High-energy magnetospheric electrons and their dependence on interplanetary conditions

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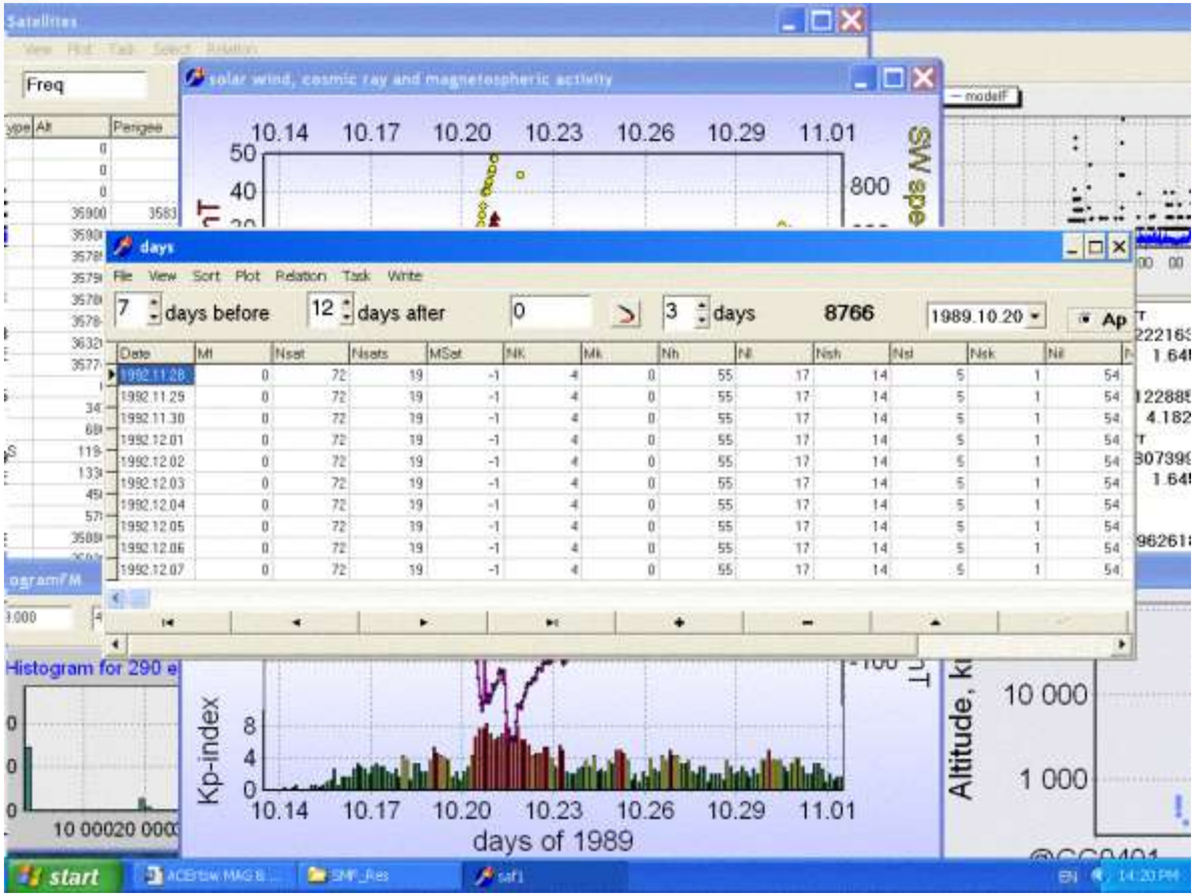
The danger of increasing of high-energy magnetospheric electrons with E>2 MeV

Why is this task so important for us?

Large enhancements in the fluxes of relativistic electrons lead to spacecraft malfunctions and have in a number of cases resulted in the failure of satellites. The anomalies were most frequently associated with false commands caused by internal electrostatic discharges.

When the accumulated charge becomes sufficiently high, a discharge or arching can occur. This discharge can cause anomalous behavior in spacecraft systems and can result is temporary or permanent loss of functionality.

Database



Database of parameters of the near-Earth and interplanetary medium: W, solar radio flux at 10.7 cm $F_{10.7}$, V_{sw}, I_{IMF}, A_p, D_{st}, CR (p>1, 10 и 100 MeV, e> 2 MeV)

Project INTAS-00-0810 **"Improvement of methods of control and prognosis of periods of dangerous influence of space weather on satellite's electronics"**

Satellite malfunction data

The main contribution was from NGDC satellite anomaly database, created by Daniel Wilkinson.

+

“Kosmos” data (circular orbit at 800 km altitude and 74º inclination)

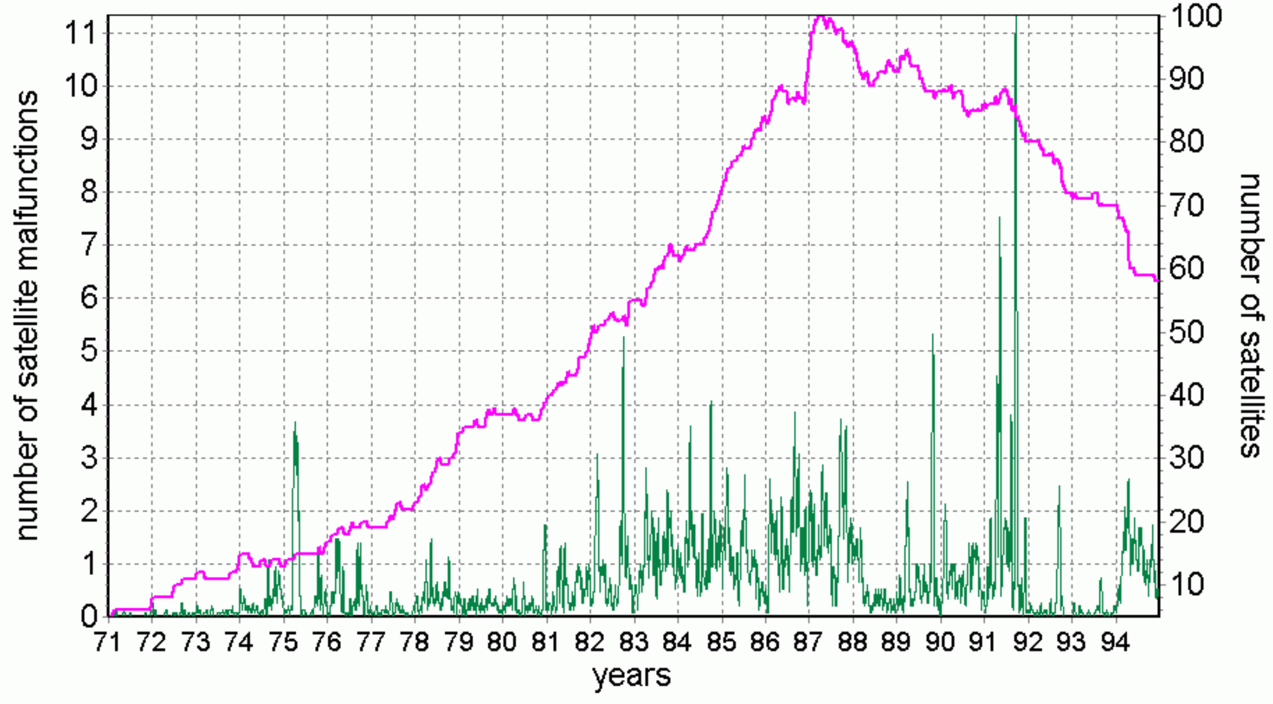
+

1994 year anomalies - Walter Thomas report (Thomas, 1995).

+ ε

The satellites characteristics - from different Internet sources:
http://spacescience.nasa.gov/missions/index.htm
http://www.skyrocket.de/space/index2.htm
http://hea-www.harvard.edu/QEDT/jcm/space/jsr/jsr.html
http://www.astronautix.com/index.htm

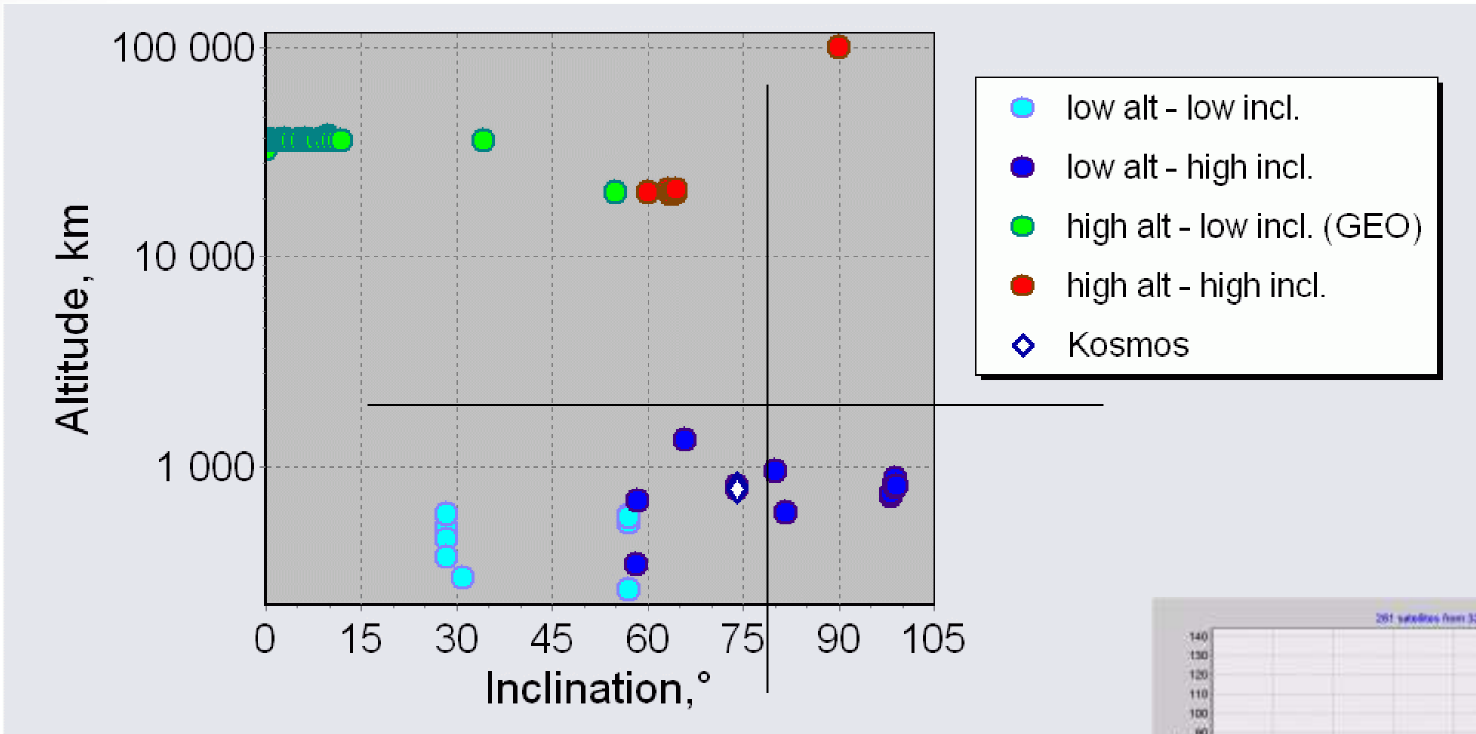
Satellite and Anomaly Number

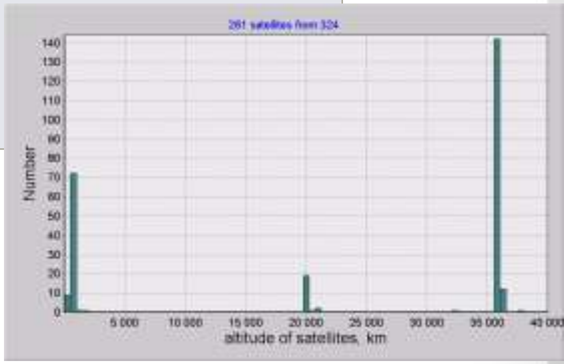


~300 satellites
~6000 satellite malfunctions

***Project INTAS-00-0810* "Improvement of methods of control and prognosis of periods of dangerous influence of space weather on satellite's electronics"**

Groups of satellites





What satellites we have? Look on altitude-inclination diagram. We can divide satellites by altitude, or by inclination or by both factors.

Period with big number of satellite malfunctions

Upper panel – cosmic ray activity near the Earth: variations of 10 GV cosmic ray density; solar proton (> 10 MeV and >60 MeV) fluxes.

Lower panel – geomagnetic activity: Kp- and Dst-indices.

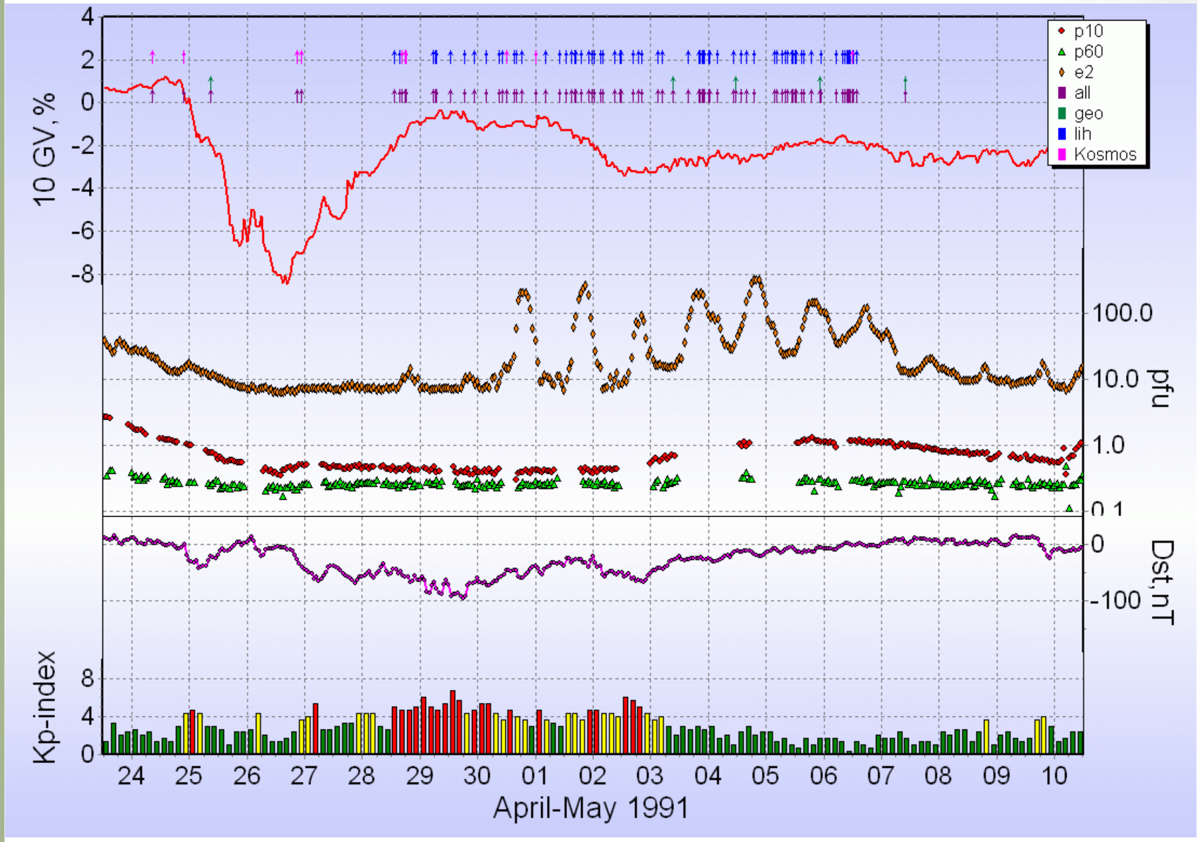
Vertical arrows on the upper panel correspond to the malfunction moments.

Look on two examples. First one – the well known period – October 89. All our topic is originated from this period with exclusively bad space weather. We see here 3 big proton events, very strong magnetic storm. In upper part the variations of ground level cosmic rays. These proton events were ground level enhancements. And these arrows are moments of satellite malfunctions. We have 3 clusters of malfunctions and they coincide with maximal proton fluxes.

Belov A., Dorman L., Iucci N., Kryakunova O., Ptitsyna N. The relation of high- and low-orbit satellite anomalies to different geophysical parameters.// in "Effects of Space Weather on Technology Infrastructure. NATO Science Series II, 2004, V.176, p. 147.

Other example

- *Upper panel – cosmic ray activity near the Earth: variations of 10 GV cosmic ray density; electron (> 2 MeV) fluxes – hourly data.*
- *Vertical arows correspond to the malfunction moments. Lower row – all malfunctions.*
- *Lower panel – geomagnetic activity: Kp- and Dst-indices.*



Here the majority of the satellite malfunctions coincides with period of magnetic storm and enhancement of high-energy electron flux. The malfunctions are absent entirely in the high altitude - high inclination group, which played the main role in preceding example. Only a few malfunctions were in GEO group and huge majority – in “blue” group (low altitude - high inclination). We see entirely other subset of satellites comparing with first example.

Belov A., Dorman L., Iucci N., Kryakunova O., Ptitsyna N. The relation of high- and low-orbit satellite anomalies to different geophysical parameters.// in "Effects of Space Weather on Technology Infrastructure. NATO Science Series II, 2004, V.176, p. 147.

Models of the anomaly frequency

high alt.- low incl.

cc=0.40

- **e>2 MeV**
- Apd, AEd, sf
- Vsw
- p60d, p100
- da10

low alt.-high incl.

cc=0.21

- **e>2 MeV**
- CRA
- Apd, sf
- Vsw_{max}
- Bzd

high alt.-high incl.

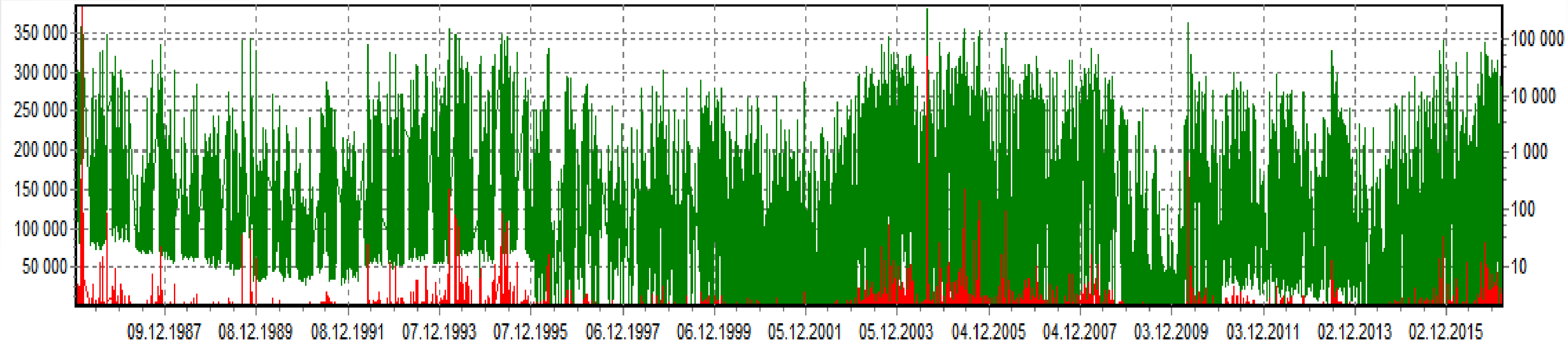
cc=0.51

- **p>100 MeV, p60d**
- Bznsum

The parameters used to simulate anomaly frequencies for different orbits are listed here. Green, blue and red group. Main role is for electrons in green and blue group, especially – green. In red group protons are much more important than other indices.

Belov A., Dorman L., Iucci N., Kryakunova O., Ptitsyna N. The relation of high- and low-orbit satellite anomalies to different geophysical parameters.// in "Effects of Space Weather on Technology Infrastructure. NATO Science Series II, 2004, V.176, p. 147.

The electron flux in 1986-2016



High energy electron flux (>2 MeV) in 1986-2016

The daily fluence was chosen as the main characteristic of the >2 MeV electrons measured by the GOES satellites at geostationary orbits, since it was most closely associated with malfunctions of the satellites' electronic equipment. For 1986–2017, daily fluence *F* of high-energy (>2 MeV) electrons measured by the GOES satellites varied within wide limits, from 1.4×10^4 to 9.3×10^9 electrons $(cm^2\ sr\ day)^{-1}$.

The aim of this work was to study the behavior of high-energy magnetospheric electrons using data from the GOES satellites for 1986–2017, and to identify the main patterns in the behavior of the solar wind speed and the *Ap* index of geomagnetic activity before and during increases in the fluence of electrons at geostationary orbit.

Typical examples of electron enhancement events

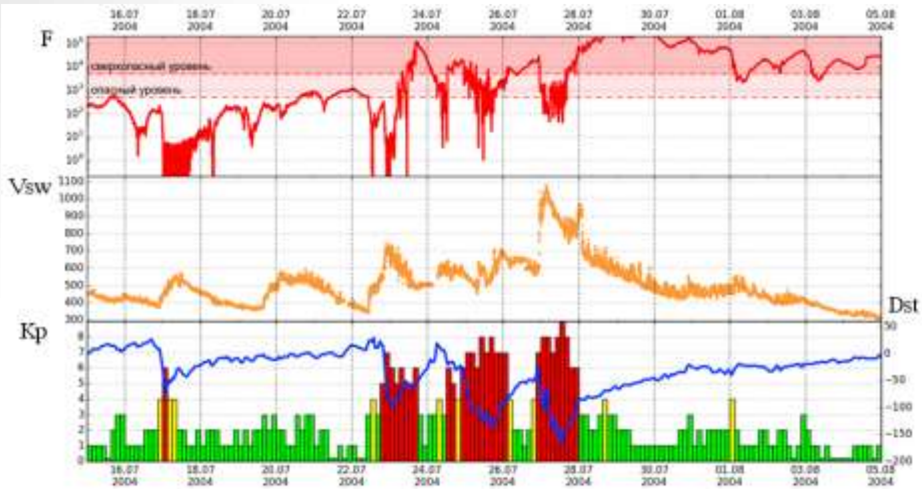
In this work, we assumed that the electron flux begins to grow when the daily fluence exceeds 10^8 electrons $(\text{cm}^2\ \text{sr day})^{-1}$. Increases from this level are typically considered to be dangerous.

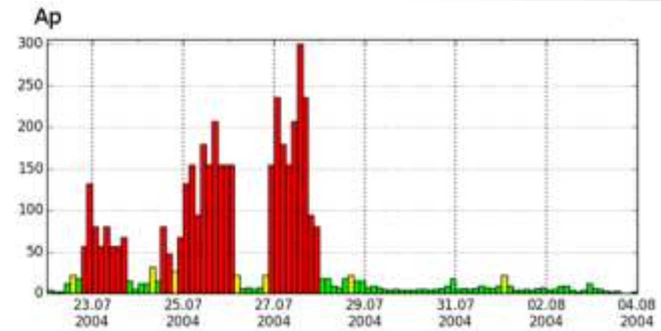
The example of the behavior of flux of high-energy (> 2 MeV) electrons and other parameters in May-June 2013.

The example of the behavior of the flux of high-energy (> 2 MeV) electrons and other parameters in December 1999 - January 2000.

The example of the behavior of the flux of high-energy (> 2 MeV) electrons and other parameters in January - February 2000.

The event with the maximum electron fluence





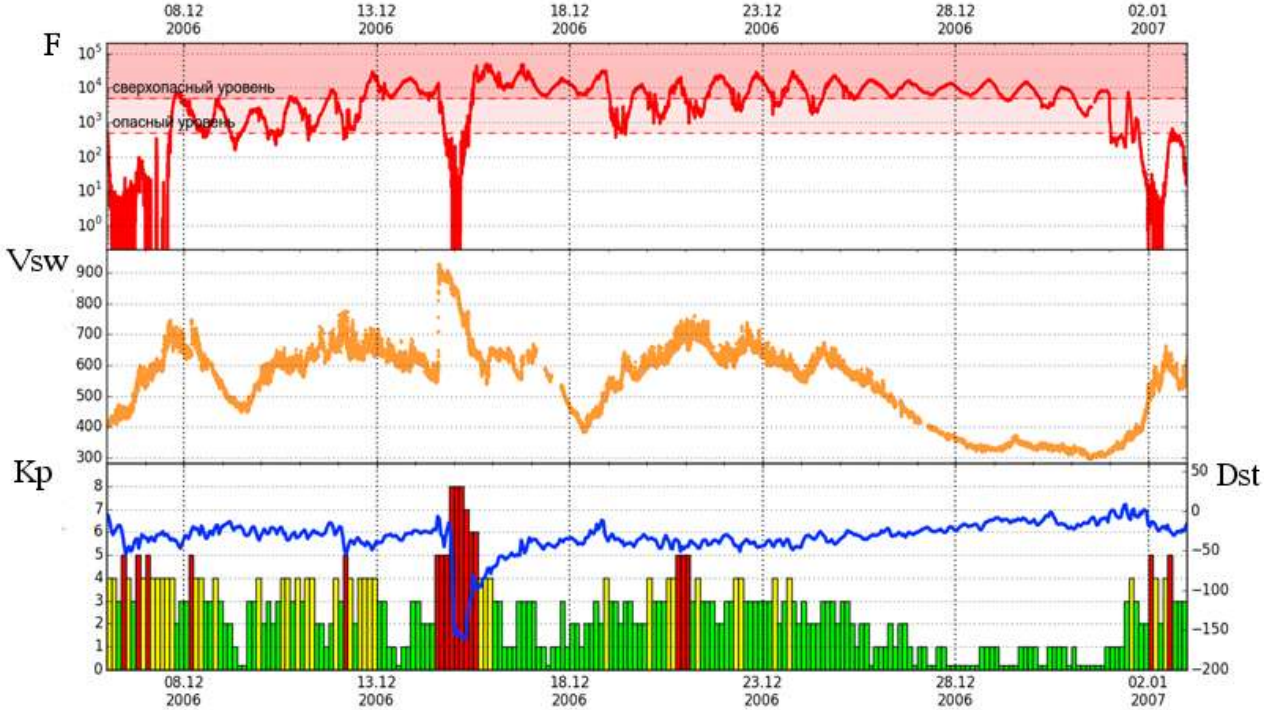
Severe Geomagnetic Storm (Ap = 300, Kp=9^{-})

The maximum fluence for these 21 years was 9.3×10^9 electrons (cm^2 sr day)$^{-1}$, which was observed on July 29, 2004.

NMDB: Real-Time Database for high-resolution Neutron Monitor measurements (www.nmdb.eu)

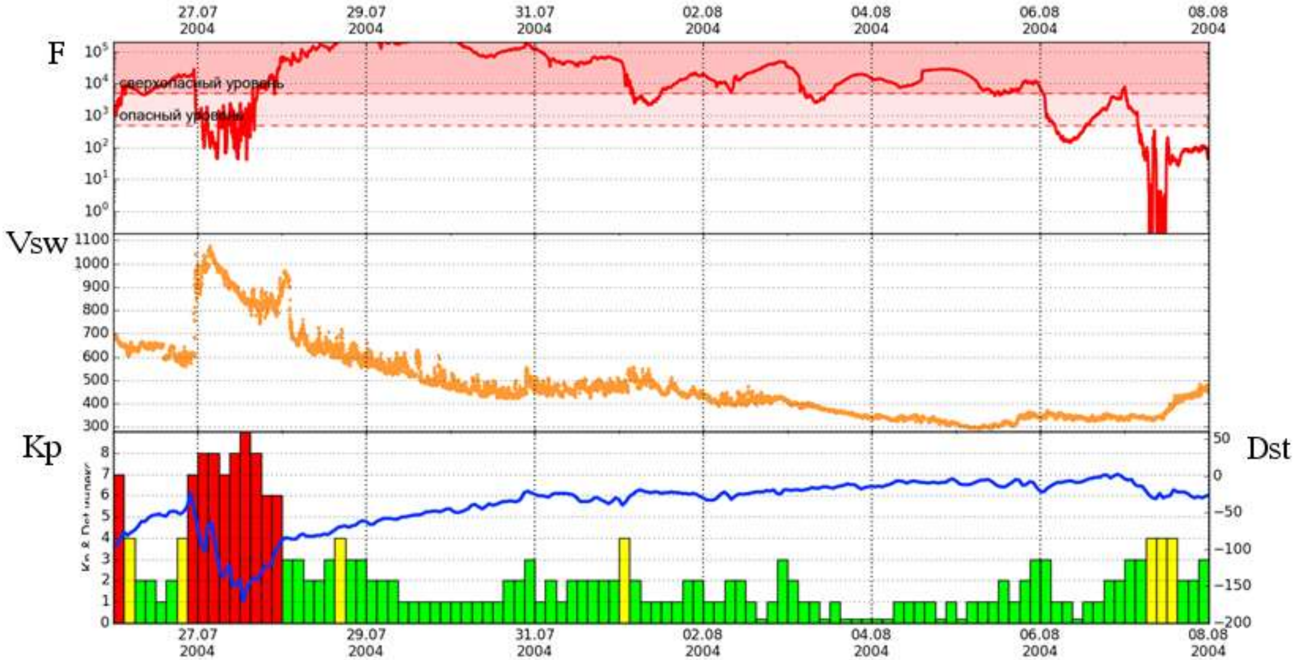
We acknowledge the NMDB database (www.nmdb.eu), founded under the European Union's FP7 programme (contract no. 213007) for providing data

The longest event in December 2006



Electron enhancements generally lasted longer than 1 day, while the longest event (22 days long) was observed from December 10 through 31, 2006.

Event with maximum total fluence



A no less important characteristic of an electron flux increase (in addition to the maximum daily fluence) is probably total fluence *S* over the period of growth. In our catalog, the largest total fluence is found for the event lasting from July 28 to August 5, 2004: 2.6×10^{10} electrons cm^{-2} sr^{-1}.

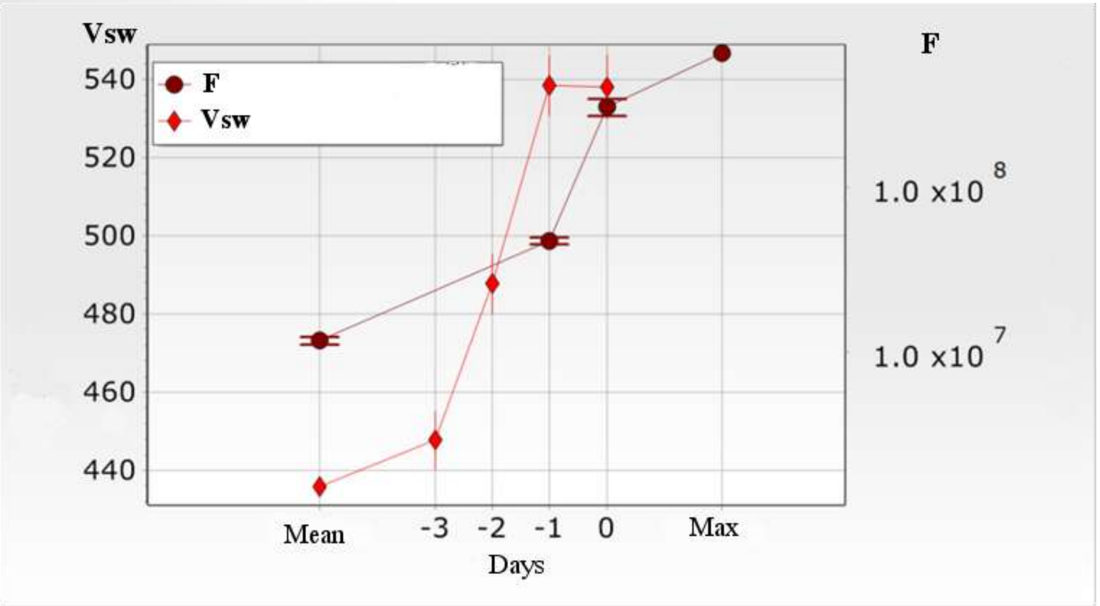
The connection of electron fluence enhancements with key parameters

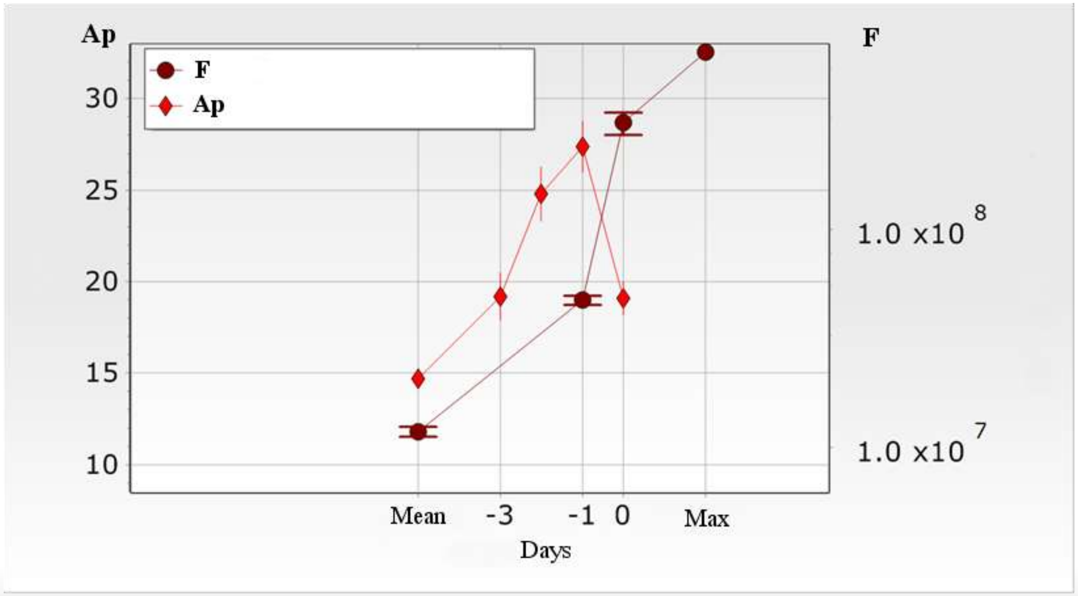
Parameter / Day	Mean for all days	-3	-2	-1	0	Maximum
$F/10^7$, $cm^{-2}\cdot sr^{-1}$	1,18±0,06			**4,7**±0,2	**31,0**±3,7	65,6
V_{SW}, $km\cdot s^{-1}$	436±2	448±7	488±8	**538**±8	**538**±8	
A_p, 2nT	14,7±0.2	19,2±1.3	24,8±1,5	27,4±1,4	**19**,1±0,9	

Mean values for key parameters of electron flux enhancements

We used our catalog of electron fluence enhancements to determine the average values of key parameters. From the catalog of electron flux increases, we took the days when increases started and designated them Day (0). It is more interesting that substantially greater key parameters are observed on Days 0: the solar wind speed is 538 ± 8 km s^{-1}, while the *Ap* index is 19.1. In other words, we would expect Days (0) to be disturbed on average, and this is true for both the interplanetary medium and the Earth's magnetosphere.

The average behavior of the Ap and Vsw of near the onset of electron enhancements

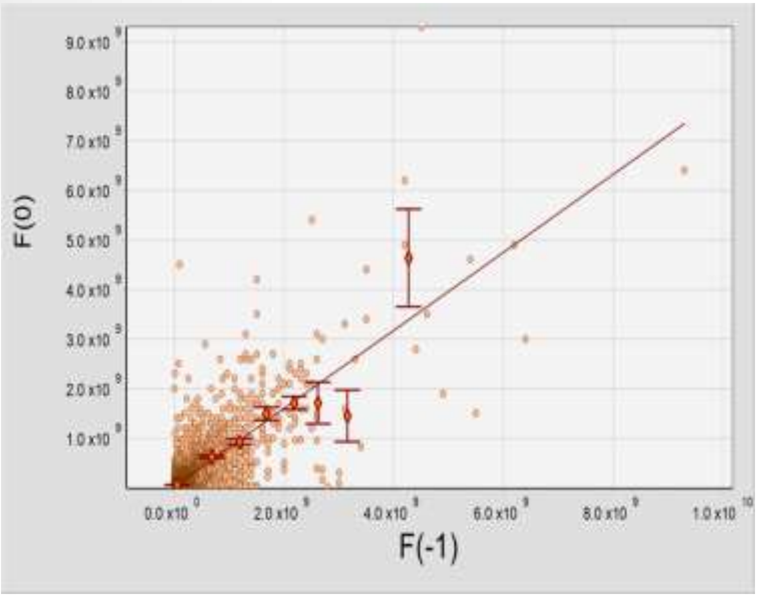


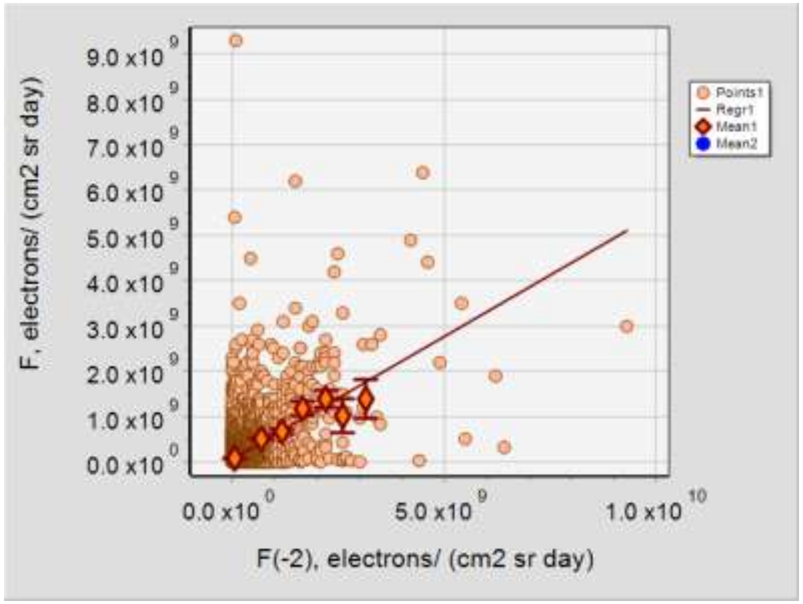


The solar winds speed grows as early as 3 days before the start of the electron flux increase. On Day (–1), it reaches a maximum that lasts 2 days, including Day (0). This growth is characteristic of high-speed streams from large coronal holes.

The *Ap* index begins to grow 2–3 days before the increase in the electron fluence, and on Day (–1) it reaches a level that is roughly double the average values for these years. We may state that the electron flux increase begins at the time of a magnetic storm (most likely a small one) during the waning geomagnetic activity.

The connection of electron enhancements with interplanetary parameters





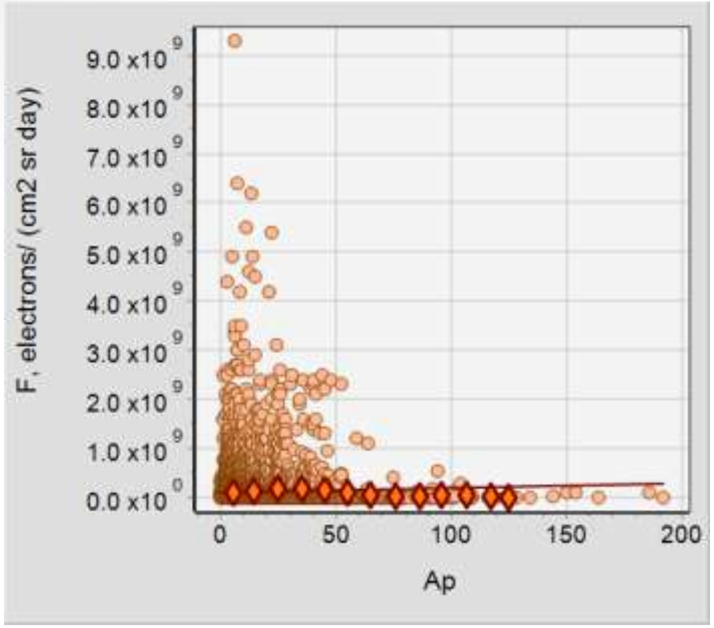
r = 0.86

r = 0.55

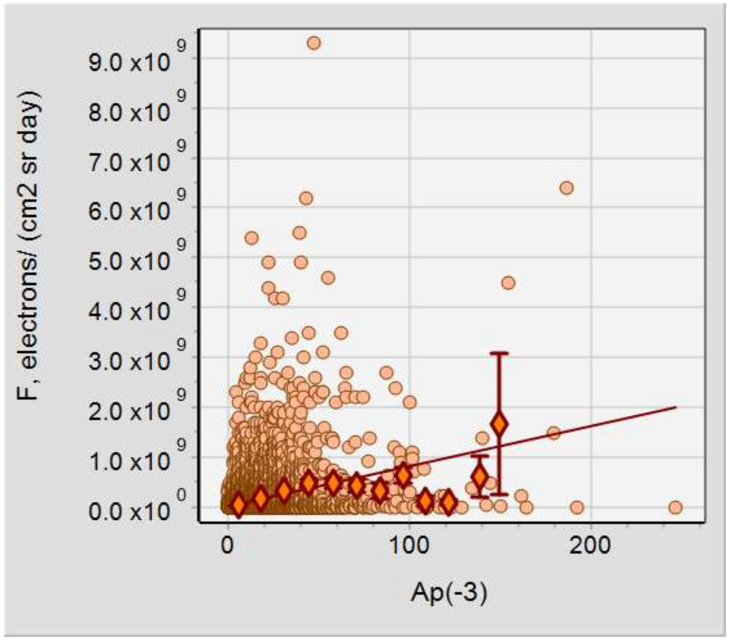
The connection of the daily fluence of high-energy (> 2 MeV) electrons F (0) with the fluence on the previous day. The straight line corresponds to linear regression.

The connection of the daily fluence of high-energy (> 2 MeV) electrons F (0) with the fluence on the (-2)-day. The straight line corresponds to linear regression.

The connection of electron enhancements with interplanetary parameters



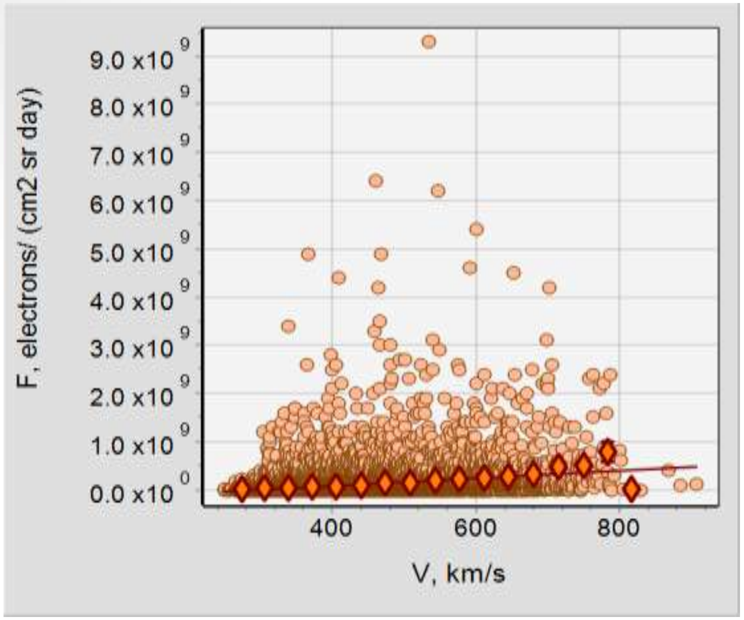
r = 0.03



r = 0.32

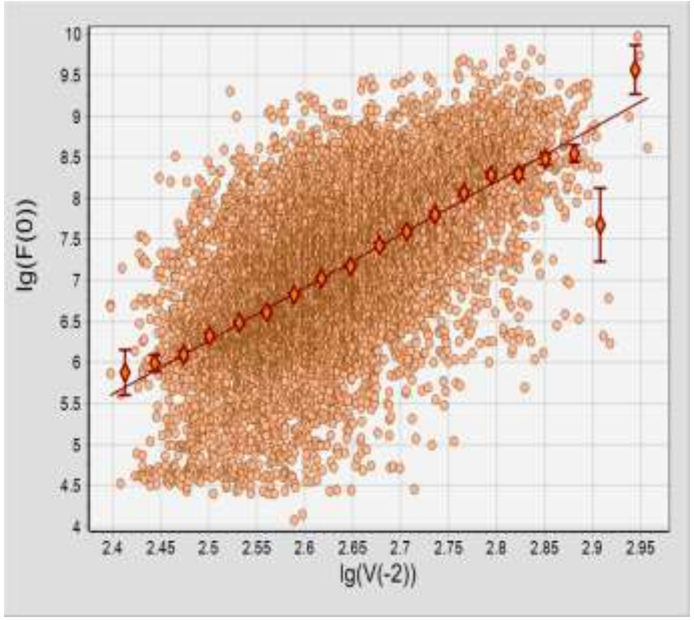
Correlation of the daily fluence of high-energy (> 2 MeV) electrons F (0) with the Ap-index of geomagnetic activity at the same day and on (-3)-Day.

The connection of electron enhancements with interplanetary parameters



r = 0.23

Correlation of the daily fluence of high-energy (> 2 MeV) electrons F (0) with the solar wind speed on 0-Day.



r = 0.61

The coefficient of correlation between the logarithm of the solar wind speed on Day (−2) and the logarithm of the electron fluence is 0.61.

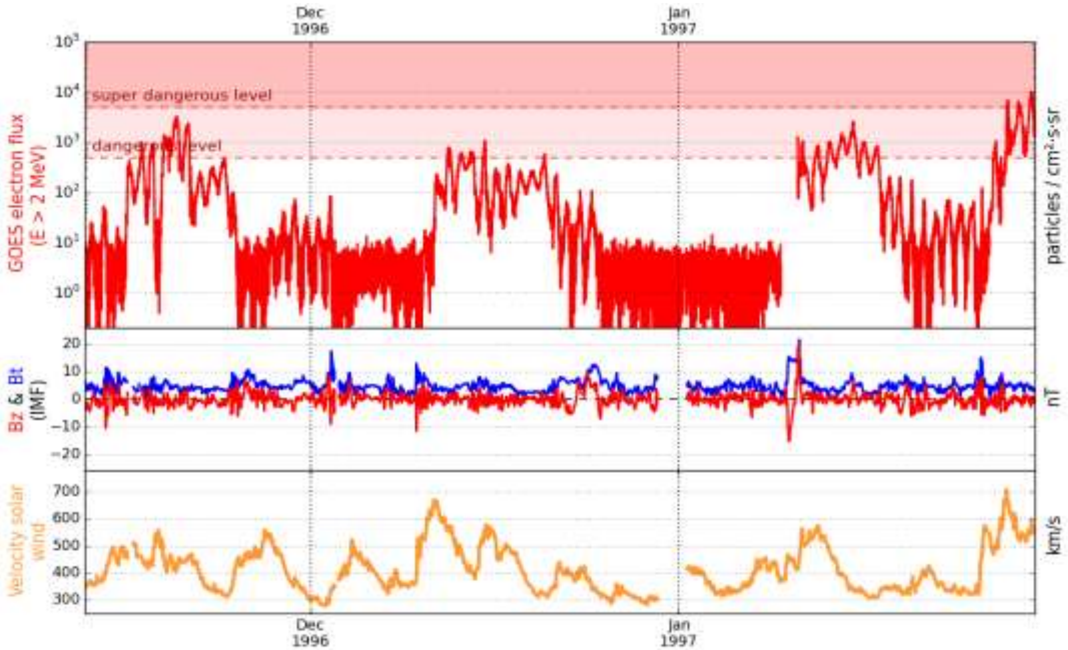
Since the solar wind speed varies within relatively narrow limits while the electron fluence changes by several orders of magnitude this is very strong dependence.

Coefficients of the correlation between the electron fluence and different parameters

Parameter	Day (0)	Day (- 1)	Day (– 2)	Day (-3)	Day (– 4)
Electron fluence	1	**0.86**	0.56	-	-
A_p-index	0.03	0.17	0.29	**0.32**	0.28
V_{SW}	0.23	0.36	**0.61**	0.37	-

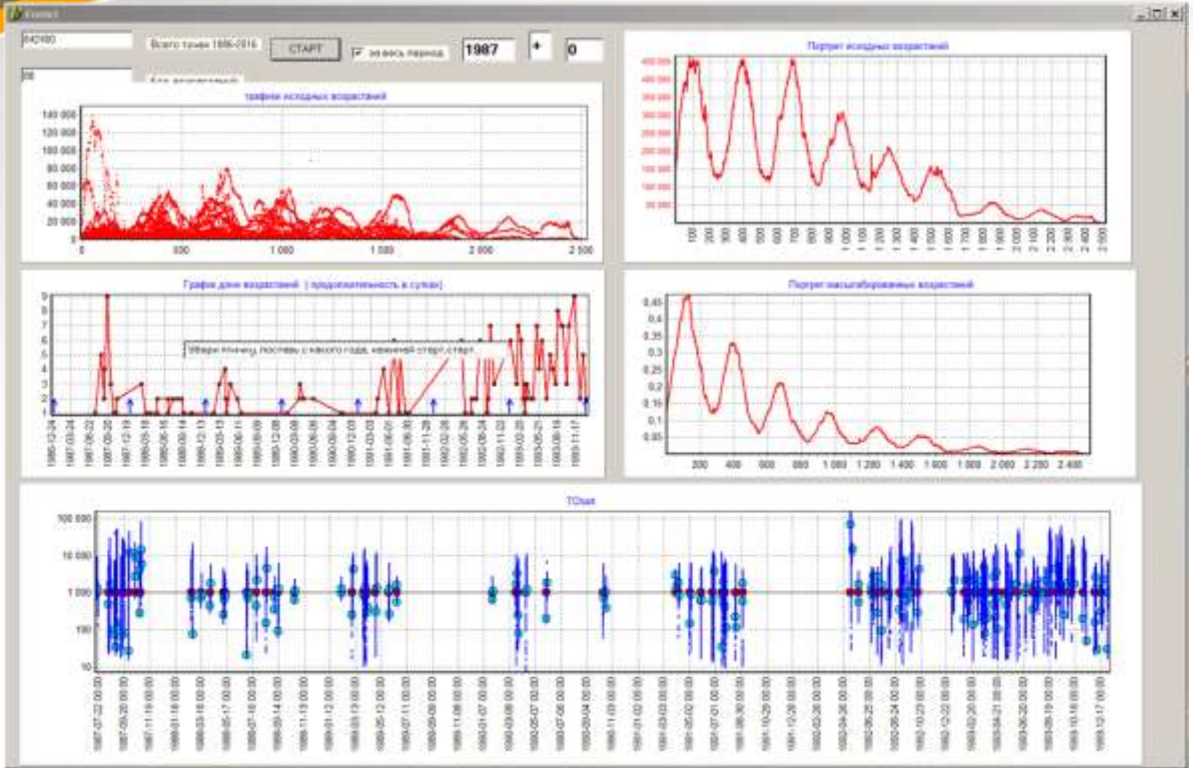
The coefficient of the correlation between the fluence $F(0)$ and Ap-index of geomagnetic activity on the same day ($Ap(0)$) is near zero ($\rho = 0.03$). However, the correlation grows if the Ap indices of previous days are used. The coefficient of the correlation between the fluence $F(0)$ and $Ap(-3)$, $\rho = 0.31$. This correlation should be useful for predicting the electron fluence. The closest association with high-energy magnetospheric electrons is found for the solar wind velocity Vsw.

27-day recurrence of electronic increases

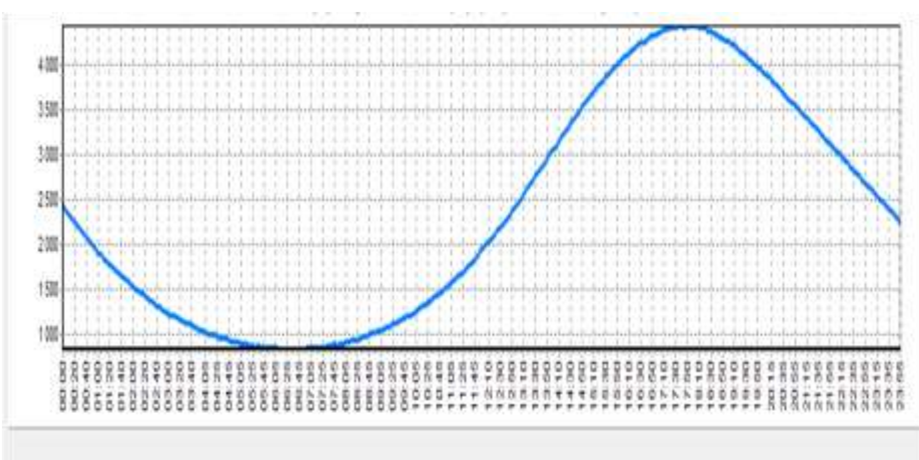


The flow of high-energy electrons and solar wind parameters in November 1996 - January 1997

This period of three solar rotations shows that sometimes electron fluxes are very recurrent. Probably, this is due to the recurrence of coronal holes.

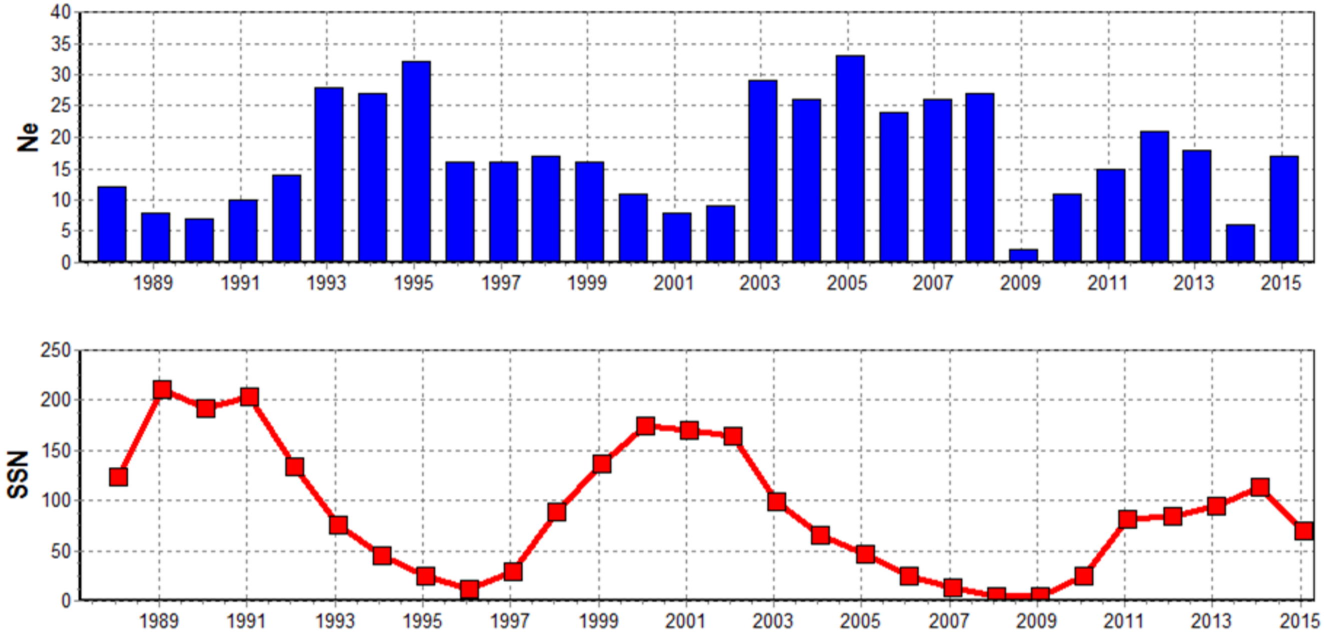


The averaged portrait of the scaled electron increase in which, after a sharp increase in the electron flux on the first day, diurnal waves clearly appear, decreasing in amplitude over an average of three days.



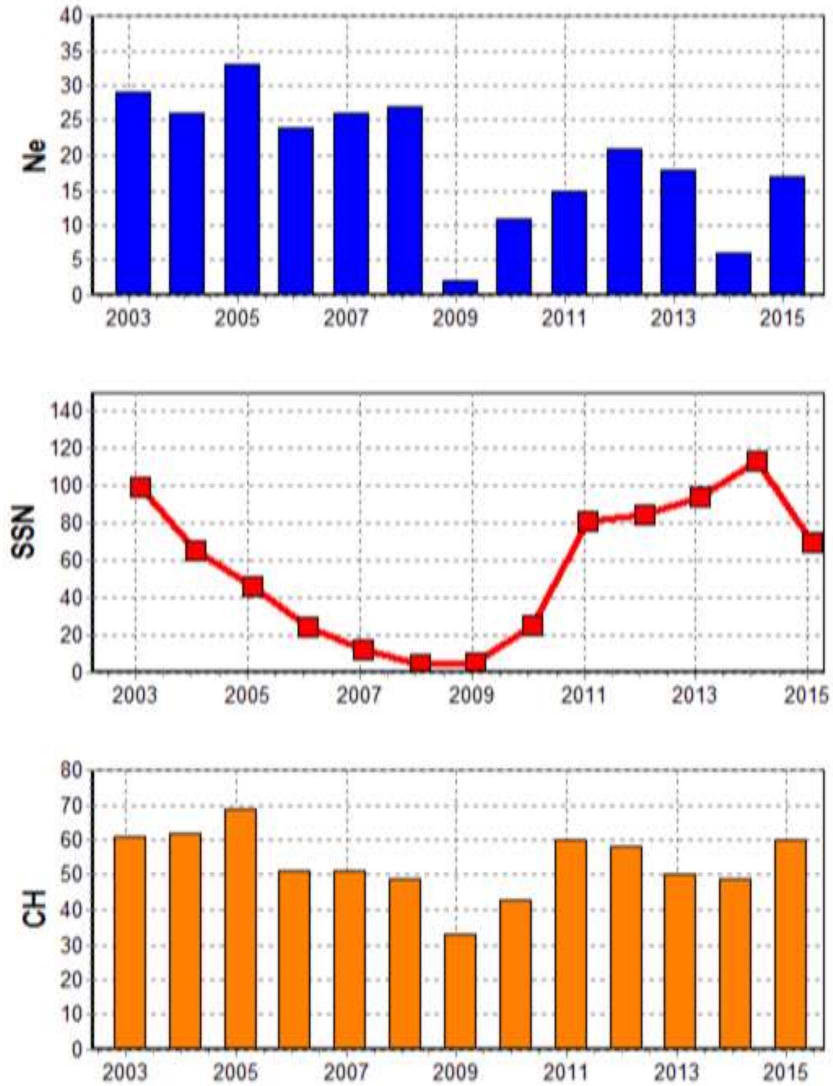
The averaged behavior of the daily variation of high-energy electrons in the geostationary orbit for 1986-2017.

How change the number of electron enhancements in solar activity cycles?



The maximum number of electron enhancements occur during the declining phases of solar activity.

Electron Enhancements and Coronal Holes



The number of electron enhancements, sunspot numbers and the number of coronal holes in solar activity cycles.

The number of electron enhancements correlates well with the number of coronal holes.

CONCLUSIONS

- ✓ **The flux enhancements of high-energy magnetospheric electrons are associated with substantial interplanetary and magnetospheric disturbances, but lag behind them 1–3 days.**

- ✓ **A much faster solar wind speed is observed as early as 3 days before the onset of the electron flux increase and reaches its maximum value by the time it starts.**

- ✓ **The electron fluence is weakly associated with the level of geomagnetic activity on the same day, but correlates to the *Ap* index of geomagnetic activity observed 2–3 days earlier.**

- ✓ **The fluence of the high-energy magnetospheric electrons is quite closely associated with the solar wind speed, especially with the value measured 2 days earlier.**

- ✓ **The maximum number of electron enhancements occur during the declining phases of solar activity.**

- ✓ **The number of electron enhancements correlates well with the number of coronal holes.**

Thank you for attention !