Abstract. The paper discusses the outer electron belt dynamics, adiabatic and nonadiabatic mechanisms of increases and losses of energetic electrons.

Under undisturbed conditions, the outer electron belt gradually empties: in the inner magnetosphere due to electron losses in the atmosphere and in the quasi-trapping region due to losses at the magnetopause because drift shells of electrons are not closed there. The latter process does not occur in normal years due to the masking replenishment by freshly accelerated particles, but in years of extremely low activity it leads to a significant decrease in the electron population of the belt.

During the magnetic storm main phase, the first reason for the decrease in the electron flux intensity is the adiabatic cooling associated with conservation of adiabatic invariants and complemented by injection of electrons into the atmosphere and their losses at the magnetopause. Electron flux increases involve $E \times B$ electron injection by the induction electric field of substorm activation and by the large-scale solar wind electric field, with pitch energy diffusion along with adiabatic heating in the recovery phase.

The rate of electron flux recovery after a storm is determined by the ratio of nonadiabatic increases and losses; hence the electron flux represents a continuous series from low to very high values. The combination of these processes determines the individual character of radiation belt development during each magnetic storm and the behavior of the belt in the quiet time.

Keywords: magnetosphere, electrons, radiation belt, replenishment and losses.

INTRODUCTION

Existing reviews on radiation belts (RB) [Parks, Winkler 1968; Vernov et al., 1969; Friedel et al., 2002; Millan, Thorne, 2007; Shprits et al., 2008a] describe in sufficient detail both the structure of RB and its formation. According to the traditional theory [Tverskoy, 1964, 1965], the RB formation is attributed to the combination of slow radial diffusion of electrons driven by small magnetic field pulses with losses in the atmosphere due to pitch-angle diffusion. In principle, this explains the observed spatial structure of trapped electrons with a slot region between inner and outer radiation belts.

During magnetic storms, this pattern is disturbed; there occur dynamic variations, decreases, and increases in energetic electron fluxes. Fluxes of energetic “killer” electrons attract greater attention of researchers, there are works devoted to the prediction of their mean or maximum values [Li et al., 2001; Simms et al., 2016] (see also the review [Potapov, 2017]).

A large number of papers analyze the RB dynamics during magnetic storms [Baker et al., 1997; Li et al., 1997; Reeves et al., 1998; Yu et al., 2015; Hwang et al., 2015; Turner et al., 2017]; a lot of these studies have been carried out at SINP MSU [Vernov et al., 1965; Kuznetsov et al., 1966; Bakhareva, 2003; Ivanova et al., 2000; Kalegaev et al., 2015; Antonova, 2005; Lazutin, 2012; Kalegaev, Vlasova, 2014; Dmitriev et al., 2010, 2014; Slivka et al., 2006; Tverskaya et al., 2005; Vernov et al., 1969]. Accordingly, it seems appropriate to review current ideas about the RB dynamics. Note that the review is based largely on studies carried out at SINP MSU.

In the review, we first describe the RB dynamics during magnetic storms and then the mechanisms of replenishment and losses of energetic electrons; finally, we examine the behavior of RB in the quiet time. This paper is intended for use by readers familiar with the basic concepts: particle motion and adiabatic invariants, dynamics of fields and currents during magnetic storms, etc.

MAGNETIC STORMS

Figure 1 shows energetic electron and proton fluxes measured by the low-orbit satellite SERVIS from February 5 to February 25, 2004, in particular during the February 11, 2004 magnetic storm. Flux intensity dips are observed in all storms on all RB shells in a wide range of energies and for particles of different types. These dips are largely caused by a change in the structure of the magnetosphere when subject to the so-called...
Figure 1. Electron and proton fluxes measured by SERVIS-1 when it passes over the $L$ levels in the Northern Hemisphere on February 5–25, 2004. A magnetic storm with a minimum $Dst = –110$ nT occurred on February 11, 2004.

$Dst$ effect. This effect is necessarily present in the storm main phase, but there may be additional nonadiabatic losses, in particular precipitation of particles into the atmosphere. If there are no nonadiabatic processes (losses or accelerations), the RB configuration and particle fluxes should fully recover after a storm.

But often this does not happen. After a storm, the electron flux can return to the pre-storm level as well as exceed it or not recover completely. In the well-known paper [Reeves et al., 2003], storms are divided into these three types. In fact, this division is arbitrary (see Figure 3, a, c in [Reeves et al., 2003]). If we do not pay attention to the difference in the marks assigned by the author, after the storm there is a continuous series of electron flux intensities lower or higher than pre-storm ones. We think that this series is created by different ratios of particle flux losses and increases during the storm: if the losses exceed replenishment, the flux is not fully recovered, if they do not exceed replenishment, the flux after the storm is higher than the pre-storm one.

**ADIABATIC VARIATIONS**

**DAWN-DUSK ASYMMETRY**

When studying time variations in electron flux intensities during a storm, a false impression of disappearance of particles may be created when we, instead of the magnetic drift trajectory varying during the storm, use the $L$ coordinate of undisturbed level, which is usually given in a database of measurements from low-orbit satellites.

Our Figure 1 (as in many Figures from other papers) uses $L$ as an indicator of the normalized distance to the top of a field line, but it is improper to use the undisturbed level parameter $L$ to describe the particle dynamics during a magnetic storm. Let us illustrate this statement by a concrete example.

At the beginning of the storm main phase, the ring current asymmetry creates a situation where the electron flux on the dusk side decreases, while the dawn flux remains undisturbed (Figure 2). In [Lazutin, 2016], this effect has received a simple explanation: the drift shell in the attenuated dusk magnetic field is adiabatically displaced to lower latitudes. Since many Figures represent electron fluxes as a function of the $L$ coordinate calculated for the quiet magnetic activity level and not for the corresponding moments of the storm, we can consider the presented picture as a result of the displacement of the drift shell toward Earth.

Figure 2. Six consecutive electron profiles recorded by SERVIS-1 on the dawn and dusk sides in the 0.3 MeV channel during the main phase of the July 25, 2004 magnetic storm.
Other articles demonstrate the significance of pitch-angle diffusion in velocities for electron flux increases (Summers et al., 1998; Horne et al., 2005; Demekhov et al., 2006; Foster et al., 2017). Acceleration to energies of the order of 1 MeV occurs in RB with a maximum at \( L \approx 4-7 \). The condition for the effective increase in the electron flux is a high substorm activity, which produces freshly accelerated electrons with a 20–100 keV energy serving as the initial flux; and a high power of chorus is observed.

Relativistic electrons are accelerated due to parasitic diffusion by waves generated by less energetic electrons. Such two-stage acceleration is described, for example, in [Jaynes et al., 2015; Foster et al., 2017].

According to [Summers et al., 2004], the characteristic time of acceleration and losses is approximately the same and is about a day, but it varies greatly depending on parameters of a medium.

Exotic, but real process is the electron precipitation due to parasitic resonance with electromagnetic ion-cyclotron (EMIC) waves [Summers, Thorne, 2003; Lazutin et al., 2011; Ni et al., 2015; Kubota, Omura, 2017]. EMIC waves are generated by ring current protons during the storm main phase. Since the cyclotron frequency of protons is much lower than the cyclotron frequency of electrons, the interaction occurs as a result of Doppler frequency shift in the opposing wave and particle motion. In this case, the longitudinal electron velocity should be very high, and hence it causes precipitation of electrons only with an energy of several MeV.

### LOSSES AT THE MAGNETOPAUSE

Sufficiently convincing arguments for the mechanism of electron dropout at the magnetopause have been put forward in [Dmitriev, Chao, 2003; Shprits et al., 2006; Millan, Thorne, 2007; Kim et al., 2008; Saito et al., 2010; Matsumura et al., 2011; Turner et al., 2012; Hudson et al., 2014; Lazutin, 2016]. In the quasi-trapping region, drift shells are not closed; on the night side, electrons drift with adiabatic invariants remaining unchanged to the morning magnetosphere—magnetopause boundary; protons, to the evening boundary (and vice versa on the dayside); then they go from the closed field lines to the turbulent magnetosheath. This continuous outflow of electrons from RB increases during the storm main phase, when the \( Dst \) effect shifts drift shells of electrons from Earth [Reeves et al., 2003]. Moreover, magnetic storms often occur with sharp increases in solar wind plasma density and velocity, causing an abrupt shift of the magnetopause to Earth and an increase in losses of electrons from the outer magnetosphere [Dmitriev, Chao, 2003].

Due to the pitch-angle diffusion, a small part of electrons (a few percent) can return from the magnetosheath to drift orbits, as evidenced by the so-called drift echo effect [Vampola, Korth, 1992], but most of the particles go to the magnetotail [Daibog et al., 2015] and to interplanetary space.

As a result, the quasi-trapping region should quickly empty; however, as can be seen from measurements made at the geostationary orbit (see, for example, 53
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Electrons >0.6 & 2.0 MeV, 2009

Figure 4. Electron fluxes and magnetic activity indices (moderate disturbances): “sinusoidal” electron flux variations — manifestation of the day-night asymmetry of the magnetospheric magnetic field; 1 — an electron flux decrease during the storm main phase; 2 — electron losses at the magnetopause; 3 — an electron flux increase due to radial drift from the center of RB.

Figure 5. Earthward shift of the low-latitude slope of RB during the chain of magnetic storms in July 2004 and magnitude of the vertical component of the interplanetary magnetic field.

Figure 4), it does not empty due primarily to the oncoming acceleration; and in the absence thereof, due to the diffusion of particles from the region of radiation belt maximum (a region closer to Earth), which is opposite to the radial diffusion from Earth. Radial diffusion from a region with a high particle flux into a region with a lower one is described, for example, in [Shprits et al., 2006]. As a result, the electron density in RB decreases if, of course, there is no replenishment due to particle acceleration. Intervals of slow decrease in the intensity of electron fluxes are shown in Figure 4; in these time intervals the Kp index is low, the substorm activity is absent. The rest of the time, the replenishment of electron population due to substorm activity masks this process.

ACCELERATION PROCESSES.

SLOW E×B DRIFT

There is a wide variety of mechanisms for accelerating energetic electrons in the magnetosphere. We have already said that electrons can accelerate at resonance with VLF waves. Along with the cyclotron resonance, we can expect a drift resonance with magnetospheric Pc5 pulsations or solar wind pulsations with a period of the order of several minutes. Acceleration of this type is mentioned, say, in [Elkington et al., 1999; Ukhorskiy et al., 2006]. The acceleration of electrons due to the radial electric drift or their shift to the region of a stronger magnetic field is faster and more efficient. A large-scale electric field is driven by the solar wind. The Akasofu index representing the effectiveness of the solar wind effect on Earth’s magnetosphere contains the velocity...
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Figure 6. Relaxation of excess electron flux after the July 2004 storms

acceleration and the increased particle flux remaining unchanged for many days are observed as a result of chains of successive magnetic storms. Such an unusual case is described in [Kuznetsov et al., 2009; Yang et al., 2014]. Using data from the former paper, we show in Figure 5 how the low-latitude boundary of electrons and protons, trapped in RB, shifts (those days, RB was filled with solar protons). The earthward shift is driven by the $E \times B$ drift. This is confirmed by the equal velocity for particles of all energies and types.

Moving to the region of higher magnetic field strength, particles increase their energy. This causes an increase in the particle flux. Figure 6 [Lazutin et al., 2012] shows that RB gets rid of such an overpopulation for a long time. Note that strong storms may result in the formation of additional energetic electron belts in the vicinity of the slot region, which also exist for months [Vernov et al., 1965; Kuznetsov, 1966; Logachev, Lazutin, 2012].

ACCELERATION PROCESSES.

FAST $E \times B$ SHIFT

An electric field can also be short-term, caused by a rapid change in the magnetic field at the time of SC or substorm activation. The shift of electrons and protons by an SC pulse deep into RB, detected during measurements made by CRRES [Li et al., 1993] on March 24, 1991, was analyzed in [Pavlov et al., 1993]. The SC pulse is double – a positive pulse followed by a negative one; therefore, if particles are not transferred by the magnetic drift to the night side on time, an increase in their energy (and flux intensity) is eliminated adiabatically. The particles which have a 1–3 min half-period of drift pass to the night side, where they also experience a radial drift with acceleration driven by a negative pulse. We can thus estimate the lower limit for particle energies for which the mechanism will operate — on the order of a few MeV. If we consider that high SC pulses (from 50 nT and higher) occur at most twice a year, the shift of electrons with an energy of several MeV by an SC pulse to a greater depth does not play an important role in RB dynamics.

Much more often there is a pulsed dipolization of the magnetic field at the moment of breakup or re-activation of a substorm. It leads to the fact that along with the increase in the flux of low-energy (to several keV) electrons, responsible for auroras and accelerated by a longitudinal electric field, there is an impulsive increase in the flux of energetic electrons in the auroral magnetosphere. Characteristics of these increases have been extensively studied using both balloon [Anderson, 1965] and satellite observations, in particular CREES measurements in the equatorial plane. As a rule, these electrons appear in a quasi-trapping region, have an energy 20–200 keV, and cause subsequent acceleration by the radial $E \times B$ drift, mentioned above [Tang et al., 2016]. At the same time, during magnetic storms when the region of substorm activations shifts to Earth, the substorm electric field pulse shifts electrons to the center of RB, to the region of high magnetic field strength, and the ultimate energy of freshly accelerated electrons can reach several MeV [Lazutin, 2013]. Consequently, the electron flux gradient along the outer RB slope increases; and in the quasi-trapping region the particle flux gradually increases due to the outward drift. The electron acceleration via the substorm shift has also been considered in [Kabin et al., 2017; Gabrielse et al., 2016, 2017].

Nishida [1976] has put forward an idea of electron “recirculation” according to which electrons, once accelerated by electric drift, move again to a distant field line and are accelerated in this way many times. The idea suggested for Jupiter’s magnetosphere has found
Zhenpeng Su et al. [2014] emphasize the difference between subrelativistic (\(\sim 0.1 \text{ MeV}\)) and relativistic (2–5 MeV) electrons: the former provide up to 100% of flux increases due to the shift deep into RB; the latter, only 20%; in this case, the increase takes a few minutes. According to the calculation, the interaction with choruses gives 60–80% of increases in the flux of energetic electrons (0.2–5.0 MeV), which take a longer time (~6 hr). A similar difference in the behavior of electrons of different energies has been revealed in the statistical analysis carried out by Ying Xiong et al. [2015]: the flux of 0.3–2.5 MeV energetic electrons increases in 87% of storms, whereas the flux of 2.5–14 MeV electrons, only in 35% of storms.

RADIAL TRANSPORT

Radial transport, shift, injection, diffusion – there are many terms and mechanisms; and not to get confused and not to confuse readers, we briefly describe these mechanisms.

To Earth, a particle flux is transported with acceleration by pulsed substorm injection and \(E\times B\) drift in a large-scale electric field during a magnetic storm, by wave and pulsed radial diffusion. The last mechanism (the slowest according to [Tverskoy, 2004]) is responsible for the formation of the electron radiation belt.

At the end of the storm main phase there occurs a returned adiabatic transport to Earth.

Moreover, both during the storm and during the quiescent period, a continuous electron flux from Earth is observed as a result of drift due to the negative radial gradient of trapped particles.

THE QUIET MAGNETOSPHERE

The alternation of the above processes leads to the fact that the outer electron radiation belt “breathes” all the time, and not only the intensity of fluxes of its inhabiting particles varies, but also dimensions of RB itself do. These variations are most pronounced in a quasi-trapping zone.

Electron flux measurements made by a geostationary satellite along with magnetic activity indices are exemplified in Figure 4, in which we show several characteristic variations of electron fluxes. A rapid quasiharmonic variation with a period of 24 hr (the orbital period) is associated with the day-night asymmetry of the magnetosphere. Besides the rapid adiabatic decrease in electron flux intensity during the storm main phase (1), we see intervals with a slow decrease in intensity (2) during periods of low substorm activity and, conversely, of its slow increase (3), which is not induced by momentary activity but by the outward gradient radial drift from deeper RB regions (3).

These variations are generally short-lived, flux intensity decreases are compensated by increases, and the average monthly RB remains stable. At the same time, there may be long-term depletions of the radiation belt, which have been discussed in a number of papers. Thus, in [Jaynes et al., 2014], a long-term decrease in RB electron flux is explained by the fact that in a quiescent period, without acceleration, all losses are attributed to 700 keV – 2 MeV electron precipitation (up to 92% and more). Ukhorskiy et al. [2015], on the contrary, note that losses at the magnetopause are responsible for most of the losses at \(L>5\), whereas at smaller \(L\) the decrease is adiabatic.

Even during years of minimum solar activity, the level of magnetic disturbances remains sufficient to mask the depletion of the outer RB, and only in the particularly deep minimum of 2009 there was a significant depletion [Kataoka, Miyoshi, 2010; Li et al., 2011; Lee et al., 2013; Lazutin, 2017]. Magnetic activity in those years was indeed very low, as derived from the distribution of the number of days with high and low \(K_p\) indices.

Figure 7 shows that there are much more intervals of a slow electron flux decrease, and of course they coin-
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Cide with periods of low substorm activity. Finally, the depletion of RB is detected by comparing histograms of distribution of days with different electron flux levels in 2009 with years of higher magnetic activity (Figure 8). We mean the depletion of the entire RB because a decrease in the particle flux on the periphery of RB leads, due to diffusion, to the depletion of RB as a whole.

CONCLUSION

At the time free from magnetic disturbances (substorms), the outer electron radiation belt gradually empties. This process occurs on inner shells of RB due to precipitation of particles into the atmosphere and in a quasi-trapping zone because electron drift shells are not closed there. This causes losses at the magnetopause. The quasi-trapping region does not empty immediately due to radial diffusion of particles outward from the center of RB. The depletion is not well pronounced in ordinary years due to replenishment by freshly accelerated particles, but in years of extremely low activity, it leads to a considerable decrease in the electron population of the belt.

During the storm main phase, the major mechanism for the decrease in the intensity of electron fluxes is adiabatic cooling associated with conservation of adiabatic invariants. An additional reason is the precipitation of electrons from RB to the atmosphere and magnetopause. As a result, the intensity of electron fluxes in RB decreases. The L coordinate calculated for the undisturbed configuration of the magnetospheric magnetic field is often used in plots of low-orbit satellite measurements. In these cases, we should remember that this representation does not show the real drift trajectory.

The rate of electron flux recovery after a storm is determined by the ratio of increases and losses, and flux values constitute a continuous series from low to very high values.

The electron flux increases consist of the following processes:

- The fast $\mathbf{E} \times \mathbf{B}$ electron shift, accompanied by an energy increase, deep to Earth by a pulsed induction electric field of substorm activation during a magnetic storm.
- This abrupt increase in the auroral electron flux intensity serves as the basis for the second, slower increase in the electron flux in RB due to electron injection to Earth by a large-scale electric field of the solar wind. A chain of several storms can sometimes increase the electron flux by several orders of magnitude, and this overpopulation of RB may decrease for months. In addition, there may appear additional RBs in a slot region.

On the periphery of RB, in the quasi-trapping region, an increase in particle fluxes is ensured by the anti-earthward energetic electron drift, which replenishes the quasi-trapping region (geostationary region) with a 2–3 day delay.

The electron flux intensity in RB decreases mainly due to losses at the magnetopause, which become more intense during the storm main phase due to the adiabatic shift of drift shells and during periods of low substorm activity. During the extremely low activity of 2009, this mechanism led to significant losses of RB particles.

The resonance of electrons (cyclotron, drift) with VLF emission and pulsations leads both to their pitch-angle diffusion to the loss cone and their dropout in the atmosphere, and to an increase in the energetic electron flux in parasitic resonance at the emission produced by a large flux of less energetic particles.

The combination of these processes forms the individual character of radiation belt dynamics during each magnetic storm.

REFERENCES


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