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216

Mapping of the Precipitation Regions to the Plasma Sheet

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The progress in the mapping of the auroral regions in the Earth's polar ionosphere to outer magnetosphere reflects our growing understanding of the gross magnetospheric structure. Several "natural tracers" were identified and used by us for the mapping scheme advocated for more than a decade. A "natural tracer" is a plasma boundary identifiable at different altitudes which, from physical reasons, is aligned along the magnetic flux tube (accounting for cross-field convection). The boundaries' locations describe the current state of the magnetosphere. The following tracers to the tail were used in our studies: the low-latitude Soft Electron precipitation Boundary; the large-scale Convection Boundary, or an Alfven Layer; the Plasmapause; the Stable Trapping Boundary for high energy electrons; the precipitating hot ion Isotropy Boundary; the two types of Velocity-Dispersed Ion Structures: VDIS-1 (adjacent to an electron inverted-V structure within the oval), and VDIS-2 (just poleward from the oval). A new "Wall Region" concept related to non-adiabatic (non-MHD) ion dynamics allows to add its effects in the list of "natural tracers". Another newly discovered structure in the tail is the Low Energy Layer of counter-streaming low-energy (<100 eV) ions and electrons at the outer edge of the Boundary Plasma Sheet. Its physical origin in the far tail, and respective source location, are debatable. Physical limits to the MHD-mapping approach are placed by plasma and field fluctuations and turbulence, by finite Larmor radius effects including non-adiabatic particle dynamics, by finite Alfven propagation times in the magnetosphere, and by various medium- and large-scale disturbances—"auroral activations".

1. Introduction. Some History and Limitations

The start of the Sputnik era coincided with the time of world-wide coordinated geophysical observational programs in the frame of the International Geophysical Year. Processing of unique sets of multivarious geophysical data (at that time nearly without automatisation) and their analysis in many aspects changed the existing concepts concerning the near-Earth space, its structure and dynamics. It was like a conquest of a new world, and new domains appeared in geophysics: Earth's magnetosphere, radiation belts, magnetospheric tail with the lobes and plasma sheet in between. Auroral physics became an important part of the magnetospheric research. Magnetospheric generators of polar electrojets and 3D global current systems began to be analyzed with their electric fields and magnetic variations within the magnetosphere, and its structure gradually began to be clarified.

One of significant discoveries of this epoch was the discovery by Feldstein (1960, 1963) and Khorosheva (1962) of the auroral oval—an ever present band of discrete bright, but variable auroral features around magnetic pole. Its form appeared to be more or less stable in invariant latitude-magnetic local time frame at similar disturbance levels measured by the K_p- or Q-indices. The oval was found to be displaced to the nightside and it was suggested to be a result of global magnetospheric distortion due to solar wind pressure (Feldstein, 1960, 1963). Thus an intimate relation of the auroral oval with the global magnetospheric structure became an important topic of research.

Measurements of trapped particles first revealed that the outer edge of the Van Allen belt (the Stable Trapping Boundary, STB) has an asymmetric form similar to the oval, and is nearly colocated with it (O'Brien, 1963; Frank *et al.*, 1964, Akasofu, 1968). Feldstein and Starkov (1970) have shown that this colocation extends to all levels of geomagnetic activity and the average location of the Stable Trapping Boundary (Λ_s) within statistical errors coincides with the equatorial boundary of the statistical auroral oval. Auroral oval location was proposed by Akasofu (1968) as a natural magnetospheric coordinate system. Thus the STB appeared to be the first natural boundary dividing important plasma domains—the inner magnetosphere with trapped energetic particles, the Van Allen belt, and the outer magnetosphere with its tail. In early models the mapping of the nightside auroral oval to the tail plasma sheet was a common point (Akasofu *et al.*, 1967; Akasofu, 1968). Vasyliunas (1968, 1970) analyzing data from OGO satellites have shown that there is a definite inner boundary of the nightside plasma sheet. It is projected to the equatorial edge of the oval at different levels of magnetic activity (Vasyliunas, 1970) and is located close to the STB (Frank, 1971).

A band of diffuse auroral emission and unstructured soft electron precipitation was discovered equatorward from the auroral oval of discrete forms by Lui and Anger (1973). Equatorial boundary of soft electron precipitation (STB) was first studied by Galperin *et al.* (1977) and Gussenhoven *et al.* (1981, 1983), and a close connection, or colocation, of this boundary with the plasmapause was demonstrated.

At the polar side of the oval a band of weak diffuse red (630 nm) auroral emission was found by Eather (1969); it was initially called "soft zone", and later Polar Diffuse Auroral Zone. Measurements in this region of particle precipitation with high sensitivity revealed spectra characterized by very soft auroral electrons, often quite inhomogeneous, but mostly without appreciable field-aligned acceleration (Valchuk *et al.*, 1979). High energy electrons were also present in this zone up to the so called "Background Boundary", Λ_b and sometimes their trapped pitch-angle distribution was noted (McDiarmid *et al.*, 1975). Thus there was an evidence that the Auroral oval and Polar Diffuse Auroral Zone are located on closed field lines.

The spectacular discoveries of the Plasma Sheet Boundary Layer (PSBL) with high energy ion beams by Williams (1981) and Eastman *et al.* (1984, 1985) revived the long sought hope to locate the Distant Neutral Line, DNL, in the tail. Many researches considered the role of the DNL in generation of discrete auroral forms of the oval starting from the pioneering work by Akasofu and Chapman (1961). At some point the public opinion shifted to a concept of the mapping the auroral oval to the PSBL, and not to the Plasma Sheet as was believed earlier.

Since that time our research has indicated support for the original concept of the mapping of the auroral oval to the whole body of the nightside plasmasheet in the tail. The details are described in Feldstein and Galperin (1985) (further in the text, FG85) and in Galperin and Feldstein (1991) (further, GF91).

In this paper we review recent progress in the area of mapping the nightside auroral features as observed both from the ground and from auroral imagery from space to a "steady" oval. Main attention is directed to the "research tools" in the mapping problem—to various "tracers" which help to delineate the field line tracing in the real magnetosphere, and to physical limitations of such concepts for the Earth's magnetospheric tail.

2. "Natural Tracers"

By a tracer we mean a characteristic plasma signature which is experimentally identifiable at widely different altitudes and which, for some physical reason, is aligned with a magnetic flux tube, or at least, do not deviate from it appreciably (for example, due to $\vec{E} \times \vec{B}$ drifts). Such a tracer can be used as a "tool" in experimental field line tracing within MHD limits. In our work we used several natural tracers and have introduced some new ones based on the work of our and other research groups. Besides that, artificial field-line tracers, such as energetic electron beams emitted from rockets or satellites, can be of great value.

We consider now in some detail only two highly significant such tracers, but will indicate several others below.

The most significant tracer, and often the easiest to be measured from a satellite equipped with high energy particle detectors with pitch-angle resolution (or scanning), is the so called Stable Trapping Boundary, STB or Λ_s—"sharp boundary", for high energy electrons (see, for example, O'Brien, 1963; McDiarmid *et al.*, 1975). Its signature is a disappearance of the typical trapped particle anisotropy (of an intensity peak at 90 degrees pitch angle with a nearly empty loss cone) for decreasing magnetic rigidity of particles with increasing invariant latitude. It is accompanied by a drop in intensity (sometimes initially a narrow isotropic intensity burst, but then a drop). According to contemporary views this isotropisation is usually due to non-adiabatic scattering of the trapped particles in the near-equatorial tail region where dipole magnetic field becomes stretched. Precisely it occurs where the particles Larmor radius becomes nearly equal to the magnetic field curvature radius at the equatorial edge of the neutral sheet cross-tail current (Sergeev and Tsyganenko, 1982; Bosqued *et al.*, 1992, 1993a,b; Ashour-Abdalla *et al.*, 1992a,b, 1993; Sergeev *et al.*, 1993). This boundary divides the two main magnetospheric regions with fundamentally different character of the dominant energetic particle cross-field motion. In the former it is composed from gradient and curvature drifts of particles trapped in the inner magnetosphere (Van Allen belt). In the latter it is the $\vec{E} \times \vec{B}$ bulk plasma drift (mostly sunward in the near tail) outside the trapping boundary together with non-adiabatic particle motions within the neutral sheet.

It is very significant that the STB lies at, or close to, several other principal magnetospheric plasma boundaries: the Isotropy Boundary for trapped energetic ions, IB, the inner boundary of the plasma sheet (Vasyliunas, 1968; Frank, 1971); the Region I/ Region II interface of the large-scale field-aligned currents (Potemra, 1977) and the boundary between largely unstructured ("diffuse") auroral precipitation, and the auroral oval of bright discrete auroral forms (see, Feldstein and Starkov, 1970; Valchuk *et al.*, 1979; FG85; GF91; Weiss *et al.*, 1992). However, in the paper by Weiss *et al.* (1992) the outer part of the Van Allen belt which is located inside of the STB, but adjacent to it, is called "anisotropic (central) plasma sheet". The Van Allen belt in their scheme is apparently bounded not by STB, but by a boundary which seems to be analogous to the SEB, or convection boundary, or plasmapause. The region between the SEB and STB where low energy plasma from the plasma sheet is injected during disturbances, but decays during prolonged quietness was named "Remnant Layer", RL, in FG85. However, it was stressed there that the RL is located inside the Van Allen belt, and bounded from the polar side by STB. Thus to our opinion, the difference between our scheme and that of Weiss *et al.* is merely in terminology.

Another point of concern with the STB is that as was shown by Imhof *et al.* (1993), the detailed latitude profiles of particle ridgidity vs latitude can be inconsistent with the non-adiabatic particle scattering concept. A trapped particle cut-off at the dayside magnetopause can also be of importance, at least, occasionally, during magnetopause inward motions.

Recently Newell *et al.* (1995) proposed a convenient operational algorithm to find a boundary which is located close to, or coincident with, the diffuse/discrete auroral boundary. The algorithm uses low-energy electron precipitation data measured from a DMSP satellite and is based on the values of correlation coefficients between sequential particle energy spectra parameters. While in the "diffuse" zone the correlation is high, it usualy drops abruptly within the "discrete" zone. The resulting location of the "small-scale fluctuation boundary", at least for moderately disturbed conditions and a substorm expansive phase, appears to be within a band of isotropisation of high

Table 1. Main magnetospheric plasma boundaries and their "natural tracers" at the nightside.

	OPTICAL FEATURES	CORRELATED WITH:		
	AIRGLOW no auroral emission	PLASMASPHERE Region of dense thermal plasma		
BOUNDARY 1 TRACERS:	EQUATORIAL BORDER OF WEAK DIFFUSE AURORAL EMISSION mostly 630 nm, can be pulsating	"ZERO ENERGY" PRECIPITATING PARTICLES BOUNDARY (ZEB)	INSTANTANEOUS LARGE-SCALE CONVECTION BOUNDARY (ECB)	SHARP DROP ON A RADIAL THERMAL DENSITY PROFILE (PLASMAPAUSE) Density drops formed earlier at lower L can be also present. (PP)
	DIFFUSE AURORAL ZONE (unstructured emission)	REMNANT LAYER Region of large-scale convection within the outer radiation belt (RL)		
BOUNDARY 2 TRACERS:	EQUATORIAL AURORAL ARC AND/OR OTHER BRIGHT DURABLE DISCRETE AURORAL FEATURES	STABLE TRAPPING BOUNDARY Λ_s FOR OUTER BELT ELECTRONS OF > 50keV (STB)	ISOTROPY BOUNDARY FOR TRAPPED ENERGETIC IONS OF > 50keV (IB)	REGION 1/REGION 2 LARGE-SCALE FAC BOUNDARY (RIR2B)
	AURORAL OVAL of bright discrete durable auroral features	CENTRAL PLASMA SHEET Region of hot plasma on stretched field lines in the tail (CPS)		

Table 1. (continued).

BOUNDARY 3 TRACERS:	POLEWARDMOST BRIGHT STEADY ARC, OR BAND, OF THE AURORAL OVAL	POLEWARDMOST INVERTED-V WITH POWER FLUX $Q > 1 erg/cm^2 * s$	CONVECTION SHEAR OR REVERSAL, IMPULSIVE AND WAVELIKE CONVECTION SURGES (CSR)	POLEWARDMOST INTENSE SMALL-SCALE FA CURRENT SHEET OF $J_{par} > 2 \mu A/m^2$
	POLAR DIFFUSE AURORAL ZONE of weak diffuse 630 nm emission, splashes, wave motion, VDIS-2 events	BOUNDARY PLASMA SHEET (BPS) INCLUDING PLASMA SHEET BOUNDARY LAYER (PSBL) AND LOW ENERGY LAYER (LEL) energetic particle beams (BPS)		
BOUNDARY 4 TRACERS:	POLAR BORDER OF POLAR DIFFUSE 630 nm EMISSION, impulsive motions, waves (PDAB)	DECREASE OF PRECIPITATION TO VERY LOW LEVELS (usually $Q < 10^{-2} erg/cm^2 * sec$, $E_{av} < 1 keV$) (PIB)	BOUNDARY OF LARGE-SCALE CONVECTION IN THE POLAR CAP which is antisunward for IMF $Bz \leq 0$ or sunward for IMF $Bz \gg 0$ (PCB)	OPEN/CLOSED MAGNETIC FIELD BOUNDARY (OCB)
	POLAR CAP (absence, or extreme weakness, of auroral light emissions)	TAIL LOBES region of open field lines (TL)		

energy trapped particles of different ridgidity, i.e. close to the STB for high energy electrons (not measured by DMSP). This new boundary quantifies the distinction between "diffuse" and "discrete" visible aurora. It is appealing from its clear physical meaning: the appearance of small-scale structuring of the precipitation. But, it still needs to be further studied and its location to be compared with the classical STB for various conditions, and in particular during recovery phase.

The other very important magnetospheric plasma boundary which we shall briefly consider here, is the poleward boundary of the auroral oval. Often a bright auroral arc can be seen for a long time at this boundary during expansive and recovery phase of substorm. It gave the ground to Elphinstone *et al.* (1995a,b) to name this configuration "the double oval". But poleward from it particle fluxes drop about an order of magnitude, and the average energy decreases to less than about 1 keV. This simultaneous sharp drop of the electron and ion precipitation intensity (see, Troshichev *et al.*, 1995) is a definitely identifiable boundary—the poleward edge of the auroral oval.

A band of a weak electron precipitation with very low energy exists adjacent to the poleward edge of the oval. It can be as narrow as some tens of km, but can extend much wider in poleward direction during quiet times. It was called Polar Diffuse Auroral Zone from measurements of the 630 nm auroral emission, but weak electron precipitation within this band with energy usually less than about 0.5 keV can be fairly inhomogeneous, with acceleration bursts of low energy electrons of $\leq$1 keV (Valchuk *et al.*, 1979). Occasionally high energy electrons with trapped pitch-angle distributions were found in this zone by McDiarmid *et al.* (1975), and it was concluded that the respective field lines are closed. Thus it may be supposed that the Polar Diffuse Auroral Zone lies inside the open/closed field line boundary (see, FG85 and GF91).

Kovrazhkin *et al.* (1987) and Zelenyi *et al.* (1990) found within the Polar Diffuse Auroral Zone specific VDIS-2 events (Velocity-Dispersed Ion Structures of the second type) from low-altitude AUREOL-3 satellite in about 10% of passes. The VDIS-2 events were shown to be corresponding in width and velocity dispersion direction (energy increase with increasing latitude) to the projected to ionosphere velocity- dispersed ion beams of the Plasma Sheet Boundary Layer (PSBL) as measured in situ from ISEE orbits by Eastman *et al.* (1985), Frank (1985), and Takahashi and Hones (1988). This inference was confirmed by Frank and Craven (1988) who traced a field line from the ISEE location inside the PSBL to the oval poleward boundary with a bright arc. Several dozens of such comparisons using Tsyganenko-Usmanov model for various magnetospheric conditions were presented by Craven (1990) (and private communication, 1995). These results are consistent with the PSBL mapping to, or close to, the poleward edge of the auroral oval (with the precision $\sim \pm 1°$ of latitude up to $\sim$14 R_E from 8 cases). It must be noted that the Polar Diffuse Auroral Zone was not noted from the DE-1 auroral images in these cases.

The study of the VDIS-2 from AUREOL-3 data was extended by Bosqued *et al.* (1993a,b), and they evaluated their occurrence probability per pass as 18%. From the AKEBONO satellite data at altitudes up to about 10,000 km, i.e. mostly above the field-aligned acceleration altitudes within the oval, the occurrence probability of the VDIS-2 increased to about 40% (Saito *et al.*, 1992). Measurements from AKEBONO satellite confirmed that the VDIS-2 events occur poleward from the inverted-V events typical for the oval (Saito *et al.*, 1992; Yamamoto *et al.*, 1993; Fukunishi *et al.*, 1993) which eliminated objections from Lyons (1992a). Onsager and Mukai (1995), in a case study from AKEBONO data, successfully modeled an observed VDIS-2 as a result of a velocity-filter effect on a field-aligned particle injection at the distant tail region, $5R_E$ wide, located just inward from the neutral line (which was supposed to be at $60R_E$). Thus now the origin of the VDIS-2 events in the distant tail seems to be accepted by the magnetospheric community. However, the origin of the bright poleward arc of the "double oval" (Elphinstone *et al.*, 1995a,b) remains debatable (see below).

A VDIS-2 event thus also can serve as a very important natural tracer for the PSBL. This finding supported the conclusions described in detail in FG85 and GF91 that the PSBL maps to the Polar Diffuse Auroral Zone, but not to the whole auroral oval as some researchers initially suggested (Eastman *et al.*, 1985; Rostoker and Eastman, 1987; Lyons and Nishida, 1988, and others), and some apparently still suppose (see, for example, Lyons, 1991, 1992a). However, outside the near—midnight region the situation can be different, see Burke *et al.* (1994).

These two tracers, the STB for energetic electrons and/or IB for ions, and VDIS-2, were considered here in more detail because of their utmost importance in the mapping problem and also as examples of their use to track the locations of magnetospheric plasma boundaries at a particular time from particle measurements.

Other tracers were also found and used by many researchers for these purposes. Velocity-dispersed ion structures of another type, VDIS-1, were occasionally found within the auroral oval adjacent to, but equatorward from, a prominent inverted-V electron precipitation structure (Bosqued *et al.*, 1986). They were shown to be a result of an upward acceleration of H^+ and O^+ ions above an inverted-V structure in the conjugate ionosphere. These ions can reach ionospheric altitudes in the conjugate hemisphere after crossing the CPS when they escape deceleration by the similar upward directed field-aligned electric field of the conjugate inverted-V. One possibility for such an escape is due to an enhancement of the dawn-dusk electric field drift, and this causes the velocity-filter effect for ions dring their traversal of the CPS. Evidently, closed and not too extended field lines of the oval and CPS are thus traced by the VDIS-1 events.

A stable auroral arc located at the midnight oval equatorial border was supposed by Galperin *et al.* (1992) to be a result of non-adiabatic westward ion motion forming a "quasi—Pedersen current". These features of the ion motion arise in the near-Earth plasma sheet region where plasma—sheet ions meet the condition of strong non—adiabatic scattering (Buchner and Zelenyi, 1987). This strong scattering region in the near-Earth CPS was named "the wall region" by Ashour-Abdalla *et al.* (1992b, 1993). If measured and tested experimentally, these features of the ion motion together with the corresponding field-aligned currents associated with the equatorial oval arc, and its observable location, also can serve as tracers to the wall region.

Those described above and other natural tracers together with some results from the use of artificial tracers-electron beams, were used in the construction of the mapping scheme described in detail in FG85 and GF91. At the same time, a search for new tracers is still in progress. The use of tracers is especially important for a reliable extension of the mapping results presented below for the near-midnight meridian, to other local times and for other geophysical conditions (IMF $B_z \gg 0$, substorm phases, large magnetic storms, etc.).

A collection of tracers is given in Table 1 grouped by their appearance at, or close to, the boundaries between the main plasma domains of the magnetosphere including the tail. The locations of these tracers, or signatures, assigned to a particular plasma boundary, do not necessarily precisely coincide, and some of them can be absent or unidentifiable in a particular case, or a satellite pass. Usually such a boundary is a band of a finite width, with some gradients, and some experience is desirable in its identification. Still, together they help to determine an approximate location of a particular plasma boundary, at least, in majority of cases during steady geophysical conditions (IMF $B_z \leq 0$, near-midnight meridian). However, there can be abnormal cases, or satellite passes, when an identification, and even significance of these boundaries is doubtful due to various modes of the ever-changing magnetosphere, but we believe that such cases are a minority (however, interesting in itself).

3. Models and Puzzles of the Distant Tail

A radical step forward in the quantitative analysis of the gross magnetospheric structure was the construction, from comprehensive magnetic field measurements in the magnetosphere combined with theoretical considerations, of global magnetospheric models by Tsyganenko (1987, 1989, 1990). The arguments concerning magnetic flux conservation used by many researchers, and in particular in FG85, became quantitative within these models and based on a large body of magnetic field measurements throughout the magnetosphere. The resulting field line tracings using these models confirmed the mapping scheme advocated by FG85 and GF91. They were additionally supported by analyses of various multipoint measurements of auroral and magnetospheric phenomena (see, for example, Frank and Craven, 1988; Craven, 1990; Elphinstone *et al.*, 1991; Elphinstone *et al.*, 1995a,b). These magnetospheric models, as a new powerful "research tool", apparently served for magnetospheric community as the final argument to accept the mapping of the whole auroral oval consisted of discrete bright forms, to the whole body of the tail Central Plasma Sheet with the Neutral Sheet within it, as was advocated in FG85 and GF91.

Extension of these models to the growth phase stretched tail conditions were made by McIlwain (1991, 1992) and by Pulkkinen *et al.* (1991a,b, 1992). Further progress in these directions was reported at the IAGA-95 in Boulder by Pulkkinen *et al.* (1995). Results of development of new fully analytical global magnetospheric models organized by AE and Dst-indices, by IMF components and with other new advances, were reported by N. Tsyganenko during IAGA-95 symposium (Tsyganenko, 1995). We can state that to our knowledge, all these new models and their developments appear to be fully consistent with the basic mapping scheme presented in FG85 and GF91.

At the same time, obviously, a mapping scheme reflects the level of understanding of magnetospheric physical processes involved, and of real knowledge of the gross magnetospheric structure based on comprehensive in situ measurements. Certainly, more detailed global observations of auroral phenomena and of the tail features bring new interesting results and conjectures concerning substorm and other types of variations, about LLBL and cusp/cleft phenomena, etc. And even in the near-midnight meridian, it seems that our level of knowledge and understanding of the gross structure of the tail currents and fields, especially for the distant tail, is still inadequate, despite spectacular experimental results recently demonstrated by the analysis of the GEOTAIL data (Nishida *et al.*, 1995a,b; Berchem *et al.*, 1995; Frank *et al.*, 1995; Matsumoto, 1995; Mukai, 1995).

For example, a theoretical analysis by Vasyliunas (1995) indicates a possible existence of an unidentified additional boundary at the open tail magnetopause in the form of a rotational discontinuity, or a standing Alfven wave, which divides the field lines reconnected at the front magnetopause and those emerging from the tail lobes. This boundary must vary with the IMF direction.

Another such problem is that according to the cited above magnetospheric models, all the magnetic flux tubes exiting from the oval will close through the Neutral Sheet (i.e. be connected to the opposite hemisphere) within, say $100R_E$, and only open tail lobe lines from the polar caps extend much further. It is well known that the tail of the magnetosphere extends to thousands R_E (see, for example, Intrilligator *et al.*, 1969; Vaisberg *et al.*, 1972). Important magnetic fluctuations in the distant neutral sheet, rapid penetration of a significant part of the IMF B_y component, frequent passage of plasmoids with dissipating boundaries (slow shocks) and moving magnetic loops revealed by the GEOTAIL studies raise a question of the tail stability against cross-tail diffusion of the solar wind plasma. What is the limiting length of the tail and its structure at distances much higher than $100R_E$? It is composed of opened field lines with one or both ends in the solar wind. How can the tail be so long and stable in the changing solar wind? It seems that we still are missing some essential physical aspects of the tail current structure and stability.

In particular, if the theta-shape cross-tail current (in the YZ-plane) form the tail structure, and if it consists of gradient-drift currents carried by tail plasma particles as some researchers believe, the absence of drastic changes in the tail during a plasmoid passage presents a problem. Indeed, during a Travelling Compression Region (TCR) event the magnetic field and its gradients in the tail lobes change significantly (see, Slavin *et al.*, 1990, 1992, 1994). Hence gradient drifts of the tail plasma particles must also change at this location, as well as the cross-tail current carried by these particles. If this is indeed so, not only a simple adiabatic compression is expected in the tail lobes, but important magnetic transients, which apparently are not observed. How can the tail be so stable against such a disturbance if these concepts are true?

It seems that the self-consistent distant tail configuration(s) including magnetic field, tail plasma particles' drifts and tail currents, needs further study to provide answers to the above questions. An important step in this direction is made by Winglee (1994), who introduced explicitly currents and fields at the magnetopause in his 2D model. This led to a number of very interesting inferences, in particular to the generation of the FA currents at the tail magnetopause. Such currents may be also tested as a tracer when a 3D extensions of this approach will be available.

Recent comprehensive MHD magnetosphere modelling for varying Interplanetary Magnetic Field (IMF) conditions (see, for example, Ogino *et al.*, 1994; Ogino, 1995) shows that after a change in the IMF direction magnetic loops appear within the magnetospheric tail with both ends in the solar wind, and can be present for a long time. In this not infrequent situation, even without a substorm, a tracing using stationary models between such a "detached" loop region in the tail and the polar cap will lead to errors. Thus for a realistic ever changing IMF it is not quite clear where is the region in the polar ionosphere where a particular distant tail region and its magnetopause maps to at a particular time. And when it does map to the polar cap, in which conditions and where such a footprint is to be found, and what signatures it can have. An inadequacy of the stationary MHD mapping concept for the distant tail (see next section) could play a principal role in providing answers to these problems.

4. Limitations of the MHD Mapping Concept

It is well-known that the MHD concept of magnetic field lines and of frozen-in plasma is often very effective, especially in the inner magnetosphere and near tail. However even in these regions where thermal plasma is relatively dense and magnetic field can be reasonably stable (except substorms), non-MHD processes are prominent and cannot be neglected for many quantitative analyses, in particular for calculations of cross-tail and FA currents, and for ion precipitation processes.

The obvious limitations of an MHD approach are:

1. Larmor radius of particles must be much less than any characteristic space scale of the plasma and field macroparameters;
2. Time scale of any variations of these parameters must be much longer than any gyroperiod and Alfven transit time in the system;
3. Particle distribution function must be close to a maxwellian.

These limitations in particular assure that the amplitude of magnetic field variations during any gyroperiod must be negligibly small.

If we apply these limitations to the distant tail data according to measurements from ISEE-3, GALILEO and GEOTAIL spacecraft, it becomes evident that they are all violated in the neutral sheet. In particular, the amplitude of the magnetic field variations (of order of several nT) is an order of magnitude higher than the average value of the minimal magnetic field in the Neutral Sheet evaluated as $B_z \sim +0.26$ nT at ~200 R_E (Heikkila, 1988; Owen and Slavin, 1992). The time scale of these magnetic field fluctuations appears to be much less than an ion gyroperiod while the average plasma velocity is antisunward—opposite to the $\vec{E} \times \vec{B}$ drift in the dawn-dusk electric field. Recent results from the GALILEO (Frank *et al.*, 1994) and GEOTAIL (Frank *et al.*, 1995; Mukai, 1995) spacecraft have shown that the ion distribution function in the distant tail Central Plasma Sheet usually consists of one or several beams, sometimes with a cold plasma core, i.e. is very far from a maxwellian. When all the MHD limitations are violated in the distant tail Neutral Sheet (but not necessarily in the tail lobes), the validity, and even use, of the mapping concept needs to be reconsidered. In these conditions details of ion distribution functions, especially well defined ridges, can be used as a kind of tracers and help to evaluate distances to the particle source (see, for examples, Martin and Speiser, 1988; Speiser and Martin, 1992; Elphic *et al.*, 1995).

At the same time it is astonishing how good the contemporary global MHD models (for example, such as described in Usadi *et al.*, 1993; Ogino *et al.*, 1994; Ogino, 1995) and Large Scale Kinetic (LSK) models (see, Ashour-Abdalla *et al.*, 1993, 1994) describe the general properties of the tail. According to Walker and Ashour-Abdalla (1995) it is due to a very limited volume in the distant plasma sheet where non-adiabatic processes and strong fluctuations take place.

However, the rapid plasma and field variations observed in the distant plasma sheet must lead, in particular, to a very efficient cross-tail diffusion in the XY-plane, so that the LLBL and even magnetosheath plasma of higher density will easily penetrate inside the Neutral Sheet from the flanks (probably, with the Bohm diffusion speed). Another efficient way to populate the distant Neutral Sheet by the magnetosheath plasma is by injection from the Plasma Mantle: ion trajectories are sinking in the Z-direction to the XY-plane due to dawn-dusk electric field $\overrightarrow{E} \times \overrightarrow{B}$ drift (Pilipp and Morfill, 1978; Ashour-Abdalla *et al.*, 1993, 1994). The resulting mixture of plasma flows and inherent fluctuations within the distant Neutral Sheet can well retain an antisunward velocity component from their sources. This velocity component will be superimposed on the sunward $\overrightarrow{E} \times \overrightarrow{B}$ drift velocity component, so that the average velocity can be either sunward or antisunward. But with such irregular distribution functions the value of average velocity has a limited physical sense, especially if not all the distribution function is measured.

However, as was found by Nishida *et al.* (1995b) from the GEOTAIL data, detailed plasma measurements when sorted for positive/negative B_z and tailward/sunward plasma flows, are consistent with the general dawn-dusk electric field in the distant tail. Apparently these rapid variations then indicate the importance of localized currents in the distant Neutral Sheet. If these small-scale cross-tail currents have a divergence, and if they are on the magnetic field lines that reach polar ionosphere, auroral phenomena will appear at the ionospheric footprint-presumably, somewhere poleward from the Polar Diffuse Auroral Zone (or, within it?). Up till now no such regions were identified which can be definitely ascribed to the footprint of the distant tail activity (at $\sim$200 R_E). However, observers in the polar cap often note localized splashes of rayed auroral forms, and weak precipitation spikes are not too rare on a polar cap crossing by a low-altitude satellite. Where and how they originate in the far tail or in the lobes? There are reports about encounters in the lobes with a "warm envelope of the plasma sheet"—a relatively cold and dense plasma (Zwolakowska *et al.*, 1992) now also observed from the GEOTAIL. Further work on this intriguing problem of mapping, i.e. of delineating the gross structure and self-consistent plasma configuration of the distant magnetospheric tail, will benefit from recent comprehensive measurements from the GEOTAIL together with the INTERBALL and other high-altitude satellites.

Thus, the extreme length and apparent stability of the tail appears as one of important unsolved problems. It can be noted that the tail of the Jovian magnetosphere is the largest detail of the whole Solar System, and the basic physics of these long magnetospheric tails is still not understood!

5. Resulting Mapping at Near-Midnight during Steady Conditions and IMF $B_z \leq 0$

5.1 *Inner magnetosphere (region of stable trapping)*

Let us summarize the gross structure of the plasma domains in this rather well studied region. The two main plasma domains within the stable trapping zone are: 1) the plasmasphere where cold plasma accumulates and large-scale magnetospheric convection is practically absent, or very weak, and 2) the outer part of the outer Radiation Belt where large-scale magnetospheric convection penetrated into some more or less well defined boundary. This Convection Boundary, CB, between these two plasma domains during steady periods corresponds to a drop in thermal plasma density. It is due to enhanced loss, to the outer magnetosphere or magnetopause, of the thermal plasma accumulated at high altitudes from the upper ionosphere source. This boundary often is named Plasmapause if it occurs at density levels of order of 50–100 particles per cc. During quiet times a smooth (equilibrium) plasma density radial profile of a power law form $N(L) \sim L^{-\gamma}$, where $\gamma \sim 3$ to 4, can extend up to $L \sim 8$. There the convection boundary can be located at rather low thermal plasma densities at high enough altitudes above the contracted auroral oval. The terminology for such a distant small thermal plasma density drop is not commonly established, so it may not simply be named "Plasmapause". Thus, due to different time scales, the CB and the "Plasmapause" do not necessarily coincide, and the terminology used can sometimes be misleading.

The high latitude boundary of the trapping zone—the so called Stable Trapping Boundary, STB, can be formed by losses due to the non-adiabatic scattering at the nightside at the inner edge of the Neutral Sheet cross-tail current, (as discussed in Section 2). However, there is another possibility of formation of the sharp decrease of trapped particle intensity: a loss, enhanced by the shell-splitting process, by a drift-trajectory crossing the dayside magnetopause which can be accompanied by some rigidity-dependent isotropisation. The relative importance of these two loss/isotropisation mechanisms changes with changing magnetospheric conditions and remains to be explored in more detail. Probably this is one of the reasons for peculiar latitude profiles of the isotropisation boundary for different rigidities as observed by Imhof *et al.* (1993).

The diffuse auroral zone is located between the Convection Boundary and the State Trapping Boundary. It is formed by precipitation of low energy particles from some part of the Ring Current. (But the Ring Current certainly can extend to latitudes much lower than the diffuse auroral zone.) These particles were injected to respective L-shells during recent disturbances, their average energy generally decreases inward. This precipitation decays in time and greatly decreases during prolonged quiet periods (Newell *et al.*, 1995). That is why it was called the "Remnant Layer" in FG85.

The resulting mapping according to the scheme by FG85 and GF91 is shown in the upper rows of the Table 2. It is supported by many direct comparisons and now as we believe can be considered as firmly established and agreed by the magnetospheric community (if terminology differences are resolved).

5.2 *Near and middle tail* $(10 < R < 50R_E)$

The main plasma domain in the near and middle tail is the Central Plasma Sheet (CPS)—the principal reservoir of the hot plasma with temperature and density increasing toward the Earth and toward the central plane (XY-plane for zero tilt) where the Neutral Sheet (NS) is located. Their main characteristics in the near tail were recently summarized by Huang and Frank (1994), and Traver *et al.* (1994).

The NS by its plasma pressure compensates the deficit of the magnetic pressure due to diamagnetically decreased magnetic field at the interface between the two tail lobes, where, by contrast, the plasma pressure is negligible. Contrary to opinions based on the previous measurements with low time resolution, the CPS and NS appear to be quite variable, dynamic and

Table 2. Resulting mappings for near and middle tail.

AURORAL ALTITUDES		MAGNETOSPHERIC PLASMA DOMAINS
DIFFUSE AURORAL ZONE located equatorward of the bright discrete auroral forms of the auroral oval proper; Region 2 of large-scale FAC	⟺	REMNANT LAYER located within the Outer Radiation Belt till the boundary of stable trapping Λ_s
AURORAL OVAL with bright discrete auroral forms and strong localised FA currents; Region 1 of large-scale FAC	⟺	CENTRAL PLASMA SHEET (CPS) includes the Neutral Sheet; Plasma diamagnetic effect is significant
POLAR DIFFUSE AURORAL ZONE of 630 nm emission; weak low energy electron precipitation and VDIS-2 events located just poleward from bright oval auroras. Splashes and poleward expansions	⟺	BOUNDARY PLASMA SHEET (BPS) includes Plasma Sheet Boundary Layer (PSBL) and Low Energy Layer (LEL). Velocity-dispersed ion ion beams in PSBL; counterstreaming very low energy electron and ion beams in LEL
POLAR CAP Very weak light emission and low energy precipitation (Polar Rain). Occasionaly solar electrons and solar cosmic rays.	⟺	TAIL LOBES Extremely low plasma density

inhomogeneous (Baumjohann *et al.*, 1990; Angelopulos *et al.*, 1992, 1993). They well can be the site of sources for small-scale intense field-aligned currents which feed discrete auroras within the auroral oval (Sergeev *et al.*, 1986). These small-scale currents are the result of divergence of the large-scale cross-tail current carried by the CPS hot plasma. At the same time, ionospheric plasma contribution for the Central Plasma Sheet can be very important, and not only during substorms (Daglis *et al.*, 1994; Yau *et al.*, 1995).

Adjacent to the CPS outer (polar) boundary is the Boundary Plasma Sheet (BPS) with specific characteristics. Along with general decrease of the hot plasma density and temperature toward the boundary, intensive field-aligned velocity-dispersed ion and electron beams are observed there (Williams, 1981; Takahashi and Hones, 1988). The sign of the velocity dispersion (velocity decrease toward central plane) is consistent with the $\vec{E} \times \vec{B}$ drift in the dawn-dusk electric field. Earthward directed beams are at least partly reflected by magnetic mirror at lower altitudes and return to the tail as tailward beams. As was mentioned above, the projected beams characteristics are consistent with the VDIS-2 events at low altitude as their ionospheric footprint.

Thus the BPS with its field-aligned ion beams is mapped to the Polar Diffuse Auroral Zone, adjacent to, or just poleward from, the Auroral Oval of bright durable discrete auroras (FG85, GF91). The polewardmost bright arc of the oval (when the double-oval condition prevails) can be excited by field-aligned accelerated particles from the distant CPS, or from dissipating plasmoid(s) formed during recent disturbances, involving a New Neutral Line, NNL (as a single, or multiple, X-line), or from an extended region of turbulent NS (see below).

The outer part of the BPS has some peculiar characteristics. It contains low energy (≤ 100 eV) counterstreaming ion and electron beams called Low Energy Layer, LEL (Parks *et al.*, 1992). LEL must map to the poleward boundary of the Polar Diffuse Auroral Zone (Feldstein and Galperin, 1994) close to, or at, the open/close magnetic field boundary. Thus in our terminology the BPS includes both PSBL and LEL.

The resulting mapping scheme according to FG85 and GF91 is shown in the Table 2.

5.3 Processes in the distant tail

The origin of the PSBL energetic particle beams and an additional feature at the PSBL outer part—the Low Energy Layer (LEL)—remains debatable. Zelenyi *et al.* (1990) and Onsager and Mukai (1995a,b) suppose that a DNL (and/or a finite width region just inward from it) can be the source of these particle beams. They constructed respective phenomenological models which are in good accord with observations. Ashour-Abdalla *et al.* (1994, 1995) constructed comprehensive large-scale kinetic models with particle sources at the Plasma Mantle and in the LLBL, based on the account of non-adiabatic ion motions during ion encounters with the NS. These two approaches contrast in that in the former there is some particular location of the source for the PSBL particle beams—a narrow steady-state DNL (and/or a relatively narrow adjacent CPS region), while in the latter approach the beams emerge from the distant NS all along tens of R_E distances up to about 100 R_E. In the former approach the DNL location and particle beam emission characteristics are model dependent, while in the latter the DNL is supposed to be located at the far edge of the NS—the open/closed field boundary, and do not play an important role in the PSBL beams formation. Plasma characteristics in the distant tail are indeed quite different at distances significantly lower, and higher, than about 80–100 R_E (see, Borovsky *et al.*, 1995). But a realistic evaluation of the width, and time/space evolution, of the reconnection region will need at least two-point measurements in the distant tail.

Thus the Polar Diffuse Auroral Zone mapping to intermediate altitudes (Saito *et al.*, 1992; AKEBONO satellite) and to PSBL at 15–30 R_E (Williams, 1981; Takahashi and Hones, 1988; Frank and Craven, 1988; Craven, 1990) seems to be well established. But further mapping of the PSBL ion beams to their source (or sources) in the distant tail is still an important unsolved problem of the distant tail structure.

This uncertainty to some extent is connected with the uncertain origin of the bright auroral arc often observed at the polar boundary of the oval. It needs a powerful and relatively persistent source in the distant tail. We believe that it is mapped to the outer CPS with turbulent NS, where some transition from a more regular CPS state to a more fluctuating, turbulent, occurs. This is because this arc is located equatorward from the Polar Diffuse Auroral Zone or, inward from the PSBL, which from the available evidence originates from a distant closed field region. The mapping of this arc to CPS, or PSBL, or to a dissipating plasmoid(s), or else, will probably remain bebatable until the physical origin of the arc's source is clarified.

It seems to us rather doubtful that a well defined narrow quasi-stationary DNL may exist in a highly variable, turbulent distant NS in "steady" conditions. We suppose that a large-scale turbulent NS region, of tens of R_E along the GSM X direction, which is centered somewhere about 80–100 R_E, can act as a converter of the magnetic energy to the plasma kinetic energy. If one looks outside this CPS region, the conservation laws will lead to the observable effects which resemble "patchy 2D reconnection", while at a closer look a variety of small-scale bursty non-linear processes could be operational within the distant CPS, and no single narrow quasi-steady DNL will appear. It can be suggested that this extended, but thin turbulent tail region can be the source of field-aligned ion beams, traceable by VDIS-2 events and thus can be mapped to the BPS. With an average minimum magnetic field (in Z direction) in the distant tail of $\sim$0.3 nT, a distance of 10 R_E along the $-X$ direction will map to ionospheric altitudes as a band of order

Table 3. Tracers: Tested(T) and provisional(P).

BOUNDARY TRACER	SYMBOL	STATUS
PLASMAPAUSE	PP	T
EQUATORIAL BOUNDARY OF LARGE-SCALE CONVECTION	CB	T
SOFT ELECTRON PRECIPITATION BOUNDARY	SEB	T
STABLE TRAPPING BOUNDARY FOR HIGH ENERGY (> 50 keV) ELECTRONS OF THE VAN ALLEN BELT	Λ_s STB	T
ISOTROPY BOUNDARY FOR ENERGETIC IONS	IB	T
REGION1/REGION2 INTERFACE OF LARGE-SCALE FIELD-ALIGNED CURRENTS	R1R2	P
HOMOGENEOUS AURORAL ARC-ASSOCIATED FA CURRENTS	AAC	P
BOUNDARY OF SMALL-SCALE FLUCTUATIONS IN PRECIPITATING AURORAL ELECTRON SPECTRA	FAE	T
MHD FIELD-LINE RESONANCES IN THE mHz FREQUENCY RANGE	FLR	P
VDIS-1: VELOCITY DISPERSED BAND OF IONS ACCELERATED UPWARD ABOVE AN INVERTED-V STRUCTURE (INSIDE THE OVAL)	VDIS1	T
VDIS-2/PSBL ION BEAMS: VELOCITY-DISPERSED BAND OF PROTONS (POLEWARD FROM THE OVAL)	VDIS2	T
HIGH-LATITUDE BOUNDARY OF CONJUGATE IONOSPHERIC PHOTOELECTRONS	PHB	P
POLAR BOUNDARY OF PRECIPITATING IONS	PCBI	T
POLAR BOUNDARY OF PRECIPITATING ELECTRONS	PCBE	T
BACKGROUND MEDIUM-ENERGY ELECTRON PRECIPITATION BOUNDARY	Λ_b	T
RIDGES IN ENERGETIC IONS DISTRIBUTION FUNCTION AS THE SOURCE TRACER	RIDF	P

of 50 km width which is comparable to a minimal Polar Diffuse Auroral Zone width, or even less than that. Obviously a replacement of a single quasi-steady DNL by a wide highly turbulent NS as a main reconnection region in the distant tail is only a hypothesis which hopefully can be tested using the GEOTAIL data. We note however that it does not contradict to the model results of Onsager and Mukai (1995) (who adopted similar finite region at 55–60 R_E).

Evidently, there still remains much to discover in the structure and mapping of the distant tail regions.

6. Concluding Remarks: New Tracers and Tracings Wanted!

It is obvious that a search for new tracers is needed, as well as other experimental and model approaches to relate the outer magnetosphere plasma domains and particular features to the respective regions of the near-Earth magnetic field and polar ionosphere (see, Spence, 1995). A short list of suggestions for both tested and yet not fullyexplored tracers is given in Table 3. Some of these tracers, for example, the suprathermal conjugate photoelectron boundary, can be used also in the magnetospheres of other planets to delineate their structure and mapping schemes.

Hopefully multipoint measurements from the GEOTAIL, INTERBALL, POLAR and CLUSTER high-altitude satellites will further clarify the structure and dynamics of the Earth's outer magnetosphere and will lead to confident mapping at other local times, and for substorms and strongly northward IMF B_z conditions. As for the distant tail, the invaluable data from the ISEE-3 and GEOTAIL demonstrate the need of a more advanced kinetic theory and models for their understanding, so it seems difficult to propose a reliable mapping now.

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