Analysis of powerful heliospheric non-geoeffective event of the 28 April, 2015 in muon flux

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Abstract. The coronal mass ejection (CME) that occurred on April 28, 2015 is analyzed. The passage of the ejection did not cause geoeffective disturbances in the near-Earth space. At the same time, the CME had a significant impact on the flux of cosmic rays registered on the Earth's surface by the muon hodoscope URAGAN.

1. Introduction
Cosmic rays represent a powerful instrument for the study of a variety of dynamic processes in the interplanetary space, including coronal mass ejections. The disturbances caused by the solar activity have a direct impact on the fluxes of primary and, therefore, secondary cosmic rays. In recent years, a new direction of investigation of the processes in the interplanetary space – muon diagnostics [1] – becomes more and more popular. Muon diagnostics is based on the analysis of the muon flux registered by the wide-aperture coordinate detectors – muon hodoscopes – which allow real-time reconstruction of tracks of all muons registered from the celestial hemisphere [2, 3].

The largest ejection of the 24th solar cycle occurred on July 23, 2012. This CME had a high velocity that reached ~ 3000 km/s. At the same time, its front was directed opposite from the Earth and was registered only by the STEREO-A satellite [4]. Despite the non-geoeffective character of the CME in July 2012, it had a strong effect on the cosmic ray flux detected on the Earth's surface by the muon hodoscope URAGAN [5].

The paper presents an analysis of another powerful coronal mass ejection that occurred at the end of April 2015 at the phase of the solar activity decrease. The maximum rate of emission reached ~ 2000 km/s. At the same time, the geomagnetic conditions in the near-Earth space are characterized as quiet. So this event, as the CME of July 23, 2012, was of non-geoeffective character.

In this paper, the results of 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 counting rate of the flux of registered muons, but also its local anisotropy, are provided.
2. Muon hodoscope URAGAN and experimental data

Muon hodoscope URAGAN [2] (55.7°N, 37.7°E, 173 m above sea level) is the coordinate 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, 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 muon flux.

To study the URAGAN integral counting rate, 10-min data summed over all modules and corrected for the barometric and temperature effects are used [6]. For the study of two-dimensional variations of muon flux registered by the muon hodoscope URAGAN, a local anisotropy vector \( \vec{A} \) [7] 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: \( r = \vec{A} - \langle \vec{A} \rangle \). 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:

\[
r_h = \sqrt{r_x^2 + r_y^2}.
\]

Its value depends on the state of the heliosphere and can be \( 10^{-4} \)–\( 10^{-3} \). 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 \( 2.45 \times 10^{-4} \) and rms-deviation is \( 1.28 \times 10^{-4} \). Taking into account that distribution of \( r_h \) is close to the Rayleigh’s one, for values more than \( r_h / \sigma_h > 5 \) the probability of random deviation is less than 1%.

3. Coronal mass ejections on 28 April, 2012

The considered coronal mass ejection of the halo-III class occurred on April 28, 2015 at 17:48. The CME average speed was ~ 1700 km/s [8]. Figure 1 shows the snapshot of the CME according to the data of the LASCO C2 coronagraph which is installed on the SOHO spacecraft [9]. It is worth noting that the satellites STEREO-A and -B have come together at one point on the back side of the Sun and information from them is absent in the database CACTus SECCHI-A and -B for the 2015 [10].

![Figure 1. Snapshots of the coronal mass ejection on April 28, 2015 according to the data of the LASCO C2 coronagraph.](image-url)
Figure 2 shows data on the state of the interplanetary magnetic field, solar wind and the Earth's magnetosphere (Kp- and Dst- indices) according to the OMNI database [11] for the period from April 20 to May 10, 2015. The vertical solid line indicates the beginning of the CME, the dashed lines show the times of passage by the CME of the distances of 1 and 2 AU. From the graphs it is seen that in this period the disturbances in the interplanetary space and in the Earth's magnetosphere were not observed.

![Figure 2](image)

**Figure 2.** 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 3 shows the muon hodoscope URAGAN data in the same period (from April 20 to May 10, 2015). The graph on the top presents the integral counting rate and the graph on the bottom shows the projection of the relative muon flux local anisotropy vector. The vertical lines mark the periods of time similar to figure 2.

From the upper graph in figure 3 it can be concluded that during the passage of the ejection through the heliosphere in the period from April 28 to May 2, 2015 no abrupt changes (for example, Forbush
decreases) in the counting rate behavior were observed. However, it can be seen that since April 26 the increase of the muon hodoscope URAGAN integral counting rate is seen during the quiet state of the interplanetary magnetic field and from April 30 to May 5 its decrease is observed.

Analysis of the local anisotropy parameter provides additional information about the variations of the cosmic ray flux. In the period from April 25 to April 28 the maximal (peak) values of $r_h/\sigma_{rh}$ were $\sim 6.4$. On April 30 the drastic increase (in 2 times) of the $r_h/\sigma_{rh}$ parameter is took place. The peak value of $r_h/\sigma_{rh}$ was 12.8. After that, during the following four days a gradual decrease was observed. Table 1 shows the peak values of the projections of the relative local anisotropy vector $r_h/\sigma_{rh}$. It is seen that there was their gradual decrease by $\sim 10\%$ approximately every 25 hours. Thus, at each revolution of the Earth around its axis the CME impact on the muon flux registered by the hodoscope is detected.

**Table 1.** Peak values of $r_h/\sigma_{rh}$ parameter.

| Time of the peak $r_h/\sigma_{rh}$ | Maximum value $r_h/\sigma_{rh}$ |
|-----------------------------------|---------------------------------|
| 30.04.2015 06:00                  | 12.8                            |
| 01.05.2015 07:00                  | 11.4                            |
| 02.05.2015 08:00                  | 11.2                            |
| 03.05.2015 08:00                  | 10.2                            |
| 04.05.2015 10:00                  | 9.5                             |
| 05.05.2015 09:00                  | 7.1                             |

4. Conclusion

Registration of muons in the hodoscopic mode enables to investigate with a single setup not only the intensity of the cosmic ray flux, but their local anisotropy sensitive to the changes in the heliosphere. Such non-geoeffective ejections have little effect on the muon flux counting rate, in contrast to the local anisotropy parameters, that provide more detailed information about variations of the cosmic ray muon flux sensitive to the disturbances in the heliosphere caused by the passage of the CMEs.

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