Non-geoeffective interplanetary disturbances observed by muon hodoscope URAGAN

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The most powerful coronal mass ejections that occurred at the stage of the increase of the 24th solar cycle are considered. The feature of these CMEs is that they were directed to the opposite side from the Earth and, therefore, were of non-geoeffective character. Particular attention is given to the most powerful events in July 2012. The passage of such ejections through the heliosphere caused variations of the cosmic ray flux in the interplanetary space. These changes were detected by the muon hodoscope URAGAN (MEPhI, Moscow) as variations of the angular distribution of the muon flux at the Earth's surface.

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1. Introduction

Studies of various solar disturbances are performed using the detectors placed on satellites in outer space. However, information obtained from the satellites has a point character and is limited by the position of the detector in space. Cosmic rays represent a powerful tool for the study of the heliosphere and its dynamics which has a direct impact on the flux of the primary, and correspondingly, the secondary cosmic rays [1].

In this work the coronal mass ejections (CMEs) that occurred in 2012 - 2014 at the phase of the solar activity increase are analyzed. These CMEs were of non-geoeffective character, i.e. had no direct impact on the Earth and near-Earth space. The largest events of the halo-III and halo-IV classes which were registered by the coronagraphs of the STEREO-A spacecraft are considered. For the estimation of geoefficiency of these events, the OMNI2 database [2] which contains information on the interplanetary magnetic field and the solar wind from different satellites (ACE, GOES, etc.), as well as the indices of geomagnetic activity, was used. We selected the events during which the geomagnetic conditions on the Earth were quiet and Kp-index was less than 4. The series of CMEs in July 2012 which was caused by the active region 1520 on the Sun is of a particular interest. The velocity of the most powerful CME that occurred on July 23, 2012 reached ~ 3000 km/s [3].

In this paper the analysis of data of the muon hodoscope URAGAN, the part of the Unique Scientific Facility "Experimental complex NEVOD" (MEPhI, Moscow), which allows to explore not only the integral flux of registered muons but also its local anisotropy, is presented.

2. Muon hodoscope URAGAN and experimental data

Muon hodoscope URAGAN [4] (55.7°N, 37.7°E, 173 m above sea level) is the coordinate-tracking detector that allows to investigate the variations of the muon flux angular distribution on the Earth's surface. Muons retain the direction of the primary particles motion, which allows to study primary cosmic rays in the interplanetary space. URAGAN consists of four independent supermodules (SM). Each SM is assembled of eight layers of gas-discharge chambers (streamer tubes) equipped with two-coordinate system of external readout strips which provides a high spatial and angular accuracy of muon track detection (correspondingly, better tnen 1 cm and 1°) in a wide range of zenith (0°-80°) and azimuthal (0°-360°) angles in the real time mode. Data are accumulated by minute intervals and contain matrices of two-dimensional angular distribution of the registered muon flux.

To study the URAGAN integral counting rate, 10-min data summed over all supermodules and corrected for the barometric and temperature effects are used [5]. For the study of two-dimensional variations of the muon flux registered by the muon hodoscope URAGAN, a local anisotropy vector $\vec{A}$ [6] which is the sum of the unit vectors of particle tracks normalized by the total number of tracks is used. Local anisotropy vector $\vec{A}$ indicates the average arrival direction of muons which is close to the vertical. To study its deviations from the mean value $\langle\vec{A}\rangle$, the relative anisotropy vector which represents the difference between the current vector and the average anisotropy vector calculated over a long period of time is used: $\vec{r}=\vec{A}-\langle\vec{A}\rangle$. For the analysis of muon flux variations, the horizontal projection of the relative anisotropy vector r_h which characterizes the "side impact" on the muon flux angular distribution is used: $r_h=\sqrt{r_x^2+r_y^2}$.

Value of r_h depends on the state of the heliosphere and can be of the order 10^{-4}-10^{-3}. To estimate the statistical significance of the observed deviations, the experimental data of 2009 (minimum of solar activity) were used. For 2009, the mean value is 2.45×10^{-4} and rms-deviation is 1.28×10^{-4}. Taking into account that the distribution of r_h is close to the Rayleigh's one, for values $r_h/\sigma_{rh} > 5$ the probability of random deviation is less than 1%.

3. Coronal mass ejections in July, 2012

In July 2012, there was a series of large-scale CMEs which were caused by the active region 1520 on the Sun. The first large event occurred on July 12 and was directed to the Earth that caused a strong disturbance in the Earth's magnetosphere on July 14. Further, at the rotation of the Sun and, as a consequence, of the spot 1520 to the back side of the Earth, the events which did not cause any disturbances on the Earth have occurred. The first of them is the event of July 17, 2012 which was registered by the SOHO and STEREO-A satellites. The next large-scale event occurred on July 23 and was registered by the STEREO-A satellite only. The first event was of the halo-III class, the solar wind velocity was approximately 1000 km/s [7]. The second event of July 23 was of the halo-IV class, the maximum velocity reached 3000 km/s [3].

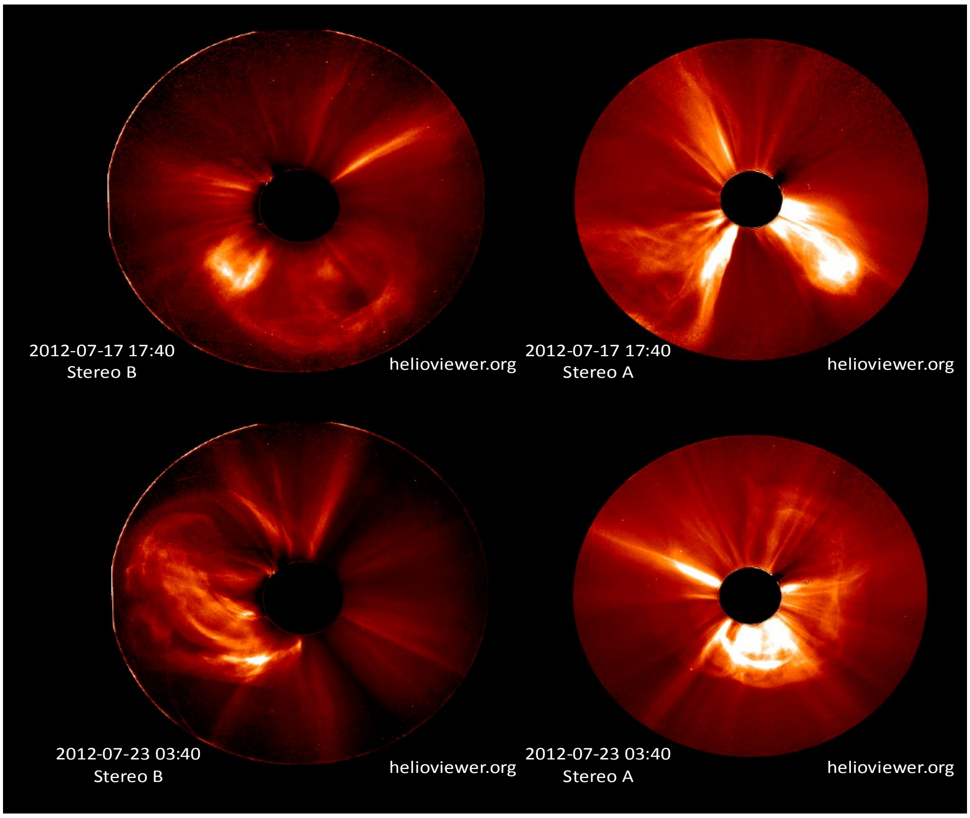

Figure 1: Snapshots of CMEs on July 17 and 23 according to the data of the COR2 coronagraphs installed on the STEREO-B (left) and STEREO-A (right).

Figure 1 shows the snapshots of CMEs on July 17 and 23 according to the data of the COR2 coronagraphs installed on the STEREO-B (left) and STEREO-A (right) [8]. It can be seen that these events have been registered by STEREO-A only. The passage of these CMEs through the interplanetary space was simulated by the Goddard Space Weather Lab [9]. Figure 2 shows the snapshots of the first CME on July 20, 12:00 UT and of the second CME on July 24, 12:00 UT. These snapshots illustrate well the magnitude of the disturbances and the front direction of each CME in relation to the Earth. According to these figures, it is possible to conclude that the peripheral part of the CME on July 17 could cause insignificant changes in the near-Earth space.

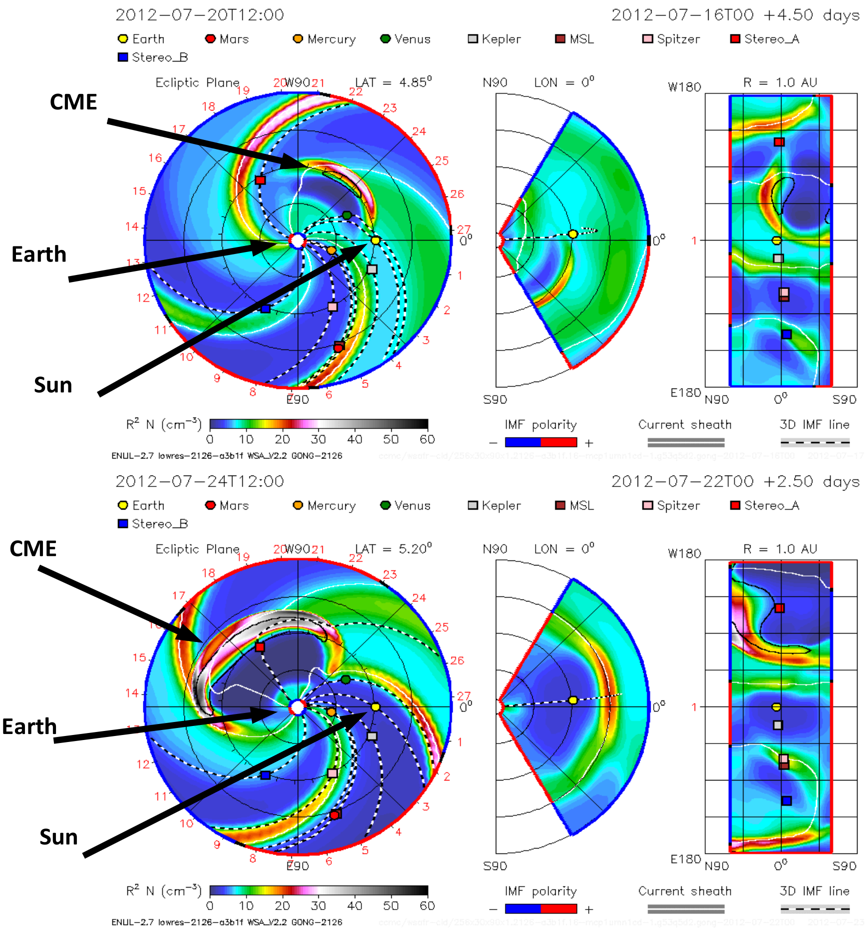

Figure 2: Snapshots of the Goddard Space Weather Lab model on July 20 (top) and July 24 (bottom) 2012 12:00 UT.

The data on the state of the interplanetary magnetic field in the near-Earth space, the solar wind and the state of the Earth's magnetosphere according to the OMNI database for the period from July 10 to August 10, 2012 are shown in Figure 3. The lines show the periods of the ejection passage through the interplanetary space. The disturbance of the interplanetary magnetic field and the Earth's magnetosphere on July 14-16 has been caused by the ejection on July 12 which is not considered in this work. In subsequent periods, such disturbances were not observed.

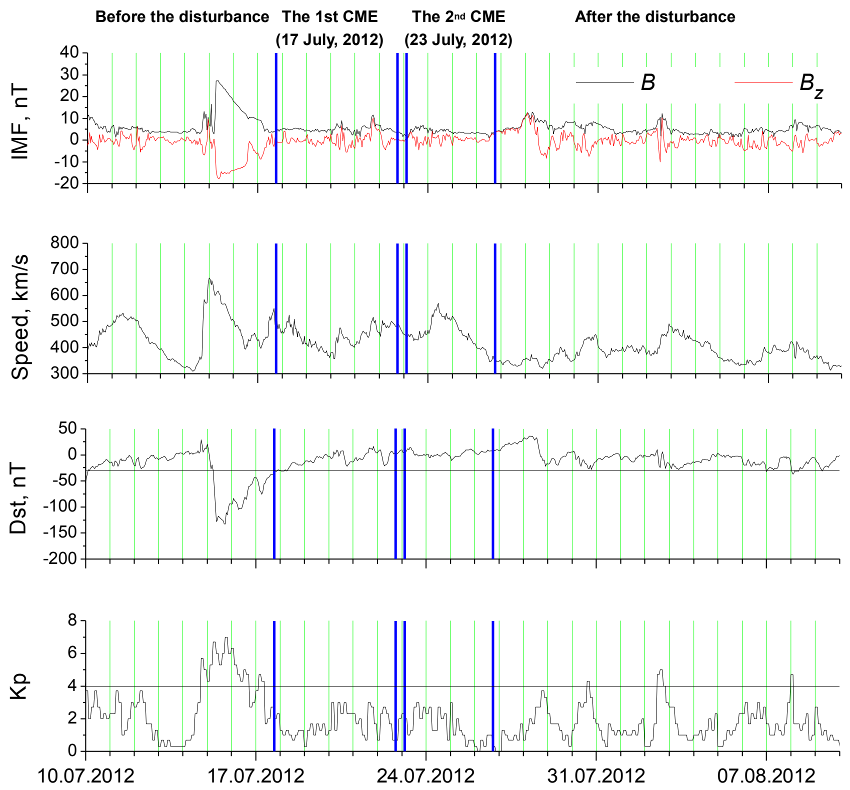

Figure 3: From the top downwards: induction of the interplanetary magnetic field *B* and *Z* component, solar wind velocity, *Dst* and *Kp* indices of geomagnetic disturbance.

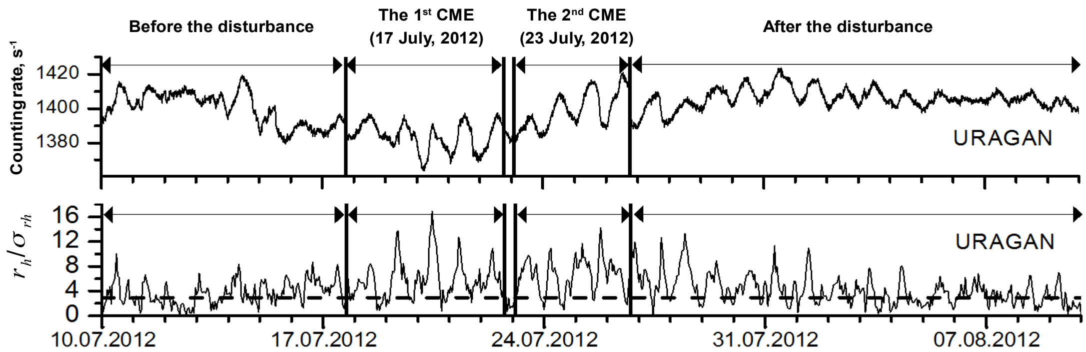

Figure 4: Counting rate of the muon hodoscope URAGAN (top) and projection of the relative local anisotropy vector of muon flux (bottom).

Figure 4 shows the data of the muon hodoscope URAGAN in the period from July 10 to August 10, 2012. The top graph shows the integral muon counting rate during this period, the bottom one represents the projections of the relative muon flux local anisotropy vector (the dashed line indicates the average value of $r_h/\sigma_{rh} = 3.02$ (the rms-spread of these values for the period from 2007 to 2014 was 1.87). From the top graph, two Forbush decreases which occurred on July 14-15 with the decrease amplitude of 1.79% and on July 19-20 with amplitude of ~ 1% can be observed. During the period from July 20 to July 27, a gradual recovery of the muon hodoscope counting rate is observed. At the same time, during the most powerful events on July 23 there were no abrupt changes in the counting rate behavior. Analysis of the local anisotropy parameter r_h/σ_{rh} gives the opposite results. During the geoeffective CME on July 12, the magnetic storm and the corresponding Forbush decrease we observed the suppression of the average value of this parameter. During the subsequent coronal mass ejections we observed strong changes of peak r_h/σ_{rh} values (by 2-3 times). At the same time, the spread of these values increased by 2 times in comparison with the preceding period. The approaches to the analysis of disturbances in July 2012 were used to search for and analyze other non-geoeffective CMEs from 2012 to 2014.

4. Non-geoeffective CMEs in 2012 -2014

The search of non-geoeffective events was conducted using the CACTus database [7] which is automatically generated on the basis of the data of the COR2 coronagraphs installed on the STEREO-A and STEREO-B satellites. According to these data, the events of halo III and IV classes registered by the STEREO-A were selected. In the period from 2012 to 2014, 14 events with quiet conditions in the near-Earth space and the Earth's magnetosphere were selected. The time Δt during which the CME passed a distance of 2 a.u. was estimated for each event. Then, according to the OMNI data the average values of the magnetic field B, solar wind velocity V and Kp-index in the time interval $t_0+\Delta t$ (t_0 is the time of the CME beginning according to the CACTus (COR2 STEREO-A data) were calculated. The data are summarized in Table 1. The obtained values of $\langle B \rangle$ and $\langle Vsw \rangle$ considering their spread do not exceed the average values calculated for the period of observations of the interplanetary magnetic field and solar wind from 2005 to 2014 ($\langle B_{2005-2014} \rangle$ = 5.1 nT, σ_B = 2.7 nT; $\langle Vsw_{2005-2014} \rangle$ = 419 km/s, σ_{Vsw} = 101 km/s). Kp-index did not exceed 4 for all events.

Table 1: The list of the selected events.

No.	CME beginning t_0	Halo	V_{CME}, km/s	Time of passage of 2 a.u. Δt, hours	$\langle B \rangle$, nT	σ_B, nT	$\langle Vsw \rangle$, km/s	σ_{Vsw}, km/s	Kp
1	26.05.2012 21:24	IV	1041	40	3.96	0.54	356	7	*2*
2	17.07.2012 14:24	III	1136	37	5.23	0.35	467	36	4
3	23.07.2012 02:54	IV	1562	27	5.67	1.22	456	28	3
4	20.09.2012 15:24	IV	1785	23	3.41	0.81	502	51	2
5	23.09.2012 15:24	IV	1041	40	3.58	079	345	12	1
6	26.10.2012 11:54	III	694	60	4.50	0.65	329	14	2
7	05.03.2013 03:54	IV	1785	23	3.07	0.51	353	13	3
8	13.05.2013 11:24	III	1785	23	5.68	1.23	364	11	3
9	24.09.2013 21:24	III	961	43	3.29	0.42	393	36	3
10	11.10.2013 07:54	IV	1388	30	3.44	0.62	377	13	4
11	26.10.2013 11:54	III	781	53	4.24	1.01	284	9	2
12	02.11.2013 05:24	IV	961	43	4.58	1.17	348	22	3
13	25.02.2014 00:24	IV	1785	23	3.13	0.44	414	27	2
14	05.03.2014 14:24	III	961	40	4.32	0.65	457	17	1

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Table 2 summarizes the data of the analysis of the muon hodoscope URAGAN counting rate and the values of the relative local anisotropy vector r_h/σ_{rh} projection. Thus, from 14 considered events the significant variations of r_h/σ_{rh} are observed in 5 events (peak values of r_h/σ_{rh} > 10). The variations of r_h/σ_{rh} in which the peak parameter value exceeds the average value for 2007 – 2014 ($\langle r_h/\sigma_{rh}\rangle_{2007-2014}=3.02$, rms-spread equal to 1.87) by more than 3 rms are observed in three cases, and by more than 2 rms – in four events. In most events, during the CMEs which are of non-geoeffective character we observe significant variations of the muon flux local anisotropy.

Counting rate analysis shows that in most events there are no abrupt variations. In four events, the Forbush decreases (FD) with amplitude of ~ 1% or less are observed. In these events, the decrease happened considerably later than the ejection occurred, i.e. when the CME left the Earth's orbit at a distance of more than 1 a.u.

Table 2: Peak values of r_h/σ_{rh} parameter and amplitudes of the FD during the selected CMEs.

No.	CME beginning t_0	Halo	Maximum value r_h/σ_{rh}	Time of the peak r_h/σ_{rh}	FD	Amplitude of the FD, %
1	26.05.2012 21:24	IV	12.46	28.05.2012 09:00	30.05.2012	1.01± 0.10
2	17.07.2012 14:24	III	16.89	20.07.2012 11:00	20.07.2012	1.00 ± 0.09
3	23.07.2012 02:54	IV	14.24	25.07.2012 19:00	—	—
4	20.09.2012 15:24	IV	7.83	21.09.2012 09:00	—	—
5	23.09.2012 15:24	IV	8.89	26.09.2012 07:00	—	—
6	26.10.2012 11:54	III	7.89	26.10.2012 22:00	—	—
7	05.03.2013 03:54	IV	8.62	05.03.2013 08:00	—	—
8	13.05.2013 11:24	III	10.70	14.05.2013 09:00	15.05.2013	1.09 ± 0.11
9	24.09.2013 21:24	III	6.44	25.09.2013 07:00	—	—
10	11.10.2013 07:54	IV	7.41	13.10.2013 13:00	14.10.2013	0.55 ± 0.06
11	26.10.2013 11:54	III	9.47	30.10.2013 19:00	—	—
12	02.11.2013 05:24	IV	5.71	03.11.2013 19:00	—	—
13	25.02.2014 00:24	IV	10.57	28.02.2014 08:00	—	—
14	05.03.2014 14:24	III	6.97	08.03.2014 19:00	—	—

5. Conclusion

Thus, the CMEs of non-geoeffective character have a weak influence on the counting rate of cosmic ray muons registered at the Earth's surface. At the same time, the local anisotropy of the muon flux is sensitive to the changes in the heliosphere that were caused by these CMEs. Hence, registration of muons in a hodoscopic mode allows to use a single setup to investigate solar ejections directed to the opposite side from the Earth.

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