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Relationship between the Fluence of Magnetospheric Electrons with Energies above 2 MeV and Geomagnetic and Interplanetary Characteristics in 1987–2021

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Abstract—Coefficients of correlation are calculated for the daily electron fluence, solar wind velocity, and the *Ap*-index of geomagnetic activity with different delays, along with electron fluences obtained for subsequent days using a dataset from 35 years (1987–2021) of measuring magnetospheric electron fluxes with energies of more than 2 MeV in geostationary orbits, solar wind velocity, and geomagnetic activity. A three-parameter model is developed that allows the fluence of high-energy magnetospheric electrons for the next day to be predicted on the basis of the prehistory of the behavior of the fluence, data on the *Ap*-index of geomagnetic activity, and measurements of the solar wind speed. Model calculations are in good agreement with experimental data with a high coefficient of correlation (0.82) for the period 1987–2021.

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INTRODUCTION

Studies of the correlation between relativistic electron fluxes in the radiation belt and different parameters of the interplanetary medium began long ago by considering correlations between electron fluxes of different energies exceeding 0.7, 1.55, and 3.9 MeV, the solar wind speed (*Vsw*), interplanetary magnetic field, and other interplanetary parameters. A correlation was found between the electron fluxes of the radiation belt and *Vsw*. The dependence of the electron flux on the velocity of the solar wind and the state of the interplanetary field was also considered in [2–5]. However, experimental data for the period 1989–2010 showed that the relationship between the electron flow and *Vsw* is much more complicated than was thought. Instead of an approximately linear correlation between *Vsw* and the logarithm of the electron flux, the authors of [6] presented a distribution in the form of a triangle in which electron fluxes with energies of 1.8–3.5 MeV averaged over one day had a clearly defined lower limit that depended linearly on *Vsw* and was virtually independent of the *Vsw* upper limit. Although *Vsw* is related to the electron flux in a complicated way, it is still a key parameter for predicting the strength of the electron flux.

The complexity of the physical processes in the interaction between the solar wind and the magnetosphere, which accelerates electrons and fills the radiation belts with them, results in a multifactorial dependence of the relativistic electron fluxes on the state of the interplanetary medium and magnetosphere. Fluxes of high-energy electrons change when the magnetosphere interacts with high-speed solar wind streams, producing magnetic storms [7–11]. However, not all magnetic storms increase the electron flux in the outer radiation belt. Electron fluxes are often reduced during and after magnetic storms them [12]. The dependence of the flux of high-energy electrons on disturbances in the magnetosphere is not clear and requires further study.

In this work, we focus only on correlations between daily electron fluences and near-Earth and interplanetary outer space parameters with different delays.

DATA SET

The diurnal fluence (total flux per day) of relativistic magnetospheric electrons with energies above 2 MeV was chosen to characterize the behavior of electrons of magnetospheric origin in geostationary orbits. Information on high-energy electrons and character-

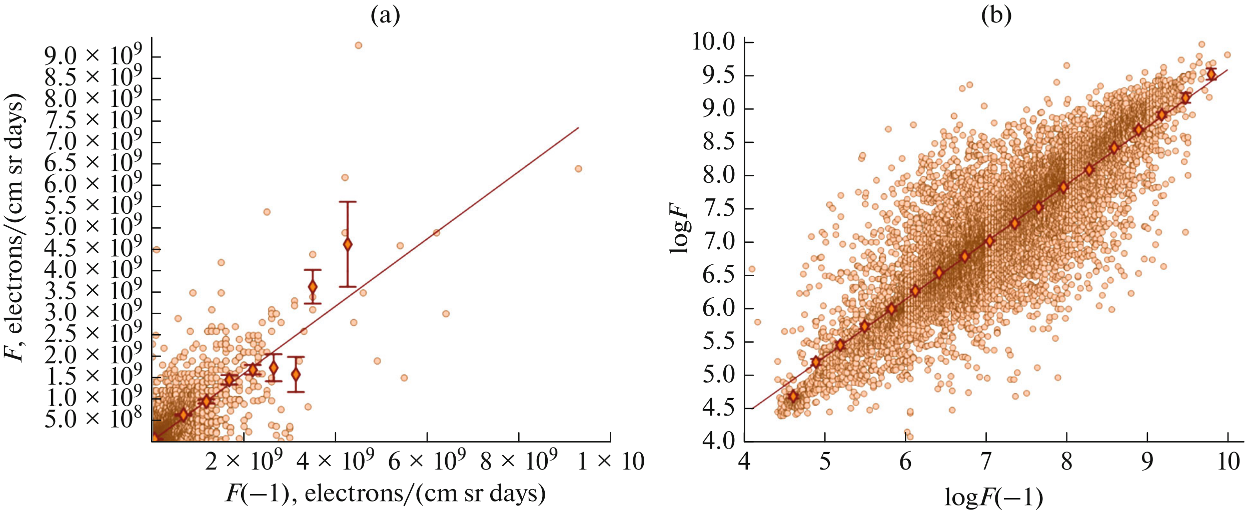

Fig. 1. Correlation between daily fluence $F(0)$ of high-energy electrons (>2 MeV) and the previous day's fluence $F(-1)$: (a) linear regression (straight line), (b) power representation.

istics of solar and interplanetary (geomagnetic) activity (SGA) is collected in the database created and maintained at the Pushkov Institute. This database contains information about the diurnal electron fluences measured by spacecraft of the GOES series (ftp://ftp.swpc.noaa.gov/pub/lists/particle/) for the period 1986–2021; solar wind parameters from the OMNI database [ftp://spdf.gsfc.nasa.gov/pub/data/omni/high_res_omni]; and geomagnetic activity in the form of indices *Kp* [ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap/wdc], *Dst* [http://wdc.kugi.kyoto-u.ac.jp], and *Ap* [ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap/wdc]. The SGA database is updated daily.

CORRELATION BETWEEN VARIATIONS IN THE DAILY ELECTRON FLUENCE WITH INTERPLANETARY AND GEOMAGNETIC CHARACTERISTICS

To study the relationship between variations in the diurnal electron fluence and interplanetary and geophysical characteristics, we used different daily parameters averaged over the period of observations of high-energy electrons (>2 MeV) on the GOES satellites (June 1987–2021).

Correlation of the Electron Fluence and Those of Earlier Days

There are sharp changes from day to day in the fluence behavior of high-energy (>2 MeV) electrons, but its considerable inertia is evident. It is assumed there is a strong statistical relationship between the current value of $F(0)$ and the fluence values $F(-1)$, $F(-2)$ observed on earlier days.

Figure 1 shows the relationship between fluences $F(0)$ and $F(-1)$ for neighboring days is quite close (coefficient of correlation $K_F = 0.79$, Fig. 1a). If we compare fluence $F(0)$ to $F(-2)$, the relationship becomes weaker (coefficient of correlation $K_F = 0.55$) but remains quite clear. The strongest coefficient of correlation $K_F = 0.86$ is observed for a power representation (Fig. 1b).

There is also a positive relationship (coefficient of correlation 0.79) between $F(0)$ and F_R, being the average daily electron fluence for the last solar evolution (the last 27 days).

An obvious quasi–27 day repeatability is observed in addition to the inertia of the electron fluence, so there is a correlation between today's fluence and the one measured 27 days ago. Considering the shifts in solar structures (especially coronal holes) rotating together with the Sun, it is better to average the fluence for 26–28 days from today. Obtained index F_{27} thus correlates with $F(0)$ with a coefficient of 0.39. We recall that the coefficient of correlation of the daily fluence of electrons to that of the previous day was 0.79, testifying to the inertia of high-energy electron flows.

All of the above indices associated with the prehistory of the electron fluence dynamics ($F(-1)$, $F(-2)$, F_R, F_{27}) thus correlate positively with the current value of the daily fluence and can be used to create predictive models.

Correlation with Indices of Geomagnetic Activity

High-energy electrons behave in a complex manner during geomagnetic disturbances, and their flux

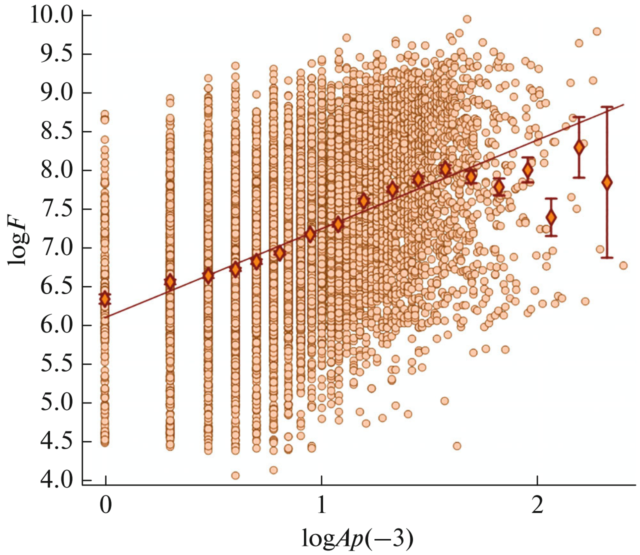

Fig. 2. Correlation between the electron fluence and the Ap-index of geomagnetic activity on day −3.

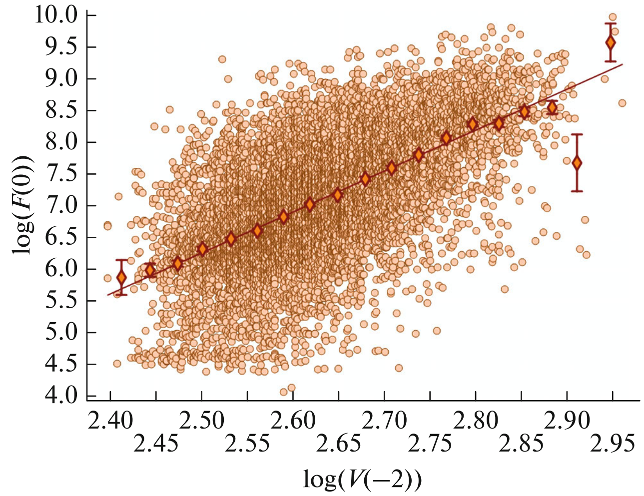

Fig. 3. Correlation between the diurnal electron fluence and the solar wind speed with a shift of 2 days in a power representation.

can vary by several orders of magnitude both up and down [13, 14]. It is therefore difficult to expect a close correlation between the electron fluence and geomagnetic indices. The coefficient of correlation between fluence $F(0)$ and $Ap(0)$ index of geomagnetic activity on the same day is close to zero: $K_{Ap} = 0.03$. However, the correlation grows if we use the Ap-indices of previous days. The coefficient of correlation between fluence $F(0)$ and $Ap(-1)$ is $K_{Ap} = 0.17$. The coefficient of correlation between fluence $F(0)$ and $Ap(-2)$ of two days earlier is $K_{Ap} = 0.3$. Between $F(0)$ and $Ap(-3)$, respectively, $K_{Ap} = 0.32$. Such a correlation should be useful in predicting the electron fluence. The correlation dips slightly upon a shift of a day more, and the coefficient of correlation between $F(0)$ and $Ap(-4)$ becomes $K_{Ap} = 0.29$.

Even better results are obtained from a nonlinear correlation with a power function. The coefficient of correlation between the logarithm of Ap on day (−3) and the electron fluence logarithm is 0.43 (Fig. 2). The strongest coefficient of correlation is observed with the Ap-index measured 3 days earlier.

Table 1. Coefficients of correlation between the daily electron fluence and different parameters

Parameter	0 day	−1 day	−2 day	−3 day	−4 day
Electron fluence	—	0.79	0.55	—	—
Ap-index	0.03	0.17	0.30	0.32	0.29
Solar wind speed	0.24	0.37	0.43	0.38	—

Correlation with Solar Wind Speed

Out of all characteristics of the interplanetary medium, the closest correlation with the solar wind velocity was found for the fluence of high-energy magnetospheric electrons.

We calculated the linear regression characteristics for the electron fluence's correlation with the solar wind speed upon a shift from zero to three days. The corresponding coefficients of correlation are shown in Table 1 along with the results discussed above. There is a significant correlation for all shifts, and it is strongest for the solar wind velocity upon a shift by two days.

Even better results are obtained from a nonlinear correlation with a power function (Fig. 3), where the coefficient of correlation between the logarithm of Vsw on day (−2) and the fluence logarithm is 0.60. Since Vsw changes within relatively narrow limits and the fluence changes by several orders of magnitude, the dependence is very strong: $F \propto V^{6.51 \pm 0.08}$.

A close correlation between the electron flow fluence and that of the previous day is expected, due to the high inertia of observations of electron flows. A calm day with a weak electron flux is almost always followed by a similar quiet day. If the electron flux lasts long enough, the probability of a strong fluence the next day is quite high. The correlation between the solar wind speed and the Ap-index may seem weak and unconvincing. Due to the long period of the study, however, the error in the coefficients of correlation is minor, so there is no doubt about their predictive importance.

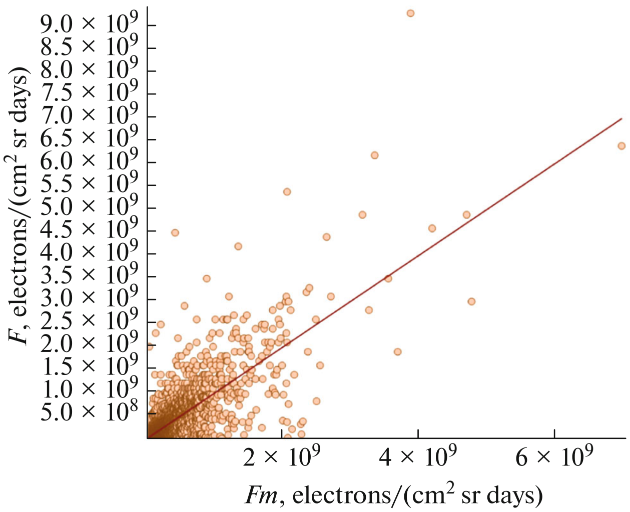

Fig. 4. Correlation between the measured daily fluence of high-energy electrons (>2 MeV) and the fluence calculated using the three-parameter model. The line is the linear regression.

Based on our analysis, we concluded that in order to create an effective predictive model for the fluence of high-energy magnetospheric electrons, it is best to combine indices associated with the prehistory of a fluence and others that include the solar wind speed and the level of geomagnetic activity.

The combination of such indices is useful for creating a multiparameter model of the diurnal fluence of high-energy magnetospheric electrons using formula (1), where

$$F_M = a + bF + cV + dAp. \quad (1)$$

Modeling the diurnal fluence of high-energy magnetospheric electrons (>2 MeV) with three different indices yielded the best results with coefficient of correlation $K_N = 0.82$, using the previous day's fluence $F(-1)$, the previous day's solar wind velocity $V(-1)$, and geomagnetic activity index $Ap(-2)$ from two days earlier (Fig. 4).

For the chosen parameters and statistical errors of regression coefficients, we obtained

$$\begin{aligned} F_M &= (-1.29 \pm 0.11) \times 10^8 \\ &+ (0.882 \pm 0.010) F(-1) \\ &+ (1.62 \pm 0.21) \times 10^6 V(-1) \\ &+ (3.65 \pm 0.38) \times 10^5 Ap(-2). \end{aligned}$$

CONCLUSIONS

The calculated coefficients of correlation between the fluence of high-energy magnetospheric electrons with energies more than 2 MeV, the solar wind speed, and the *Ap*-index of geomagnetic activity for the period 1988–2021 showed that the fluence of high-energy magnetospheric electrons was barely related to the level of geomagnetic activity on the same day, but it did correlate with geomagnetic activity index *Ap* observed 2–4 days earlier with coefficients of correlation of 0.30, 0.32, and 0.29, respectively. The correlation between the logarithms of the electron fluence and the *Ap*-index grew to 0.44. The electron fluence correlates quite closely with the solar wind speed, especially with the speed measured two days earlier (with a coefficient of correlation of 0.43). The correlation between the logarithms of electron fluence and the solar wind speed is 0.60. This indicates a strong relationship between the electron fluence and the solar wind velocity because the latter varies within rather narrow limits while the electron fluence varies by several orders of magnitude.

Based on the obtained dependences between the fluence of high-energy electrons and the parameters of the near-Earth and interplanetary medium, we developed a three-parameter model that allows us to predict the daily fluence of high-energy magnetospheric electrons. The model is based on the prehistory of the fluence behavior, data on the *Ap*-index of geomagnetic activity, and the solar wind speed measurements. The model shows good agreement with experimental data with a coefficient of correlation of 0.82 for the entire period 1987–2021.

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CONFLICT OF INTEREST

The authors declare they have no conflicts of interest.

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