Identification of solar coronal mass ejections in cosmic ray flux using flicker noise spectroscopy

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Abstract

In this article, we examine the possibility of applying the method of flicker noise spectroscopy to identification of anomalies in flux of cosmic rays (CR). Typically, such anomalies appear after intense solar outbursts, when the Sun emits into space giant blobs of plasma also called coronal mass ejection (CME). Identification of such anomalies in the CR flux allows us to detect CME, approaching to Earth. CMEs, powerful enough, can cause significant damage to electrical appliances. The present paper describes basic concepts of the flicker noise spectroscopy and principles of cosmic rays data processing algorithms.

Keywords: solar activity; cosmic rays; coronal mass ejection; CME; flicker noise

1. Introduction

Coronal mass ejection is the powerful ejection of solar substance from the solar corona that carries with part of solar magnetic field. In the magnetic cloud reaches Earth, it can cause a number of geomagnetic effects, such as auroras, magnetic storms, as well as electrical outage and people’s health problems. Because of increasing dependence of humanity from the electronics and various distributed information-processing systems, the problem of warning about potentially dangerous space weather events is becoming very important. Currently, the most reliable information about approaching CME obtained by heliostationary spacecraft ACE (Advanced Composition Explorer). It launched in 1997 and located between the Earth and the Sun at the Lagrange point L1 at a distance of about 1.5 million km from Earth. It measures the parameters of solar wind and can identify abrupt changes of the...
interplanetary magnetic field. Since ACE is almost nearby to Earth, the delay time of its forecast is about 1 hour. For many years, cosmic rays have used to study physical processes taking place in near-Earth space. The main part of the CR falling to Earth is the high-energy protons. We assume that it is possible to make a conclusion about state of interplanetary magnetic field using the variations of CR flux. Trajectory of cosmic rays particles changes during passing through the CME magnetic cloud. As a result, the CR flux obtain fluctuations. Usually these fluctuations are very small and hidden in the noise [1, 2]. Therefore, it is necessary to apply special methods of extracting hidden information from signal to identify these fluctuations. We use flicker noise spectroscopy described in the next section. The source data were obtained from the Moscow neutron monitor located in the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN) [8].

2. Flicker noise spectroscopy

In physical processes related to transport phenomena, random structures can appear. Structures, appearing in a random environment, are similar to the peaks that appears at random locations and at random times. The gaps between the peaks characterized by low intensity and long distance. The common name of this process – intermittency [6]. The good example of intermittency is so-called superdiffusion or Levy random walk (Levy flight) [5]. The flicker noise spectroscopy method based on these inferences. The main idea is to give information significance to irregularities of analysing signal - bursts, jumps, etc. Random signal fluctuations are related to the so-called structural function [4]:

\[
\Phi^2(\tau) = \left\langle \left[ V(t) - V(t + \tau) \right]^2 \right\rangle; \langle \ldots \rangle = \frac{1}{T} \int_{-T/2}^{T/2} (\ldots) dt
\]

In this paper we use only part of this method related to calculation of measure of nonstationarity of the analysed time series. This measure is called a nonstationarity factor (NF) [3,4] and calculated the next way. For every point of the time series we calculate two values \(Q_k\) and \(P_k\). Actually they are structure functions, calculated inside time window of length \(T\) and integrated over all scales \(\tau\):

\[
Q_k = \frac{1}{\alpha T^2} \int_{0}^{\alpha T/t_k + T} \int_{t_k}^{t} \left[ V(t) - V(t + \tau) \right]^2 dtd\tau,
\]

\[
P_k = \frac{1}{\alpha T^2} \int_{0}^{\alpha T/t_k + T - \Delta T} \int_{t_k}^{t} \left[ V(t) - V(t + \tau) \right]^2 dtd\tau.
\]

Then we get value of NF using formula:

\[
C(t_k) = \frac{Q_k - P_k}{(Q_k + P_k)/2} \frac{\Delta T}{T} \approx \frac{\Delta Q}{Q} \frac{\Delta T}{T}.
\]

Value \(T\) is parameter of this method. It’s associated with a characteristic time of restructuring the analysing signal at all spatial scales. This technique let us to see hidden variations of the CR flux by peaks on the plot of NF. To check the reliability of identification we use open interplanetary magnetic field data from the Goddard Space Flight Center database obtained via ACE spacecraft [7].

3. Data processing

In the paper, we study cosmic rays flux time series. These series are very sophisticated in terms of processing.
Usually characteristics of underlying heliospheric processes changes over time. Hence, amplitude and frequency of the corresponding time series also vary over time. Weather conditions also has direct influence on the number of registered neutrons. In a result, we dealing with a very noisy, non-stationary time series, which have a pronounced trend of unknown form, caused by changes in weather conditions. Hence, first of all we should throw this trend away. Partially it can be done using correction for atmospheric pressure. In the paper, we use already corrected series from IZMIRAN database (Fig. 1).

![Fig. 1. Example of neutron monitor’s time series for period 06.02 - 07.03.2011](image)

Other difficulty is noise i.e. there are many relatively equal jumps in these series. So, the contributions of each jump in resulting nonstationarity factor overlap and do not allow to see a clear picture. To dispose of physically meaningless random peaks of NF we use the fact that positions of peaks, corresponding to the regular component does not depend on choice of the averaging interval $T$. Therefore, we perform point wise product of NF series calculated with different values of $T$. After this procedure informative bursts will "reinforce" each other and meaningless - vice versa eliminate. As a result, we will see bursts corresponding to anomalies in the flow of the CR.

Consider neutron flux time series for period 6th February – 7th March 2011. The plot of this series is shown in Fig.1. After applying described algorithm, we can get time series for NF (Fig.2).

![Fig. 2. Resulting time series for NF (nominal values) for period 06.02 - 07.03.2011](image)

The graph in Fig.3 shows direct measurements of magnitude of near-Earth magnetic field made by ACE spacecraft [7]. How we can see bursts of magnetic field 15th, 18th February and 1st of March corresponds to peaks of NF, placed at the same locations.
Fig. 3. ACE spacecraft near-Earth magnetic field data for period 06.02 - 07.03.2011

4. Conclusion

The obtained results show that the method of flicker noise spectroscopy allows us effectively infer physical meaningful hidden components, in time series of neutron monitor. With the right choice of parameters and simple treatment we can obtain legible signals that are likely can be considered as an "image" of the CME. However, the amplitude of these signals is often do not speak anything about the power of the solar flare occurred. Typically, useful information represents only the position of the burst in time series. Also, let us note that there is significant number of false positives in the results i.e. bursts of nonstationarity factor without any noticeable anomalies in the solar wind. Apparently, such results related to magnetic clouds moving past the Earth, but still powerful enough to affect on the flux of cosmic rays. NF calculation algorithm can be quite simply adapted to real-time work that is also an advantage.

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