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# MAGNETOSPHERIC SUBSTORMS AND RELATIVISTIC ELECTRONS

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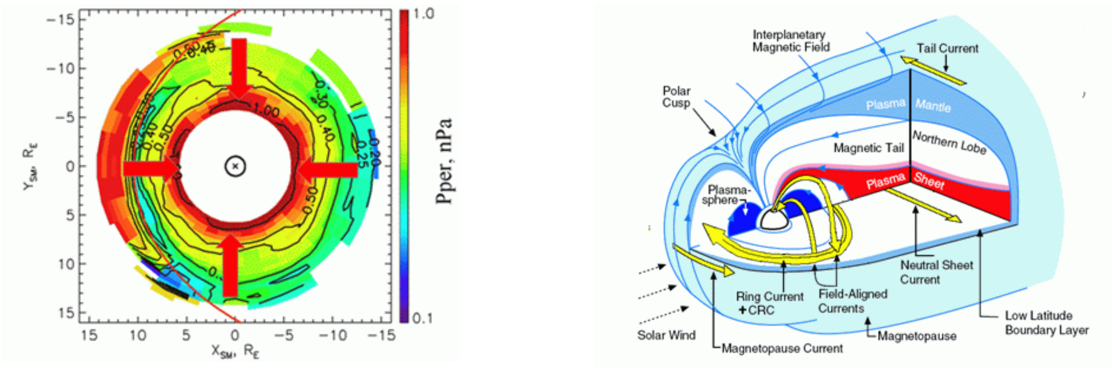
## Abstract
The most recent findings on the dynamics of the outer radiation belt (ORB) and the physics of magnetospheric substorms are examined. Specifically, we investigate the relationship between storm time substorms and the energetic electron population that forms the ORB. Traditionally, storm time substorms have been considered as the primary source of energetic electrons, which are further accelerated during storms to contribute to the formation of the ORB. However, several observations have demonstrated that large magnetospheric substorms can generate high-energy electrons even in the absence of magnetic storms. Substorms introduce dispersionless injections of energetic electrons deep into the magnetosphere from the geosynchronous orbit during storm times. The injected electrons undergo additional acceleration via the betatron mechanism during the storm recovery phase, thus increasing the ORB population. To gain a better understanding of this process, it is crucial to study plasma sheet turbulence, substorm onset processes, and the brightening of auroral arcs. By analyzing the aforementioned findings, this study aims to highlight the need for reanalyzing of the role of auroral processes in the formation of the ORB.

## 1. Introduction
During the last years, the problem of the acceleration of the outer radiation belt (ORB) relativistic electrons is considered to be one of the most important unresolved problems of magnetospheric dynamics in spite of the significant affords for its solution including the launch of dedicated space missions like RBSP/Van Allen probes and ARASE. It was finally established that the outer electron belt can almost disappear during the main phase of the storm. An increase in ORB relativistic electron fluxes occurs for the recovery phase of about half of the magnetic storms, a drop in fluxes compared to pre-storm levels takes place for about a quarter of magnetic storms, and a recovery of fluxes to a similar level also during about a quarter of the storms. It is difficult to understand the observed patterns using the standard approach, which ignores the ring current dynamics and the main features of substorm dipolarizations. In this paper, we summarize the results of studies of the role of substorm processes in the acceleration of relativistic electron. We try to outline areas of work that could lead to the creation of an adequate self-consistent picture of processes inside the magnetosphere leading to the ORB formation.

## 2. Topology of magnetospheric currents and substorms
The main feature of the development of magnetic storms is the displacement of the auroral oval to lower latitudes. For example, during the magnetic storms of February-March 2023, discrete forms of aurora were observed at the latitude of Moscow. Such feature shows that the substorm onset and development takes place deep inside the magnetosphere which is difficult to understand by assuming the ordinary suggestion of substorm development due to reconnection in the geomagnetic tail. It has been conclusively proven that field line stretching and local dipolarizations are observed at small L during storm time substorms (see, for example, [*Nosé et al.*, 2016] and references therein). In many cases, such results were discussed within the framework of the traditional assumption of the movement of the plasma sheet towards the Earth during a storm. However, this point of view did not take into account the existence of a plasma ring surrounding the Earth, the boundaries of which during the daytime coincide with the closest to the Earth boundary of the low-latitude boundary layer. The average pressure gradient of the magnetospheric plasma in this ring is directed toward the Earth at all MLTs, which means the existence of an outer part of the ring current (cut ring current - CRC). The characteristics of the plasma in the ring are similar to the characteristics of the plasma in the plasma sheet. That is why for the long time, the night part of the CRC to geocentric distances ~10-13Re has been considered as the part of the closest to the Earth plasma sheet (see the review [*Antonova et al.*, 2018a]). Fig. 1 illustrates this statement. Red arrows in Fig. 1 show the direction of the plasma pressure gradients, yellow arrows show CRC and field-aligned currents. Compression of the magnetospheric magnetic field in the daytime by currents at the magnetopause leads to

splitting and shifts to higher latitudes of the surface of the minimum magnetic field at the magnetic field line, which, unfortunately, was not taken into account when creating magnetospheric magnetic field models and substorm models. The existence of the outer part of the ring current indicates the closed nature of the drift trajectories of particles, the Larmor radii of which are small compared to the inhomogeneity of the magnetic field. Therefore, the CRC region became the region where energetic particles can be trapped mainly on Shabansky trajectories. Discussed scheme is in a rather good agreement with the results of [*Vorobjev et al.*, 2018], which analyzed 163 isolated substorms and showed that the increase of $|Al|$ produces the decrease of storm index SYM-H. The existence of CRC region as a part of the ring current also explains the recovery of fluxes after quarter of the storms due to the action of adiabatic effect [*Antonova et al.*, 2018b].




a b

**Figure 1.** Distribution of plasma pressure at the equatorial plane during quite conditions (a) and the scheme of the magnetosphere including the high latitude continuation of the ordinary ring current (b).

The most popular point of view, formed before the launch of the RBSP/Van Allen probes, was that substorms provide injection of a seed population of electrons inside the magnetosphere, which are then accelerated to relativistic energies by one of the wave mechanisms [*Baker et al.*, 2005]. The traditional theories of substorm require the reconnection or current disruption in the geomagnetic tail. The development of substorm and the formation of a seed population of electrons in the magnetotail required rapid radial transport of particles into the magnetosphere. Particles accelerated during substorm dipolarizations inside the geostationary orbit will be immediately captured inside the magnetosphere, unlike particles accelerated in the tail. Therefore, dipolarizations within the geostationary orbit removed the problem of the formation of a seed population, but required modification of the basic concepts based on the assumption of reconnection in the magnetotail as the main cause of substorm activations.

## 3. Magnetospheric turbulence and substorms

Along with tail theories of substorms, a theory of substorm was developed, based on the analysis of magnetosphere-ionosphere interactions starting from the work of [*Tverskoy*, 1972]. Thus, in the works [*Antonova*, 2002; *Stepanova et al.*, 2002], a substorm onset was associated with the instability of the system of upward field-aligned currents and the penetration of cold ionospheric plasma through the boundary of the region of field-aligned potential drop leading to the acceleration of auroral electrons. This theory explained the occurrence of substorm activations without a trigger in the solar wind or in the magnetotail. However, it also fits well with the results of observations of triggered substorms, since the brightening of the auroral arc requires only a sharp change in the local convection in the presence of an upward field-aligned current in a region of field-aligned potential drop. Bursty bulk flow (BBF) are ordinarily considered as the substorm expansion phase trigger. The MMS observations of BBF in a burst mode show a large increase of turbulent fluctuations in the tail during BBF which produce effective particle acceleration [*Ergun et al.*, 2022]. However, BBF are observed much more frequently than magnetospheric substorms. That is why it possible to find a suitable disturbance before the onset of most of substorms. It is necessary to mention that the plasma sheet of the Earth is a turbulent region (see [*Borovsky et al.*, 1997] and reviews [*Ovchinnikov and Antonova*, 2017; *Antonova and Stepanova*, 2021]). High level of electric field fluctuations with amplitudes, which are 1-2 orders of magnitudes larger than amplitudes of electric fields of magnetospheric convection are constantly observed [*Ovchinnikov et al.*, 2023].

The level of turbulent fluctuations is increased during magnetospheric disturbances including the generation of more or less regular phenomena such as Pc5 fluctuations and chorus waves. Interactions with such waves are ordinarily proposed as a possible solution of the problem of ORB formation. Acceleration by chorus waves during the resonant interaction of waves and particles is considered as the main accelerating mechanism for a seed population of electrons. At the same time, it was necessary to take into account that the energy density of waves is at least two orders of magnitude higher than the energy density of accelerated electrons [*Shklyar*, 2021]. The difficulty of using this mechanism is related to the fact that the pitch-angle diffusion coefficient in cyclotron wave-particle interaction is orders of magnitude higher than the energy diffusion coefficient (see, for example, [*Orlova et al.*, 2012]. That is why at maximum recorded amplitudes of such waves the acceleration time was at least several hours. At the same time the appearance of relativistic electrons during substorm dipolarizations was also recorded (see [*Pinto et al.*, 2020] and ref. therein). It was possible to clarify the role of chorus waves only producing a careful analysis of wave and particle evolutions.

A thorough analysis of variations in the fluxes of relativistic electrons along the orbits of the RBSP/Van Allen probes satellites shows (see [*Kim et al.*, 2023] and references in this work) that inside the magnetosphere, sharp changes in the fluxes of relativistic electrons occur only at the moment of substorm dipolarizations. Between dipolarizations, the electron fluxes do not change. When analyzing individual depolarization at 15:50 UT during storm 17 March 2013 Foster et al. [2017] suggest the action of nonlinear interaction with the same cyclotron waves due to simultaneous small amplitude chorus observations. However, the well localized interaction of electrons with high frequency electrostatic waves appeared due to field-aligned electron beam relaxation during substorm onset seems to be more probable and deserve special attention. Obviously, the mechanisms associated with the emergence of large induction fields during dipolarization also have an advantage. It should be noted that disruption of the adiabatic motion of electrons in the local dipolarization region does not lead to the loss of particles from the trap.

An important partially explained feature of the ORB formation is described by the Tverskaya relation [*Tverskaya*, 2011] which connects the position of the ORB maximum formed during a magnetic storm with the maximum value of the module of minimum the Dst index during the storm. Numerous results confirming the validity of the Tverskaya relation for magnetic storms of the RBSP/Van Allen probes period have shown the need to include this feature in the modeling of the ORB formation. Currently, there is a theory, developed in [*Tverskoy*, 1997; *Antonova*, 2006], linking the occurrence of the ORB maximum with the formation of the maximum ring current pressure during a storm. The theory predicts a coincidence of the position of such a pressure maximum with the position of maximum of relativistic electrons predicted by the Tverskaya's relation. Determining the position of the maximum plasma pressure as known is difficult due to the slow motion of the high-altitude satellites in the equatorial plane. At present, it has been possible to determine the position of the maximum pressure for a number of cases. Fig. 2 shows the Tverskaya relation (black lines with positions of ORB maxima in a number of storms selected by black signs) and positions of plasma pressure maxima selected for a number of storms (color signs).

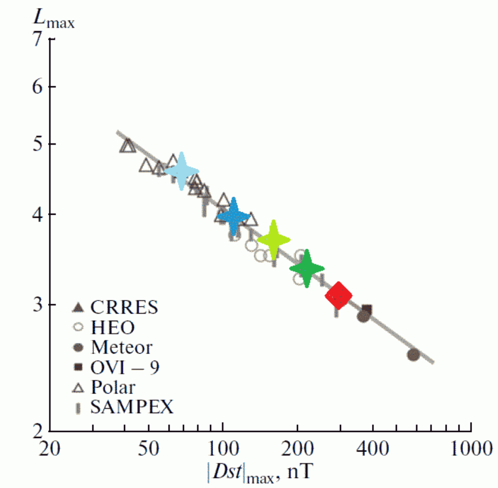



**Figure 2.** The dependence of the pressure maxima position during a number of magnetic storms on $|Dst|_{max}$ during storms May 29, 2010, with |Dst| = 85 nT (inconspicuous blue sign); October 8–9, 2012, with |Dst| = 111 nT (dark blue sign); December 19–22, 2015, with |Dst| = 155 nT (inconspicuous green sign); March 1–8, 1982, with |Dst| = 211nT (dark green sign); Bastille Day event (July 2000) with |Dst| > 300 nT (red square) (adapted from the work [*Antonova et al.*, 2023]).

## 4. Conclusions and discussion

The performed analysis reviles a number of features leading to the modification of existing concepts of substorm development and ORB formation.

- Storm time substorm observations and observed large level of tail fluctuations lead to considerable modifications of substorm theories as it is easy to find the plasma sheet disturbance before the most of substorm onsets.
- It is necessary to reanalyze the role of the auroral processes in the ORB formation.
- Storm time substorm injections form the plasma pressure maximum during a storm calculated using the Tverskaya's relation.
- Selection of the mechanism leading to the nonadiabatic ORB acceleration requires the analysis of thin auroral arc brightening during substorm onset and substorm dipolarizations.

The study of storm time substorms can help not only to predict the position of the ORB maximum according to the Tverskaya's relation but to clarify the nature of magnetospheric substorms and to develop the program of the prediction of the appearance of high fluxes of relativistic electrons.

## Asknowlegments
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