Search of predictors of geoeffective heliospheric events by means of muon hodoscope URAGAN

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Abstract. The flux of charged primary cosmic rays (PCR) is modulated by changes of interplanetary magnetic field which depend on various heliospheric processes. After interaction of PCR with nuclei of atoms of the Earth’s atmosphere, these modulations are transferred to a flux of secondary muons. Muon hodoscope URAGAN allows to trace changes not only of intensity of the muon flux, but also its angular distribution in a wide range of zenith angles (0-80º). Some results of searching of predictors of geoeffective heliospheric events by means of muon hodoscope URAGAN are presented.

1. Introduction
The flux of charged primary cosmic rays (PCR) is modulated by changes of interplanetary magnetic field which depend on various heliospheric processes. The Earth magnetosphere is substantially subject to influence of dynamic processes in the interplanetary environment: strong disturbances of the interplanetary magnetic field result in reorganization of the magnetic field inside magnetosphere, to development of geomagnetic storms and substorms. Disturbances of the interplanetary magnetic field are propagated from the Sun to the Earth with a speed of the solar wind 300-1500 km•s$^{-1}$, but the velocity of propagation of PCR is close to the light velocity. The PCR flux modulated by the disturbance reaches the near-Earth space considerably earlier than this disturbance. After interaction of PCR with nuclei of atoms of the Earth’s atmosphere, these modulations are transferred to the flux of secondary muons. Muon hodoscope URAGAN (MH URAGAN) [1] allows to trace changes not only of the intensity of the muon flux, but also its angular distribution in a wide range of zenith angles (0-80º). The results of a search of predictors of geoeffective heliospheric processes with the help of the analysis of variations of the muon flux are considered.

2. Initial data
As the initial data for searching the predictors, the URAGAN data and OMNI database were used.
At preparation of the data of MH URAGAN in real time, which are presented at the site of the Unique Scientific Facility ‘Experimental complex NEVOD’ [2], time series of hourly average values and their statistical errors for various characteristics of a registered muon flux are formed:
- $I_{sum}$ – count rate with barometric correction, $s^{-1}$;
- $A_Z$ – vertical projection of the vector of the local anisotropy with barometric correction;
- $A_S$ – horizontal projection of the vector of the local anisotropy to the north-south axis;
- $A_{E}$ – horizontal projection of the vector of the local anisotropy to the west-east axis.

The secondary characteristics are formed concerning the average values obtained during 24 hours:
- $r_{h}$ – horizontal projection of the vector of the relative anisotropy;
- $r_{S}$ – horizontal projection of the vector of the relative anisotropy to the north-south axis;
- $r_{E}$ – horizontal projection of the vector of the relative anisotropy to the west-east axis.

Among the characteristics of the muon flux, the most convenient are those which have no long-term trends. But variations of characteristics because of the daily rotation of the Earth, in our case cannot be neglected. Therefore the following characteristics were examined: $r_{h}, r_{S}, r_{E}$.

From the time series of hour values $r_{h}$, $r_{S}$, $r_{E}$, the following secondary quantities (here symbol X designates $r_{h}$ or $r_{S}$, or $r_{E}$) were calculated:

1) $\delta X_{1}$ – the ratio of the difference of the current and the preceding hour values of the characteristic X to the statistical error of this difference;
2) $\delta X_{24}$ – the ratio of the difference of the current and 24 hours prior to it hour values of the characteristic X to the statistical error of this difference;
3) $\sigma X_{24}$ – root-mean-square deviation of the hour values of the characteristic X over the period 24 hours (including the current hour).

As indicators of the condition of the heliosphere and magnetosphere of the Earth, the following parameters of the interplanetary magnetic field (IMF) and geomagnetic activity from database OMNI were used:
- $V_{SW}$ – hourly average value of the speed of the solar wind, km*s$^{-1}$;
- $B_{zGSE}$ – hourly average value of z-projection of IMF in GSE coordinate system, nT;
- $Dst$ – hourly average equatorial index of the geomagnetic activity, nT;
- $Kp$ – the planetary geomagnetic activity index.

For the analysis, the URAGAN data and OMNI data from February, 2007 till December, 2013 were used. The following criteria of the perturbed state in OMNI data were used: $V_{SW} \geq 500$ km*s$^{-1}$, $B_{zGSE} \leq -7$ nT, $Dst \leq -30$ nT, $Kp \geq 4$.

3. Searching predictors

Joint processing of time series of the URAGAN and OMNI data in a moving time window of 5 day was carried out. First for consideration the intervals in which in the first 4 days there were no disturbances, and on the last day $Kp \geq 4$ have been taken. As there were found only 65 such intervals, for the increase in statistics the intervals in which in preceding four days there could be disturbances on $V_{SW}$, $B_{zGSE}$, $Dst$ have been added, too. Thus, for the visual analysis, 130 5-day intervals in which the last day value $Kp \geq 4$ was observed, have been selected.

In the selected intervals the behaviour of horizontal projections of the vector of the relative anisotropy ($r_{h}, r_{S}, r_{E}$) and their derivative quantities were analyzed ($\delta r_{h1}, \delta r_{S1}, \delta r_{E1}, \delta r_{h24}, \delta r_{S24}, \delta r_{E24}, \sigma r_{h24}, \sigma r_{S24}, \sigma r_{E24}$). During the analysis, those projections for which in the first two days of the examined interval their values were appreciably smaller, than in the subsequent two, or qualitative by different, were marked. In figure 1, examples of the images of time series prepared for the visual analysis are shown.
Figure 1. Examples of images of time series for the interval from 05-09-2011 till 09-11-2011: a) $K_p$ and $(r_h, r_S, r_E)$; b) $K_p$ and $(\sigma_{r_{124}}, \sigma_{r_{524}}, \sigma_{r_{E24}})$. 
For each event, according to the information from weekly bulletins NOAA Space Weather Highlights (ftp://ftp.swpc.noaa.gov/pub/warehouse/) and http://www.spaceweather.com/, probable sources of disturbances have been determined (CH – Coronal Hole, CIR – Co-rotating Interacting Region, SSB – Solar Sector Boundary, SSBC – Solar Sector Boundary Crossing, HSS – High-Speed Stream, CME – Coronal Mass Ejection, Bz – Z-projection IMF). As the visual analysis of the time series \( \delta r_{h1}, \delta r_{b1}, \delta r_{E1}, \delta r_{h24}, \delta r_{b24}, \delta r_{E24} \) has not given any result, the results of the visual analysis only for \((r_h, r_S, r_E)\), and \((\sigma r_{h24}, \sigma r_{b24}, \sigma r_{E24})\) have been formulated.

For the selected 65 intervals, in 15 cases the source of the disturbance was CME, and for selected 130 intervals, in 37 cases the source of the disturbance was CME. In total, before the geomagnetic storm with \( Kp \geq 4 \), the qualitative changes in time series of the URAGAN data were observed:

1) with all sources of disturbance:
   - \((r_h, r_S, r_E)\) – in 28 cases from 130 (21%), and in 13 cases from 65 (20%);
   - \((\sigma r_{h24}, \sigma r_{b24}, \sigma r_{E24})\) – in 64 cases from 130 (49%), and in 31 cases from 65 (47%).

2) with CME as the source of the disturbance:
   - \((r_h, r_S, r_E)\) – in 11 cases from 37 (29%), and in 7 cases from 15 (46%);
   - \((\sigma r_{h24}, \sigma r_{b24}, \sigma r_{E24})\) – in 22 cases from 37 (59%), and in 10 cases from 15 (66%).

4. Conclusion
As a result of the performed search, as predictors geoeffective heliospheric processes the root-mean-square deviations \((\sigma r_{h24}, \sigma r_{b24}, \sigma r_{E24})\) of hour values \( r_h, r_S, r_E \) for the period 24 hours, including the current hour, can be used. Each of these predictors can be formulated, for example, as follows: increase of the value for a threshold size (for example, \(10^{-4}\)) within two days. That is, in a moving time window with duration of 48 hours a difference between the value at the end of the window (current value) and the minimal value (in a whole window) is determined. If this difference is more or equal to threshold value, this can mean the presence of the predictor of geoeffective heliospheric processes.

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