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The Dynamics of Relativistic Electron Fluxes in the Near-Earth Space in 2001–2005

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Abstract—This paper presents data on relativistic electron fluxes (1.5–3 MeV) measured at altitudes of 360–500 km onboard the CORONAS-F satellite. The monthly average fluxes of these particles in the Earth's outer radiation belt are shown to greatly increase from August 2001 to September 2003. The monthly average fluxes of relativistic electrons in the Earth's outer radiation belt in the period from August 2001 to July 2004 are also found to be strongly correlated with the monthly average velocities of the solar wind and values of the Kp-index, with this correlation breaking down after July 2004. This paper discusses the possible reasons for the discovered patterns.

Key words: electrons, Earth's radiation belt, solar wind.

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INTRODUCTION

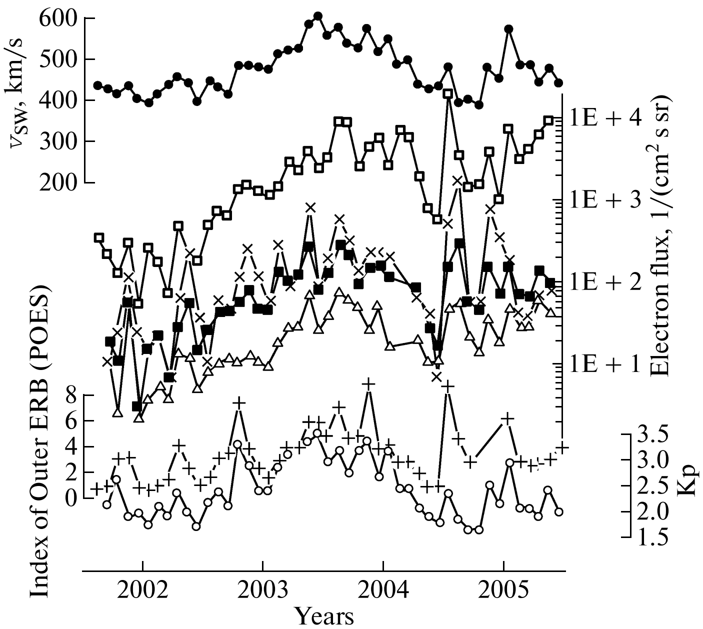
Although variations of electron fluxes in the Earth's outer radiation belt (outer ERB) have been investigated practically since the discovery of the outer belt, the problem of monitoring the relativistic electron fluxes in the outer ERB and finding the causes of the variations is still relevant. The reason is that no conventional theory for the electron acceleration to relativistic energies in the Earth's magnetosphere has so far been proposed that would provide a fairly complete description of their experimentally discovered variations. It is also important to investigate the variations in the relativistic electron fluxes from the practical standpoint, since relativistic electrons, among other factors, might cause volume ionization of microcircuits in the devices used onboard spacecraft, which may cause serious malfunctions or even the loss of spacecraft.

As described above, experimental research on the variations of electron fluxes in the outer ERB, both in Russia and abroad, has been performed by various research teams (see [1–5] and the references in these works). These studies convincingly demonstrate that there is a connection between the variations in the relativistic electron fluxes and solar wind parameters, in particular, its velocity. In [3] based on the data obtained during an experiment onboard the SAMPEX satellite (the orbit altitude was 600 km and its inclination was 82°) shows that there is a correlation between the relativistic electron fluxes in the outer ERB and the solar wind velocity (the correlation coefficient is ~0.4) with a 2-day time lag in $L = 10$ and a 4-day time lag in $L = 6.6$. Based on the analysis in [6], the conclusion was made that solar wind electrons cannot be regarded as the main source of relativistic electrons in ERB. A detailed description of the dynamics of electron fluxes in ERB with energies 0.3–3 MeV at altitudes 400–500 km during the strongest magnetic storms of 2001–2005 is given in [7–9]. The Earth's magnetosphere is also known to be strongly affected by high-velocity solar winds, both quasi-stationary and sporadic. The source of the quasi-stationary flows causing recurrent geomagnetic disturbances of medium and weak intensity in the coronal holes on the Sun; the sporadic high-velocity flows are now commonly associated with coronal mass expulsions and solar flares. The geoefficiency of the solar wind, i.e., the efficiency of the solar wind energy transfer to the Earth's magnetosphere, is also dependent on the orientation of the interplanetary magnetic field: the geoefficiency is maximal in the case of the negative, or southern, orientation and at high values of B_z.

This paper focuses not on individual events but on the large-scale dynamics of relativistic electron fluxes at low altitudes and its connection with changes in the solar wind. Earlier, we studied this question using the data measured during the first half-year period of CORONAS-F's flight [10].

MATERIALS AND METHODS

Since the Russian CORONAS-F solar observatory had a polar circular orbit (the initial altitude was 500 km and the inclination was 82.5°), the onboard devices used to register charged particles enabled one to perform long-term monitoring of their fluxes over the entire period of their operation, i.e., from August 2001 to June 2005. Using the cosmic ray mon-



Variation of the monthly average electron fluxes in the outer ERB, solar wind velocity and Kp-index from August 2001 to June 2005.

itor onboard CORONAS-F, one measured the fluxes and spectra of protons with energies of 1–90 MeV and electrons with energies of 0.3–12 MeV [11]. Electrons with energies from 300 KeV to 12 MeV were measured using a semi-conductor telescope consisting of two semi-conductor detectors 0.05 mm and 2.0 mm thick and a crystal of CsI 1.0 cm thick enveloped in a plastic scintillator 0.5 cm thick working in the anticoincidence mode. The electrons were registered in five energy ranges: 0.3–0.6, 0.6–1.5, 1.5–3.0, 3–6, and 6–12 MeV. The telescope's aperture was ~23°; the device was oriented in the antisolar direction. During the analyzed period the altitude of the orbit of the CORONAS-F satellite went from 500 to 370 km.

EXPERIMENTAL DATA ANALYSIS

During analysis of the variations of relativistic electron fluxes from 2001 to 2005 on the CORONAS-F satellite, the monthly average fluxes of relativistic electrons measured in L-from 3 to 6 and had a circular polar orbit; in the period from September 2001 to September 2003 these were found to have grown by more than an order of magnitude. A similar growth of the relativistic electron fluxes was also observed in the geostationary orbit in the experiment with the GOES-10 satellite. The figure shows the monthly average fluxes of relativistic electrons with energies from 1.5 to 3 MeV in the South hemisphere from August 2001 to June 2005 for three intervals of the L-shells (L = 3–4, sidelong crosses, L = 4–5, black squares, and L = 5–6, open triangles). The figure also shows variations in the fluxes of relativistic electrons with energies >2 MeV in the geostationary orbit (empty squares), variations in the index of the outer ERB (straight crosses) from the data of the low-altitude polar POES satellite, and variations of the solar wind velocity (black squares) from the data of the ACE satellite and the Kp-index (open circles) [12].

The figure shows that the variations in the relativistic electron fluxes measured at low altitudes onboard CORONAS-F in different L-shells are rather similar to one another and are well correlated with the data, both on the variations of the relativistic electron fluxes in the geostationary orbit and the variations of the outer ERB index from the POES data. In their turn, the variations of the relativistic electron fluxes according to the data from all the three satellites are correlated with the solar wind velocity and the Kp-index up to the end of July 2004, with this correlation breaking down in the period that followed.

The correlation coefficients of the relativistic electron fluxes measured in different experiments, as well as those with the velocity and density of the solar wind, Kp-index and the index of the outer ERB over the entire period under study (from August 2001 to June 2005) are given in Table 1. This table shows that the correlation coefficients of the relativistic electron fluxes with the solar wind parameters and the Kp-index are rather high for both the polar and geostationary orbits.

DISCUSSION

It is clearly seen from the figure that there was a marked growth in the average velocity of the solar wind

Table 1. The correlation coefficients of the relativistic electron fluxes measured in different experiments as well as with the velocity v_{sw} and density d_{sw} of the solar wind, Kp-index, and the index of the outer ERB over the whole period under study (from August 2001 to June 2005)

	e 1.5–3.0 MeV $L = 3–4$	e 1.5–3.0 MeV $L = 4–5$	e 1.5–3.0 MeV $L = 5–6$	e (GOES) > 2 MeV
e (GOES) > 2 MeV	0.66	0.9	0.82	1.00
POES index	0.72	0.71	0.64	0.71
v_{sw}	0.73	0.81	0.76	0.84
d_{sw}	–0.55	–0.8	–0.8	–0.82
Kp	0.7	0.72	0.6	0.75

Table 2. The correlation coefficients of the relativistic electron fluxes from the data collected onboard CORONAS-F and GOES-10 with the velocity v_{sw} and density d_{sw} of the solar wind and the Kp-index in different time periods

	Sept., 2001–June, 2002	Jule, 2002–June, 2003	Jule, 2002–June, 2004	Jule, 2004–June, 2005
	v_{sw}/d_{sw}/Kp			
1.5–3.0 MeV, $L = 3–4$	0.33/–0.45/0.00	0.58/–0.53/0.63	**0.84**/–0.12/**0.82**	0.04/–0.02/0.28
1.5–3.0 MeV, $L = 4–5$	0.4/**–0.87**/0.02	**0.76/–0.73/0.76**	**0.83**/–0.30/**0.77**	0.19/–0.21/0.39
1.5–3.0 MeV, $L = 5–6$	0.56/**–0.71**/0.08	**0.82/–0.82/0.75**	**0.72**/–0.32/0.62	0.35/–0.45/0.41
(GOES) > 2 MeV	0.33/**–0.87**/0.10	**0.88/–0.85/0.88**	**0.82**/–0.43/**0.73**	0.52/–0.68/0.55

in the period 2001–2003 according to the ACE measurements. In the same period an increase in the relativistic electron fluxes measured in different experiments also occurred. This fact is not surprising, since it is well known that arrival of high-velocity solar wind, as a rule, causes disturbances in the Earth's magnetosphere (which is reflected by the growth of the Kp-index). After the arrival of the high-velocity solar wind, one can observe an increase in the electron fluxes, both at low altitudes and in the geostationary orbit (e.g., [3, 4]). At same time, it is noteworthy that after the series of storms in July 2004 the above correlation of the electron fluxes with the solar wind velocity and the level of geomagnetic disturbances broke down and was not restored until at least May 2005. Table 2 presents the correlation coefficients of the relativistic electron fluxes from the CORONAS-F data at low altitudes and from the GOES-10 data in the geostationary orbit with the velocity v_{sw} and density d_{sw} of the solar wind, as well as the Kp-index for four consecutive approximately equal time periods during the time interval under study. The correlation coefficients greater than 0.7 are displayed in bold type. It is clearly seen from Table 2 that a high correlation with both the velocity and density of the solar wind was observed from the middle of 2002 to the middle of 2004. In the last year of observations (from July 2004 to June 2005), the correlation of the electron fluxes with the solar wind velocity fell sharply, especially in the near-Earth L-shells.

This observed fact may be related to the sectoral structure of the interplanetary magnetic field and solar wind flows. The interplanetary magnetic field is well known to have a sectoral structure with fields of positive and negative polarity that alternate in a cycle that is almost identical to the period of solar revolution [13]. During the decline phase of the 23rd cycle, approximately from the middle of 2002 to the middle of 2004, there was a stable two-sector structure of the interplanetary magnetic field. For each sector of the interplanetary magnetic field a recurrent high-velocity solar wind connected with vast coronal holes passing across the solar disc occurred. During one revolution of the Sun, large coronal holes appeared twice on its central meridian. These coronal holes had opposite magnetic polarities that were consistent with the geometry of an oblique magnetic dipole relative to the Sun's rotational axis at that time. One of the coronal holes was bigger than the other, which caused the dominance of one of the high-velocity solar winds over the other [14]. Thus, in 2003, the maximum velocity of one solar wind was on average 750 ± 40 km/s and the other had a velocity of 600 ± 45 km/s. The two-sector structure of the interplanetary magnetic field and large-scale structures on the Sun practically did not change until the middle of 2004. It has been pointed out [15] that since May 2004 there was a slow restructuring of the two-sector structure of the interplanetary magnetic field into a four-sector field. This restructuring of the sectoral structure was in process during June–October 2004. During and after the restructuring, in July and November 2004, several powerful eruptive events (July 28, 2004 and November 7–8, 2004) were observed, which caused strong geomagnetic storms on the Earth. From October 2004, a stable four-sector structure of the interplanetary magnetic field with three corresponding high-velocity solar winds was observed. This structure existed until September–October 2005 [16].

Thus, a high correlation between the relativistic electron fluxes with the velocity and density of the solar wind was observed in the period of the two-sector structure of the interplanetary magnetic field that was related to two high-velocity solar winds, whose source was the low-latitude coronal holes. The period when the correlation of the electron fluxes with the solar wind velocity fell sharply lies within the period when the two-sector structure of the interplanetary magnetic field was changing into a four-sector one (June 2004–September 2005).

CONCLUSIONS

Based on the research presented in this paper, we can make the following conclusions:

1. The data collected onboard CORONAS-F at altitudes of 400–500 km in the period from August 2001 to September 2003 show the significant growth of relativistic electron fluxes in the Earth's outer radiation belt.

2. The monthly average fluxes of relativistic electrons, both at low altitudes in L from 3 to 6 and in the geostationary orbit in the period from August 2001 to July 2004, are well correlated with the solar wind velocity and the level of geomagnetic activity (Kp-index).

3. In the middle of 2004 (after the July storms) the above correlation with the solar wind velocity broke down and was not restored until at least the middle of 2005.

4. A high correlation of the relativistic electron fluxes with the velocity and density of the solar wind, as well as the index of geomagnetic activity (Kp-index), was observed when the interplanetary magnetic field had a two-sector structure engendering two quasi-stationary high-velocity solar wind flows. The source of the high-velocity solar winds was vast long-term low-latitude coronal holes of different polarities. The decline in the correlation between the relativistic electron fluxes and the solar wind velocity corresponds to the period of the restructuring of the interplanetary magnetic field from a two-sector to a four-sector structure.

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