High-energy charged particle flux dynamics in the near-Earth space caused by solar-magnetospheric and geophysical phenomena


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Abstract: The results of the observation of short-term and long-term variations of high-energy charged particle fluxes in the near-Earth space in satellite experiments ARINA and VSPLESK are presented. Scintillation spectrometers ARINA (on board the Resurs-DK1 Russian satellite since 2006) and VSPLESK (on board the International Space Station since 2008) provide continuous measurements of particle fluxes in low orbits, detect and identify electrons and protons with energies in 3-30 and 30-100 MeV ranges correspondingly, and give the possibility to study energy spectra, pitch-angle distributions and time profiles of particle fluxes. High statistics of particles, accumulated during several years (2006-2012), allowed to make the detail analysis various species of particle flux variations. Solar-magnetospheric, geomagnetic and geophysical effects, observed in high-energy charged particle fluxes in the near-Earth space, are considered.

Keywords: near-Earth space, radiation belt, electron precipitation, particle flux variations, particle bursts.

1 Introduction

The ARINA and VSPLESK satellite experiments are designed for radiation monitoring the near-Earth space with the aim to study the physics origin of high-energy charged particle variations and bursts (sharp short-term increases in particle fluxes). The stationary radiation conditions in the near-Earth space are formed by the superposition of galactic cosmic rays, atmospheric albedo particle fluxes, and charged particles trapped by the geomagnetic field (radiation belt). Currently, of great interest are studies of the changes in radiation conditions in the near-Earth below the radiation belt region, which appear as variations and bursts of charged particle fluxes in a wide energy range. High-energy charged particle bursts were first discovered in 1985 in the MARI A experiment performed by the MEPhI on board the Salyut-7 orbital station [1]. Later, extensive experimental and theoretical studies in this field were fulfilled. The interrelation between electron bursts and various solar-magnetospheric and geophysical (seismic, thunderstorm, etc.) processes was established (see [2]-[11] and references therein). Among the most important experiments are: MARI A, MARIA-2 [3]-[5], and SAMPEX/PET [6]-[9] at high energies (5-50 MeV); Demeter (0.3-5 MeV) [10] and POES (0.3-2.5 MeV) [11] at low energies. These studies showed that the formation mechanism of high-energy charged particle bursts (observations are mostly related to electrons with energies on the order of several tens of MeV) is associated with local disturbances of the radiation belt and is as follows [2]-[3]. High-energy electrons trapped by geomagnetic field interact with low-frequency electromagnetic emission (EME), generated in various geophysical and magnetospheric processes, which result in pitch-angle diffusion of particles and lowering their mirror points. As a result, particles precipitate from the radiation belt to altitudes below its boundary. Precipitated particles, if their mirror points are not too deep in the residual atmosphere (above 60-80 km), drift around the Earth and form a wave of precipitated particles (referred to as the GKV wave), propagating along the L-shell containing an local disturbance region. The time of the complete longitudinal revolution of high-energy particles around the Earth is from several tens of seconds to several minutes. Therefore, for same time, the L-shell is completely filled with precipitated particles. When a spacecraft crosses such a disturbed L-shell, instruments register a particle burst which, obviously, can be observed at any longitude not necessarily coinciding with the longitude of the local disturbance region. As well as particle burst can be formed in the magnetically-coupled zone corresponding to this region. Thus, the near-Earth space region, in which particle bursts caused by radiation belt local disturbances can be observed, significantly broadens and the probability of their detection in spacecraft measurements increases. In [2]-[3], it was shown that geographical coordinates of the radiation belt local disturbance region, i.e., the position of the region over which particle precipitation occurred (e.g., over the earthquake, thunderstorm activity zone, etc.), can be determined by measuring particle burst characteristics (the detection place, energy spectrum evolution, and time profiles). Also it should be noted that for identification of particle bursts the knowledge of particle flux background with high accuracy is necessary. Background flux in the near-Earth space have mainly an albedo origin and undergo long-term variation caused by changing the geomagnetic field, 11-year solar activity cycle, solar flares and magnetospheric storms. Some results of observation of background flux changing as spatial as temporal are considered below (chapters 3.1. and 3.2). Detail analysis of background gives the possibility to extract additional particle bursts and to increase statistics of observed particle bursts. New results concerning correlation between particle bursts and lighting activity, are presented in chapter 3.3.

2 Instruments

The ARINA and VSPLESK scintillation spectrometers developed by the MEPhI are fully the same in physics schemes,
have identical physical parameters (geometrical factor, energy range, energy resolution, and others), detect and identify electrons (3-30 MeV) and protons (30-100 MeV), measure particle energies, and allow the study of energy spectra and time profiles of particle fluxes. The instrument acceptance is about 10 cm²sr. This value is several tens of times higher than the acceptance of the instrument used earlier in which the main results on observations of bursts in particle fluxes were obtained [7][9]. The physics scheme and performances of the instrument are described in detail in [15].

The ARINA and VSPLESK experiments are carried out on board the low-orbit spacecrafts. The ARINA instrument is installed in a hermetic container of the Resurs-DK1 satellite with an altitude of 350-600 km and an orbit inclination of 70°, the experiment is executed since the July, 2006 [12]. The VSPLESK instrument is installed outside the sealed volume on the International Space Station (altitude is 350-400 km, an orbit inclination is 51°, measurements are carried out since August, 2008) [14].

3 Experimental results
High statistics of particles, accumulated during several years (2006-2012) in ARINA and VSPLESK experiments, allowed to make the detail map of particle fluxes in the near-Earth space. For that a 4-th dimensional space (L-B coordinates, longitude and pitch-angle) was used. Additionally time (date) of observation was used as a fifth coordinate for taking into account the dependence of particle fluxes on phase of 11-year solar cycle and changing the global geomagnetic field. Such a detail approach allows to study various species of particle flux variations. Among them are about one thousand bursts of particles with duration about several seconds, caused by local disturbances of the radiation belt and particle precipitation from it, several-hour (day) variations, interrelated with solar flares and geomagnetic storms, year changes, induced by global drift of geomagnetic field. Some results of the study, concerning the L shell distribution of particle bursts, redistribution of particle fluxes in L shells and filling outer zones of magnetosphere (L>3) by high-energy electrons during the solar-magnetospheric events, and SAA region drift are considered below.

3.1 SAA region drift
A geographical distribution of particle fluxes has been studied on the ARINA and VSPLESK data.

It is known that there is a movement of global geomagnetic field, leading to drift SAA region. This effect is visible in particle flux in this region. In earlier works (for example, [17]) drift of South Atlantic Anomaly (SAA) region was determined as spatial changing the position of maximum of particle flux, registered in the SAA region. Such an approach gives the mean estimation of SAA drift, averaged on all L-shells composing the SAA region. On the data of various satellite experiments it was obtained the value for the mean value of drift about 0.41°±0.08° longitude/year in west direction.

In our work with the ARINA and VSPLESK data another more detail study was fulfilled. The study is based on the analysis of temporal changing the position of proton (30-100 MeV) flux maximum for each separate L-shell. We divided the SAA space (L=1.15-2.2) by separate zones with 0.05 step value. The example of the obtained results is presented in Figure 1 for L=1.55-1.60. One can see the obvious drift of position of particle flux maximum. The speed of the drift is about 0.50°±0.03° longitude/year in west direction. Analysis showed that speeds of the particle maximum drift for various L-shells are slightly different. The value of the obtained speed is in accordance with drift of global magnetic field of the Earth.

![Figure 1: Longitudinal drift of position of particle flux maximum at L=1.55-1.60 in SAA region.](image1)

3.2 Redistribution of high-energy electrons in L-shells in the disturbed magnetosphere

![Figure 2: L-distributions of 3-5 MeV electrons in the near-Earth space](image2)

Series of powerful solar flares in the March, 2012 and CME gave rise to strong disturbance of the magnetosphere of the Earth (Dst ~ -100 nT). The results of observation of L-distribution of electron flux (3-5 MeV) by ARINA and VSPLESK instruments are shown in Figure 2. New additional unstable radiation belt was generated in March.
It was observed that this belt existed during 2-3 weeks and disappeared in the beginning of April, 2012. It should be marked that such a phenomenon has been sometimes observed in the outer zone (L>3) of the magnetosphere after powerful solar-magnetosphere events.

3.3 Interrelation between particle precipitation from the radiation belt and geophysical phenomena

High statistics accumulated in ARINA, and VSPLESK experiments allowed to carry out new analysis of the particle bursts. Bursts of electrons with energies in the range 3-30 MeV at the level of 4.5 standard deviations and with duration from several seconds to several minutes were selected for processing and analysis in those experiments. At that L-shells of position of particle bursts detection in the range 1.12 - 2.2 were taken in the analysis. That is, it was chosen zone of the near-Earth space where the particles, precipitated from the inner radiation belt, could be registered. To exclude from the processing the region of the radiation belt the measurements with geomagnetic induction $B > B_0$ were selected ($B_0$ is the atmospheric boundary of the radiation belt, $B_0$ was calculated in the framework of the IGRF geomagnetic field model and MSISE residual atmosphere model).

It was identified about one thousand of bursts of electrons with energies in the range 3-30 MeV. Many experimental executed works (see Introduction), including ARINA and VSPLESK, shows interrelation between some part of particle bursts and seismic events. In [18] radiation belt local disturbances of lightning and seismic origin were analyzed. It was shown in this work that the large part of high-energy particle bursts interrelates with seismic events and thunderstorm activity. At that about 20% of particle bursts have a seismic origin.

Also in those works it has been noted several other magnetospheric and geophysical phenomena as a burst appearance reason. As for lightning, which can give rise to formation of particle bursts, that the chain of physical processes are the same with seismic one.

For time analysis of events the power lightning flashes were selected in the time interval ± 3 hours around the time of observation of particle burst. The time difference ($\Delta T$) between time of occurrence of lightning flash and time of observation of particle burst was calculated for every lightning flash in this temporal range. And histogram of $\Delta T$ was built.

We applied this procedure for all observed particle bursts. After such processing the summary histogram of $\Delta T$ was plotted. As an additional cut parameters we used the difference between L coordinates of lightning flash and particle burst ($\Delta L$) and coincidence of bursts and lightning longitudes with accuracy ±5°.

Using $\Delta L$ cut we could take into account only lightning flashes, which locate closely to the particle burst in L-space (used $\Delta L$ value was <0.05). It should be underlined that this cut is in correspondence with the physical model of the phenomenon, described above in Introduction. The $\Delta T$ histogram, obtained with using experimental data of ARINA and VSPLESK, is shown in Figure 5. One can see that there
is an obvious peak at $\Delta T=0$, that means the coincidence of appearance times of burst and lightning.

It should be noted that various checks and testing were fulfilled, in particular the uniform $\Delta T$ distribution was obtained if dates of bursts and lightning flashes were randomly mixed.

4 Conclusion

Analysis of the ARINA and VSPLESK experimental data, presented in this work, showed the drift of SAA region in 2006-2012 years in west direction with speed about $0.50^\circ \pm 0.03^\circ$ longitude/year. During solar-magnetospheric disturbances in the March 2012 ARINA and VSPLESK observed the formation of new additional unstable belt of 3-5 MeV electrons in outer zone of the magnetosphere ($L>3$). High statistics of bursts of high-energy electrons, accumulated in ARINA and VSPLESK experiments during several years allowed to appear the direct interrelation between bursts of electrons with energies 3-30 of MeV and lightning events.

References