Cosmic ray modulation in August-September 2005

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Abstract—**During the burst of solar activity in August-September 2005, close to the minimum of the present solar cycle, a significant number of powerful X-ray flares were recorded, among of which the X17.0 flare of the7th of September was outstanding. Within a relatively short period (from August 22 to September 17) two severe magnetic storms were also recorded as well as several Forbush effects. These have been studied in this report, using the hourly mean variations of the cosmic ray density and anisotropy derived from data of the neutron monitor network. A behavior of certain characteristics of the high energy cosmic rays during these Forbush effects is being analyzed together with interplanetary disturbances and their solar sources, and it is compared to the variations of geomagnetic activity. A big and long enough cosmic ray pre-decrease is selected before the shock arrival on the 15th of September 2005.**

I. INTRODUCTION

The descending phase of the 23-rd solar cycle evolved into a quarry of extreme events on the bright manifestations of the Sun [1]. The solar activity burst in August-September 2005 appears to be the last one in the series of the significant bursts during this current cycle. Within less than one month (from August 22 to September 17) 30 M-class and 11 X-class solar X-ray flares (SF), were recorded. Out of these 41 events, the peak one was the X17.0 flare occurred on the 7th of September. It actually is the fifth one in the most powerful flare list, throughout the regular X-ray observations, since 1975. In order to perform a confrontation to the amount of the events registered within the previous six months, it is noted that only 10 flares of M-class were recorded and none of X class. The majority of flares in September occurred at the eastern part of the visible solar disk. The X17.0 SF originated at longitude 77°E before long another powerful SF (X6.2) appeared at longitude 66°E at the 9th of September. Both events generated at the same active region on the Sun (AR10808).

It is commonly pointed out that from such remote eastern flares the proton fluxes cannot be observed near Earth, given ground level enhancements (GLEs) as an exception. However, in a hypothesis under consideration both these eastern flares were followed by a significant proton enhancement near Earth. The proton flux for >10MeV particles increased up to 1000 pfu [2], [3]. By the data from Rosetta /SREM [4], which was located 30° behind the Earth at a distance ~1.3 AU, the proton flux that was registered reached 100 000 pfu. Such great proton fluxes from the eastern flares (even if to consider all flares with >45ºE longitudes) had never been observed before. Apparently, an assumption on unusually effective acceleration of solar particles can be established for this considered case, probably including particles with energy >10MeV, even though such high energies did not get to Earth, because of the eastern source location.

Two extreme magnetic storms were registered on the 24th – 25th of August and 11th -14th of September 2005. In the first case, Kp-index of geomagnetic activity reached the value 9- and Dst index fall down to -216 nT. The significant events on the Sun and in the heliosphere naturally modulated the galactic cosmic rays. Notably cosmic ray (CR) variations were observed during this time. In order to study these variations, the hourly characteristics of CR density and vector anisotropy derived by data of the neutron monitor network. Among the numerous effects in CR during both cases, three Forbush decreases are noticeable: 24th - 25th August (amplitude 6.4% for CR with rigidity 10 GV), 11th of September (12.1%) and 15th of September (5.1%). Contradictory to the situation in July 2005 [5], when powerful flares occurred on the western limb or behind the limb, the events of this considered period turned out to be much more geoeffective. In all these cases very fast shocks arrived at the Earth and their mean velocity exceeded

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1100km/s. On the 15th of September a big and long lasted pre-decrease in CR density was observed prior to the shock arrival. This contribution focuses on the analysis of modulation effects in CR due to the solar activity burst in August-September 2005.

II. DATA AND METHODS

In this study a data base, created in IZMIRAN, which includes parameters as CR density and anisotropy, data on solar wind (SW), interplanetary magnetic field (IMF), as well as solar data and data of the geomagnetic activity indices has been used. As sources of this data base, the updating measurements on GOES and OMNI base, have been utilized [1],[2].

Parameters of the CR variations (density and anisotropy for CR of 10 GV) were calculated by the global survey method (GSM) [6], [7] using data of 43 neutron monitors of the world wide network. Longitude and pitch-angle distributions of the CR variations have been calculated by the “ring” station method [8], [9].

III. RESULTS AND DISCUSSION

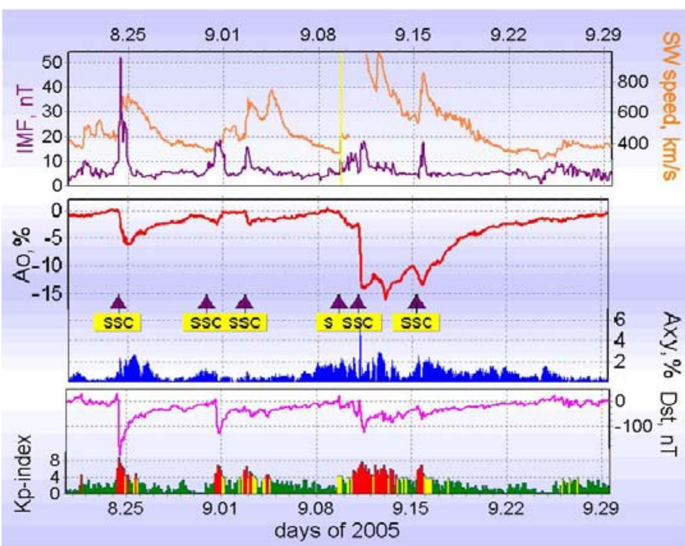

Fig.1: Parameters of the solar wind (upper panel), density (A0) and anisotropy (Axy) of the CR (mid panel), and Dst and Kp indices of geomagnetic activity as well (lower panel) in August-September 2005. SSC – correspond to the moments of shock arrival at the Earth.

Time profiles of solar wind velocity, IMF intensity and CR density as well as data of the ecliptic component of anisotropy and geomagnetic activity for the period from 20th of August to 29th of September 2005, are presented in Fig. 1. As can be seen by the evolution of all parameters, each episode of solar activity has resulted well pronounced disturbance in the interplanetary space. Many shocks were produced and despite the remote source location reached the Earth and caused strong geomagnetic storms. Each disturbance modulated the galactic cosmic rays (GCR) creating series of significant Forbush effects (FE). The main parameters, characterizing the situation on the Sun, in the interplanetary space, in the geomagnetic field and in the GCR during this period under consideration, are given in Tables I and II.

TABLE I

The most significant solar flare events related to cosmic ray irregular behavior of the August-September 2005 events. It provides the dates and time of SF occurrence as well as their assignment on the face of the Sun.

Associated flares			
Date	Time (UT)	Lat. (°)	Long. (°)
22.08	16:46	13°S	65°W
07.09	17:17	11°S	77°E
09.09	19:13	12°S	67°E
10.09	21:30	13°S	47°E
13.09	19:19	10°S	09°W

TABLE II

Basic disturbances of the interplanetary space in August-September 2005 (Vm – mean velocity of the disturbance propagation from Sun to Earth; VH-product of the maximum SW velocity and IMF intensity in the fixed time near Earth;

A_0 – is the CR density variation, Axy- equatorial component of the CR anisotropy derived by GSM method from neutron monitor network; Kp & Dst – indices of geomagnetic activity)

Interplanetary disturbances				**FE**		**Kp**	**Dst**
Date	Time (UT)	Vm (Km/s)	VH	A0 (%)	Axy (%)		nT
24.08	4:43	1113	18.7	6.4	2.61	8.67	-216
09.09	14:01	931	3.21	3.2	2.37	5.67	-60
11.09	01:14	1328	8.89	12.1	5.84	7.67	-123
12.09	06:00	1282	4.77	5.1	2.87	7.00	-84
15.09	09:04	1118	1.53	4.2	1.52	3.33	-38

A series of disturbances in the interplanetary and near Earth space, initiated with the M5.6 western flare on 22nd of August, the offspring of which was a very intense perturbation in the solar wind. In particular, the IMF intensity exceeded 50 nT and the mean velocity of the propagation (Vm) was 1113 km/s. This disturbance triggered an extreme geomagnetic storm with the Kp index around 9- and the Dst one down to –216 nT. The VH product - which characterizes the possible magnitude of the FE originated from such conditions [10], had the very big value of 18.71. Nevertheless, the amplitude of the FE did not exceed the value of 6.4%, which is evidently in agreement to the far western location of the source (65°W). Although it should be pointed out that this magnitude is a record for all western flares near the limb over the last 40 years.

Another two shocks arrived at the Earth and created two moderate magnetic storms (Kp~5-6) and two small Forbush decreases ~ 2-2.5% on the 31st of August and 2nd of September, respectively. The picture of a disordered period, which will probably be the last one before the minimum of the solar activity in the 23rd cycle, completed by a series of four

FEs from 9th – 15th of September. The first effect in this series is affiliated to the shock arrival on the 9th of September, which is associated to the X17.0 flare occurred on the 7th of September at longitude 77°E. Resembled to the event on the 24th of August, this effect may be considered as some deflection from the normal evolving of the FE.

If such a flare occurred more close to the center of solar disk we would observe a giant Forbush decrease, but in our case the rather far eastern source location did not allow the disturbance observation near Earth in full measure. The jump of the SW velocity and IMF intensity was very small, the amplitude of the FE was only 3.2% and the geomagnetic activity was very weak.

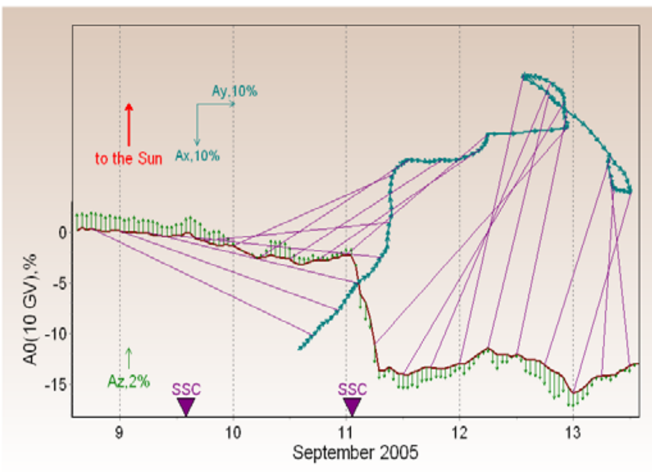

Fig.2. Behavior of the CR density (A0) and the ecliptic component of the CR anisotropy (Ax-Ay) with rigidity 10 GV from 9 to 13 September 2005. Vertical vectors represent north-south component of the anisotropy. Triangles mark the timing of the shock arriving.

In contrary to the previous effect, the next disturbance on 11th of September associated with the X6.2 flare at longitude 66°E, created a strong geomagnetic storm and caused a large FE characterized by a fast decrease of CR intensity down to ~12% and a high anisotropy of GCR up to 5.8% in the ecliptic component for the particles of 10 GV. The created ejecta were propagated with the velocity of 1328 km/s, the SW speed increased up to 980 km/s and the intensity of the IMF was up to 20 nT. The VH parameter had the value 8.9 - that corresponds to a magnitude of ~12% of the Forbush decrease [8]. Two more FEs of less magnitude (5.1 and 4.2%) are noted in Fig. 1. These were occurred at the minimum of the main effect from 11th of September and delayed its recovery. As it is clear from Table I, on the 12th of September another disturbance arrived at the Earth. It was propagated with high speed on the background of the already existing disturbed conditions. At this time solar wind velocity rose up to 997 km/s, the big storm was evolving at the Earth and parameter VH had the value of 4.77 - which corresponded to ~5% magnitude of the FE.

The series of FEs with the corresponding onsets on 9th, 11th and 12th of September are presented in some other way in Fig. 2. The variation of the CR density in every 6 hours is connected to the corresponding time on the vector diagram of the ecliptic component of anisotropy for these events. The behavior of the anisotropy vector clearly demonstrates a certain response on the arrival or approach of different disturbed structures.

The last FE in this series is also related to a disturbance arrived on the 15th of September, after the X1.5 flare which did not produce strong changes either, in the parameters of interplanetary space or in the geomagnetic situation, but led to a significant Forbush decrease (4.2%). It is interesting that a shock came a little bit later then the onset in density decrease, so this case appears to be a good example of pre-decrease in the CR intensity [8], [9]. As one can see in Fig. 3 the CR anisotropy started to change direction long before the shock arrival (from about 3 UT on the 15th of September). After the minimum intensity, while the recovery of the FE begins, the anisotropy vector changes again its direction, now on the usual - from ~18 UT. This continued for several days until the end of the recovery of the CR intensity.

In Fig 4, the distribution of the CR variations from different stations for 14th -15th of September is presented by the asymptotic longitudes as it was calculated by the "ring station" method [8]. It is worth mentioning that around 3 UT on the 15th of September the picture of the distribution is sharply changing. The narrow region of the longitudes (in a sector 90°-180°) with low CR intensity stands out against the background of the strong increase of CR variations. This peculiarity became especially well pronounced from ~6 UT – 3 hours prior the SSC. As it was described in [8],[11], the pitch-angle distribution of the CR variations, before the disturbance arrival, often assume a specific form when an abrupt change from negative to positive means of the CR variations occurs - along the magnetic force line of the IMF. It is also seen in Fig. 5, where the pitch-angle distribution is plotted for the 7th hour on 15th of September, i.e. two hours prior the shock arrival.

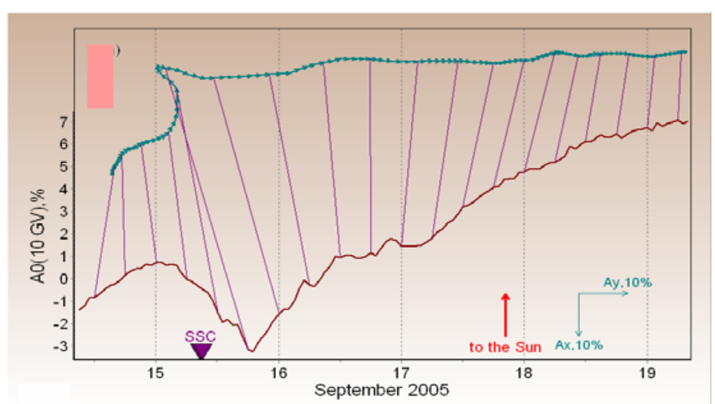

Fig.3: Forbush effect on the 15.09.2005: Behavior of the CR density and anisotropy in the time period from 15th to 19th of September 2005.

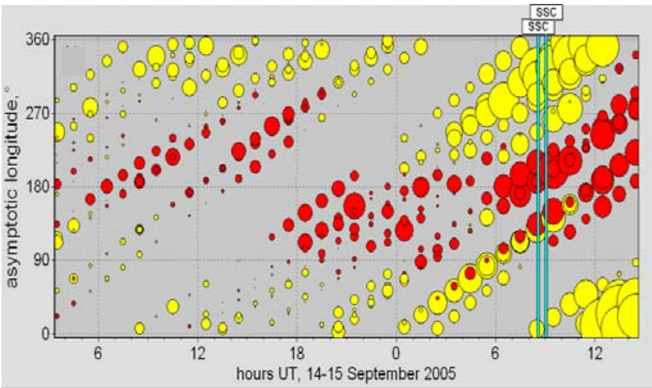

Fig. 4: Forbush effect on 15th of September 2005: Distribution of the CR variations by the asymptotic longitudes after reduction of the isotropic part (red circles-decrease of intensity, yellow-increase relatively to the base value; the size of circle is proportional to the amplitude variation; vertical lines indicate the timing of the shocks)

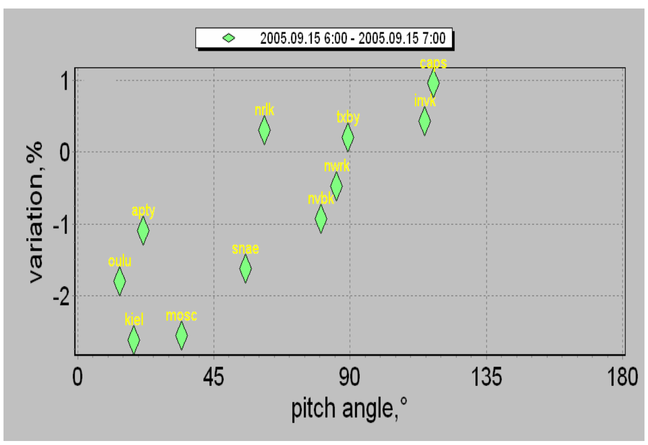

Fig. 5: Forbush effect on 15th of September 2005: Pitch-angle distribution of the CR variations in two hours prior the SSC.

IV. CONCLUSIONS

Perturbation of the interplanetary space in August-September 2005 caused a series of modulation effects in CR, which was the result of solar flare activity close to the minimum of the solar cycle. In the forming of the disturbed situation three eastern, one central and one western, CMEs associated with X-ray flares, took part. Modulating effect of disturbed regions on the galactic cosmic rays revealed in the series of Forbush effects - three of which are distinguished by the magnitude of CR density decrease: 24th -25th of August (magnitude 6.4% for the CR with rigidity 10GV), 11th of September (12.1%) and 15th of September (5.1%). In all these cases very fast shocks arrived at the Earth with the mean velocity of propagation exceeding 1100km/s. Western (22/08) and eastern (07 and 09/09) flares were very remote sources, but even in these cases the significant effects in CR and in the Earth's magnetosphere were recorded. On the 15th of September a big and long lasted pre-decrease in the CR density preceded the shock arrival, which is clearly isolated also by the longitude and pitch-angle distribution of the CR intensity.

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