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PLATEAU REGIONS IN THE MAGNETOSPHERIC PLASMA PRESSURE DISTRIBUTION AND LARGE-SCALE FIELD-ALIGNED CURRENTS

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Abstract
The radial distribution of the magnetospheric plasma pressure frequently shows the existence of definite features such as local increases and decreases. Regions with near to constant radial plasma pressure distribution were observed using INTERBALL/Tail probe and THEMIS mission satellites. Such regions were named the plasma pressure plateaus. In spite of the simultaneous observations near the same plateau pressure distribution by two satellites at near the same orbits with time delay ~30 min, it is essential to precisely separate purely temporal pressure changes from spatial variations. We compare the results of THEMIS observations with the predictions of *Tsyganenko and Mukai* [2003] model of magnetotail plasma pressure distribution using observed IMF and solar wind conditions from the OMNI data base. We also determine the projection of the observed pressure plateau to *Iijima and Potemra* [1978] picture of field-aligned currents using TS01, TA16 models. We show that observed plasma pressure profile cannot be the result of the temporal pressure changes.

1. Introduction
Problem of large-scale magnetosphere-ionosphere interactions and the formation of the dawn-dusk large scale electric field continues to be one of the most actual magnetospheric problems. Such field at ionospheric altitudes is supported by large-scale field aligned currents frequently named Birkeland currents. Long history of Birkeland current studies start from observations of *Zmuda and Armstrong* [1974], *Iijima and Potemra* [1976, 1978]. The statistical distribution of downward and upward currents was obtained and the main current systems, which includes Region 1 and Region 2 field-aligned current systems were selected. Iijima and Potemra field-aligned currents continue to exist during quiet geomagnetic conditions when plasma flow velocity is much smaller than the Alfvén and sound velocities. Therefore, they are generated in the conditions of magnetostatic equilibrium when the Ampere force is compensated by plasma pressure gradients. The proof of such point of view requires the determination of magnetospheric plasma pressure gradients and configuration of magnetospheric currents. In spite of multiple satellite observations such problem is not solved till now. That is why any new information about the location of field-aligned current sources is rather important.

Region 1 and Region 2 currents have different signs at definite geomagnetic latitudes. Region of the change of the sign is the region of near to zero field-aligned current. Statistical distributions of Region 1 and Region 2 currents frequently have noticeable latitudinal gaps, which are seen as trapezoidal variations in the low orbiting magnetic field distortions. Such gaps can correspond to regions with near to zero plasma pressure gradients as in the condition of magnetospheric equilibrium field-aligned current density is determined by Grad-Vasyliunas-Boström -Tverskoy [*Grad*, 1964; *Vasyliunas*, 1970; *Boström*, 1975; *Tverskoy*, 1982] equation:

$$j_{||} = \mathbf{b}[\nabla W \times \nabla p] B_i / B_e \quad (1)$$

where $j_{||}$ is the density of field-aligned current, B_i and B_e are the magnitudes of the local magnetic field at ionospheric altitudes and in the geomagnetic equator, **b** is the unit vector along the magnetic field, $W=\int dl/B$ is the specific volume of the magnetic flux tube, p is the plasma pressure. $j_{||}$ is near to zero if $\nabla p \approx 0$.

Distribution of the pressure plateau regions has not been extensively studied, although in some events such regions have been identified. It was shown using data of INTERBALL/Tail probe [*Pisarenko et al.*, 2003; *Antonova*, 2003; *Kirpichev*, 2004] that pressure plateau regions can exist at geocentric distances of ~10 R_E. The pressure plateau regions were identified by *Kirpichev and Antonova* [2022] during the passage of two THEMIS satellites (A and D) in February 2009. This study analyzed nighttime radial profiles of plasma pressure (ion plus electron). The stable existence of plateau plasma structures was confirmed, within which pressure did not actually change (the pressure gradient within these regions at distances from 8 to 11 R_E were significantly lower than the gradients outside of these regions). It was also shown that stable plateau pressure distributions can exist for periods larger than 30 min. It is well known that it is very difficult to separate purely temporal pressure changes from spatial variations especially taking into account that magnetic field line stretching is usually observed in the analyzed region before the substorm expansion phase onset. Possible way of such verification is the comparison of observed plateau with the model prediction sequentially calculated in accordance with magnetospheric boundary conditions during plateau observation. The real proof of the quasi-stationary pressure plateau existence can be the coincidence of its projection to the ionospheric altitudes with the quasi-stationary region with very small field-aligned current value such as the gap between Region 1 and Region 2 field-aligned currents in the *Iijima and Potemra* [1978] picture of field-aligned current distribution.

In this paper we compare selected plasma pressure plateau with the *Tsyganenko and Mukai* [2003] model (TM2003) of the geomagnetic tail pressure distribution. We project observed in [*Kirpichev and Antonova*, 2022] plasma plateau regions to ionospheric altitudes using TS01 [*Tsyganenko*, 2002] and TA16 [*Tsyganenko and Andreeva*, 2016] magnetic field models and compare the projections with the *Iijima and Potemra* [1978] quiet time field-aligned current distribution.

2. Data Analysis

The measurements from two devices ESA and SST (THEMIS mission) [*Angelopoulos*, 2008; *McFadden et al.*, 2008; *Sibeck and Angelopoulos*, 2008] was used to estimate the plasma pressure (ion plus electron). We employed the methodology provided in the SPEDAS 5.0 software by the THEMIS team http://themis.ssl.berkeley.edu/ [*Angelopoulos et al.*, 2019].

Three upper panels at Figure 1 show components of local magnetic field in solar-magnetospheric (SM) coordinate system for THEMIS D measurements February 02, 2009 from 00:58 till 09:25 UT when plasma pressure plateau was observed from 8.25 till 11 R_E (which corresponds to the time interval from 02:03 to 06:14) in radial pressure distribution (triangles at lower panel) with bin selection ~0.28 R_E. Symbols show the median values. Blue vertical lines select pressure plateau region. To produce the projection of definite equatorial region to ionospheric altitude it is necessary to use the magnetic field model. We used TS01 and TA16 models. Median values of solar wind and IMF parameters are determined for every bin using OMNI data base. Model calculations are produced for every bin. Red lines show TS01 magnetic field values, green lines are TA16 values. It is possible to see that two selected magnetic field models reproduce the observed magnetic field distribution with different accuracy. However, the difference of measured and model values is not very much and it is possible to use these models for the plateau region projection to ionospheric altitudes with definite care understanding difficulties of such projection.

Forth panel in Figure 1 shows the comparison of TM2003 tail plasma pressure model with experimental data. Blue dashed line is the model ion pressure in accordance with TM2003 model. Green rectangles show the approximation errors calculated using median OMNI values for every bin. For a qualitative comparison, the radial behavior of the model pressure was obtained starting from distances of 9.5 R_E, which is slightly closer to the Earth than the model applicability limit (R>10 R_E in the night sector). For the events of February 02, 2009 and February 13, 2009 from [*Kirpichev and Antonova*, 2022] the model gives the sharp increase in pressure as the distance decreases from ~11 R_E. Situation with other events is not so clear. At the same time, the experimental data show that, on average, the pressure at these distances near to constant. To improve visualization in the lower panel of Figure 1, the red dashed line shows the trend for the pressure profiles. The red arrow indicates difference in slopes. Therefore, our analysis shows that observed plateau can not be formed as the result of the change of external boundary conditions during period of plateau registration.

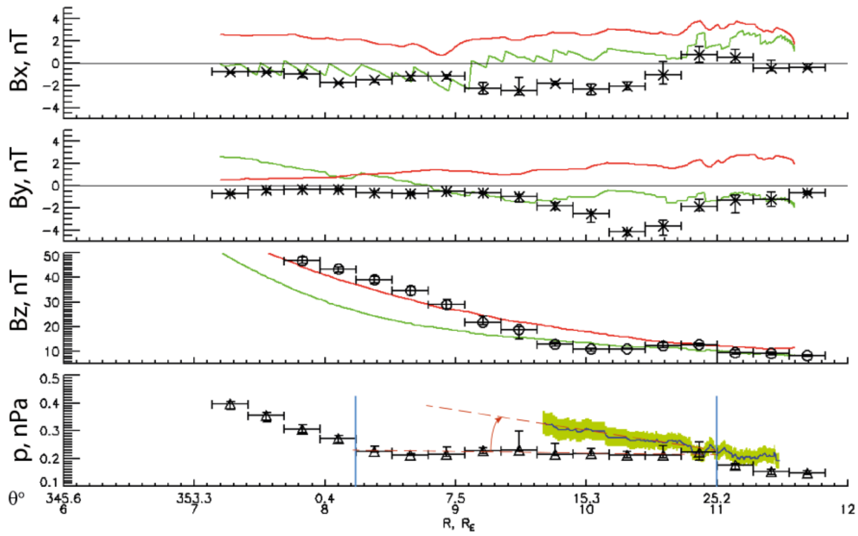

Figure 1. Components of the local magnetic field in the SM coordinate system (B_x is shown by ×, B_y is shown by *, B_z is shown by circles) and plasma pressure for the event February 02, 2009. The azimuthal angle θ, calculated from midnight to dawn, is indicated on the horizontal axis alongside the radial distance.

Figure 2 shows *Iijima and Potemra* [1978] field-aligned current picture and projections of plateau region for event 02.02.2009 onto ionospheric heights using the TS01 (red line) and the TA16 (green line) models of the geomagnetic field. Both projections actually fell into the gap between the current sheets Regions 1 and 2. Near the same situation take place for the event February 03, 2009 from [*Kirpichev and Antonova*, 2022]. However, better coincidence with the gap in Iijima and Potemra picture is observed for TA16 projection. The situation with other events is not so clear. Projections are shifted at larger latitudes. However. they are located in the Region I field-aligned current location. Such feature can be explained as the result of overstretching of models with the predetermined geometry of magnetospheric currents [*Antonova et al.*, 2018].

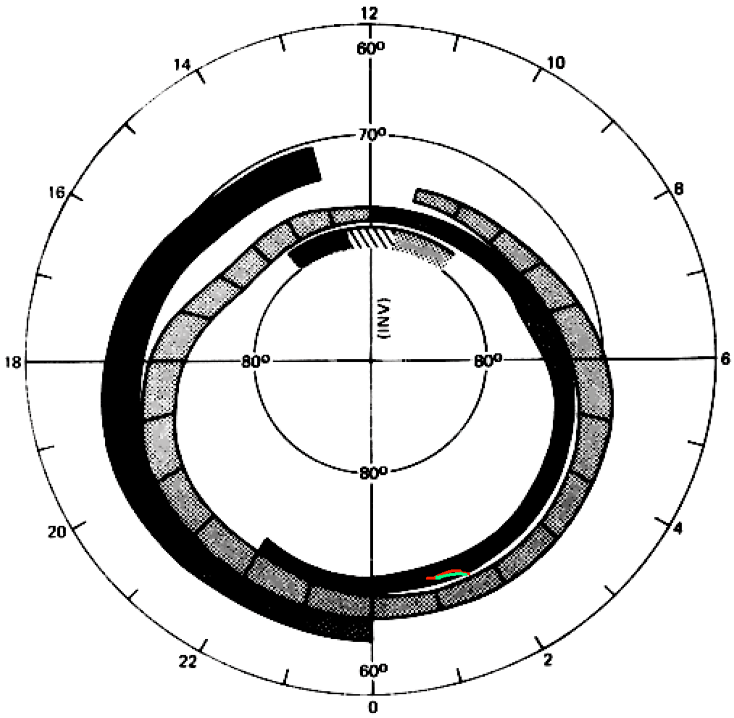

Figure 2. Projection of plasma plateau region onto ionosphere on 02.02.2009 using TS01 (red line) and TA16 (green line).

3. Conclusions

Our analysis supports the conclusion of [*Kirpichev and Antonova*, 2022] paper about the formation of plasma pressure plateau between sources of Region 1 and Region 2 field-aligned currents of *Iijima and Potemra* [1976, 1978]. We show using *Tsyganenko and Mukai* [2003] ion pressure model that plasma pressure plateau can not be observed as a temporal phenomena during period of plateau registration. Projections to the ionospheric heights using TS01 and TA16 models and comparison with Iijima amd Potemra field-aligned current picture coincide with gap between field-aligned current sheets of Iijima and Potemra. This coincidence is a good confirmation of the assumption about the generation of field-aligned currents by pressure gradients near the equatorial plane. The important result of our finding is the possibility to identify the position of the boundary of Region 1 and Region 2 sources of current systems as the results of different models frequently suggest the source of the Region I currents in the magnetospheric boundary layers or very far from the geocentric distance ~10 R_E. The existence of the gap between sources of Region 1 and Region 2 currents during quiet geomagnetic conditions at geocentric distance 8.5-11 R_E supports the conclusion of their generation by ring current plasma pressure gradients (see [*Antonova et al.*, 2023] and references therein).

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