Tail Plasma Domains and the Auroral Oval—Results of Mapping Based on the Tsyganenko 1989 Magnetosphere Model

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We apply the magnetosphere model of TSYGANENKO (1989) to project into the ionosphere the tail plasma domains (with density $>0.1 \text{ cm}^{-3}$) as measured by PROMICS-2 on Prognoz-8. The Plasma Sheet Boundary Layer (the separatrix layer) in our data is easily recognizable as a region distinct from the Central Plasma Sheet only when the plasma sheet expands at the beginning of substorm recovery. During weakly disturbed and quiet periods and at flanks the separatrix layer is not seen by our plasma instrument. However, when both the electron temperature and ion mass composition are taken into account we usually see three distinctly different plasma domains in the tail: the region A (we call it tentatively the warm envelope of the plasma sheet) dominated by the solar wind originated plasma with cold electrons ($T_e \leq 100 \text{ eV}$), the region B (called here the high-latitude plasma sheet) with the electron temperature less than 1 keV, density fluctuations, irregular spectra and presence of cold oxygen ion beams (field aligned and/or conical) and the region C (called here the hot core of the plasma sheet) with electron energy density $\approx 1 \text{ keV/cm}^3$ where the hot oxygen ions dominate over the doubly ionized helium. This classification of plasma sheet subregions is similar to the one discussed by FELDSTEIN and GALPERIN (1985). We suggest that the warm envelope originates from the stagnating Low Latitude Boundary Layer. The warm envelope of the plasma sheet maps in most cases poleward of the statistical auroral oval of Feldstein-Starkov. The hot core of the plasma sheet maps into the equatorward half of the statistical oval and is connected to $R < 15 R_E$ in the equatorial plane. The high latitude plasma sheet with the field aligned and/or conical O^+ beams maps immediately poleward and/or into the poleward half of the F-S oval and is mostly on the field lines which close at $R < 60 R_E$.

1. Introduction

One of the most controversial problems in the auroral physics is related to the subject of aurora mapping to the corresponding regions in the magnetosphere. (For recent reviews see MENG and MAUK, 1991; SANDAHL *et al.*, 1990; SISCOE, 1988; FELDSTEIN and GALPERIN, 1985.) There are several reasons why this problem is so long standing. One of them is lack of a realistic magnetic field model. With an advance of the new TSYGANENKO (1987, 1989) magnetosphere models which are tuned to proper modeling of the near tail with its thin current sheet the situation somewhat improved.

Another reason for problems with auroral mapping is related to lack of a widely approved terminology for different auroral luminosity structures to be mapped. We may refer to the statistical oval of discrete auroras of FELDSTEIN and STARKOV (1967) which is smooth and relatively wide, especially at higher K_p . On the other hand, 1-s auroral snapshots from Viking reveal that the instantaneous auroral distribution usually splits into the relatively thin and

smooth belt continuous at all local times and the dynamic, discrete features connected to the continuous oval but protruding deeply into the dark region poleward of it. The continuous oval on Viking's pictures is seen as a diffuse band of emissions delineating the most equatorward extent of the instantaneous auroral distribution (ELPHINSTONE *et al.*, 1990). From the ground it is seen as an active (even during quiet period) narrow rayed arc extending from the evening through midnight to the morning side (SHEPHERD *et al.*, 1990). The auroral substorm manifest itself not only in brightening and widening of the continuous oval but also in complex transformation of the poleward region of discrete arcs (SANDAHL *et al.*, 1990; SHEPHERD *et al.*, 1990; ELPHINSTONE *et al.*, 1991a). The instantaneous auroral distribution taking together the continuous oval and poleward discrete structures in the midnight sector may extend, e.g., from 64° to 76° geomagnetic latitude (SANDAHL *et al.*, 1990). The continuous oval itself can be wide during the substorm when at the onset a bulge of enhanced emissions forms in the midnight sector followed by poleward expansion as well as the westward/eastward propagation of disturbance along the oval (e.g., CRAVEN and FRANK, 1990). Several degrees of latitude wide auroral distribution will project into the vast expanse of the magnetospheric tail comprising different plasma regimes. So, one should specify each time what is to be mapped, e.g., the thin continuous oval, the poleward discrete features connected to the oval or the widened substorm-time oval. ELPHINSTONE *et al.* (1991a, b) mapped Viking's instantaneous auroral distribution along the magnetic field lines into the magnetosphere using Tsyganenko 1987 magnetic field model. They found that the thin continuous auroral oval lies on closed magnetic field lines crossing the equatorial plane in the region of maximum cross-tail current at $XGSM \approx -6 R_E$. The poleward boundary of the thin continuous oval may map as close as at $XGSM \approx -10 R_E$ in the equatorial plane, but the arc system in the midnight sector poleward and parallel to the main auroral distribution maps as far as at $XGSM = 50-60 R_E$ in the tail what is close to the model boundary between open and closed magnetic field lines in the tail.

It should be mentioned that such a geometrical mapping strongly depends on the magnetic field model and should be confirmed by independent analysis relating different auroral luminosity structures and accompanying particle precipitation (so called Boundary Plasma Sheet and Central Plasma Sheet precipitation—for a recent review see, e.g., SANDAHL *et al.*, 1990) with the relevant source plasma observations in the tail. Here we come to another difficulty related with auroral mapping. It seems that in spite of years of measurements we have no comprehensive classification of tail plasma domains. The main plasma region in the tail is the plasma sheet. The simplistic division of the plasma sheet into the Central Plasma Sheet and its outer "skin", the Plasma Sheet Boundary Layer equivalent to the separatrix layer between closed and open magnetic field lines where the counterstreaming ion beams appear (EASTMAN *et al.*, 1984, 1985; TAKAHASHI and HONES, 1988) seems not to describe the plasma sheet structure in a complete way. E.g., such a region, found on Prognoz-8, as "the hot plasma in tail lobes" apparently above the plasma sheet proper as reported by JIMENEZ *et al.* (1984) (see also BELOVA *et al.*, 1987) is not taken into account. Moreover, the PSBL footprint in the ionosphere should be marked by a narrow region ($\approx 1^\circ$ of latitude) of velocity dispersed ion precipitation at the poleward boundary of the main BPS precipitation region as pointed by ZELENYI *et al.* (1990). Immediately the question arises where the rest of BPS precipitation region maps in the magnetosphere.

Another classification of plasma sheet subregions proposed mainly in Russian literature is extensively presented and discussed by FELDSTEIN and GALPERIN (1985). They distinguish the central (low latitude or main) part of the plasma sheet populated by electrons with mean

energy ~ 1 keV and the outer (high-latitude) plasma sheet populated by softer electrons with the average energy decreasing to ~ 0.4 keV. These two classifications, the one based on the 3-dimensional plasma measurements and distinguishing regions with different shape of the ion distribution function (beams in PSBL vs isotropic distribution in CPS) and the other, based on the average values of moments of the electron distribution function both seem not to tell the whole story about the plasma sheet structure. According to our opinion a more detailed classification of tail plasma domains is necessary to remove rest of our problems with auroral mapping.

We propose an alternative tail plasma classification based on the combined criteria taking into account the range and variability of plasma parameters (electron temperature and density), the ion mass composition (H^+ , He^{++} and O^+), the plasma wave activity and the shape of plasma distribution function for O^+ (cold beams or hot isotropic oxygen plasma).

This study is an extension and complementation of an earlier Prognoz-8 study of the tail plasma domains (JIMENEZ *et al.*, 1984; BELOVA *et al.*, 1987). This earlier study was based on the data from the Russian SKS plasma instrument with limited possibility of ion mass composition diagnosis as well as the narrower energy range and solid angle coverage than PROMICS-2.

2. Instrumentation and Orbit

Plasma data are from PROMICS-2. PROMICS-2 was the second in a series of Swedish-Russian collaborative experiments (R. Lundin was the principal investigator). It consisted of three energetic ion composition spectrometers (ICS). Two ICS:s (D1 and D2) were oriented perpendicularly to the spin axis and covered the energy range 0.05–19 keV. The third (D6, 0.27–4.4 keV) was oriented 10° from the spin axis (which was parallel to the ecliptic plane and directed toward the sun). The experiment also comprised three E/Q charged particle spectrometers measuring positive ions and electrons in the energy range 30 eV–40 keV. Mainly the basic, low speed mode of operation (so called “solar wind mode”) was available during the analysed period. In this mode ion and electron energy spectra from D3 and D4 were obtained in 32 steps during 330 seconds (while the spin period was ~ 120 s). ICS D6 gave 3 spectra of H^+ and He^{++} and one spectrum of O^+ (all in 16 steps with full spectrum scanned in 4.86 s) within one spin period every 20 minutes. D1 and D2 ICS:s were in an integral mode and measured an integral flux of four ions (D1— He^{++} , O^+ ; D2— He^+ , H^+) in the energy range 0.05–16 keV every 20 s. Wave experiment consisted of a double probe as a sensor and an aboard spectrum analyser which measured the spectral densities of electric field fluctuations in the range 2–105 Hz at 9 frequencies (bandwidth ~ 2 Hz). Full spectrum was obtained every 30 s.

Prognoz-8 had highly elliptical orbit with inclination angle 65° and apogee $\sim 30 R_E$. Satellite trajectory in GSM coordinates is shown in Figs. 1(a) and 1(b) (the ordinate axis is the distance to the model neutral sheet along the ZGSM or ZSM axis).

3. Tail Plasma Domains

We take into account all plasma samples with the ion density $N > 0.1 \text{ cm}^{-3}$ excluding strongly flowing mantle or LLBL when adjacent to the magnetopause. According to our analysis of 11 tail crossings (marked on the pictures by numbers as in the Table 1) the following plasma domains can be found in the tail:

Fig. 1(a). Prognoz-8 trajectory in XGSM-DZNS coordinates. DZNS is a distance to the model neutral sheet along ZGSM axis or along ZSM axis (for $R \leq 10 R_E$) respectively according to GOSLING *et al.* (1986) or LOPEZ (1990).

Fig. 1(b). Prognoz-8 trajectory in YGSM-DZNS coordinates. Plasma domains are marked as described in Fig. 1(a).

Table 1. Prognoz-8 tail crossings.

No.	DTP No.*	Start	End**	Average K_p
1	168	04:00 19.07.81	15:00 19.07.81	2+
2	171	04:00 23.08.81	14:25 23.07.81	4+
3	174	00:00 27.07.81	13:40 27.07.81	4+
4	176	22:00 30.07.81	13:00 31.07.81	2+
5	180	16:00 03.08.81	12:25 04.08.81	3+
6	190	03:00 23.08.81	09:05 24.08.81	4+
7	194	03:00 27.08.81	08:25 28.08.81	3+
8	196	21:00 30.08.81	07:45 01.09.81	0+
9	199	04:00 04.09.81	07:05 05.09.81	3°
10	211	16:00 15.09.81	04:47 17.09.81	2°
11	213	18:00 19.09.81	04:00 21.09.81	3+

*DTP = data taking period. **Time of the neutral sheet crossing.

- a domain type A: a region of relatively dense (up to several ions per cm^3) and warm plasma with $T_e \leq 0.1$ keV (usually κ -distribution with $kT = 30\text{--}50$ eV and $\kappa = 2\text{--}5$), with significant fluxes of He^{++} seen in denser regions (the $\text{He}^{++}/\text{H}^+$ ratio of integral flux in the energy range 0.05–16 keV is typically 0.04–0.02). This plasma may be pervaded by cold ($kT \sim 5$ eV, $E \approx 100$ eV–1 keV) and field aligned oxygen beams, the same which are often seen in the lobes. We tentatively name this region the warm envelope of the plasma sheet. An example of plasma data registered within the domain A is shown in Fig. 2. These data come from a moderately disturbed period ($AE = 200\text{--}450\gamma$) of quasi-stationary convection. Prior to $\sim 00:34$ UT (August 28, 1981) the satellite was in the lobe. The exit from the domain A back into the lobe took place about half an hour later than shown in the Fig. 2 and is related to the plasma sheet thinning before a sudden and giant impulse in AE indices ($\delta AE \approx 400\gamma$) at $\sim 03:25$ UT. The hot post-break up plasma sheet with separatrix signatures at the boundary reached the satellite at 03:49 UT (not shown in Fig. 2).

- a domain type B: He^{++} depressed in comparison to the warm envelope, instead, as a rule, O^+ are observed in the form of field aligned beams (at highest latitudes) and/or conical beams. Most spectacular O^+ beam events are related to substorm activity. Electron temperature is 0.2–0.5 keV in its outermost part (domain B1) and up to 1 keV further into the sheet (domain B2). Density is less than 1 cm^{-3} , fluctuations of N are observed. For the domain B the most characteristic is the strong wave activity at frequencies less than 100 Hz. The domain B is also most variable in response to substorm activity. It is named the high-latitude plasma sheet because the electron average energies are the same as characteristic for the region called the outer (high-latitude) plasma sheet by FELDSTEIN and GALPERIN (1985). An example of plasma data registered within the domain B is shown in Fig. 3. These observations were made during a strong substorm (maximum $AE \approx 900\gamma$ at 03:15 UT). The substorm expansion phase started at about 02:55 UT (the satellite was in the lobe at that time). The substorm recovery began at 04:00 UT and lasted up to 06:00 UT when AE dropped to $\sim 50\gamma$. Later (not shown in the Fig. 3) the satellite registered the quiet HLPS (with less intense O^+ beams) and at 08:35 UT entered the hot core.

- a domain type C: $T_e \geq 1$ keV, $n \approx 1 \text{ cm}^{-3}$, wave activity completely suppressed, oxygen fluxes are hot (~ 1 keV) and isotropic—no beams, electron and hydrogen ion fluxes are also

Fig. 3. PROMICS-2 raw data recorded in the region B. For a detailed description see Fig. 2.

Fig. 4. PROMICS-2 raw data recorded in the region C. For a detailed description see Fig. 2.

isotropic with neither strong flow signatures nor density fluctuations (both present in the domain B). Prognoz-8 photoelectron fluxes are near background in this region. The boundary of the region C is most easily distinguished just by a sudden dropout of the photoelectron fluxes as measured by SKS plasma instrument ($E \geq 18$ eV) (JIMENEZ *et al.*, 1984). This domain is tentatively named the hot core of the plasma sheet and is the same region as the low-latitude (central or main) plasma sheet discussed by Feldstein and Galperin. An example of plasma data registered within the domain C is shown in Fig. 4. These observations were made during quiet period ($AE \sim 50\gamma$) following a strong substorm (maximum $AE \approx 600\gamma$ at 06:15 UT). Photoelectron dropout on SKS took place at about 10:30 UT, and low frequency electric field fluctuations ceased at 11:00 UT. Starting at $\sim 10:54$ UT, a population of high energy electrons ($E > 20$ keV) appeared as indicated by an increased count rate in the high energy range of D4 spectrometer. The nominal neutral sheet (LOPEZ, 1990) was crossed at $\sim 13:00$ UT. Near the neutral sheet the satellite spin plane is nearly tangent to the magnetic field line so the loss cone and 90° pitch angle are scanned 2 times every 120 s spin period and 5 or 6 times during 330 s energy sampling period. The spin modulation of counting rates with 5 or 6 maxima during 330 s indicates either trapped (maximum at 90°) or butterfly (minimum at 90°) pitch angle distributions. Note that O^+ fluxes from D1 in the hot core are isotropic in contradistinction to the region B where the cold beams of O^+ are mostly observed. The ratio O^+/He^{++} of integral fluxes from D1 ICS is much higher than 1 in the hot core.

Limited data set of only 11 tail crossings during very different geomagnetic conditions (from super quiet, $AE < 50\gamma$ —case No. 6 to strongly disturbed, $AE \approx 1500\gamma$ —case No. 2 and 3) does not allow us to make any well founded statistical studies of the variability in location and properties of the different plasma domains as a function of magnetic activity. However, some regularities are immediately evident. E.g., the domain A is especially extended along ZGSM axis during northward IMF periods and at flanks (ZWOLAKOWSKA *et al.*, 1992). During disturbed conditions it may appear in the growth phase of substorm and then disappears at the expansion. When the domain A is contiguous to the main body of the plasma sheet, there are no clear signatures of the separatrix layer at the boundary of plasma sheet—a relatively smooth transition is observed between the lobe and the domain A as well as between the domains A and B. In two cases (events 2 and 3) of strong substorm activity the domain A was observed to penetrate deeply into the region normally occupied by the domain C. Details of these events and the interpretation are given in (POPIELAWSKA *et al.*, 1992; KOPERSKI and POPIELAWSKA, 1992). It would be interesting to know whether the penetration of cold plasma ($T_e \leq 100$ eV) into the equatorial inner magnetosphere ($R < 10 R_E$) is a rule during strong substorms.

The location of the domain B seems to be most variable in response to substorms. This domain may expand to more than $10 R_E$ above the neutral sheet (case No. 4 and 6) at the beginning of substorm recovery and be absent as close $\sim 0.5 R_E$ above neutral sheet just before the sudden increase of AE in course of substorm expansion phase (case No. 2 and 3). From this point of view a least easy to budge is the domain C as its outer (high-latitude) boundary varies merely between $\sim 3 R_E$ and $\sim 0.5 R_E$ above the neutral sheet (at $R < 15 R_E$).

The hot core partially overlaps the ring current region. However, both the satellite orbit and the plasma instrument are not well suited for measurements in this interesting region of the magnetosphere. Moreover, we have neither the precise measurements of the magnetic field nor the information on the instantaneous satellite orientation. Both are necessary for interpretation of plasma and energetic particle measurements in a region with significant gradients of B .

4. Tail Plasma Domain Mapping

These 3 plasma domains are mapped with the help of T89 model (for the actual K_p) and IGRF 1980 inward into the ionosphere as shown in Fig. 5, and outward into the $\min |B|$ surface as shown in Fig. 6. Low-altitude projections (in the corrected geomagnetic latitude—corrected MLT coordinates) are compared with the position of the statistical auroral oval of FELDSTEIN and STARKOV (1967). The FS auroral oval is a good reference frame for statistical studies on the auroral ionosphere-magnetosphere coupling and represents an average (for given Q , K_p or AE) region where discrete aurorae appear at an observer's zenith.

The results are following:

- The domain A partially lies on the field lines which may be open as they reach the flank magnetopause or the distant tail at $R \geq 60 R_E$. This domain maps well poleward of the FS oval during quiet conditions. During disturbed periods it maps immediately poleward or even into the oval itself (events 2 and 3), and in such cases it is on closed T89 model field lines.
- The domain B1 (with $T_e = 0.2\text{--}0.5$ keV) lies partially on the field lines connected to the distant tail ($R \geq 60 R_E$) and maps immediately poleward of the FS oval.
- The domain B2 lies on the field lines which close at $R \leq 50 R_E$ and maps into the poleward half of the auroral oval. With increasing activity this region encompasses the field lines mapping to progressively lower latitudes within the oval.
- The domain C often maps into the equatorward half of the oval. For the two flank

Fig. 5. Projection of the tail plasma domains (at $DZNS \geq 0$) into the ionosphere. The auroral oval position of FELDSTEIN and STARKOV (1967) for $K_p = 3^+$ is shaded. Plasma domains are marked as described in Fig. 1(a). Lines crossing the corrected latitude 70° in the clockwise order starting at ~ 06 MLT represent the tail traversals No. 1–11, respectively.

Fig. 6. Mapping of tail plasma domains (at $DZNS \geq 0$) into the min $|B|$ surface (in YGSM-XGSM coordinates). Plasma domains are marked as described in Fig. 1(a).

crossings during weakly disturbed period the projection of the domain C covered the full range of auroral latitudes for the appropriate K_p . With increasing activity the hot core is found at field lines projecting into lower latitudes up to the equatorward boundary of the FS oval. The domain C is connected to $R \leq 15$ equatorial distances on the min $|B|$ surface.

All field lines coming out the statistical auroral oval close at geocentric distances $R \leq 60 R_E$. The poleward boundary of the FS oval traces approximately the expected boundary between the LLBL and the plasma sheet in the equatorial plane. The 1989 magnetosphere model of Tsyganenko does not contain a near-Earth neutral line, even for most disturbed conditions. This model gives merely a local minimum of the magnetic field line curvature radius at $10\text{--}15 R_E$ in the equatorial midnight region. If the near-Earth neutral line forms in the tail during substorms, some of our mapping results may be far from reality.

5. Summary and Discussion

When Tsyganenko 1989 model is used for mapping, the statistical oval appears to be connected to the vast magnetospheric reservoir of plasma between $R \sim 5\text{--}7 R_E$ to $R \approx 60 R_E$. This region is populated by at least 3 different plasma domains. The equatorward half of the

FS auroral oval is connected to $R \leq 15$ geocentric distances occupied by a hot core of the PS. Rest of the oval maps into the high latitude plasma sheet—the most dynamical tail plasma domain. The warm envelope of the plasma sheet (northward IMF) maps well poleward of the FS oval during quiet conditions. We suggest that this plasma is a source of the high latitude arcs delineating the “inner” auroral oval of ELPHINSTONE *et al.* (1990).

The relation of PSBL (the separatrix layer) to our warm envelope and the high latitude plasma sheet is unclear. Distinct separatrix signatures are seen in PROMICS-2 data only at the edge of the high latitude plasma sheet when the plasma sheet expands at the beginning of substorm recovery. In such situations we see higher energy electrons coming up to 5 min earlier than the post-break up hot ions. Our detector D6 looking toward the Sun is able to see only the slowest and coolest PSBL beams from the range specified by TAKAHASHI and HONES (1988). So, we cannot see the region of the velocity dispersed ion beams (as well as the earthward flowing beams) and the actual extent of the PSBL is unknown. However, the high latitude plasma sheet is sometimes so extended along Z-axis that it rather cannot constitute the PSBL as a whole. The typical PSBL traversal time range from a fraction of minute to more than 10 minutes with mean values of about 5–6 minutes according to BAUMJOHANN *et al.* (1988). These authors used a photoelectron signature as a fiducial mark of boundary between the PSBL and CPS. At Prognoz-8 we usually see the photoelectron flux drop-out (at $E > 18$ eV) just before the entrance into the hot core of the plasma sheet.

Our results are only in partial agreement with results of JIMENEZ *et al.* (1984). Our warm envelope is called by them “the hot plasma in the lobes” (“hot” in opposition to the cold ion beams usually found in the lobes). Their interpretation is based on the revealed by them “similarity of the characteristics of the rarefied plasma in the tail and the denser plasma sheet”. They suggest the plasma sheet origin of this “hot plasma in the lobes”. BELOVA *et al.* (1987) proposed the Kelvin-Helmholtz instability of the plasma sheet surface as a source of the detached “hot” plasma in the tail. However, as was shown above, the warm envelope is often denser and always much cooler than the main body of the plasma sheet (HLPS and the hot core). High content of He^{++} allows us to suggest that the source of this plasma domain is the stagnating LLBL. EASTMAN *et al.* (1985) also found the cold plasma component within the plasma sheet and suggested that this cold component comes directly from the flank LLBL. The horizontal transport of the LLBL plasma from flanks into the central part of the tail must be very effective especially during the northward IMF conditions.

Jimenez *et al.* mapped their plasma domains using the Mead-Fairfield magnetosphere model and the dipole internal field. With differences in details, result of mapping is similar to our mapping: “hot plasma in the lobes” maps poleward of the Feldstein-Starkov oval. Their CPS samples are in most cases equivalent to our hot core samples and for this region the differences in mapping are substantial as their CPS projections overlap the whole oval latitude range, while our hot core projections are mainly in the equatorward half of the oval.

Ion mass composition of discussed plasma domains is in perfect agreement with the statistical results of LENNARTSSON (1987, 1988). He found the significant fluxes of He^{++} and dense plasma sheet during quiet conditions with northward IMF when we see the extended and dense warm envelope. During disturbed conditions the warm envelope thins or disappears and the HLPS with its intense cold oxygen beams is more extended. In such a way the transition realizes from the quiet-time plasma sheet to the hot and less dense plasma sheet with high oxygen content typical for disturbed conditions.

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