

## Recurrent and sporadic Forbush-effects in deep solar minimum

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**Abstract.** The effects of high-speed solar wind streams from low-latitude coronal holes and coronal mass ejections (CMEs) on cosmic ray intensity in 2007 are studied. The database on Forbush effects created at IZMIRAN, with cosmic ray density and anisotropy calculated by the Global Survey Method (GSM) on the basis of Neutron Monitor network data has been used. The behaviour of the mean characteristics by all the Forbush-effects in 2007 caused by coronal holes (interplanetary magnetic field intensity and solar wind velocity, 10 GV cosmic ray density and equatorial component of the cosmic ray anisotropy) is calculated by the epoch method. Features of the Forbush-effects caused by high-speed solar wind streams from low-latitude coronal holes and coronal mass ejections are described.

### 1. Introduction

The Forbush effect (FE) result from the influence of coronal mass ejections (CMEs and ICMEs) and/or high speed streams of the solar wind from the coronal holes on the background cosmic rays [1-5]. Thus, interplanetary disturbances create the Forbush-effects (FEs) are both of sporadic and recurrent nature. It would be desirable to leave only one class of sources and not consider recurrent phenomena as FEs. But this is practically impossible because the solar wind disturbance is often a result of the interaction of different factors [5,6], both of sporadic (coronal ejections, flares, filament disappearances) and recurrent (coronal holes, streamer structure) origin. It is reasonable to divide the FEs into groups by their solar sources: sporadic and recurrent [1], where the first group is being connected with disturbances of the interplanetary medium caused by coronal mass ejections (ICMEs), while the events in the latter group are usually caused by streams of high-speed solar wind from the low-latitude coronal holes (CHs). Solar wind recurrent high speed streams may be the main reason of many FEs, but these effects are never too large. It seems the limiting value of FE caused by coronal holes does not exceed 5%. Herewith in the large recurrent FEs it is also possible to find the contribution of CMEs. We may certainly state that all FEs of large magnitude and the majority of FEs of middle and small magnitude are caused by CMEs. During the minimum solar activity the large CMEs are rare, so the observable FEs are mainly caused by CHs. The goal of the present investigation is to study the influence of high-speed solar wind streams (HSSs) from low-latitude CHs and coronal mass ejections (CMEs and ICMEs) on cosmic rays (CRs).



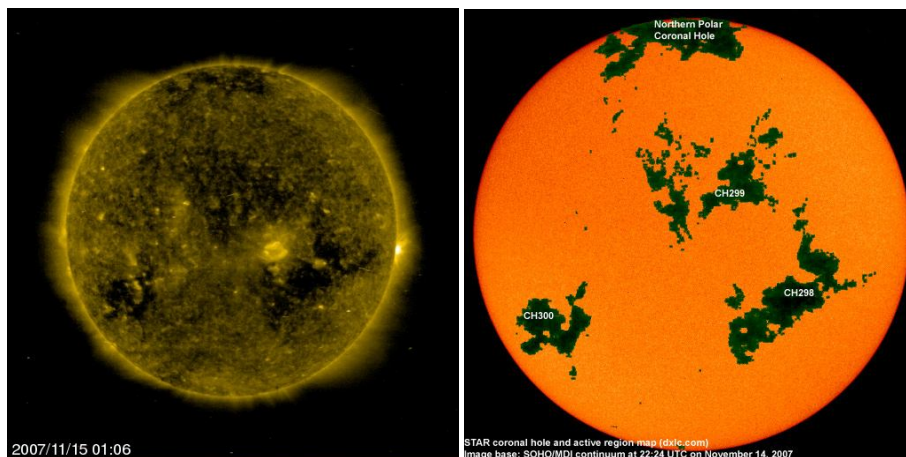
## 2. Data and methods

The parameters used in this analysis include cosmic ray density ( $A_0$ ) and anisotropy ( $A_{xy}$  equatorial component of the first harmonic of the anisotropy), solar wind data (velocity and density), interplanetary magnetic field intensity ( $B_{IMF}$  and  $B_z$ ) as well as solar data and geomagnetic activity indices ( $K_p$  and  $Dst$ ). Using the global survey method (GSM, [7,8]) for the calculation of the CR density variations and anisotropy vectors we operated the whole bulk of experimental material through the year 2007. The CR parameters were supplemented by the information on the interplanetary medium taken from the OMNI database (<http://omniweb.gsfc.nasa.gov/ow.html>), and by the data of geomagnetic activity (<ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap/wdc>). The CR parameters were calculated for particles with a rigidity 10 GV which is close to the effective rigidity of the particles being registered by the world wide neutron monitor network.

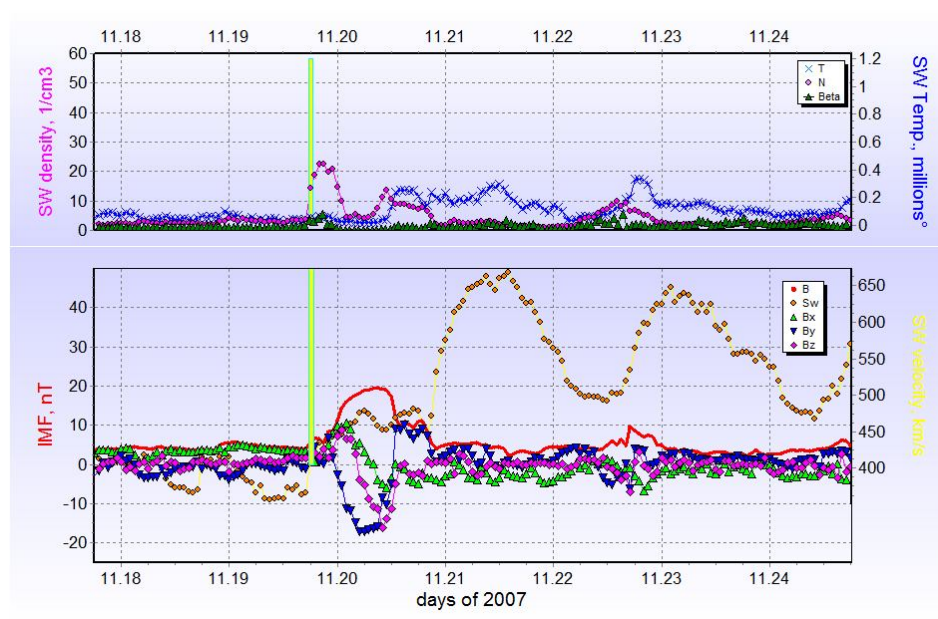
One of the advantages of the year 2007 for our study is a possibility to observe the high-speed streams from CHs without significant CME influence. The background velocity of the solar wind during this year was usually so low that the streams of medium-speed (and sometimes also below than that) were noticeable resulting in an interaction with the low-speed solar wind and in additional modulation of the CR. Also, this year falls on a long period of a large number of CHs which has started at the end of 2002. The numerous (nearly 50) and diverse CHs were the main source of interplanetary perturbations in 2007, while the CME-caused disturbances were a minority, and the CMEs connected with a big solar flares were nearly absent. The events caused by solar filament disappearance were a little more frequently in 2007, but not so often as from CH.

## 3. Analysis of the events

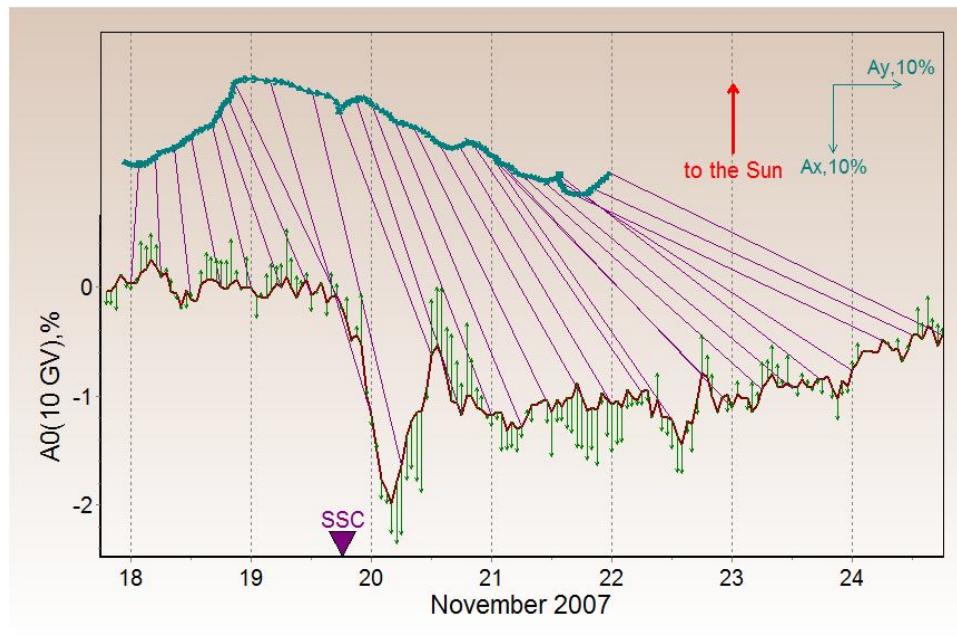
Let us consider FE caused by HSS from recurrent coronal hole and CME. The north coronal hole CH299 (figure 1) has appeared on the disk of the visible Sun and came up to a geoeffective position on November 14-15 2007. The amplitude of the effect in cosmic rays was  $AF = 2.0$ , the maximum equatorial anisotropy was  $A_{xy} = 1.83$ . As in many such events the increase of the solar wind density and the interplanetary magnetic field were observed (figure 2). The short and deep Forbush effect was due to the CME partial halo. It is interesting, that this Forbush effect is not accompanied by a disturbance of the Earth's magnetic field ( $K_{p_{max}} = 3$ ). Then the CR intensity decreased gradually, which was the result of the impact of the overlay effects from CME and CH299, because the coronal hole actually consists of two parts, which led to a slightly increased solar wind HSS. The sharp turn of the vector of equatorial anisotropy occurred before the start of the FE on 19th November (figure 3). It may be noted that the anisotropy behaves quite smoothly in FEs caused by the HSSs from CHs, than in FEs caused by CMEs. As a rule the cosmic ray anisotropy sharply changes its direction under the influence of CME.



**Figure 1.** Coronal hole CH299 (adopted from (<http://www.solen.info/solar>))



**Figure 2.** Behaviour of the solar wind parameters: IMF intensity, solar wind velocity, density and temperature during November 17-24, 2007.

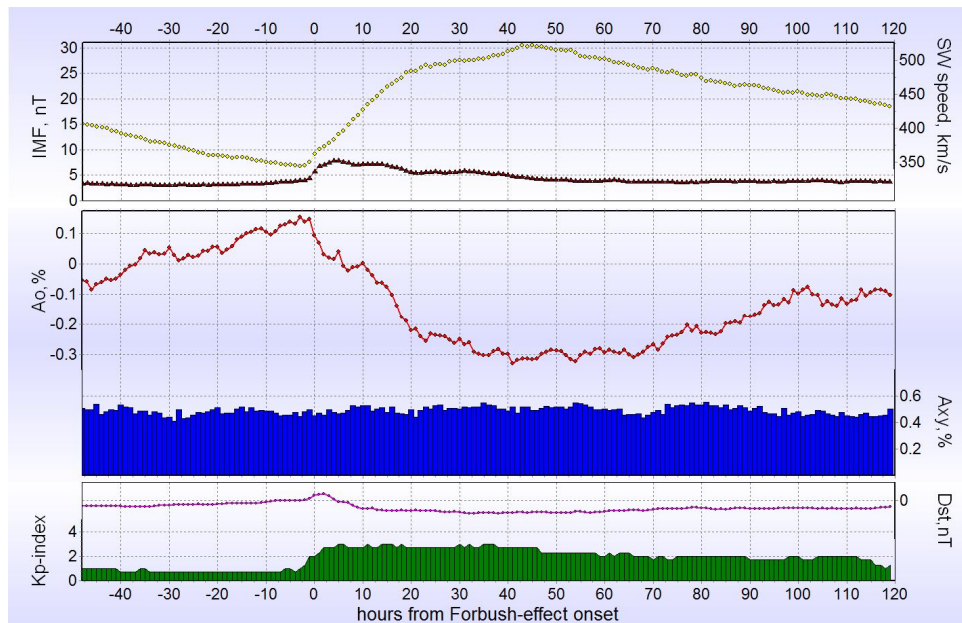


**Figure 3.** Behaviour of the 10 GV CR density ( $A_0$ , brown line) and equatorial component of the first harmonic of CR anisotropy ( $A_{xy}$  – dark green vector diagram) during November 17-24, 2007. Vertical green lines mean the North-South anisotropy for each hour. Thin solid lines connect parts of the vector diagram and the curve of density every 6 hours. The triangle SSC (Sudden Storm Commencement) marks the moment of shock arrival and the onset of the Forbush effect.

As we defined earlier [9], the magnitude of the IMF significantly affected the magnitude of the FE. In the event of 19-20 November, 2007 it is clearly visible: the large magnitude of effect for this class of FEs the (2%) is associated with a large magnitude of the IMF (20 nT). The configuration of the interplanetary magnetic field on November 20 is one of the signs of a magnetic cloud. This CME was the result of the disappearance of the solar filament (DSF) on 15 November.

The mean characteristics averaged by all the events in 2007 caused by coronal holes, are shown in figure 4. All parameters are averaged by the epoch method where the 0-day is the day of the Forbush effect onset.

From the analysis of 48 FEs that occurred in 2007 and are associated with low latitudes coronal holes, it can be noted that the HSS from low-latitude coronal holes leads to disturbances of the magnetosphere to the level of minor (and rarely moderate) magnetic storm, on average, these events are accompanied by a disturbed level of the magnetic field (with  $K_p=4$ ). The maximum speed HSS from coronal holes was 567 km/s, the maximum value of the solar wind velocity was  $V_{sw}=698$  km/s. The magnitude of FEs in these events varies from 0.3% to 2.3%, the average value of FE is  $1.03 \pm 0.06\%$ . The maximum values of the equatorial part of the first harmonic of the anisotropy of CR reaches  $1.02 \pm 0.03$ , and it varies from a minimum of 0.64 to a maximum of 1.51.

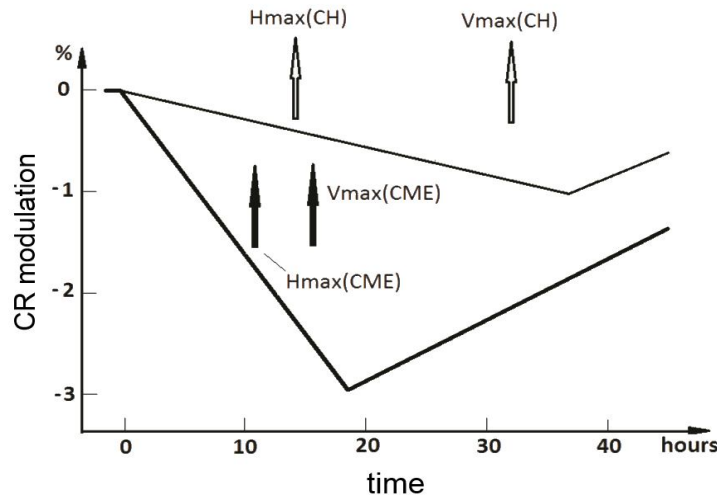


**Figure 4.** Behaviour of the characteristics averaged by all the FDs in 2007 that are caused by coronal holes: IMF intensity (black line) and solar wind velocity (yellow line, upper panel); 10 GV CR density ( $A_0$ , red line) and equatorial component of the CR anisotropy  $A_{xy}$  (blue stakes, middle panel);  $K_p$  (green stakes) and Dst-indexes (violet line, lower panel) of geomagnetic activity.

For a comparison with CH group events, the average characteristics of all events from our database including a CME, separated each from other by not less than 48 hours, are plotted in figure 5 [10]. It means that in calculation we use only those events that separated each from other by not less than 48 hours, otherwise FEs may overlap. 349 CME-caused events we picked up from the whole database for the years 1996-2010. We selected only those CME-caused events in which the values of the solar wind velocity and the interplanetary magnetic field intensity were closed to the values in the group of CH-caused events.



The comparison shows that high-speed streams of a solar wind from coronal holes created a small (on average,  $1.03 \pm 0.06\%$ ), slowly developing FE. In the CME caused events the maximum of the IMF intensity ( $t_{Hmax}$ ), the maximum of a solar wind speed ( $t_{Vmax}$ ) and the minimum of CR density are located in a compact group in the range of several hours, whereas in the CH associated events the maximum of the solar wind speed  $V_{max}$  and the CR density minimum are delayed essentially relatively to the maximum of IMF intensity ( $t_{Hmax}$ ).



**Figure 5.** Average characteristics of FEs in 2007 caused by coronal holes (48 events, upper line), and events, created by CMEs (349 events, lower line). X axis - time from FE onset, Y axis - magnitude of CR modulation.

#### 4. Conclusions

Prolonged CR decreases characterized by a late minimum in 2007. The maximum speed of HSS from coronal holes, averaged for 48 events, was 567 km/s, and the maximum IMF intensity was  $11.6 \pm 0.5$  nT, the Kp index of geomagnetic activity was  $4.08 \pm 0.13$ , the equatorial component Axy of the vector CR anisotropy varies very slightly.

The example of 2007 demonstrates that even at very quiet conditions, i.e., reduced activity of the Sun, disturbances resulting to FEs are present; these disturbances are the CHs. The data of the global Neutron Monitor network, processed by GSM, allows us to study small CR effects. A distinctive feature of the FEs caused by CHs, is their long duration, the minimum intensity of cosmic rays greatly lags the IMF intensity. FEs caused by coronal holes are quite different from the events caused by CMEs: they have a shorter duration of the FE, the time distribution - late minimum in CR intensity, which is close to the time of the solar wind velocity maximum and delayed with respect to the IMF maximum. There are large differences between recurrent and sporadic FEs in the derived CR anisotropy: the value of the anisotropy is significantly smaller for recurrence than for sporadic FEs and furthermore, it presents a more smooth, behaviour.

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