnetic storm (maximal Kp index 8) and big Forbush decrease started after a strong shock registered as SSC on 29 September at 03:01 UT. A weaker shock was observed at ISEE on 28.09 at 20:40 UT. However, it did not cause significant changes in the IMF and CR, and there was only a weak impulse in the magnetosphere at 21:05. As shown in Fig.1, the CR density gradually decreased during 24-27 September (~4% altogether) because of a series of interplanetary disturbances following a ground level enhancement on 23 September. Geomagnetic activity did not decrease lower than minor magnetic storm (Kp=5) over the period 25-29 September, and sometimes reached moderate storm levels (Kp=6+). Just before shock arrival on 29 September Kp-index was 4+. We thus see that the event under consideration occurred on a disturbed background. This is the rule rather than the exception for strong magnetic storms, and it creates additional difficulties for studying such events. It is difficult to choose a quiet base period, difficult to separate effects of approaching disturbances from aftereffects of prior ones. This is reflected in the highly variable pitch-angle distribution, as shown in Fig.2.

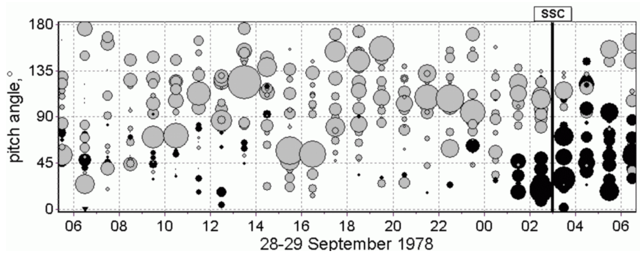

Fig. 2. Behavior of pitch-angle distribution of CR variations, as seen by different NMs on 28-29 September 1978. Grey circles – stations with positive variations, dark ones – stations with negative variations. Circle size corresponds to size of variation.

Perhaps some variations (like the CR density variations on September 28) are weak predictors of shock arrival, but they might also be caused by Earth's exit from the previous SW disturbance. We see a clearer and more typical precursor during the last 5-6 hours before the shock on 29.09, and this effect builds up with the shock approach. All stations with pitch angles <50^o record a deep decrease in CR. In effect, the Forbush decrease started earlier for these stations than at other stations, and well before the interplanetary disturbance reached Earth. Fig. 3 shows an anomalous pitch-angle distribution in the last hour before shock arrival. A deep decrease (exceeding 2.5%) was observed at stations with pitch-angles <50^o, along the sunward IMF line. This effect is considered a "loss cone" and possibly existed longer than 6 hours, but it is difficult to argue for certain, because no one station had small enough pitch-angles during the earlier hours. We also see a gap within the 50-80^o region of angles. This demonstrates once again the need for high latitude neutron monitors uniformly distributed in longitude.

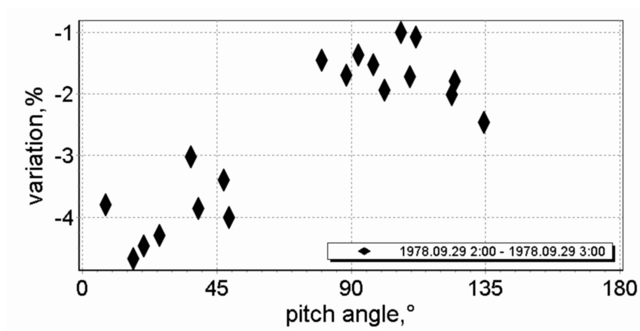

Fig. 3. Pitch-angle distribution of CR variations, as seen by different NMs (diamonds) at 2-3 UT on 29 September 1978

There is another instructive aspect of this event: One might think that a "precursor" observed after a disturbance has already started is a useless precursor. However, in such cases where several disturbances are expected, it is very difficult to say in advance, when and in which form they will come. In the case under question it would be easy to draw an erroneous conclusion (from the solar wind and geomagnetic data) that the main disturbance arrived already on the evening of 28.09 (20:40 UT), that it is not dangerous and will not cause a big magnetic storm. However, the cosmic ray behavior warned of a second approaching shock. It indicated that the main disturbance was ahead and could be dangerous. Indeed, the main shock with a magnetic cloud behind arrived several hours later (Gosling et al., 1990), and geomagnetic activity rose to severe magnetic storm (Kp=8) level.

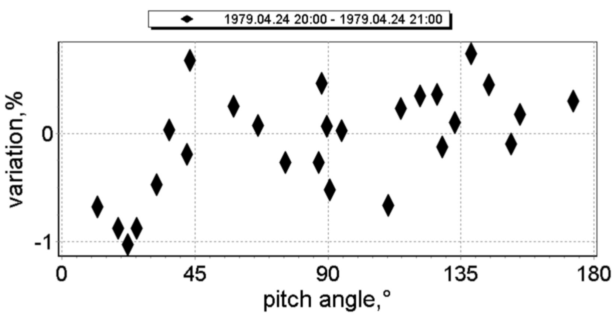

Fig. 4. Pitch-angle distribution of cosmic rays, as measured by different NMs (diamonds) at 21st hour on 24 April 1979.

The intensity deficit at small pitch angles is often not as big as in the example discussed above. The deficit was about 1% in the event on 24 April 1979, but in this case the available stations were distributed uniformly in pitch angle. Fig. 4 displays a deficit near the sunward IMF, and a sudden jump from lower to higher intensity around 35-50?. The shock arrived 3 hours later (23:58 UT), and just after this a severe magnetic storm started.

Usually the loss cone is observed close to the IMF line from the sunward direction. However, there also seem to be cases where it appears in the antisolar direction. It was shown by Nagashima et al. (1994) that a postdecrease may be observed when Earth goes out of the interplanetary disturbance. In contrast, an antisolar predecrease is more rarely observed. Some examples were discussed in Belov et al. (1995), where such cases were associated with eastern interplanetary disturbances. Another possible cause of predecreases in the antisolar direction may be disturbed interplanetary field in a complicated, looplike configuration.

In the event of 13 October 1981 (Fig.5), the antisolar decrease appeared in the last hours before the shock, as evidenced by an SSC at 22:40. It is the same narrow predecrease, except that in this case the intensity deficit is concentrated at the largest (not smallest) pitch angles.

The pitch-angle distribution plotted for the 21st and 22nd hours combined (Fig.6) looks like a mirror image of distributions discussed above. In this case a magnetic storm developed quickly and reached the level of severe storm in the first hours. The CR density decreased by 8 % at the same time. Numerous powerful solar flares, one of which

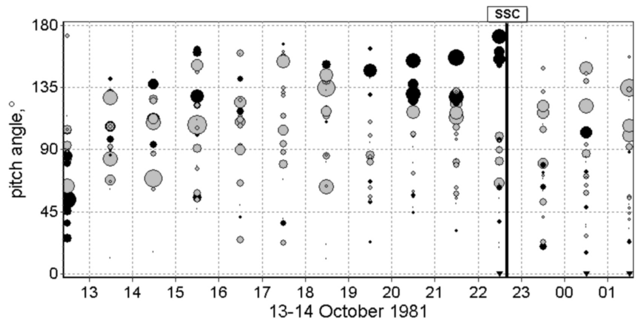

Fig. 5. Behavior of pitch-angle distribution of CR variations, as seen by different NMs on 13-14 October 1981. Grey circles – stations with positive variations, dark ones – stations with negative variations. Circle size corresponds to size of variation.

was related to the ground level enhancement on 12 October, and several filament disappearances as well, preceded the event under consideration. It produced a really complicated situation in the interplanetary magnetic field on 13 October.

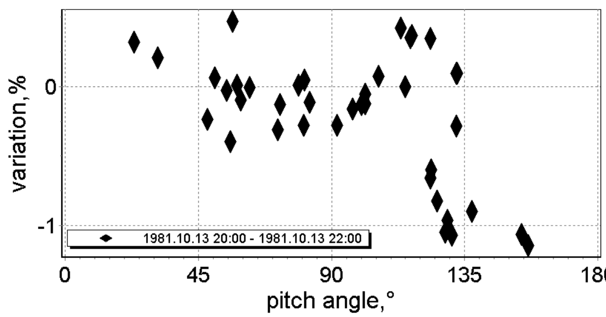

Fig. 6. Pitch-angle distribution of cosmic rays, as measured by different NMs (diamonds) at 20-22 UT on 13 October 1981.

In addition to improving basic knowledge of particle interactions with shocks, studies of precursors also suggest that cosmic ray observations may be useful for space weather forecasting. A critical issue is whether these precursors can be reliably detected far enough in advance of the associated geomagnetic disturbance to be of practical benefit.

Fig. 7 presents preliminary results of a survey of all 14 of the major geomagnetic storms in the Gosling et al. (1990) catalog. Number of occurrences is shown versus precursor "lead-time," defined as the time interval between first clear detection of the precursor and the ensuing SSC. Precursors are divided into two types: "LC" denotes a precursor with clear loss cone characteristics, in which the predecrease is confined to a narrow region around the sunward IMF; "EV" denotes a precursor in which enhanced variance of the angular distribution is observed but it is not

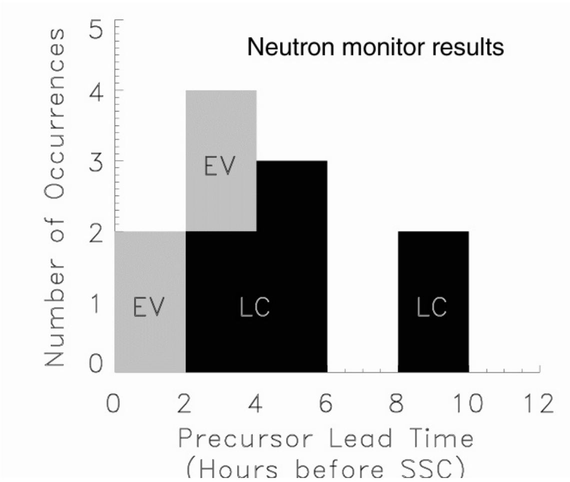

Fig. 7. Distribution of precursor "lead-time" for the 14 major geomagnetic storms cataloged by Gosling et al. (1990). Lead-time is the time from the first clear detection of a cosmic ray precursor until the storm sudden commencement.

as clearly aligned with the local IMF. We emphasize that this survey is from a preliminary analysis that used a smaller set of stations than the results reported above. When the final analysis with a larger set of stations is completed, the observed lead-times will probably increase.

Precursors were detected in 11 of the 14 Gosling et al. (1990) major storms, a detection efficiency of 79 %. A typical lead-time is 4 hours, which is significantly longer than the advance warning provided by a spacecraft at the sunward Lagrangian. It appears that cosmic rays may be one of comparatively few available diagnostics to provide information on impending disturbances in the gap time after they leave the Sun but before they reach the sunward Lagrangian.

4 Conclusion

Pitch angle anomalies in the CR distribution often appear before severe magnetic storms. Their distinctive features are the following: decrease of CR intensity within a narrow range (as a rule < 50-60^o) of pitch angles close to the IMF direction (usually sunward, more rarely antisunward); a large, sometimes exceeding 1%, difference between the CR intensity from these and from other directions; a sharp transition between the regions with different intensities; unfeasibility of fitting the pitch-angle distribution by the sum of only the first two spherical harmonics.

These anomalies are most often observed in the last hours before shock arrival, typically within 4 hours (Fig. 7). However, they sometimes span a longer period, and they sometimes persist downstream of the shock. The worldwide neutron monitor network is a good tool for detecting such anomalies in the CR pitch-angle distribution. However, sometimes the shortage of the detectors in portions of the globe is acute. Fortunately, sky coverage has recently improved with the recent (Fall 2000) completion of the *Spaceship Earth* neutron monitor network (Bieber and Evenson, 1995).

Cosmic ray preincreases caused by reflection and acceleration of ambient galactic CR from the approaching shock are frequently observed prior to Forbush decreases (and magnetic storms). However, the anomalies in the cosmic ray distribution discussed above (narrow predecrease) are a more unusual and specific phenomenon, which enhances its predictive value. At present, when data of >10 neutron monitors are accessible in real time, it would be reasonable to attempt a real time search for such anomalies, and use this information in the short-time forecasting of geomagnetic activity.

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