Auroral processes and outer electron radiation belt

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Low latitude aurora (Moscow region) during magnetic storm 16-19 March 2015

Discrete bright auroral arcs are observed at low latitudes during storm time substorms, which can be rather important for the understanding the nature of outer radiation belt.
Objective - to show that outer radiation belt formation is the consequence of auroral dynamics.

Arguments:
• auroral oval is mapped to the outer part of the ring current (in contrast with ordinary suggestion of auroral oval mapping to the plasma sheet),
• new radiation belt maximum is formed at latitudes of nearest to equator first auroral arc brightening during storm time substorms,
• formation of plasma pressure peak at distance, where the first auroral arc is mapped and the same position of the equatorial boundary of auroral electrojet,
• magnetic field distortion by hump of pressure and formation of local trap for energetic particles,
• adiabatic acceleration of electrons during storm recovery phase.
Plasma pressure at low altitudes obtained using the DMSP data

Distribution of plasma pressure and boundaries of electron precipitations in accordance with APM model (http://apm.pgia.ru/) at AL=−200 nTл, Dst=−5 nTл. Dashed line shows boundaries of DAZ and SDP, dotted line shows AOP (auroral oval precipitation) boundary [Antonova et al., 2014, doi:10.1134/S0016793214030025]

Measured values of plasma pressure using DMSP observations are too high for the most part of auroral oval mapping to the plasma sheet, where pressure is < or ~0.2 nPa.

Plasma pressure distribution at low altitudes 60 min before the substorm [Wing et. al., 2013, doi:10.1002/jgra.50160]
In the condition of magnetostatic equilibrium if the plasma pressure is near to isotropic 
\[ \mathbf{j} \times \mathbf{B} = \nabla p, \]
where \( \mathbf{j} \) is the current density, \( \mathbf{B} \) is the magnetic field, and \( p \) is the plasma pressure. ⇒ **Plasma pressure** has constant value at the field line and can be used as **natural marker** of the field line.

First results of plasma pressure comparison at the equatorial plane and at low altitudes [Antonova et al., 2014, doi:10.1134/S0016793214030025; Antonova et al., doi:10.1134/S0016793214030025] show that most part of the discrete auroral oval is mapped not to the plasma sheet. It maps to the surrounding the Earth plasma ring. **Auroral oval mapping to the plasma sheet is the result of magnetic field model overstretching.**
First auroral oval mapping to the equatorial plane by Fairfield [1968] shows the location of the equatorial boundary of the auroral oval at $L \sim 5-7R_E$. The trapping boundary of electrons with energy $>40$ keV is located at $L \sim 12R_E$ [Frank et al., 1964].

The oval **equatorial boundary** location under magnetically quiet conditions is at $\sim 7R_E$. The oval **polar boundary** location under magnetically quiet conditions is at $\sim 10R_E$. ⇒ Support of Fairfield [1968] results.
Transverse currents in the surrounding the Earth plasma ring form the high latitude continuation of the ordinary ring current (CRC)

Minimum B surface is shifted from the equatorial plane due to daytime field line compression by solar wind. Plasma pressure gradients are directed to the Earth from \( \sim 3R_E \) till the magnetopause. \( \Rightarrow \) Ordinary ring current has high latitude continuation till 10-13\( R_E \), which is necessary to take into account analyzing nature of Dst variation.

Auroral oval is mapped to the ring current region.
The Tverskaya relation [Tverskaya, 1986-2011, doi:10.1134/S0016793211010142] (the position of the maximum of outer radiation - belt of relativistic electrons injected during magnetic storms ($L_{\text{max}}$) dependence on the magnetic storm amplitude $|\text{Dst}|_{\text{max}}$). Blue star is the result of outer belt maximum position for the magnetic storm 8–9 October 2012 analyzed by Reeves et al. [2013, doi:10.1126/science.1237743] from the paper Antonova and Stepanova [2015, doi:10.1186/s40623-015-0319-7].
Tverskay relation was explained by Tverskoy [1997], Antonova [2006, doi:10.1016/j.asr.2005.05.005]

\[ |D_{st}^{\text{crit}}| = \frac{27}{70} \frac{\mu_0}{B_{eq}} p_{ex} L_{ex}^7 L_{in}^{-4} = \frac{27}{140} \frac{B_{lobe}^2}{B_{eq}} L_{ex}^7 L_{in}^{-4} \text{ nTl} \]

Formation of sharp pressure peak was predicted by B.A. Tverskoy [1997]

Appearance of pressure peak due to plasma transport from the tail and accelerated ion injections from the ionosphere [Antonova, 2006].
Electron acceleration in auroral arc is accompanied by upward ionospheric ion acceleration to the same energy (see, for example, McFadden et al., 1999, doi:10.1029/1998JA90016, Forsyth et al. [2012, doi:10.1029/2012JA017655]). Such process is greatly increased at the moment of substorm expansion phase onset at the equatorial boundary of auroral oval.


Both processes (acceleration of ions from the ionosphere in the process of first auroral arc brightening and dipolarizations) can lead to pressure peak formation.
Ion fluxes from the ionosphere can be very large in accordance with “Grader” model of thin auroral arc formation discussed by [Antonova [1979, 2002, 2012, doi:10.3103/S0027134912060033], McFadden et al. [1986], Lotko [1986], Stepanova et al. [2002].

Formation of bright auroral arc with particle flux $J \sim 10^{11} \text{ cm}^{-2}\text{s}^{-1}$ and excitation of waves in a wide spectrum range including shear Alfvén waves.
Formation of sharp pressure peak was observed for event 8–9 October 2012 [Antonova and Stepanova, 2015, doi:10.1186/s40623-015-0319-7] in accordance with data of DMSP observations at L=4.2, where outer belt maximum was observed after storm.

Plasma pressure profiles obtained from the DMSP F17 satellite data during the auroral crossing on 8 October 2012 between 21:47:40 and 21:52:50 UT mapped to the equatorial plane by IGRF (red) and Tsyganenko 2004 (blue) models.

Reeves et al. [2013, doi:10.1126/science.1237743]

Intensity of the westward auroral electrojet, obtained using the IMAGE magnetometer network near the Dst minimum on 8–9 October 2012

Seed population can be formed in the local region of increased plasma pressure.
Formation of local pressure peak leads to appearance of local magnetic hole, in which electrons can be trapped [Vovchenko et al., 2017, doi:10.1016/j.jastp.2017.08.024]

Injected in the magnetic hole electrons will be adiabatically accelerated after the magnetic field restore.
Fluxes of relativistic electrons are increased in 53-58% storms and are decreased in 17-19% storms, relativistic electron fluxes restore to the same level as before storm in 25-28% cases [Reeves et al., 2003, doi:10.1029/2002GL016513; Turner et al., 2013, doi:10.1002/jgra.50151].

Contribution of adiabatic effect is possible to evaluate analyzing electron spectra for magnetic storms with peak fluxes after the storm very similar to peak fluxes before the storm, as coincidence of fluxes can be simply explained as the result of adiabatic variations due to magnetic field changes.

RBSP magnetic storm on October 01, 2012 (increase of flux without change of spectra slope) [Antonova et al., 2017, http://pgia.ru:81/seminar]

Adiabatic effect can lead to an order of magnitude electron acceleration.
Conclusions:

• Analysis of plasma pressure distribution at low latitudes and at the equatorial plane at geocentric distances $>5-6R_E$ shows that most part of the auroral oval does not map to the plasma sheet. It is mapped to the surrounding the Earth plasma ring. Such feature helps to explain the observed near circular form of the auroral oval, coincidence of the location of first auroral arc brightening and position of substorm injection boundary.

• Position of new radiation belt maxima coincides with sharp peak of plasma pressure and the nearest to the equator position of the equatorial boundary of aurora oval and auroral electrojet.

• Pressure peak formation can be connected with first auroral arc brightening at the equatorial boundary of auroral oval and corresponding upward acceleration of ionospheric ions.

Solution of outer radiation belt problem requires the analysis of low latitude auroral processes during magnetic storms.
Thank you for your attention