Criteria for early prediction of geomagnetic disturbances caused by coronal holes during periods of low solar activity based on muon flux variations

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Abstract. Coronal holes generate a high speed solar wind. This wind is the cause of magnetic storms on the Earth during the years of low solar activity. Also a high speed solar wind creates disturbances in the interplanetary magnetic field. The disturbance may reflect cosmic rays hitting them in the direction of the Earth. As a result, it is possible to observe a change in the flux of cosmic rays on the Earth before the arrival of the disturbance. The paper identifies a criterion for early detection of cosmic ray flux increasing by the muon hodoscope URAGAN (MEPhI, Moscow) to coronal holes in years of decreased solar activity (2009-2010, 2018-2019). It was found that increases of cosmic ray intensity are visible before the main sequence of areas of increasing and decreasing cosmic ray intensities in GSE maps in 60% of the cases.

1. Introduction

The relatively quiet heliosphere during the years of minimum solar activity allows us to see the connection between the coronal holes, which generate high-speed solar wind, and magnetic storms on the Earth [1]. Consequently, the response of the muon hodoscope (MH) URAGAN can be observed from geoeffective coronal holes on the Sun's surface during years of low activity.

High-speed solar wind creates a disturbance in the heliosphere. The incoming wave from the disturbance can mirror cosmic rays in the direction of the Earth. Then, as a result of this interaction, the flux of cosmic rays on the Earth's surface can increase. Then, in the data of the MH URAGAN, an area of increased intensity of cosmic rays (CR) will be observed.

2. Experimental data and methods

The muon hodoscope URAGAN was constructed at the Scientific and Educational Center NEVOD (MEPhI, Moscow). It allows us to study dynamic processes in the heliosphere on the Earth's surface. The hodoscope registers single muons with an energy more than 200 MeV in the range of zenith angles from 0 to 80 degrees and reconstructs tracks in real time. Its counting rate is 4000 s⁻¹ [2].

The angular parameters of a track are two of the projection angle \( \theta_x \) and \( \theta_y \). Event distributions are recorded in binary matrices (90 × 90 cells) of three types: matrix of zenith and azimuth angles, projection angles, and tangents of the projection angles \((M_x = [\theta_x, \phi], M_{pa} = [\theta_{1x}, \theta_{1y}], M_{tg} = [tg\theta_{1x}, tg\theta_{1y}])\). Hourly data – the sums of matrix cells, for analyze heliospheric events and processes in the Earth's magnetosphere, are used [3]. Then these matrices are corrected for the temperature and barometric effects [4].
The graphical representation of the deviation matrix is called muonograph. Relative deviations of the intensities of the registered muon flux in units of statistical errors are calculated to obtain muonographs. This matrix is considered relative to the average values determined from the daily measurement statistics. This provides smoothing of slow trends and diurnal fluctuations in the intensity of the muon flux caused by the Earth’s rotation. For example, figure 1 (a) shows a matrix of changes in the angular distribution of events over the last hour of exposure to the MH URAGAN in relation to the normalization matrix obtained from data for the previous 24 hours, in units of statistical errors in the local coordinate system. The statistical security of the matrix is \( \sim 1.4 \times 10^7 \) events. Thin lines indicate the North-South and West-East directions; circles indicate the zenith angles of 30°, 45°, 60° and 75°. The color scale shows deviations from the average in units of standard deviations. The figure also shows information about the average atmospheric pressure, the deviation from the average integral intensity (δ), the length of the relative anisotropy vector of the muon flux (r), and the direction (ϕ) indicating the direction of change in the muon flux [5].

These matrices are then smoothed using a two-dimensional Gaussian low-pass filter. They are then adjusted for the shape of the angular distribution. This makes it possible to identify smaller details of muonographs, if there are significantly large changes in the current and normalized distributions. Figure 1 (b) shows a smoothed muonograph. Figure 1 (c) shows a muonograph corrected for the shape of the muon angular distribution. As we can see from the figures, after correcting for the shape of the angular distribution, the anisotropy caused by the diurnal variation of the muon flux disappeared. At the same time, other features of the matrix were preserved.

![Figure 1. Muonograph of the 60-minute M₄₂ matrix.](image)

Next, the muonographs are transformed into the angular distribution of primary protons at the boundary of the magnetopause in the GSE coordinate system [3]. It is assumed that muons preserve the directions of the cosmic rays that generated them. For calculations, the asymptotic directions of the particles are used, taking into account their threshold energy. Figure 2 shows a pair of GSE displays of 60-minute muonographs shown in the laboratory coordinate system of the detector in figure 1. The figure also shows: the change in the counting rate in % (δ), the direction of the interplanetary magnetic field line (red circle with a cross), the place of the Sun (image of the solar corona), and the asymptotic direction for vertical muons (straight cross).

Then, in the GSE mappings of the matrices, areas of decreased and increased intensity of the cosmic ray flux are distinguished by a value greater than 3σ or less than -3σ. For each such area, its position, the size of the solid angle (in steradians), and the amplitude of the change in the intensity of cosmic rays (in the values of σ) are calculated. And finally, a time sequence of such zones is formed (figure 3).
Figure 2. Example of GSE displays of smoothed 60-minute matrices of changes in the angular distribution of the registered particle flux in units of statistical errors. (a) – without correction for the shape of the angular distribution, (b) – with correction.

The figure 3 shows the longitude in the GSE system on a vertical scale, the angle 0° corresponds to the direction from the Earth to the Sun. The diagram shows a sequence of areas found with a correction for the shape of the angular distribution relative to the previous day. The figure also shows information about the angular size of the area (point size), and the color of the points correspond to changes in the flux intensity.

Figure 3. Areas of low and high intensity in muonographs in the GSE system.

3. Criteria for early detection of geomagnetic disturbances caused by coronal holes
Two periods of low solar activity were considered: 2008-2009 and 2018-2019. An analysis of 81 magnetic storms that occurred during these periods was made. It is determined that all the analysed storms were caused by the impact of high-speed solar wind fluxes generated by geoeffective coronal holes on the magnetosphere. For each event, the areas of decreased and increased intensity of the cosmic ray flux in the GSE system were analysed.

Figure 3 shows the GSE map of the beginning of April 2019. On the 7th of April, the response of the MH URAGAN to the coronal hole CH914 [6], which has been at geoeffective longitudes on the Sun since the 4th of April, is clearly visible. The figure shows that the main group of "spots" is located between the longitudes -45° and 90° in the time interval from 2 to 22 hours UTC. The maximum area of increase in the CR flux was registered at 17:00 at a longitude of 30°. It has a size of more than 0.5 steradians and a deviation of the CR flux within it was 6.5 σ. The maximum area of the CR flux decrease for this event was registered at 19:00 at the longitude of 80°. This area has a size of 0.4 steradian and
the deviation of the CR flux inside it is -6.2 $\sigma$. However, 07.05.2019 at 01:00 UTC, an area with a deviation of 4.5 $\sigma$ and a size of 0.4 steradian was registered at a longitude of 170°. This area is observed one hour before the main group of "spots".

GSE maps for other events were analyzed in the same way. It was noticed that 49 events out of 81 have such areas that at once satisfy the following conditions:

- the flux deviation is more than 4$\sigma$ ($\delta I > 4\sigma$),
- the area size is more than 0.1 steradian ($\Omega > 0.1$ steradian),
- at least 1 hour ahead of the rest of the group of "spots" ($\Delta t > 1$ h),
- the difference in longitude with the main group of "spots" is at least 45° ($\varphi > 45^\circ$).

A magnetic storm ($K_p > 4$) caused by high-speed solar wind from the coronal hole CH914 was registered on the Earth on 08.04.2019, at 06:00 UTC (the duration of the storm was 3 hours). This is 29 hours later than the registration of the first "spot". Figure 4 shows the distribution of the $\Delta t$ – time interval between the first "spot" and the beginning of the magnetic storm for all the analyzed events. The figure shows that, on average, the first "spot" was registered earlier than the magnetic storm by 18±4 hours.

![Figure 4](image.png)

**Figure 4.** Distribution of the time interval between the registration of the first area of change in the intensity of the CR flux and the beginning of a magnetic storm.

### 4. Conclusion

The paper defines a criterion for early detection of magnetic disturbances caused by coronal holes in the Sun during the years of solar activity minimum. It was found that in 60%±5% of events on GSE maps, there is a area of deformation of the cosmic ray flux that satisfies the specified conditions. And the detection time of this area is on average 18±4 hours earlier than the beginning of the magnetic storm.

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