










# Behavior of galactic cosmic rays density and vector anisotropy before and during high-energy magnetospheric electron flux enhancements

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## Keywords

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## Abstract

Changes in the intensity of galactic cosmic rays on Earth and beyond the boundary of the magnetosphere occur earlier than an increase in the flux of high-energy magnetospheric electrons with energy  $>2$  MeV in the geostationary orbit, so the behavior of galactic cosmic rays before and during electron flux enhancements can provide valuable information about the processes occurring in near-Earth space at this time. The density and vector anisotropy of galactic cosmic rays for 453 events of high-energy magnetospheric electron flux enhancements over the period 1996-2020 were calculated by the Global Survey Method (GSM). Some examples of these events, which are characteristic of different classes of solar sources, are considered. The behavior of the density and vector anisotropy of galactic cosmic rays before and during electron flux enhancements in events connected with the arrival to Earth of high-speed streams from coronal holes, coronal mass ejections associated with solar flares or disappeared solar filaments is revealed.

## 1. Introduction

The behavior of high-energy electrons in the Earth's magnetosphere is one of the most actual problems in the physics of magnetosphere and space weather. First of all this is due to the fact that large enhancements in relativistic electron fluxes lead to failures in the operation of spacecraft and, in some cases, led to the failure of satellites (Baker 2001; Baker et al. 2001; Belov et al. 2004; Pilipenko et al. 2006; Baker et al. 2018). The anomalies were most often associated with false commands caused by internal electrostatic discharge. Most of the anomalies were due to the accumulation of charge inside the electronic components, caused by the impact of high energy electrons ( $>2$  MeV) at a time when the fluence of such electrons exceeded a dangerous level for two days (Wrenn, Rodgers & Ryden 2002).

Cosmic rays (CRs) carry extremely important information about the state the interplanetary medium and near-Earth space, because measurements of galactic CRs (GCRs) on the Earth's surface by the worldwide network of neutron monitors are extremely accurate and allow one to calculate the behavior of their density and anisotropy beyond the magnetosphere boundary using the Global Survey Method (GSM) (Belov et al. 2018). Forbush effects (FEs) – changes in the density and anisotropy of GCRs caused by large-scale solar wind (SW) disturbances – are part of complex processes in the interplanetary and near-Earth medium. However, changes in the CRs density and anisotropy occur earlier than enhancements in high-energy electron fluxes, so information on the behavior of GCRs can be used to predict electron flux enhancements and determine their solar sources.

## 2. Data used

As main characteristics of magnetospheric electron fluxes in geostationary orbits the following were chosen: the particle flux directly measured on the GOES satellites (the number of particles·cm<sup>-2</sup>·sr<sup>-1</sup>·s<sup>-1</sup>) and the diurnal fluence (total flux per day) of relativistic magnetospheric electrons with energies > 2 MeV. Information about high-energy electrons, characteristics of solar and interplanetary activity is collected in the Solar and Geomagnetic Activity (SGA) database, created and maintained at IZMIRAN. This database contains information on diurnal electron fluences obtained onboard the GOES satellites (<https://www.ngdc.noaa.gov/stp/satellite/goes/index.html>) over a 35-year period (1987-2021), information about SW parameters are taken from the OMNI database (<https://omniweb.gsfc.nasa.gov/>), information about geomagnetic activity – Kp- and Ap-indices (<https://kp.gfz-potsdam.de/en/data#c134>, Matzka et al. 2021), Dst-index (<http://wdc.kugi.kyoto-u.ac.jp>). The SGA database is updated daily.

Electron flux enhancement catalog is given by Kryakunova et al. (2022).

## 3. Behavior of galactic cosmic rays density and vector anisotropy before and during magnetospheric electron flux enhancements

GCRs do not affect the generation of magnetospheric electrons, nor do they affect the measurements of high-energy (> 2 MeV) electrons on the GOES satellites themselves. However, changes in the density and anisotropy of GCRs are part of a complex process of changing near-Earth outer space state, which occurs due to the arrival of various types of disturbed SW from active processes on the Sun (high-speed streams (HSS) from coronal holes (CH), coronal mass ejections (CME) associated with solar flares, and disappearances of solar filaments).

To obtain a homogeneous continuous series of CRs density variations (the isotropic part of the intensity) and vector anisotropy, a database of Forbush effects and interplanetary disturbances (FEID) was created. It includes different effects in GCRs due to large-scale SW disturbances. The capabilities of the database make it possible to carry out a correlation analysis of various parameters of the interplanetary medium (SW, interplanetary magnetic field) with the CRs parameters and to study their relationships.

To calculate the GCRs flux density and vector anisotropy the GSM is used (Belov et al. 2018), which allows one to take into account the influence of the magnetosphere and atmosphere and make calculations ac-

ording to neutron monitors of the world network of ground-based CRs stations. The GSM is a technique that combines simultaneous ground-based observations of GCRs at different points and makes it possible to obtain the main characteristics of CRs variations outside the Earth's atmosphere and magnetosphere.

The global network of CRs stations consists of individual detectors (primarily neutron monitors) located at different points on the globe and collecting particles in certain cones of asymptotic directions (reception cones). In the GSM, the entire network is used as a single multichannel device, where each channel-station provides information in a certain cone of asymptotic directions, and all channels completely cover the celestial sphere. The multi-channel nature of such a device ensures the reliability and continuity of measurements. In comparison with individual CRs stations, the statistical accuracy of the network increases markedly, and the influence of hardware effects is significantly reduced. For example, a separate neutron supermonitor provides a statistical accuracy of 0.1-0.2%/h, while the entire network of stations provides accuracy of ~0.01%/h. The GSM makes it possible to determine the density (the isotropic part of the intensity) and the anisotropy of GCRs for each hour outside the magnetosphere.

The GCRs density and vector anisotropy for 453 events of high-energy magnetospheric electron flux enhancements over the period 1996-2020 were calculated by the GSM. We considered the threshold of electron enhancements to be the day when the daily fluence exceeds  $10^8$  electrons·cm<sup>-2</sup>·sr<sup>-1</sup>·day<sup>-1</sup>. The choice of the period from 1996 is due to the fact that only from this time onwards can solar sources of disturbances in CRs flux be sufficiently confidently identified according to the data of Solar and Heliospheric Observatory (SOHO), launched by the European Space Agency and NASA in the end of 1995.

Let us consider some examples of these 453 events that are typical for different classes of solar sources. We divided all the events of enhancements in the flux of high-energy magnetospheric electrons into different groups according to the types of solar sources caused the SW disturbances associated with enhancements in electron flux and FEs in CRs.

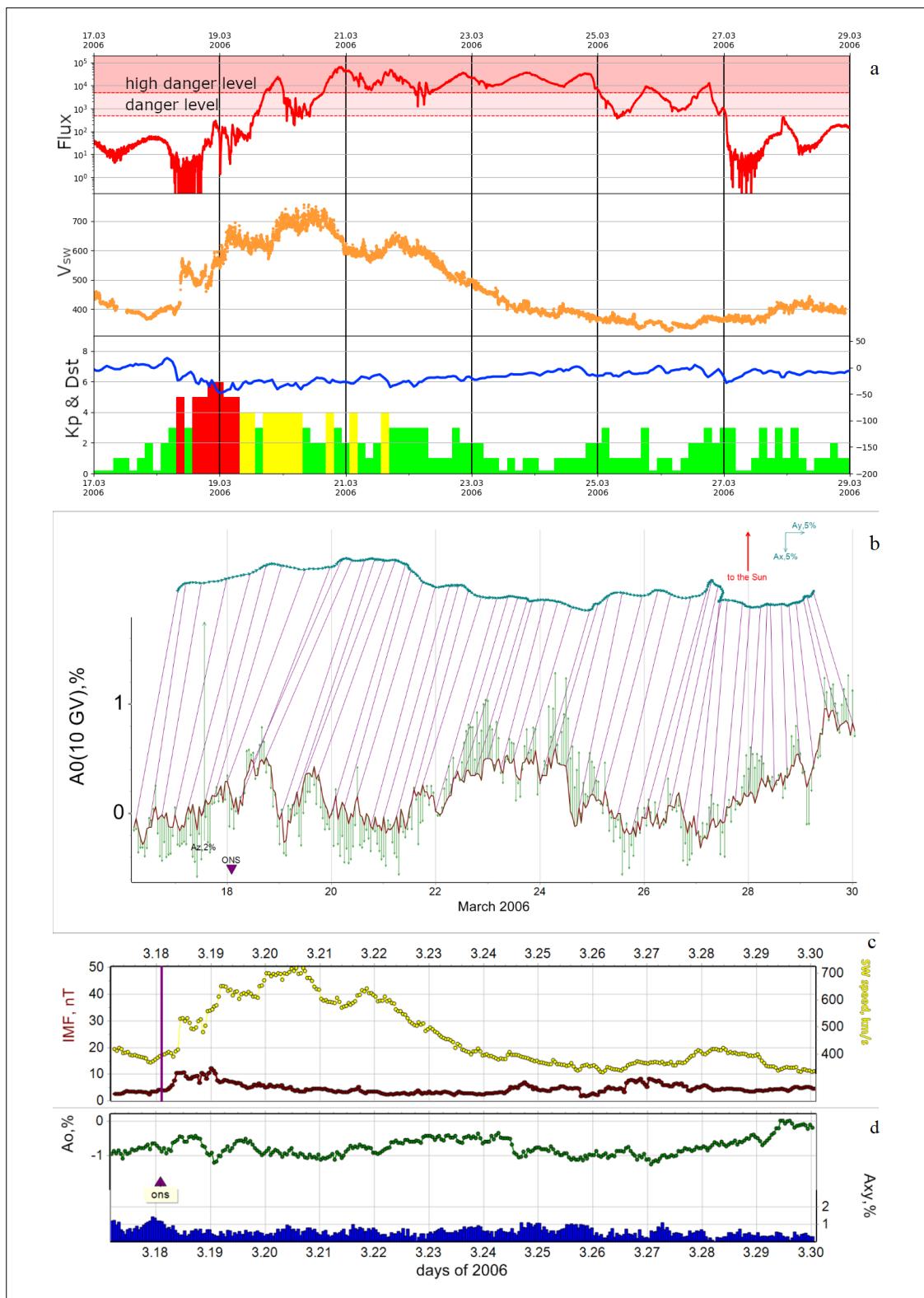
In the first, most numerous group of events, we have collected events related to the disturbances of the near-Earth space caused by the arrival of HSS from CHs.

The enhancement event on March 19-26, 2006 (see Figure 1) is characterized by a high dangerous level ( $> 5000$  particles·cm<sup>-2</sup>·sr<sup>-1</sup>·s<sup>-1</sup>) of electron flux with an energy  $> 2$  MeV. The solar source of the enhancement was an HSS with a speed of 714 km/s from a transequatorial CH, which was in the geoeffective position for 2 days (March 16-17) and then the corresponding HSS impacted the Earth for 5 days (March 18-22). The event is characterized by a smooth behavior of the vector anisotropy ( $A_{xy}$ ) and a small FE with amplitude of 1%; five three-hour periods of a small magnetic storm and two periods of a moderate magnetic storm were recorded in the geomagnetic field. In Fig. 1b and below, purple lines connect the same time points on the vector anisotropy ( $A_{xy}$ ) and CR density ( $A_0$ ) curves.

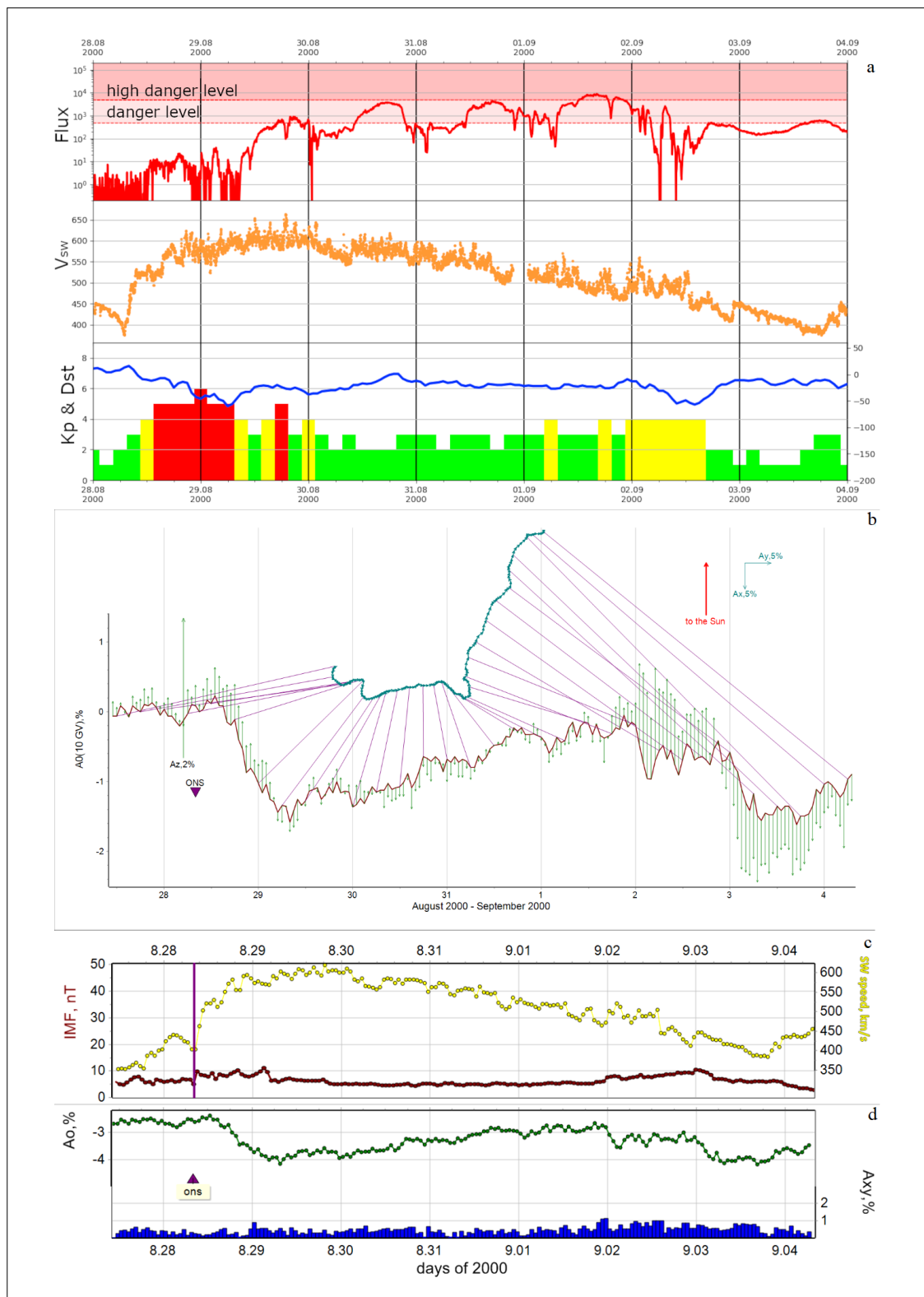
Now let us consider a group of electron flux enhancement events that solar sources were both HSS from CHs and CMEs associated with disappearance of solar filaments.

The event of a dangerous enhancement ( $> 500$  particles·cm<sup>-2</sup>·sr<sup>-1</sup>·s<sup>-1</sup>) in magnetospheric electron flux on August 29 - September 2, 2000 is accompanied by an FE of more than 1% and disturbance of the geomagnetic field to the level of a moderate magnetic storm (Figure 2). The vector anisotropy  $A_{xy}$  has a more curved appearance with the rotation of the vectors due to the propagation of GCRs through the CME associated with the disappearance of the solar filament (DSF).

The event of a dangerous enhancement in magnetospheric electron flux on May 5-15, 1998 was associated with the influence on the near-Earth medium of a CME associated with a solar flare that occurred



**Fig. 1:** An enhancement in magnetospheric electron flux and the state of the interplanetary and near-Earth medium on March 17-29, 2006. a) Magnetospheric electron flux, SW speed, Kp and Dst indices of geomagnetic activity; b)  $A_{xy}$  and density of galactic CR; c) SW speed and interplanetary magnetic field induction; d) density  $A_0$  of galactic CR and  $A_{xy}$ .



**Fig. 2:** An enhancement in magnetospheric electron flux and the state of the interplanetary and near-Earth medium on August 27 – September 2, 2020. a) Magnetospheric electron flux, SW speed, Kp and Dst indices of geomagnetic activity; b)  $A_{xy}$  and density of GCRs; c) SW speed and interplanetary magnetic field induction; d) density  $A_0$  of GCRs and  $A_{xy}$ .

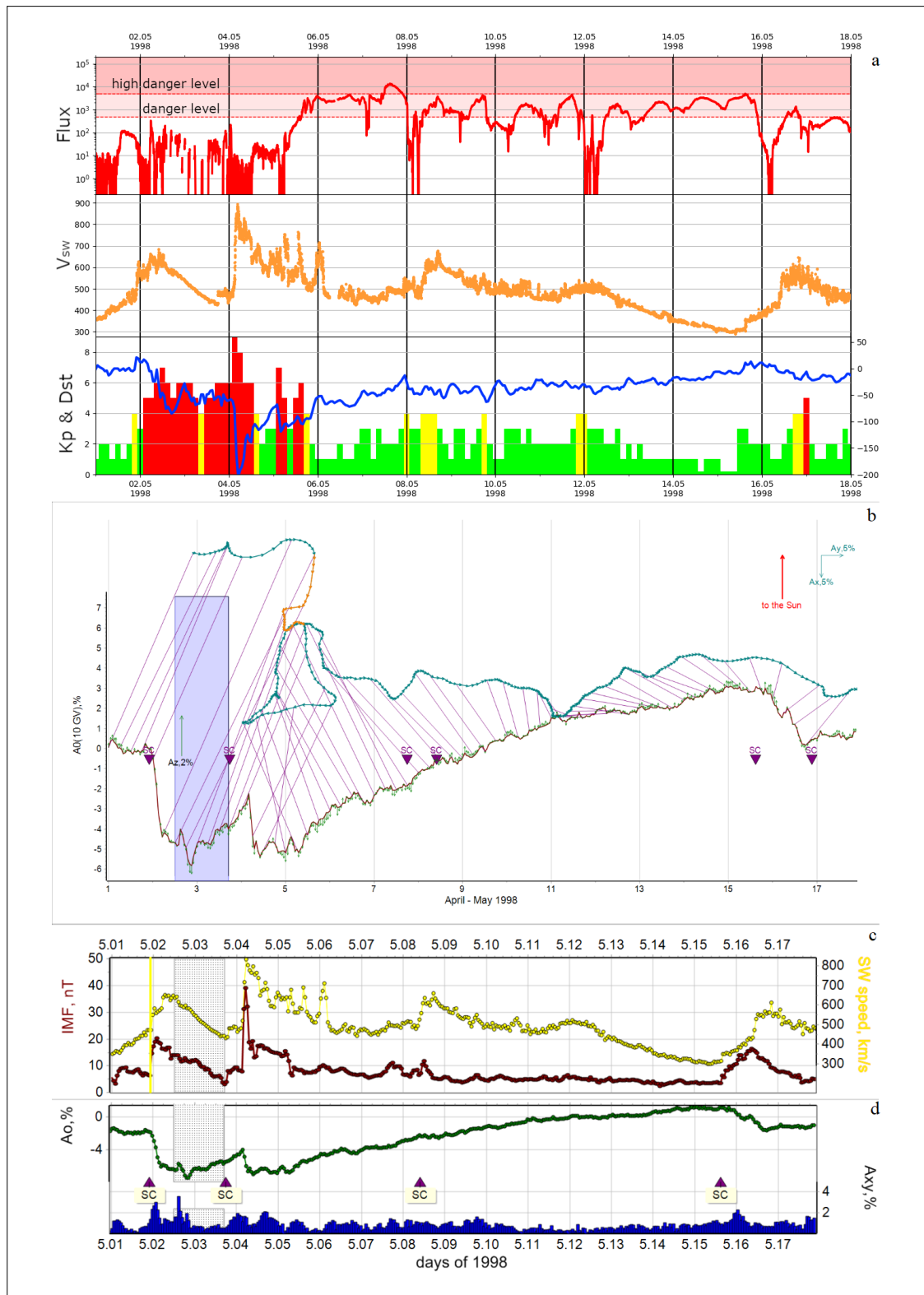
on April 29, 1998 at 16:06 UT. This event was accompanied by an FE of about 6% and a disturbance of the geomagnetic situation to the level of an exceptionally large magnetic storm (Figure 3). The vector anisotropy  $A_{xy}$  has a very complex curved appearance. The average SW speed in this event was 772 km/s. It should be noted that after an exceptionally large magnetic storm, the electron flux rose only to a high dangerous level ( $> 5000 \text{ particles} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1} \cdot \text{s}^{-1}$ ), practically not exceeding it.

## 4. Conclusion

From the analysis of 453 events of high-energy magnetospheric electron flux enhancements, in which the values of the GCRs density and anisotropy beyond the magnetosphere boundary are calculated, it can be concluded that the vast majority of electron flux enhancements are associated with the arrival of HSS from CHs to the Earth. In these events, the flux of high-energy electrons exceeds the high dangerous level most often. In this case, FEs of small magnitude (about 1%) and a smooth behavior of the vector anisotropy are observed. In events associated with other additional solar sources (two types of CMEs), an important role in increasing the electron flux is still played by HSS from CHs. In such events, a more complex, curved behavior of the GCRs vector anisotropy, large magnitudes of FEs in the CRs density, and an enhancement in the values of the equatorial component of the CRs anisotropy are observed. Single events of enhancements in high-energy electron flux caused by CMEs & solar flares are observed, however, despite large effects in the geomagnetic field, such CMEs do not cause enhancements to high dangerous levels in the electron flux.

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**Fig. 3:** An enhancement in magnetospheric electron flux and the state of the interplanetary and near-Earth medium on May 1-17, 1998. a) Magnetospheric electron flux, SW speed, Kp and Dst indices of geomagnetic activity; b)  $A_y$  and density of GCRs; c) SW speed and interplanetary magnetic field induction; d) density  $A_0$  of GCRs and  $A_{xy}$ .

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