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Dedicated to the memory of Ludmila Vasilievna Tverskaya

AURORAL OVAL AND OUTER ELECTRON RADIATION BELT

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Abstract. We try to summarize results of experimental and theoretical works demonstrating the close connection of auroral phenomena with the processes of the outer radiation belt formation in the magnetosphere of the Earth. Anomalously high relativistic electron fluxes in the outer radiation belt are frequently named electrons-killers. Such electrons formed due to seed population acceleration. The seed population is produced during storm time substorms. We discuss the auroral oval mapping to the equatorial plane and show its mapping to the outer part of the ring current. We try to show that adiabatic acceleration can be rather important in the process of formation of anomalously high fluxes of relativistic electrons.

1. Introduction

Physics of the outer radiation belt formation is ordinarily considered as selected region of magnetospheric researches mainly connected with wave-particle interactions and turbulent acceleration. However, it was known, that the formation of new outer radiation belt starts from the appearance of seed population (*Baker*, 2013) accelerated during storm time magnetospheric substorms. Most exiting findings in the physics of outer radiation belt are connected with the name of Ludmila Vasilievna Tverskaya (18.11.1937- 16.10.2012). She obtained [*Tverskya*, 1976] the dependence of the position of the new belt maximum ($L_{\max}$) for electrons accelerated during a magnetic storm on the storm Dst amplitude ($|\mathrm{Dst}|_{\max}$) having the form:

$$|Dst|_{\max} = 2.75\times10^4 / L_{\max}^4 \tag{1}$$

and later supported by numerous results [*Tverskya*, 2011; *Kuznetsov et al.*, 2002; *Slivka et al.*, 2006; *Antonova and Stepanova*, 2015]. Fig. 1 shows this dependence. Blue star on Fig. 1 corresponds to 8–9 October 2012 geomagnetic storm, analyzed by *Reeves et al.* [2013] and *Antonova and Stepanova* [2015] using data of RBSP, DMSP and ground-based observations.

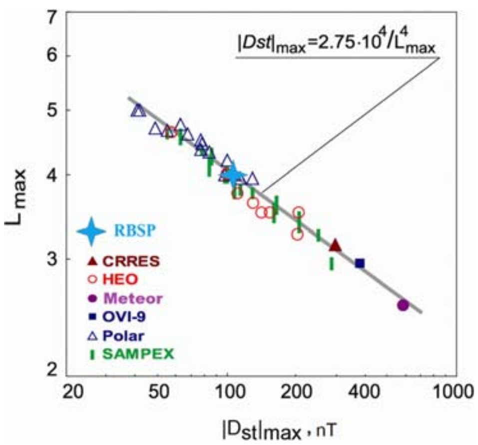

Figure 1. Tverskaya's dependence of the position of the new belt maximum for electrons accelerated during a magnetic storm on the storm Dst variation amplitude.

The dependence (1) yet is not wholly explained and obtaining of its explanation may be connected with definite modification of the standard description of the role of auroral processes in the magnetospheric dynamics. In this paper we try to shortly summarize the main findings demonstrating the deep connection of auroral processes and outer radiation belt formation. We also try to formulate problems, which require solution.

2. Auroral oval mapping

One of the main reasons, which oppressed the study of auroral processes as the source of outer radiation belt formation is the inadequate auroral oval mapping connected with overstretching of magnetic field models with pre-defined geometry of current systems. First such model was created by *Alexeev and Shabansky* [1972]. Fig. 8 of there paper shows zero radial thickness of the region of plasma sheet mapping near noon. However, from the first auroral oval observations (see, for example, *Feldstein et al.* [2014]) it was known, that auroral oval has thick structure near noon. The existence of thick auroral oval near noon is supported by multiple results of auroral imagers (DE-1, Polar, IMAGE ets.) and models of auroral precipitations NOAA (*http://www.swpc.noaa.gov/pmap/*), OVATION (*http://sd-www.jhuapl.edu/Aurora/ovation_prime*) and APM (*http://apm.pgia.ru/*). APM model classifies the regions of the auroral oval according to the kinds of electron precipitations as follows: the auroral oval precipitation region (AOP), the diffuse auroral zone (DAS) located to the equator from the AOP, and the soft diffuse precipitation zone (DAS) located to the pole from AOP. *Starkov et al.* [2003] showed that AOP statistically coincides with Feldstein auroral oval. Plasma sheet like particle fluxes are observed around the Earth till magnetopause [*Antonova et al.*, 2013, 2014a], which shows the possibility of auroral oval mapping to the ring like structure. To verify this suggestion *Antonova et al*. [2014b, 2015] analyzed the auroral oval mapping to the equatorial plane using APM model and results of observations of THEMIS mission. They used method of morphological mapping, comparing values of plasma pressure at the auroral latitudes and at the equatorial plane. The validity of the condition of magnetostatic equilibrium was suggested. They show that most part of auroral oval does not map to the plasma sheet. It is mapped to the surrounding the Earth plasma ring. Transverse currents in this ring are the outer part of the ring current. Fig. 2 illustrates this statement. Fig. 2a shows ion pressure distribution in the oval precipitation region (AOP) for quite geomagnetic conditions (AL=-100 nT, Dst=-5 nT) in accordance with *Vorobjev et al.* (2015) model of ion precipitations. Dots show boundaries of AOP in accordance with APM model. It is possible to see that ion pressure in AOP exceeds 0.2 nPa. This value is larger than typical values of plasma sheet full pressure. Fig. 2b shows plasma pressure distribution at the equatorial plane in accordance with THEMIS data. It is possible to see that isoline p=0.2 nPa surround the Earth. Existence of field-aligned potential drops in inverted V structures decrease ion pressure at the ionospheric altitudes in comparison with the equatorial plane. This effect leads to decrease of ion pressure at auroral altitudes in comparison with the equatorial plane. Therefore, Fig. 2 clearly shows the quite time auroral oval cannot map to the plasma sheet. It is mapped to the surrounding the Earth plasma ring. *Kirpichev et al.* [2016] showed that equatorial boundary of the nightside quite auroral oval is mapped to geocentric distance ~7R_E and polar boundary at geocentric distance ~10R_E.

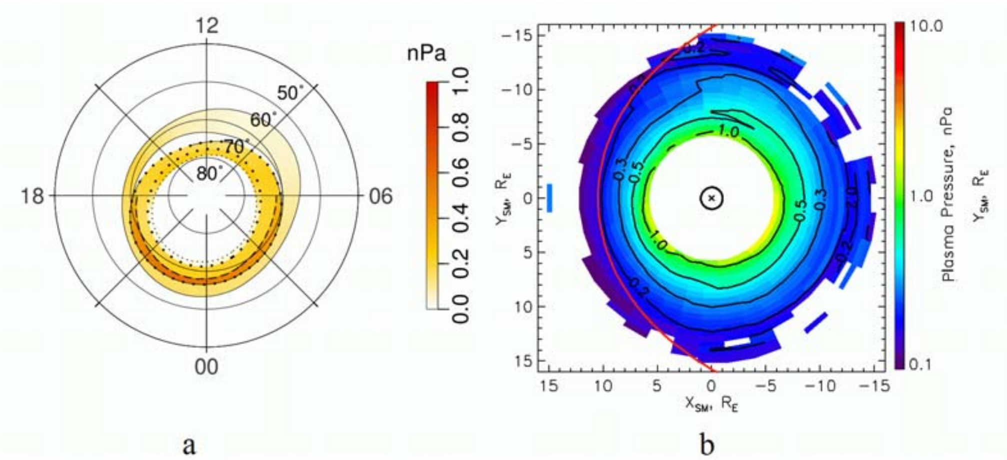

Figure 2. An example of comparison of ion pressure in AOP in accordance with *Vorobjev et al.* [2015] (**a**) with pressure distribution at the equatorial plane, obtained using data of Themis mission for quite geomagnetic conditions AL=-100 nT, Dst=-5 nT.

Mapping the equatorial boundary of the quite auroral oval to geocentric distance ~7R_E is in a good agreement with the first auroral arc brightening at the equatorial boundary of the oval (see *Akasofu* [1964] and multiple results of later works) and position of the dispersionless injection boundary [*Lopez et al*., 1990; *Spanswick et al*., 2010]. Position of the polar boundary at geocentric distance ~10R_E is in a good agreement with the position of the outer boundary of the ring current [*Kirpichev and Antonova*, 2014].

Now we have only very limited information on plasma pressure distribution at the equatorial plane during magnetic storms. However, auroral oval motion to the equator during magnetic storms is a well known phenomena. *Starkov* [1993] determined the location of the equatorial boundary of the auroral oval in dependence of the Dst index, which is in a rather good agreement with Tverskaya relation [*Tverskaya*, 2011]. This indicates the location of equatorial boundary of the auroral oval at the geocentric distances of new outer radiation belt formation during storm recovery phase.

3. Magnetic field distortion and outer radiation belt

High level of turbulent fluctuations of electric and magnetic fields at the latitudes of auroral oval in different frequency bands is practically constantly observed during magnetic storms, which made the theories of outer belt electron acceleration due to wave-particle interactions very attractive. However, other phenomena changing energetic electron spectra are observed during storms. This is the decrease of magnetic field inside the magnetosphere by developed ring current and its restore during storm recovery phase. *Tverskoy* [1997] suggested, that injection of seed population of electrons in the region of depressed magnetic field can lead to considerable particle acceleration during storm recovery phase due to betatron acceleration (adiabatic effect). *Tverskoy* [1997] theory explains the dependence (1) and predicted the formation of sharp pressure peak at L_{max}. *Antonova* [2006] shows, that it is possible to explain the value of coefficient in relation (1). However, theoretical analysis of *Tverskoy* [1997] and *Antonova* [2006] considers the case of dipole magnetic field and does not analyze nonlinear effects connected with finite values of plasma parameter. *Antonova and Stepanova* [2015] using data of DMSP observations show the sharp ion peak formation at L_{max} for the magnetic storm on October 8–9, 2012. They also show that the most equatorial position of equatorial boundary of the westward electrojet for this storm coincides with L_{max}. Such findings are in agreement with the first auroral arc brightening at the equatorial boundary of auroral oval as increase of electron flux leads to the increase of ionospheric conductivity and corresponding increase of ionospheric current. Large fluxes of downward accelerated electrons are accompanied by large fluxes of upward accelerated ions [*Stepanova et al.*, 2002]. Relaxation of ion beams creates local increase of ion pressure at the equatorial plane and formation of the peak of plasma pressure. Formation of pressure peak leads to local magnetic field decrease due to diamagnetic effect. Such local increases of plasma pressure (pressure humps) and decreases of magnetic field (magnetic holes) are really observed at the equatorial plane (see *Vovchenko and Antonova* [2015]) and references in their paper. Magnetic hole can be effective local trap for energetic particles [*Vovchenko and Antonova*, 2012] in which injected electrons can be accelerated. The restore of the magnetic field to undisturbed level will lead to betatron acceleration of electrons.

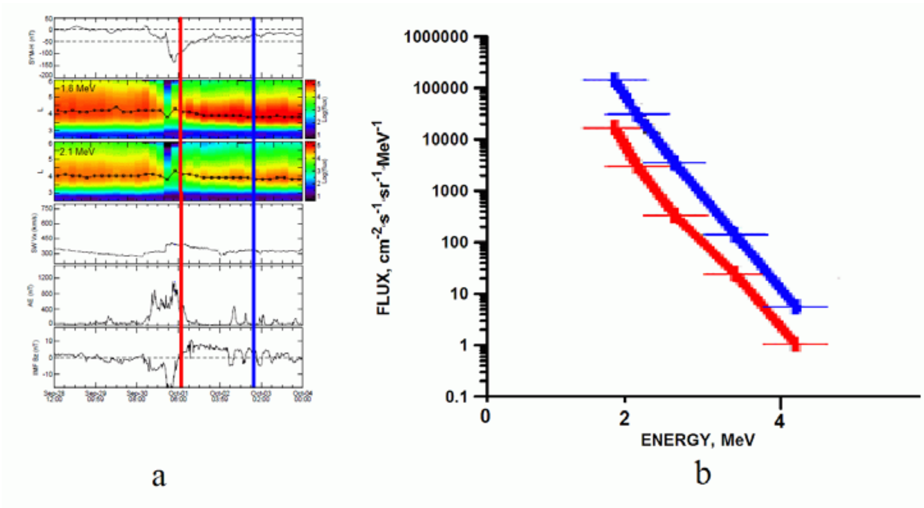

Figure 3. a - results of RBSP measurements of electron fluxes with energy 1.8 and 2.1 MeV and simultaneous ground based and solar wind parameters, **b** – electron spectra for moments shown by vertical lines on (a).

Local variations of magnetic field at the equatorial plane are not proper studied till now. Therefore, it is difficult to evaluate the contribution of large-scale magnetic field change in the formation of relativistic electron fluxes. Analysis of different mechanism contributions to the acceleration of outer belt electrons requires complex observations of electromagnetic fields and evolution of particle spectra. That is why it will be rather interesting to evaluate the contribution of adiabatic effect analyzing storms with clearly distinguished adiabatic effect. The main feature of such storms is the restore of relativistic electron fluxes after storm to near the same level as before storm. *Reeves et al.* [2003] and *Turner et al*. [2013] show that relativistic electron fluxes restore to the same level as before storm in 25-28% cases. Fluxes of relativistic electrons are increased in 53-58% storms and are decreased in 17-19% storms. Fig. 3a shows an example of variations of electrons with energy 1.8 MeV and 2.1 Mev (second and third panels) during magnetic storm on October 01, 2012, when relativistic electron fluxes are near the same after storm as before storm. Other panels on Fig. 3a show Dst, solar wind velocity, AE and IMF Bz. Electron spectra at the moments indicated on Fig. 3a by vertical lines are shown on Fig. 3b. It is possible to see the increase of flux without change of spectra slope. The simplest explanation of such spectra change is the adiabatic effect. An order of magnitude change of fluxes can mean the local an order of magnitude change of the magnetic field. However, it requires more careful analysis.

4. Conclusions and discussion

Auroral oval mapping to the outer part of the ring current change the traditional approaches to the analysis of magnetospheric activity and clarify many features, which have yet no adequate explanation including the processes leading to outer belt electron acceleration. We try to demonstrate the deep connection of auroral processes and acceleration of relativistic electrons of the outer radiation belt. The appearance of high amplitude electromagnetic fluctuations simultaneously with acceleration of outer belt electrons may be considered as the natural consequence of turbulent processes at the latitudes of auroral oval during magnetic storms. Decrease of the magnetic field in the region of auroral oval mapping to the equator and great increase of radial transport lead to relativistic electron deceleration and loses during storm main phase. At the same time, storm time substorms produce comparatively fast electron accelerations in this region and provide the seed population for outer belt electrons. The nearest to the equator position of the auroral oval equatorial boundary determines the location of formed after storm outer belt maximum. This may be connected with first auroral arc brightening during substorm expansion phase onset at the equatorial boundary of the auroral oval, as such brightening is connected with sharp increase of the downward electron flux and probable formation of ion beam of ionospheric ions to the magnetosphere. Such beam can form the peak of plasma pressure decreasing magnetic field in the region of pressure maximum and form a local trap for accelerated electrons.

Only first steps in the study of the connection of auroral processes and acceleration of electrons of the outer belt were made till now and great work is required for the verification of such connections. However, the real progress of ground based and satellite observations gives the possibility to solve the problem.

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