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PROBLEMS OF THE OUTER RADIATION BELT FORMATION AND TOPOLOGICAL FEATURES OF HIGH LATITUDE MAGNETOSPHERE

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Abstract. We analyzed the problems of formation of the outer radiation belt (ORB) taking into consideration the latest changes in our understanding of the high-latitude magnetospheric topology. This includes strong evidence that the auroral oval maps to the outer part of the ring current, meanwhile the ORB polar boundary maps inside the auroral oval. Our analysis also includes the variation of the plasma pressure distribution and the time of the acceleration of relativistic electrons during geomagnetic storm. It is shown that the maximum of ORB is formed after the geomagnetic storm in the region of plasma pressure maximum. The position of this maximum agrees with the prediction of the ORB formation theory based on the analysis of ring current development during storm. We emphasize the role of adiabatic processes in the ORB dynamics and the importance of the substorm injections during storm recovery phase for the formation of enhanced fluxes of ORB electrons after the storm.

1. Introduction

The formation of outer radiation belt (ORB) continues to be one of the most intriguing problems of magnetospheric dynamics and one of the main aims of the Space Weather prediction program. It is directly connected to the solution of magnetospheric storm and substorm problems. In spite of successive realization of ORB/Van Allen project [*Ripoll et al.*, 2020] the main problems of ORB formation continue to be unsolved. Their solution requires the extraction of adiabatic effects produced by the decrease of the magnetic field inside the ring current during storm and an adequate description of the variation of the storm time magnetic field. Not so long ago it became clear that the acceleration of electrons to relativistic energies can take place on a time scale of substorm [*Foster et al.*, 2017; *Sotnikov et al.*, 2019b] which is impossible to explain suggesting the dominant role of "quasilinear" (really linear) wave- particle interactions solving Fokker-Plank equation with predefined diffusion coefficients [*Baker et al.*, 2018].

In this report we summarize the main latest results obtained after 2017 and not included in our report [*Antonova et al.*, 2017] which are important for the solution of ORB problems. We try to show that taking into account the mapping of the main part of auroral oval to the outer part of the ring current and the validity of the Tverskaya's relation, the theory of ORB formation can explain many of observed features of the ORB formation and have predictions which are now supported by results of modelling and satellite observations.

2. Auroral oval and ORB location

The main difficulty in the understanding the ORB formation processes was the widely distributed point of view about the mapping of the auroral oval to the geomagnetic tail. Such mapping was based on the use of geomagnetic field models with predefined geometry of current systems which did not include the high latitude part of the ring current (CRC - cut ring current) region which produce the disturbance of Bz and Bx magnetic field components at the Earth [*Antonova et al.*, 2009] and in which daytime current lines are not concentrated at the equatorial plane (see, the review [*Antonova et al.*, 2018a]). Comparison of plasma pressure at the ionospheric altitudes and at the equatorial plane showed (see [*Antonova et al.*, 2015, 2018a; *Kirpichev et al.*, 2016] and references therein) that the equatorial boundary of the auroral oval during quiet time is located at ~7 R_E and the polar boundary is located at ~10-13 R_E. Such auroral oval mapping is in agreement with many observations including the position of substorm injection boundary at ~6-7 R_E and high level of observed turbulence in the Earth's plasma sheet (see the latest review [*Antonova and Stepanova*, 2021]).

The picture of the ORB formation contains the acceleration of the injected during the storm time energetic electrons to relativistic energies [*Baker et al.*, 2013]. This required to determine the position of the ORB with respect to the auroral oval. The ORB electrons have the drift trajectories which surround the Earth and the ORB outer boundary represents at the same time the trapping boundary of these electrons. A direct comparison between the locations of the trapping boundary of the elections with energies >100 keV and of the auroral particle precipitations made simultaneously during the quiet time, showed that trapping boundary is located in most cases inside the auroral oval [*Riazanseva et al.*, 2018]. Such location of the trapping boundary is possible to observe during all studied geomagnetic storms [*Sotnikov et al.*, 2019a, 2021]. It is interesting to mention that in this case the polar boundaries of the auroral oval and the ORB can be observed at the same latitude [*Sotnikov et al.*, 2019a, 2021]. Figure 1 shows an example of the crossing of the auroral oval by METEOR-M2 satellite during the magnetic storm 19-22 December 2015 [*Sotnikov et al.*, 2019a]. The upper panel in the left part of the figure is the spectrogram of electrons in the energy range from 0.13 to 16.64 keV. The bottom panel is the energy flux of auroral electrons (blue line) and the flux of electrons with energies >100 keV (orange line). The vertical dashed lines indicate the trapping boundary of electrons with energies >100 keV (orange) and the equatorial boundary of the oval (blue). The right part of the figure shows Dst, AE and AL variations during storm. Red vertical line shows the time interval of the auroral oval crossing.

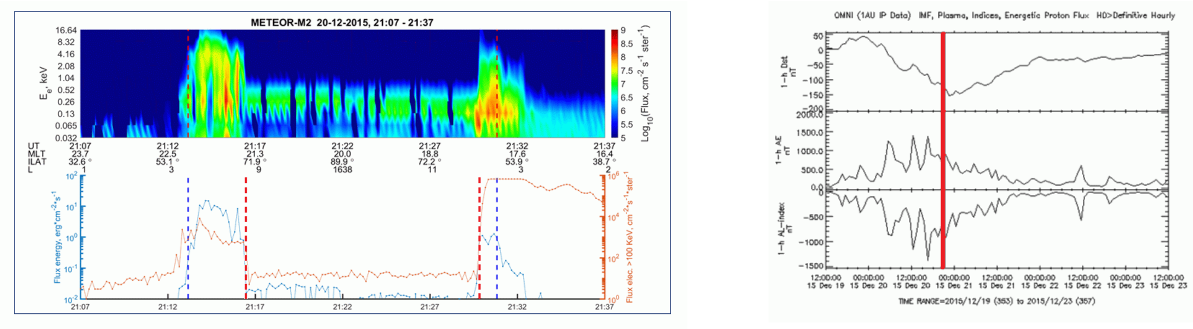

Figure 1. Oval crossing during the great magnetic storm 19-22 December 2015.

The theory developed for description of the ORB formation [*Tverskoy*, 1997; *Antonova*, 2006] was initially aimed to explain the Tverskaya's relation which connect the minimal value of the Dst index during storm with the position of the ORB maximum L_{max} obtained for all energies of relativistic electrons after storm ($|Dst|_{max} = 2.75\times10^4 / L_{max}^4$). Such dependence for the SYM-H index has the same form but with the coefficient 3.00 [*Tverskaya*, 2011]. In addition to early findings, recent studies significantly increased the number of events confirming the validity of this relation [*Antonova and Stepanova*, 2015; *Moya et al.*, 2017; *Boyd et al.*, 2018; *Zhao et al.*, 2019].

2. ORB and plasma pressure peak during magnetic storms

The existence of Tverskaya's relation is very difficult to explain by the relativistic electron acceleration due to wave-particle interactions. However, it can be explained [*Tverskoy*, 1997; *Antonova*, 2006] if a very sharp plasma pressure peak and magnetic field depression are formed and substorm injections to the region of the depressed magnetic field take place. The formation of the plasma pressure peak is ordinarily observed during storms (see [*Stepanova et al.*, 2008] and references therein). A sharp plasma pressure peak can be formed due to the adiabatic radial plasma transport by large-scale electric fields [*Tverskoy*, 1997] or due to the injections of ionospheric ions accelerated by the field-aligned electric fields [*Antonova*, 2006]. But such mechanism can create large fluxes of relativistic electrons only after beginning of storm recovery phase in the conditions of the symmetric ring current formation. The support of such scenario requires complex multi satellite observations. As a first step it is necessary to select sharp increases in the plasma pressure and analyze the value and position of the ring current pressure peak near the end of the storm main phase. It is difficult to do using data of a high apogee satellite as sharp pressure peaks could be destroyed by the processes of radial diffusion taking into consideration than the ring current crossing takes several hours. That is why the formation of sharp pressure peak was first observed using low orbiting DMSP observations [*Antonova and Stepanova*, 2015]. Its position corresponds to predictions of Tverskaya's relation. However, value of pressure maxima of the peak was much smaller than it was predicted due to limited range of ion energy observations. Larger pressure peaks localized at geocentric distances in accordance with Tverskaya's relation were observed by *Kirpichev et al.* [2018], *Stepanova et al.* [2019, 2020].

New generation of magnetic field models using data mining technique (DM) creates a possibility to select much larger ring current maxima [*Sitnov et al.*, 2020]. Distribution of ring current pressure at the equatorial plane was obtained by integrating the quasi-static force balance equation with the isotropic plasma approximation ($\nabla p=[\mathbf{j}\times\mathbf{B}]$, where p is the pressure, **j** is the current density, **B** is the magnetic field). Figure 2a adapted from [*Sitnov et al.*, 2020] shows plasma pressure distribution at the end of the main phase of 15–16 July 2000 superstorm (Bastille Day with Sym-H <−300 nT shown on Figure 2b). The vertical red line shows the moment of DM reconstruction. It is possible to see the formation of sharp pressure maximum equal to 177 nPa in the premidnight sector when SYM-H index had the minimal value. This value is much larger than earlier observed storm time pressure peaks. Figure 2c show the radial profile of pressure distribution adapted form [*Tverskaya et al.*, 2005] calculated for different values of minimal Dst in accordance with *Tverskoy* [1997] predictions. The thin lines show a plasma distribution for the storms of $|Dst|_{max}$ = 50, 100, 150, 200 and 300 nT. It is possible to see that the values of pressure maxima in Figure 2a in spite of a number of DM technique errors practically corresponds to theory predictions. The position of maximum taking into account the accuracy of DM reconstruction was near the predicted.

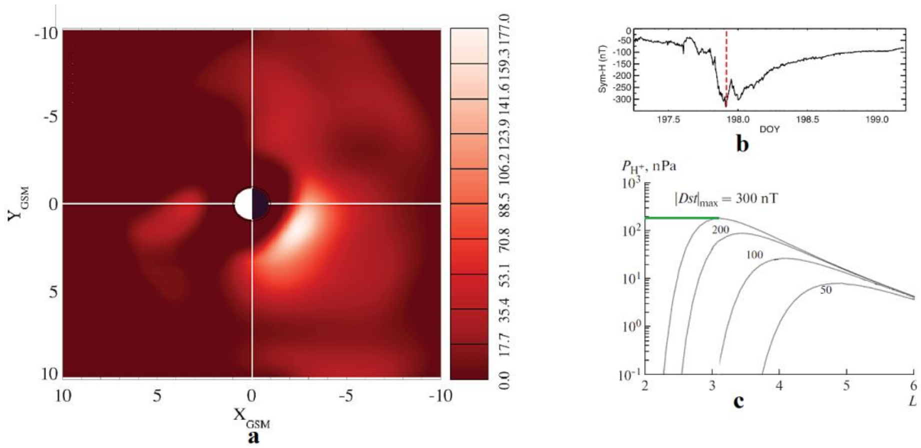

Figure 2. Comparison of DM mining picture of pressure distribution for Bastille Day superstorm 15–16 July 2000 with theoretic prediction of pressure peak value.

The position of pressure maximum corresponds to the equatorial boundary of storm time auroral oval and solar cosmic ray's penetration boundary [*Tverskaya*, 2011] which means the great modification of magnetic field at geocentric distances larger than pressure maximum. Coincidence of the westward electrojet equatorial boundary with the position of pressure maximum [*Tverskaya*, 2011; *Antonova and Stepanova*, 2015] support such modification. Appearance of relativistic electrons after storm take place only in the case of substorm development during storm recovery phase (see [*Antonova et al.*, 2018b] and references therein), which also support the theory predictions. These show that additional steps in the restore of pressure distribution during magnetic storms and verifications of [*Tverskoy*, 1997; *Antonova*, 2006] predictions are very interesting as they can lead to considerable changes in the understanding of the ORB formation processes and storm time magnetic field dynamics.

4. Conclusions and discussion

Short analysis summarizing the latest finding in the ORB formation shows the great importance of auroral processes in the relativistic electron dynamics. It was proofed that the trapping boundary of energetic electrons is located inside the auroral oval. The coincidence of the trapping boundary with the polar boundary of the auroral oval is observed in a number of storms during auroral oval crossing by METEOR-M No 2 satellite. Such findings support the early made conclusion about overlapping of ORB and the region mapped to the auroral oval. Theoretically predicted appearance of sharp pressure maximum in the ring current during storm obtained new supports including latest results of DM modelling of *Sitnov et al.* [2020]. Position of the nearest to the Earth during storm equatorial boundary of the auroral oval coincides with this sharp pressure peak position. Such position coincides with formed after storm ORB maximum in a rather good agreement with Tverskay's relation and theoretical predictions of *Tverskay* [1997], *Antonova* [2006]. Results of the study permit to predict the location of formed after storm ORB maximum and decrease or increase of relativistic electron fluxes in ORB after storm.

However, only small number of events were analyzed till now and the theory needs additional supports and development especially using analysis of auroral observations and magnetosphere-ionosphere interactions at auroral latitudes. Additional possibilities of such studies appeared with the particle observations at large altitudes. Such observations at the altitudes ~30000 km at Arase satellite [*Shiokawa et al.*, 2020] demonstrate the existence of bidirectional field- aligned electrons in the source region of the expanding auroral arcs which is important as such beams can be the source of high frequency electrostatic fluctuations relevant to the problem of relativistic electron acceleration.

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