UNSOLVED PROBLEMS IN MAGNETOSPHERIC PHYSICS
8[8h] September, 2015
Crown Spa Hotel, Scarborough, UK

AURORAL OVAL MAPPING AND THE MAIN PROBLEMS OF MAGNETOSPHERIC DYNAMICS

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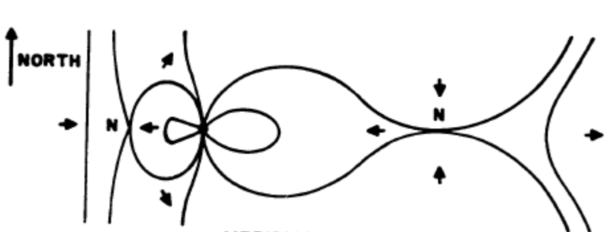
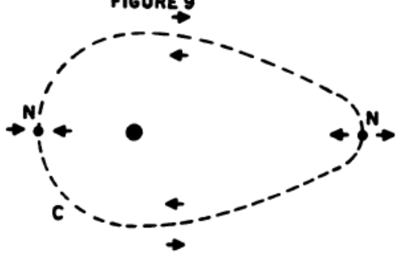
Specific topics

- Magnetosheath and magnetospheric turbulence as a reason of main unsolved problems of magnetospheric physics.
- Overstretching of magnetic field models and plasma pressure as a natural tracer of magnetic field lines.
- Comparison of pressure values at low altitudes in the auroral oval and in the plasma sheet proper and reanalysis of the problem of auroral oval mapping.
- Surrounding the Earth plasma ring and ring like shape of the auroral oval.
- Distribution of transverse currents in the ring.
- Auroral oval and outer radiation belt during magnetic storms.

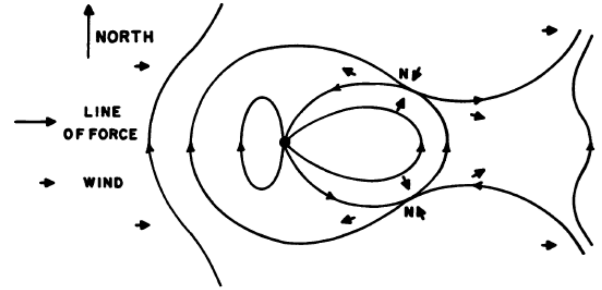
The picture of magnetospheric convection that predominates until now (Dungey [1961] model)



MERIDIAN PLANE
MAGNETIC FIELD AND PLASMA MOTION FOR THE CASE OF A SOUTHWARD INTERPLANETARY FIELD
FIGURE 9

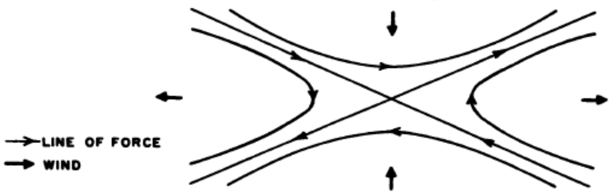


EQUATORIAL PLANE PLASMA FLOW FOR THE CASE OF A SOUTHWARD INTERPLANETARY FIELD
FIGURE 10

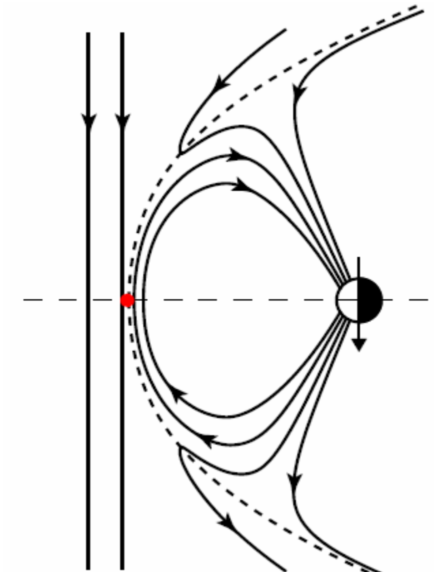


MERIDIAN
PLANE MAGNETIC FIELD AND PLASMA MOTION FOR THE CASE OF A NORTHWARD INTERPLANETARY FIELD
FIGURE 8

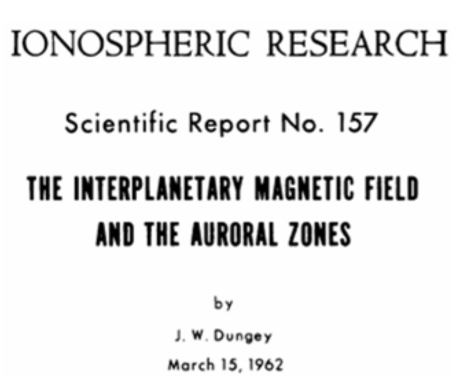
FIGURE 6



MAGNETIC FIELD AND PLASMA MOTION IN THE PLANE PERPENDICULAR TO A CURRENT SHEET NEAR A NEUTRAL POINT
FIGURE 7



Hasegawa et al. [2010]



IONOSPHERIC RESEARCH

Scientific Report No. 157

THE INTERPLANETARY MAGNETIC FIELD AND THE AURORAL ZONES

by

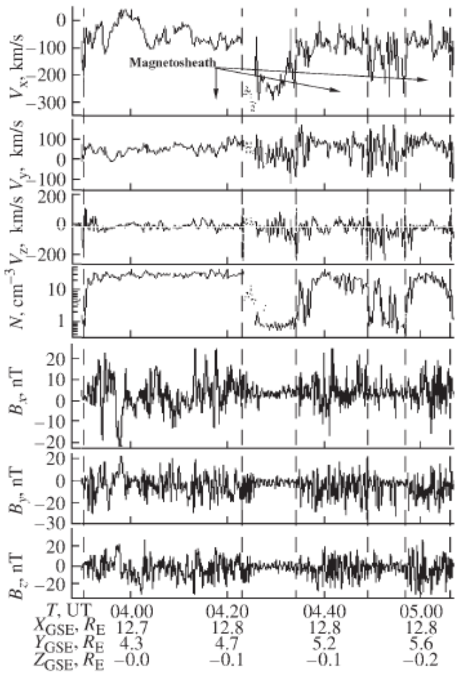
J. W. Dungey

March 15, 1962

However even in 1962, while discussing the aforementioned picture, Dungey wrote the following: ...A further difficulty is that **the flow is probably turbulent**, particularly in the "wake" of the earth, and both Pioneer I and Explorer I observations show clear indications of some hydromagnetic form of turbulence...

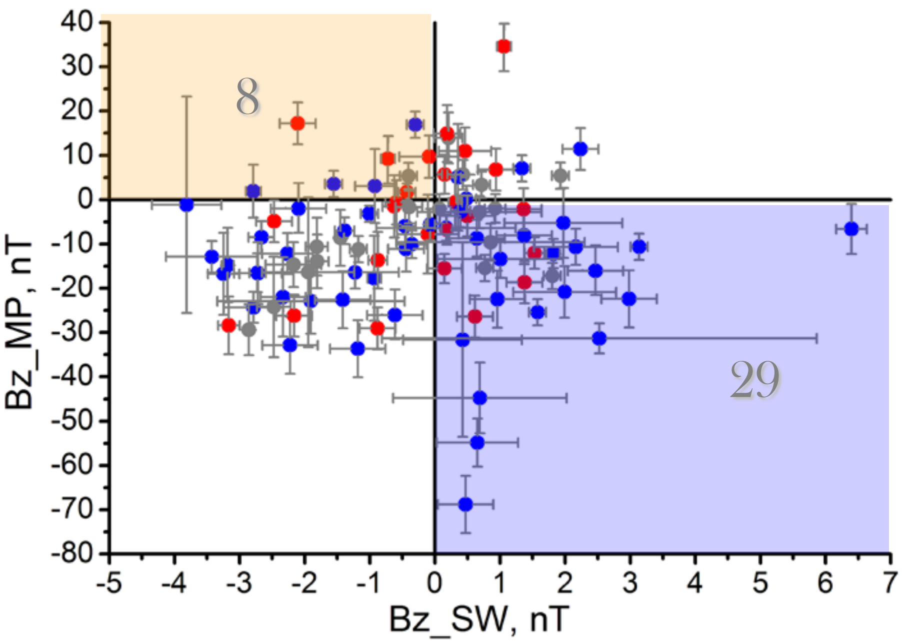
Problem No 1 for Dungey scheme: Turbulent magnetosheath

There is a significant number of experimental results showing the high level of plasma turbulence in the magnetosheath (Luhmann et al. [1986], Sibeck et al. [2000], Zastenker et al. [1999, 2002], Lucek et al. [2001], Němeček et al. [2000a,b; 2002a,b], Shevyrev & Zastenker [2005], Shevyrev et al. [2007], Gatynska et al. [2008], Šafránková et al. [2009], Savin et al. [2008-2012], Rossolenko et al. [2008], Znatkova et al. [2011], Pulinets et al. [2012, 2014] ets.).



Typical example of magnetosheath fluctuations [Rossolenko et al., 2008, 0.1134/S0010952508050018; Antonova et al., 2012, ISBN 978-953-51-0339-4]

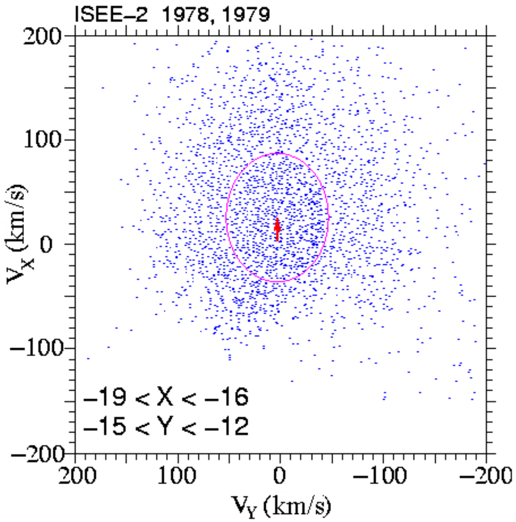
There is no clear relation between the IMF before the bow shock and the magnetic field before the magnetopause (Pulinets et al. [2014 doi:10.1016/j.asr.2014.04.023])



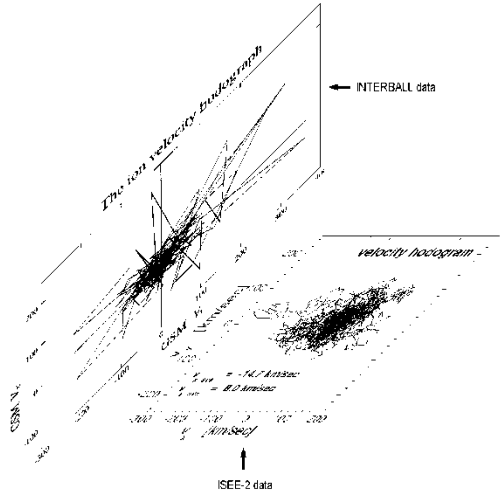
For different locations near to the magnetopause the direction of the magnetic field is different. ⇒ Problems for theories of magnetic reconnection on the magnetopause.

Problem No 2 for Dungey scheme: Turbulent plasma sheet

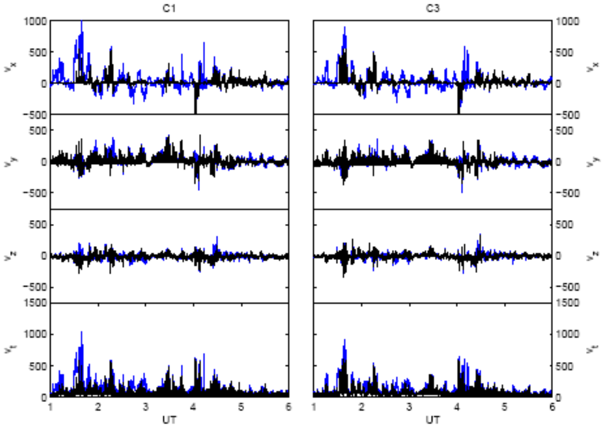
Plasma sheet turbulence was discussed by Antonova [1985, Geomagn. Aeron., 25, 517–520], Montgomery [1987, Magnetotail Physics, 203-204] and analyzed later by Angelopoulos et al. [1992, 1993, 1996, 1999]; Borovsky et al. [1997, 1998], Consolini et al. [1996, 1998], Antonova et al. [2000, 2002]; Yermolaev et al. [2000], Ovchinnikov et al. [2000, 2002], Neagu et al. [2001, 2002]; Lui [2001, 2002]; Troshichev et al. [2001, 2002]; Petrukovich and Yermolaev [2002]; Borovsky and Funsten [2003a,b]; Voros et al. [2003]; Volwerk et al. [2004]; Goldstein [2005]; Weygand et al. [2005-2007]; Nagata et al. [2008], Stepanova et al. [2005, 2009, 2011a,b], Wang et al.[2010], Pinto et al. [2011] ets.



ISEE-2 results [Angelopoulos et al., 1993]

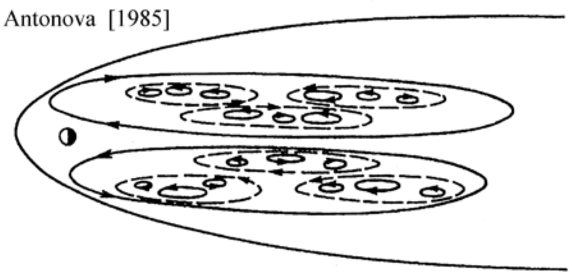


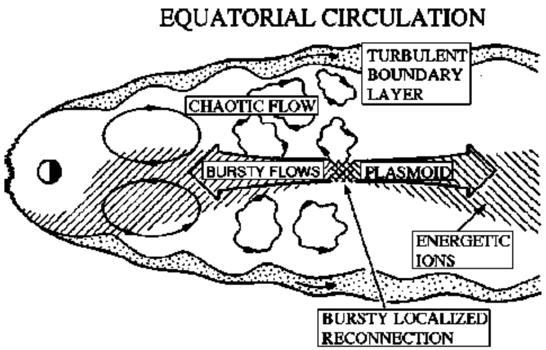
Interball/Tail probe results [Antonova et al., 2000, 2002]



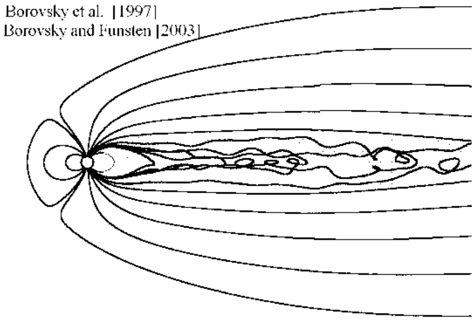
CLUSTER results [Volwerk et al., 2004]

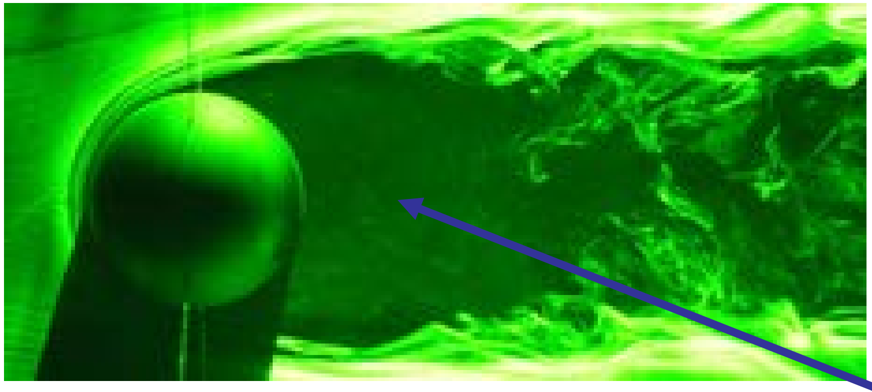
⇒ Even for laminar solar wind, the magnetospheric tail can be considered as a turbulent wake behind an obstacle, considering the very high values of Reynolds number (>10^{10} in accordance with [Borovsky and Funsten, 2003, doi:10.1029/2002JA009601]).

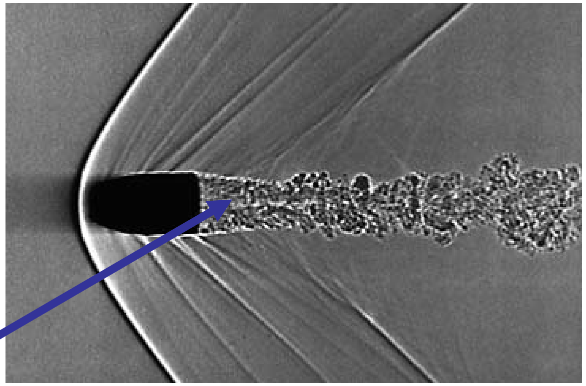




Kennel [1995]







Dead flow (region with low fluctuations) exists behind the obstacle

BBF are observed rather frequently and it is possible to find considerable disturbance in the tail before any substorm expansion phase onset. ⇒ Problem for theories of tail reconnection as a cause of substorm onset.

Models of turbulent magnetosheath and plasma sheet began to be developed

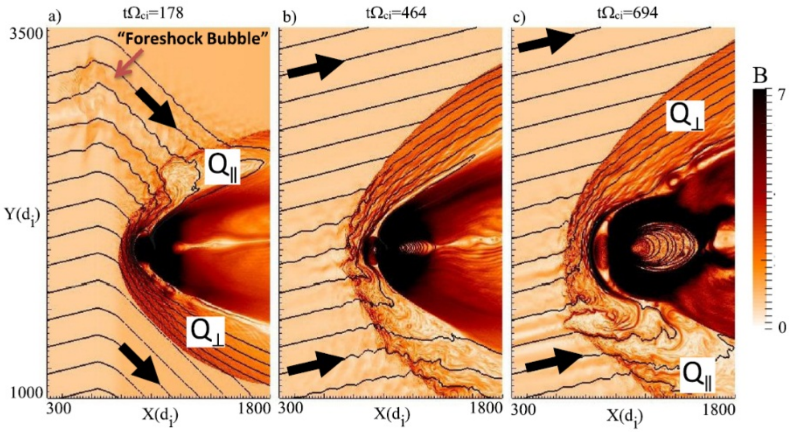
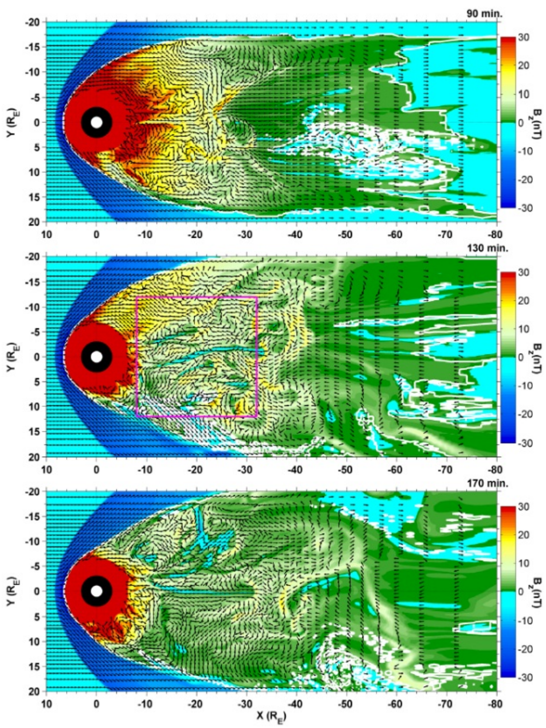
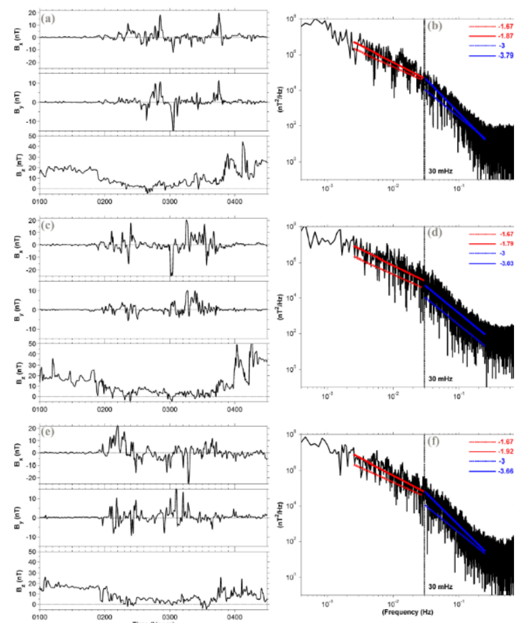


FIG. 1. (a)-(c) Time evolution of the magnetosphere in run 1 where the IMF direction changes in time. The arrows indicate the direction of the magnetic field. A large foreshock bubble is evident in panel (a). Details of this structure are shown in the next figure. The positions of the $Q_{\parallel}$ and $Q_{\perp}$ regions move due to the change in the IMF direction. Note the higher level of fluctuations associated with the $Q_{\parallel}$ magnetosheath. In panel (c), streaks of enhanced magnetic field are observed in the magnetosheath. These are associated with the formation of high velocity jet that penetrates deep into the magnetosheath.

Magnetosheath turbulence in hybrid models [Karimabadi et al., Phys. Plasmas 21, 062308, 2014]

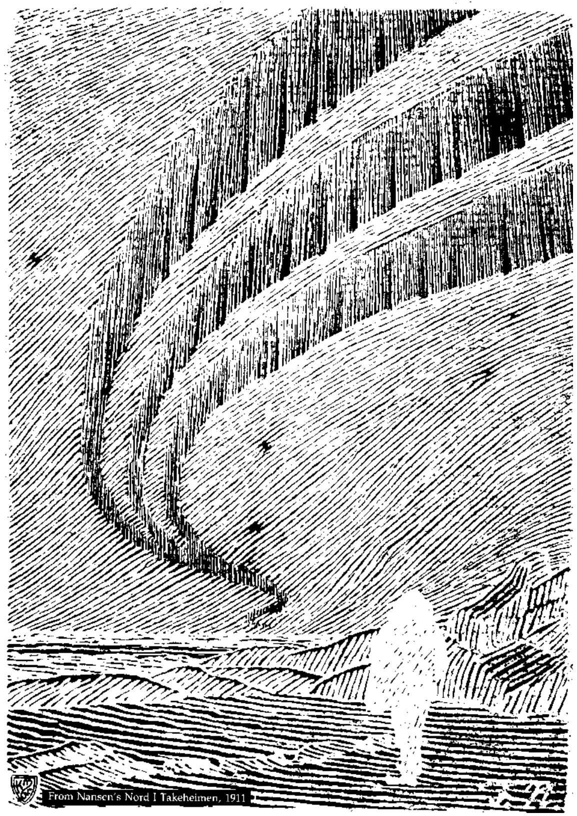




Plasma sheet turbulence in MHD models with high Reynolds number [El-Alaoui et al., 2010, doi:10.1029/2010JA015653; 2012, doi:10.5194/npg-19-165-2012]

IMF Bz=-5 nT, n_{sw}=20 cm^{-3}, V_x=500 km/s.

Problem No 3: Quite auroral arcs are constantly observed in the auroral oval. ⇒ This fact contradicts to the existence of turbulence in the plasma sheet and hence to the mapping of the auroral oval onto the plasma sheet.

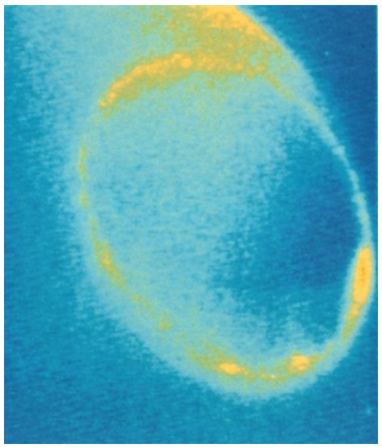


Physics of Auroral Arc Formation, ed. S.-I. Akasofu, J.R. Kan, Geophysical monograph 25, 1981 The polar aurora; woodcut by Fridtjof Nansen. The lines defining the “curtains” of the auroral arcs follow magnetic field lines.

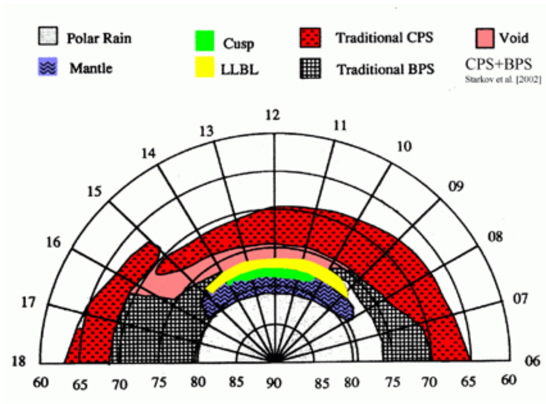
Bright auroral arcs can be observed for hours without changing their forms. ⇒ Quite auroral oval can not be mapped to the plasma sheet proper as it is the turbulent region with large level of fluctuations.

Problems arising when the auroral oval is mapped onto the plasma sheet:

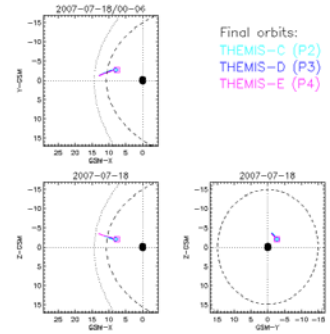
It is impossible to explain the ring-like shape of auroral oval and observations of plasma sheet like plasma near noon.

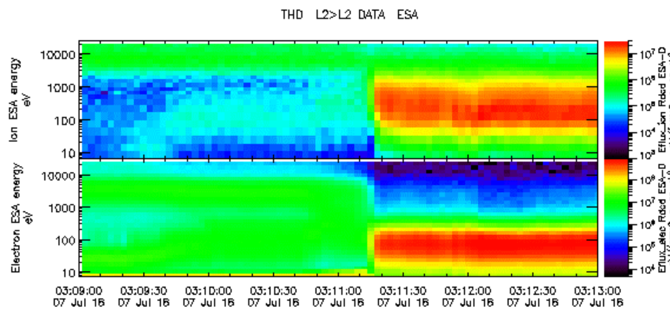


Marklund et al. [1987]



Newell and Meng [1992]





Antonova et al. [2011, IAGA BOOK, doi:10.1007/978-94-007-0501-2]

The fact that the plasma sheet like plasma surrounds the Earth is known from the first plasma measurements in the magnetosphere of the Earth.

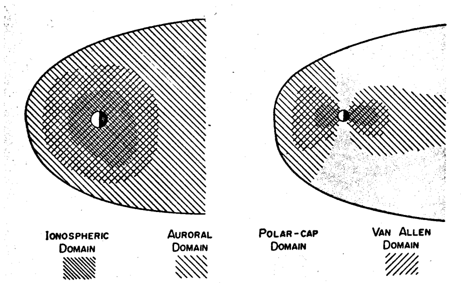
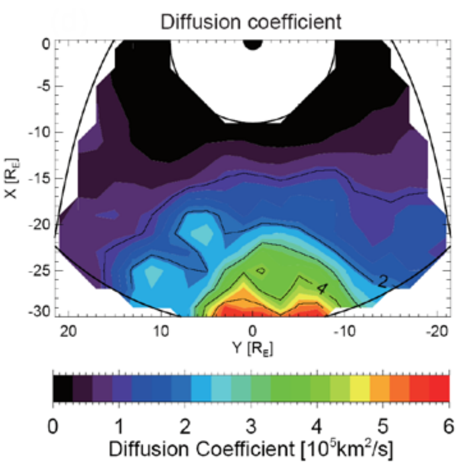


Fig. 16. The magnetospheric particle domains. Left: looking at the equatorial plane from the north pole. Right: looking at the noon-midnight meridian plane from the dusk side. (The latitudinal boundary of the auroral domain on the day side is largely conjectural.)

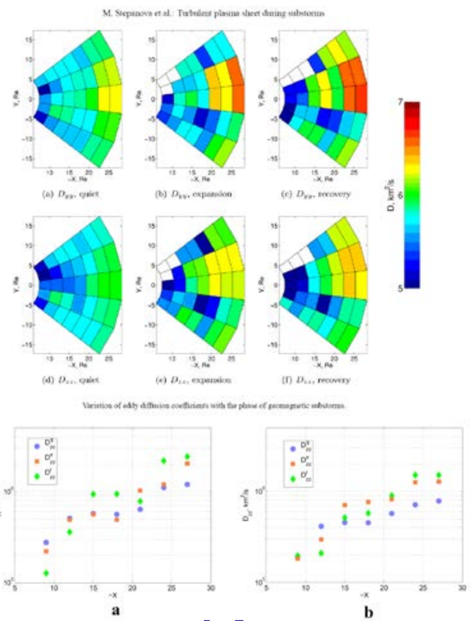
Vasyliunas [1970]

⇒ Plasma ring (with parameters similar to ones observed in the plasma sheet) surrounds the Earth.

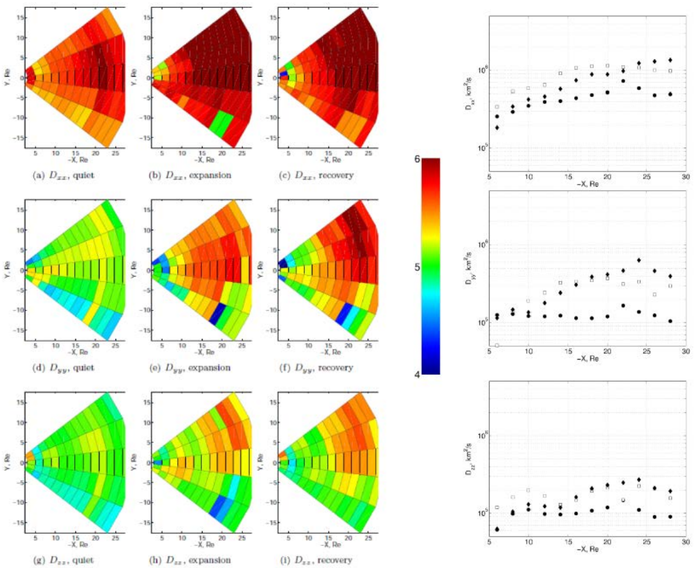
The study of plasma sheet turbulence shows the sharp decrease of eddy diffusion coefficient at geocentric distances <10R_E.



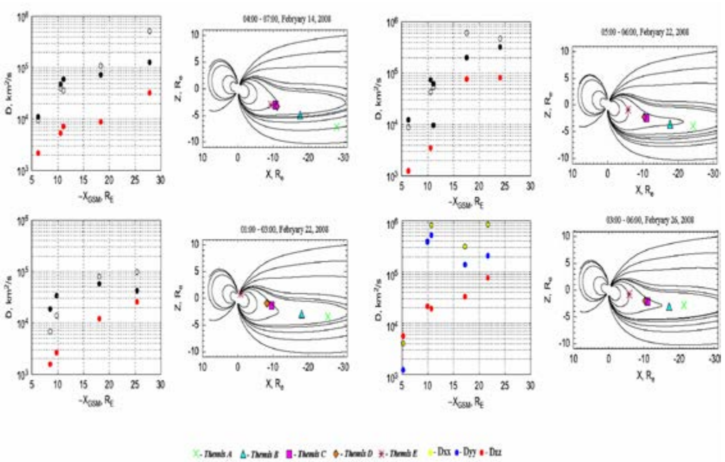
Nagata et al. [2008, doi:10.5194/angeo-26-4031-2008]



Stepanova et al. [2009, doi:10.5194/angeo-27-1407-2009]



Stepanova et al. [2011, doi:10.1029/ 574 2010JA015887]



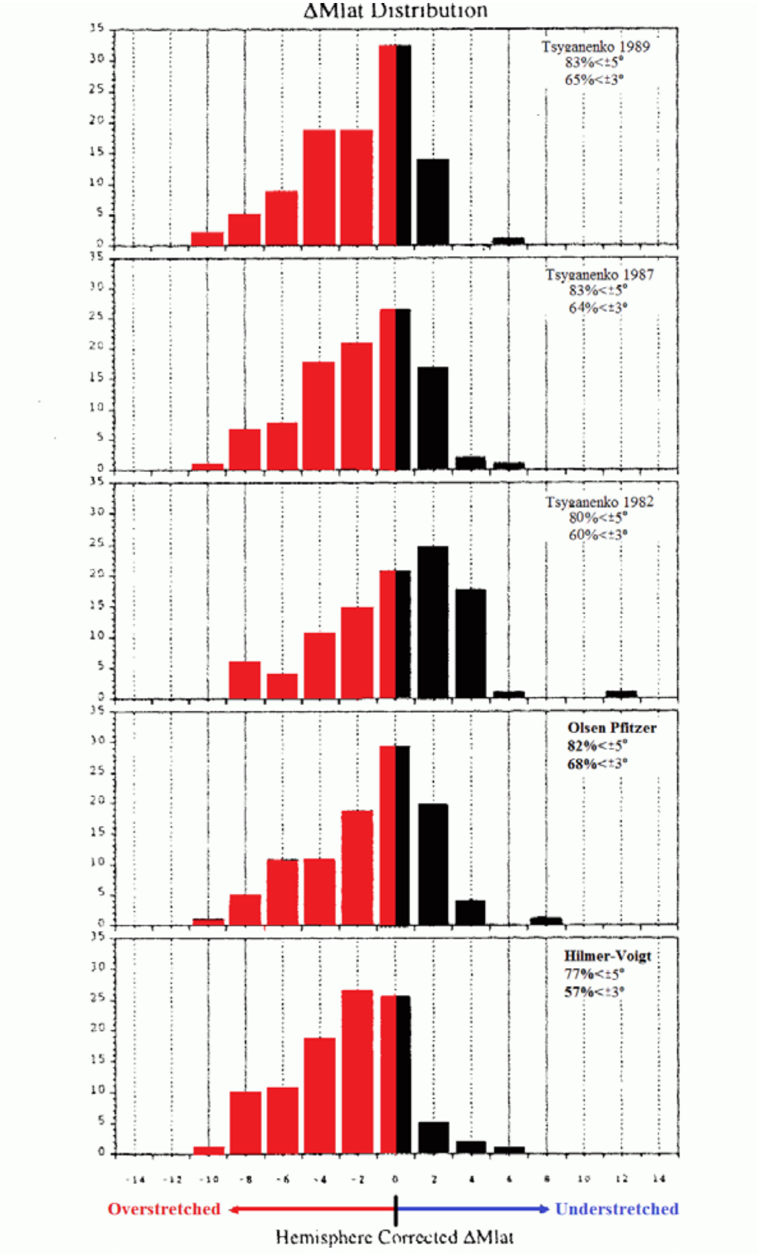
Pinto et al. [2011, doi:10.1016/543 j.jastp.2011.05.007]

⇒ The problem of the existence of quite auroral arcs can be solved if the main part of auroral oval is mapped at geocentric distances < ~10R_E .

Overstretching of magnetic field models with predetermined geometry of current systems

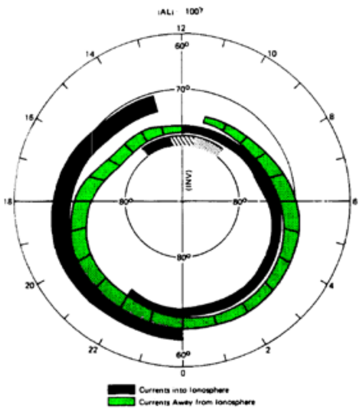
Peredo et al. [1993] concluded that both the Tsyganenko [1987] (T87) and Tsyganenko [1989] (T89) are on average too stretched in the nightside tail.

Reeves et al. [1996] showed that models of Tsyganenko-82, -87, -89, Olsen-Pfitser [1974], and Himert and-Voit [1995] are overstretched.

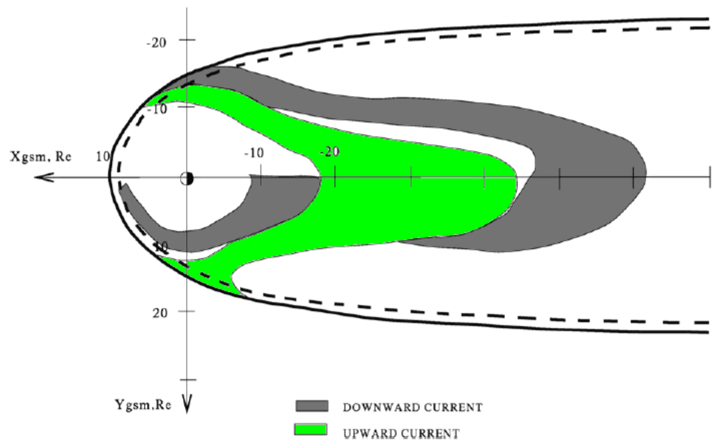


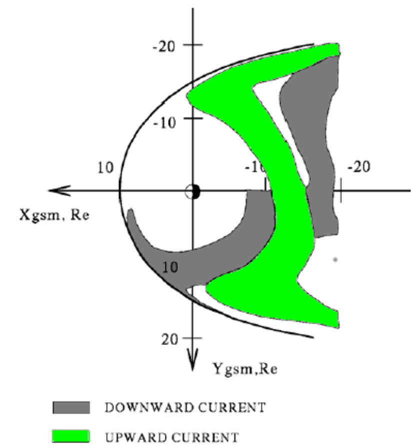
Reeves et al. [1996, Geophys. Mon. 97, p. 167-172]

Mapping of the Iijima and Potemra [1976] field-aligned current to the equatorial plane using Tsyganenko-1996 and -2001 models reveals that these models are overstretched [Antnova et al., 2006, doi:10.1016/j.asr.2005.09.042]. Xing et al. [2009, doi:10.1029/2009GL038881] came to the same conclusion.



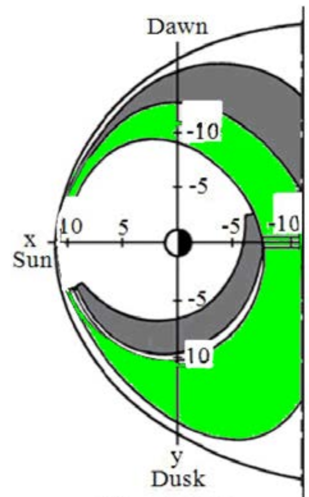
Iijima and Potemra [1976]



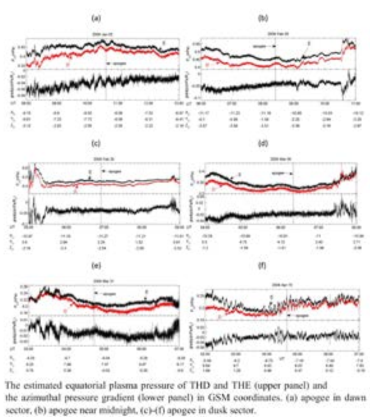


Mapping of field-aligned currents to the equatorial plane using Tsyganenko 1996 and 2001 models gives the controversial pictures (Antonova et al. [2006])

Mead-Fairfield [1975] model mapped the upward Region 1 field-aligned currents at much smaller distances. Xing et al. [2009] showed that the Region 1 currents can be generated by azimuthal plasma pressure gradients observed at ~11R_E.

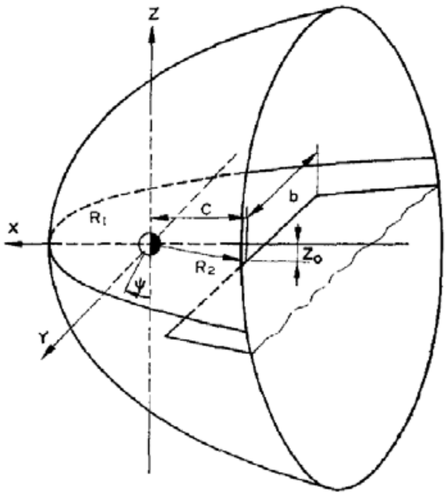


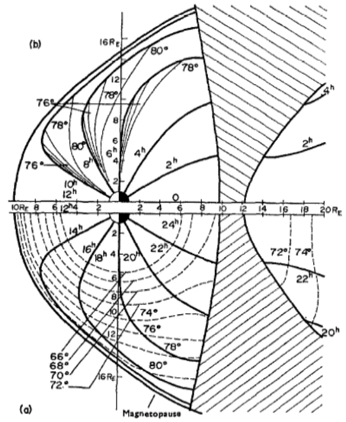
Iijima [1976]

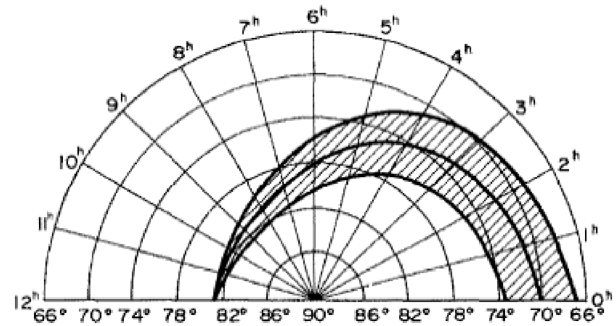


Xing et al. [2009]

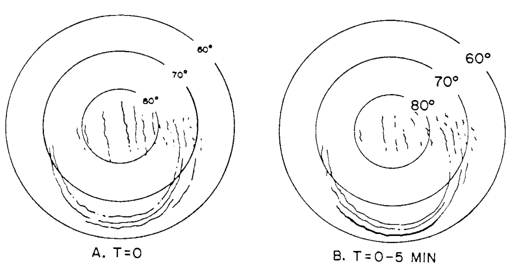
First model with selected predetermined geometry of currents was created by [Alexeev and Shabansky, 1972, PSS, v. 20, p.117-133]. Magnetic field near the boundary of thin current sheet in this model had the infinite value. Model mapped the magnetotail current sheet to near **circular structure with zero thickness near noon**. Moving current sheet along the X axis it was possible to map region of any substorm onset at large distance to the tail.



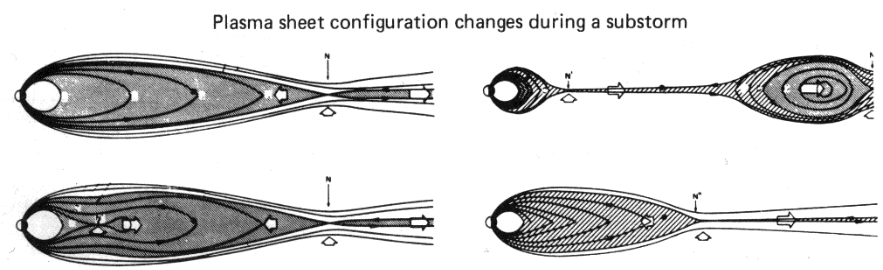




Classical auroral substorm starts at the equatorial boundary of the auroral oval [Akasofu, 1964]. Overstretched magnetic field models with predetermined geometry of current systems map this region inside the plasma sheet proper very far from the Earth to support the Hones [1979] model.



Akasofu [1964]



Hones, 1979

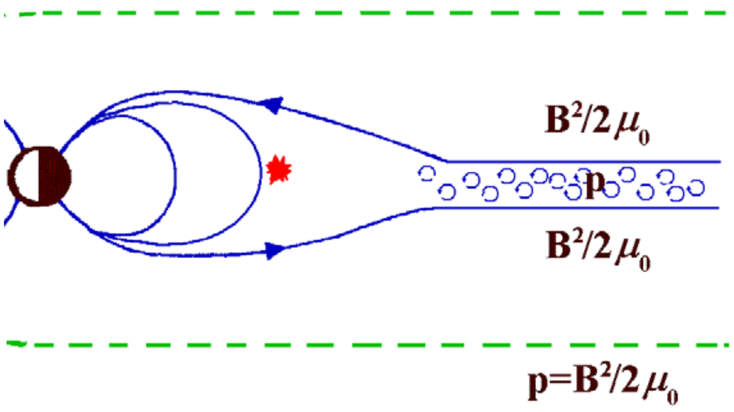
The overstretching of magnetic field models with predetermined geometry of current systems can explain the nonrealistic auroral oval mapping into the turbulent plasma sheet.

⇒ It was necessary to search the way of auroral oval mapping without using any magnetic field model.

The applicability of the condition of the magnetostatic equilibrium in the case of the magnetosphere of the Earth is supported by the results of Michalov et al. [1968], Stiles [1978], Spence et al. [1989], Tsyganenko [1990], Baumjohann et al. [1990], Kistler et al. [1993], Petrukovich [1999], Tsyganenko and Mukai [2003] ets.).

In magnetostatic equilibrium if the plasma pressure is near to isotropic $[\mathbf{j}\times\mathbf{B}]=\nabla p$, where **j** is the current density, **B** is the magnetic field, and p is the plasma pressure.

⇒ Plasma pressure is constant along a field line.



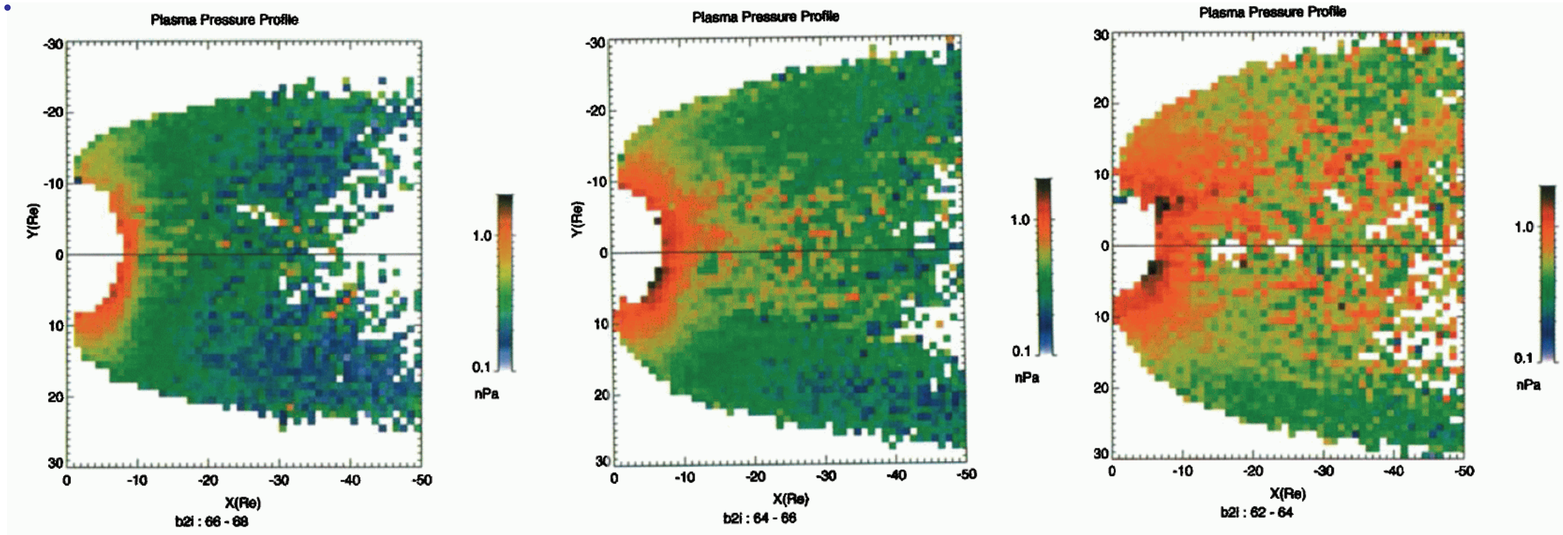
Across the plasma sheet

$$p+\frac{B^2}{2\mu_0}=const$$

p<0.2 nPa in the plasma sheet proper

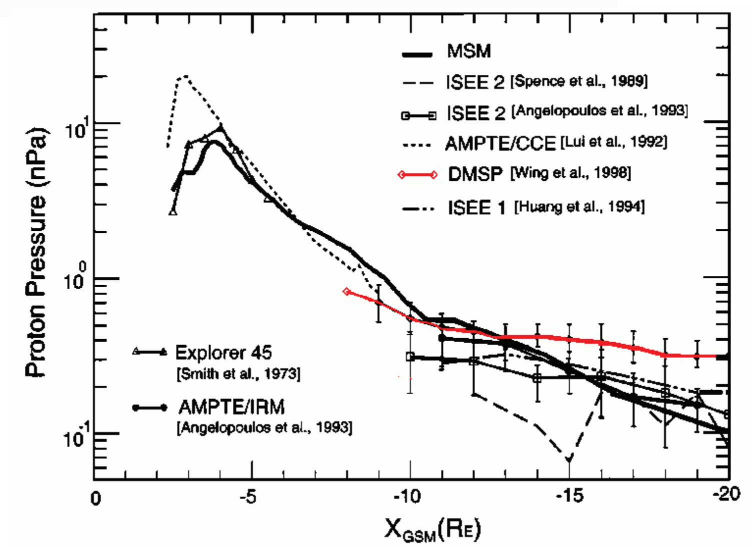
Plasma pressure can be used as natural marker of the field line.

Wing and Newell [1998] obtained the distribution of plasma pressure using the data of DMSP satellites and mapped it into the equatorial plane using the Tsyganenko-1989 model.



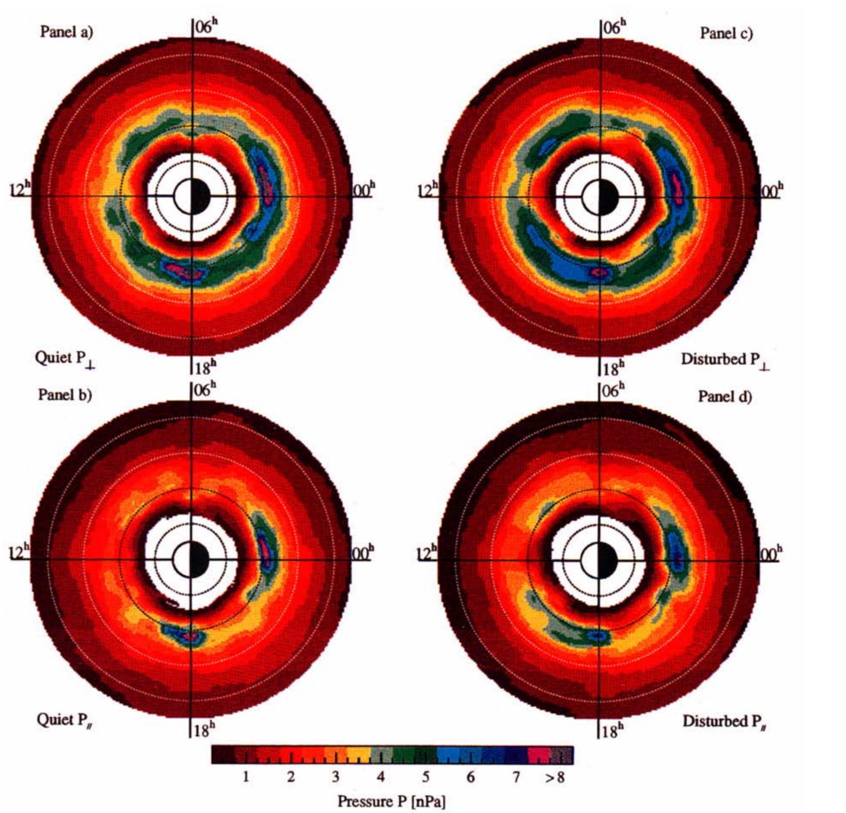
Wing and Newell (1998)

Wang et al. [2001] showed a strong discrepancy between the results of Wing and Newell [1998] and the direct observations at the equatorial plane obtained using Explorer 45, ISEE 1 and 2, AMPTE/IRM. Obtained by Wing and Newell values of plasma pressure are larger than the values observed in the plasma sheet proper: $p<0.2$ nPa (see, for example, [Tsyganenko and Mukai, 2003] $<P_{CPS}>=0.229$ nPa). This discrepancy is due to the overstretching of Tsyganenko-89 model.

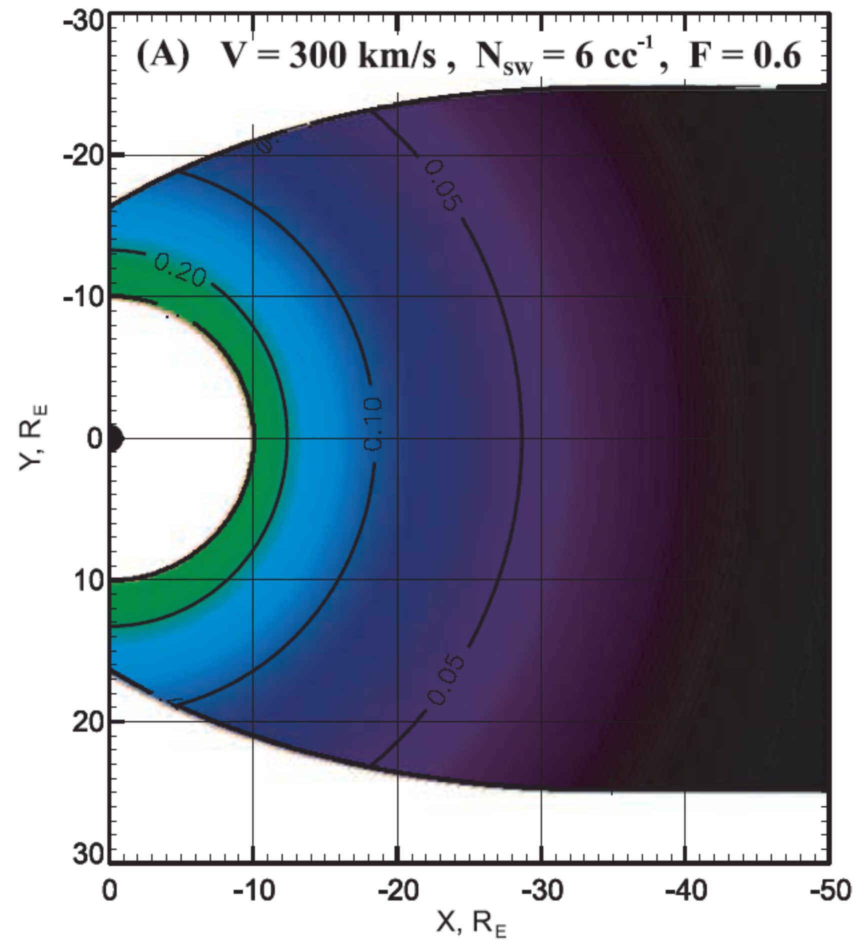


Wang et al. [2001, doi:10.1029/2000JA000377]

Plasma sheet-like plasma surrounds the Earth on the quasidipole magnetic field lines.

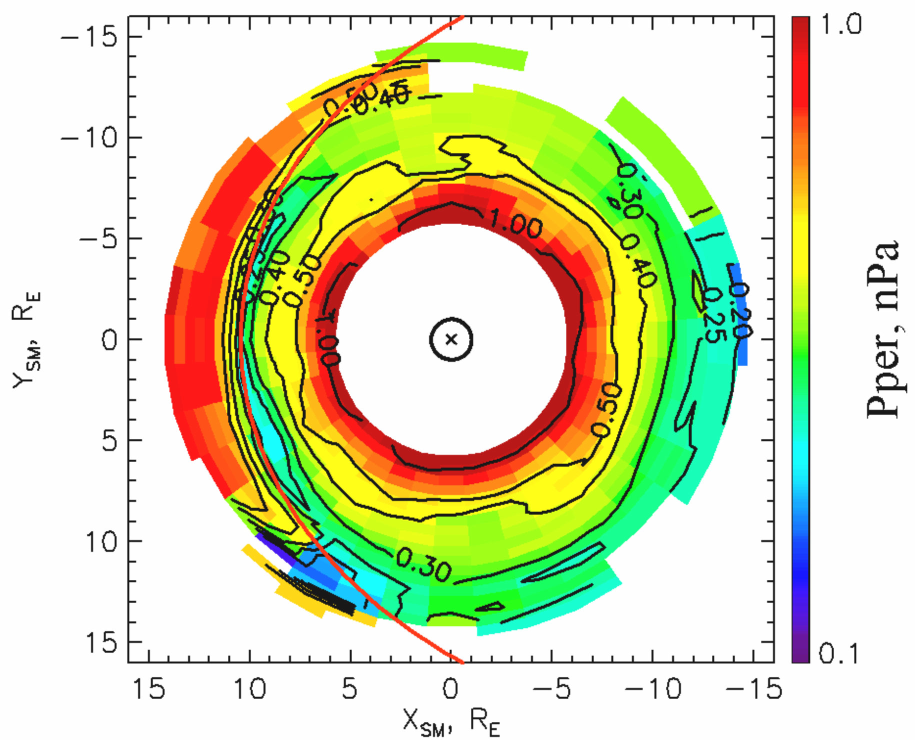


Results of DeMichelis et al. [1999] of plazma pressure distribution at the equatorial plane using data of AMPTE/CCE at geocentric distances <8.8Re.

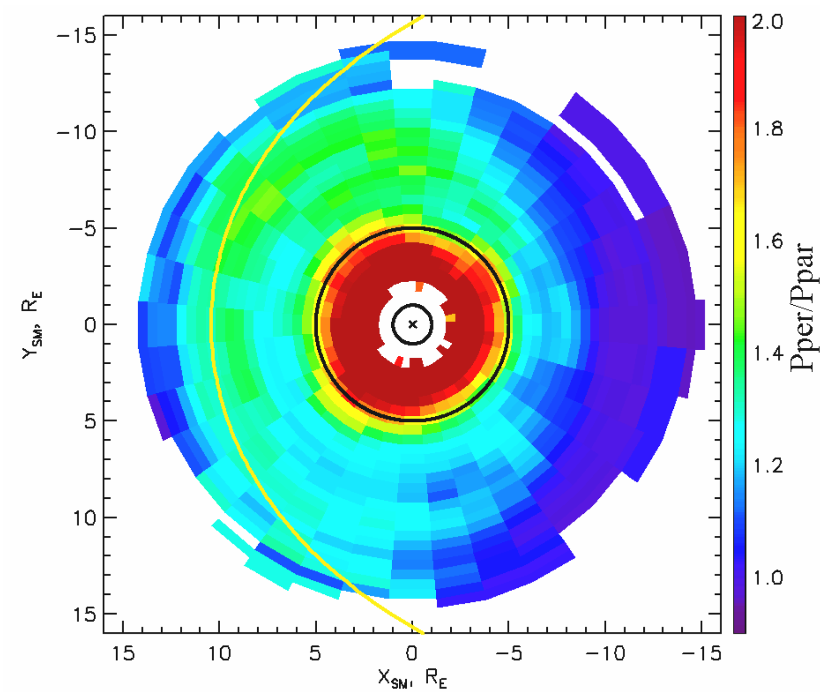


Tsyganenko and Mukai [2003] model obtained using data of Geotail observations (half-ring structures in the plasma pressure distribution). Green half-ring does not cross the magnetopause and naturally must have the daytime continuation.

Plasma pressure distribution in the surrounding the Earth plasma ring and pressure anisotropy in accordance with THEMIS data from Antonova et al. [2014, doi:10.1016/j.jastp.2013.12.005]

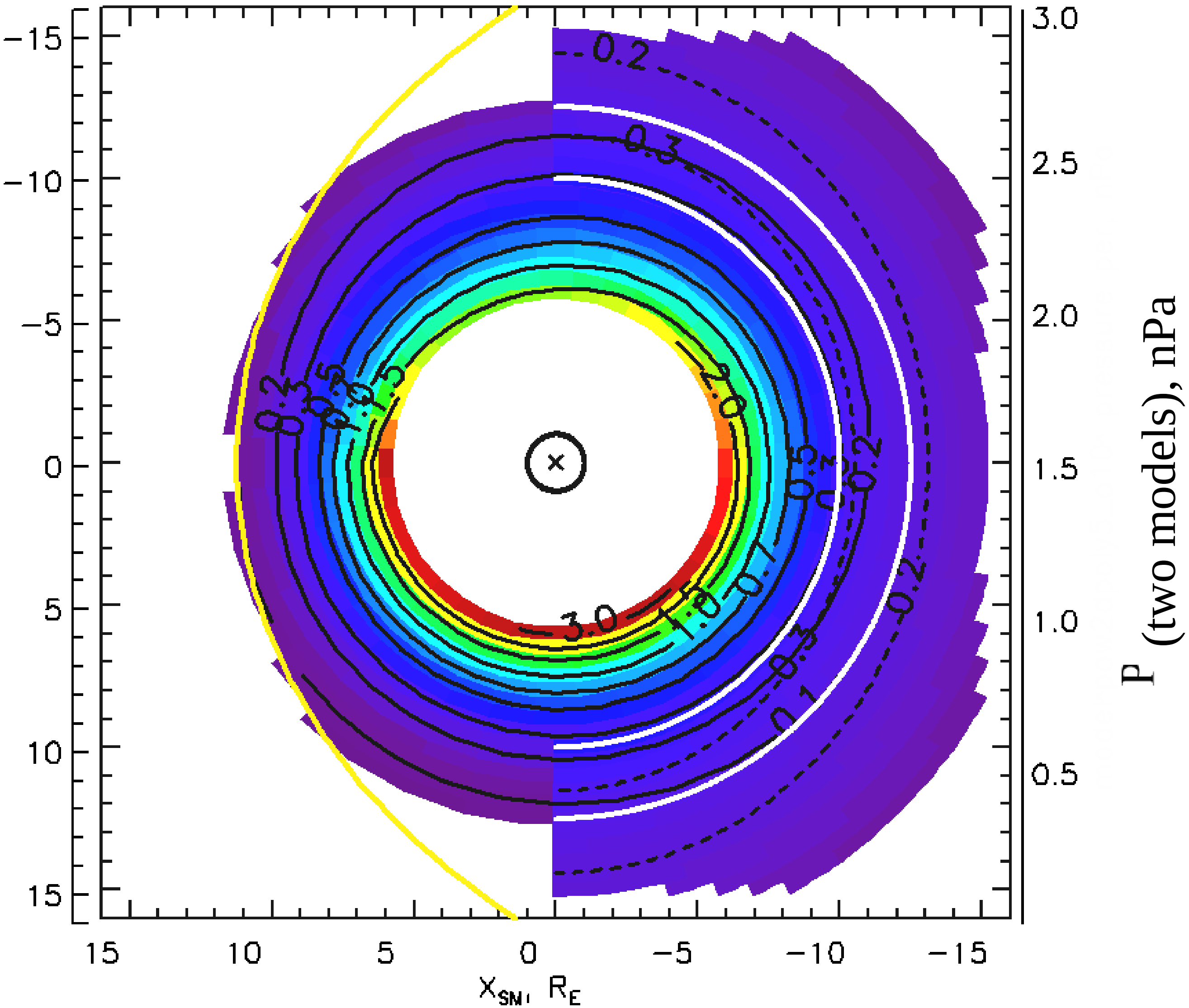


Averaged distribution of plasma pressure in the surrounding the Earth plasma ring obtained using data of THEMIS mission for the period between the April 2007 and September 2012 (Dst>-20 nT, AE<100, P_{din}=1.8±0.2, IMF B_z=0.2, IMF B_y=0)



Anisotropy of plasma pressure in the surrounding the Earth plasma ring obtained using data of THEMIS mission for the period between the April 2007 and September 2012 (Dst>-20 nT, AE<100, P_{din}=1.8±0.2, IMF B_z=0.2, IMF B_y=0)

Comparison between the obtained model and the Tsyganenko-Mukai [2003] model at X<0 shows very good coincidence between them



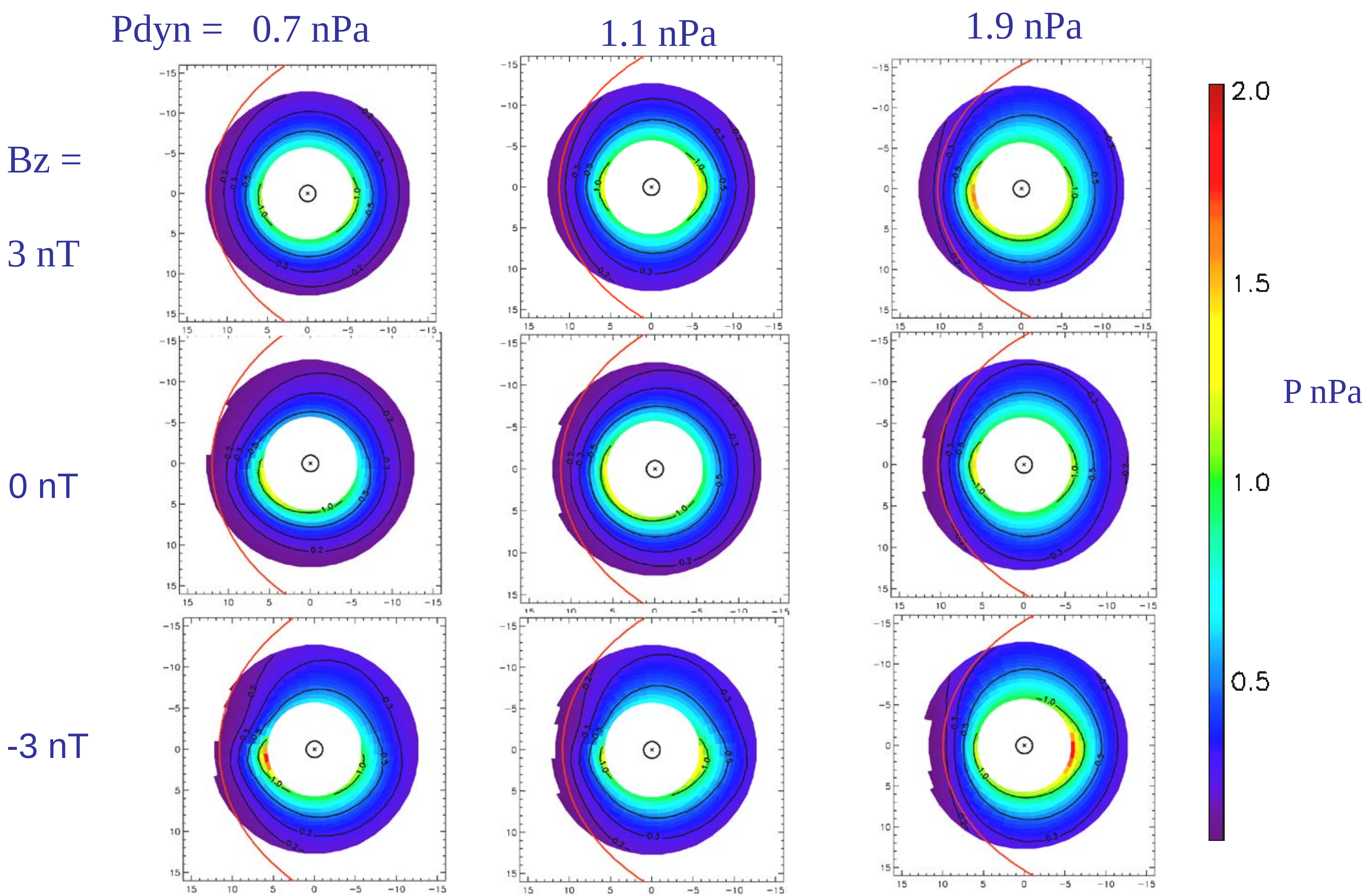
Pdyn = 1.1 nPa

Bz = 0.2 nT

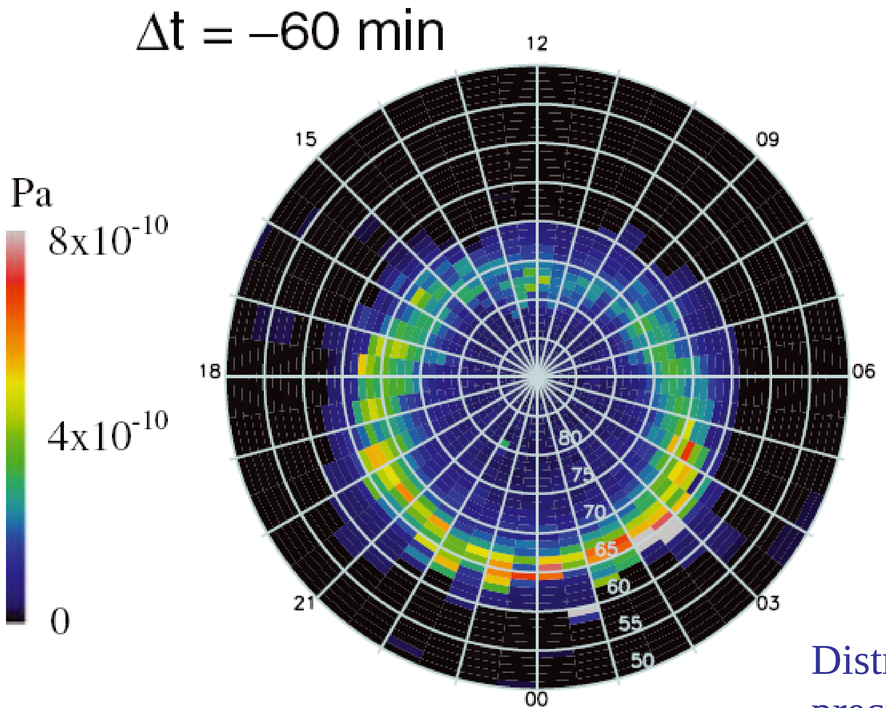
F = 1.6 nT

$$\left(F = B_{\perp}\sqrt{\sin(\theta/2)}\right)$$

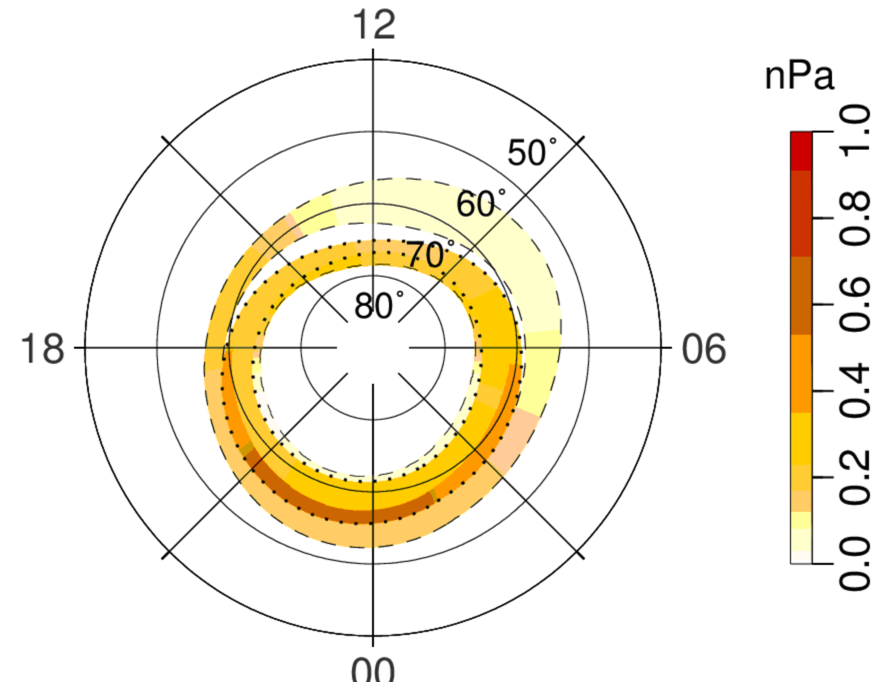
Model of plasma pressure distribution at the equatorial plane for different values of the solar wind Pdyn and IMF (http://stdad.iki.rssi.ru/pressuremodel/pressure.php)



Plasma pressure at low altitudes obtained using the DMSP data



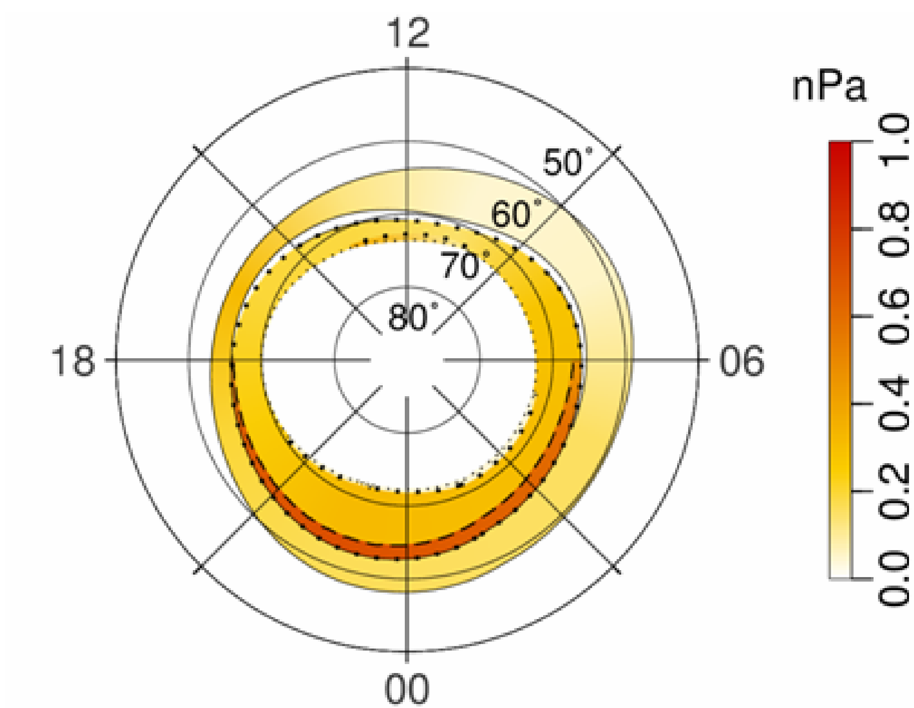
Plasma pressure distribution at low altitudes 60 min before the substorm [Wing et. al., 2013, doi:10.1002/jgra.50160]

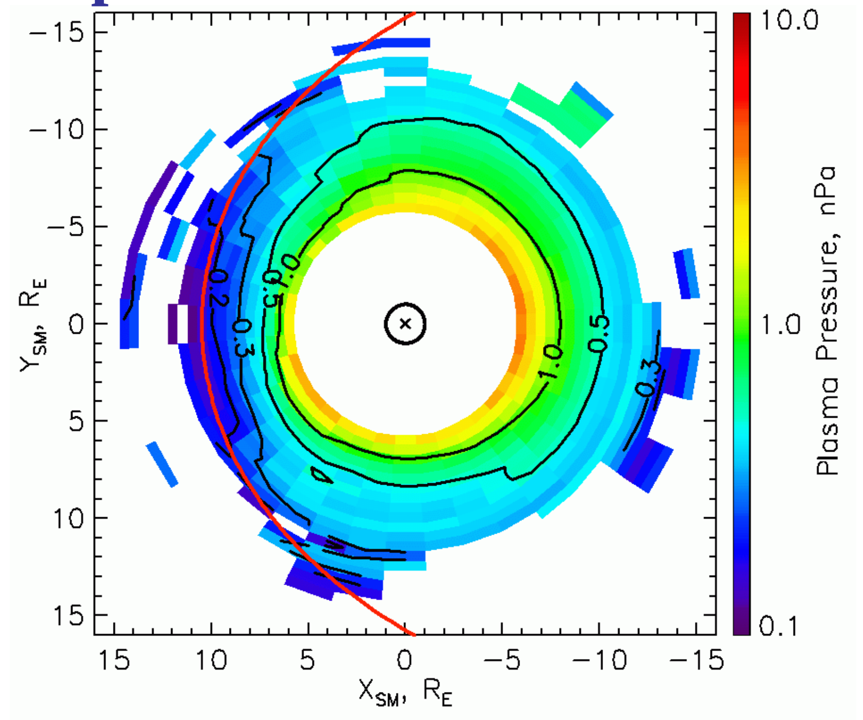


Distribution of plasma pressure and boundaries of electron precipitations in accordance with APM model (http://apm.pgia.ru/) at AL=-200 нТл, Dst=-5 нТл. Dashed line shows boundaries of DAZ and SDP, dotted line shows AOP (auroral oval precipitation) boundary [Antonova et al., 2014, doi:10.1134/S0016793214030025]

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

Comparison of plasma pressure distribution at low altitude and at the equatorial plane





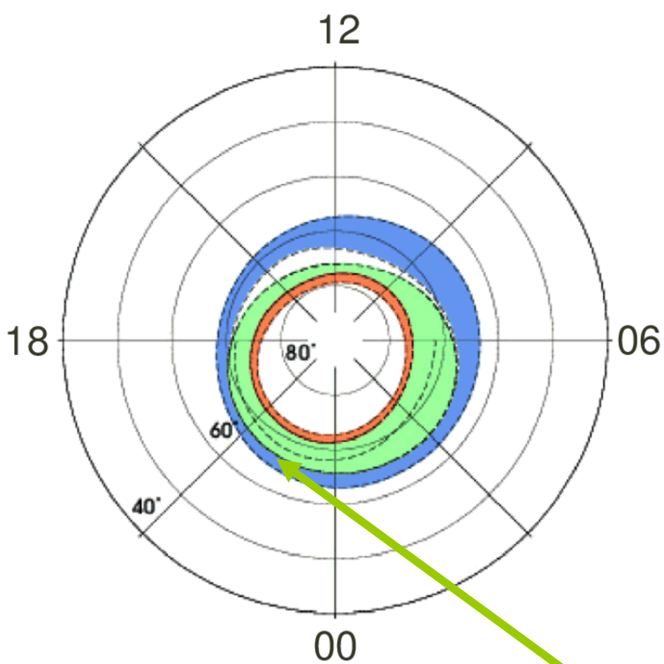
Comparison of plasma pressure distribution (AL=-600 nT, Dst=-5 nT) at low altitudes according to the APM model and plasma pressure at the equatorial plane using the THEMIS datas [Antonova et al., 2015, doi:10.1186/s40623-015-0336-6].

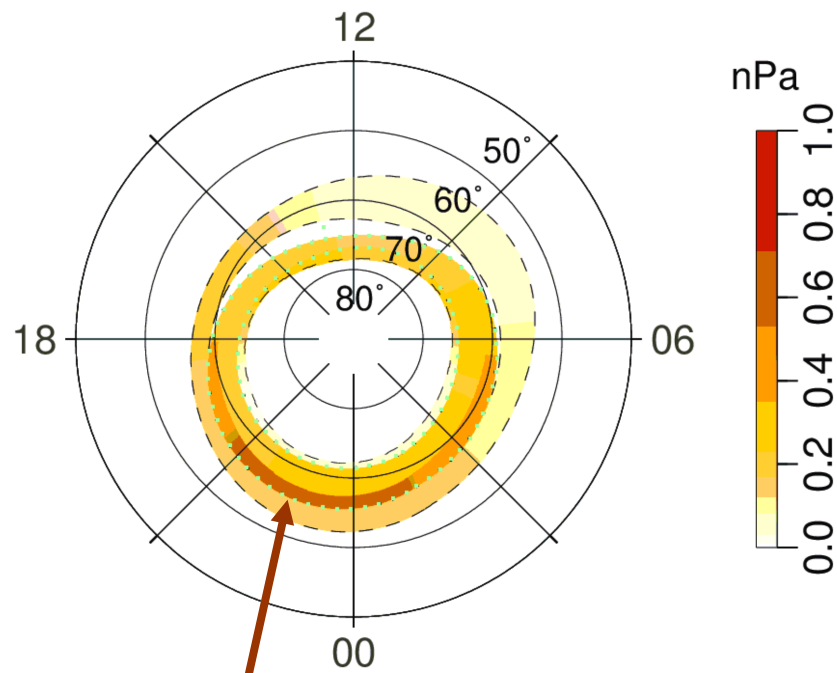
Most part of the discrete auroral oval should not be mapped into the plasma sheet proper, but rather into the plasma ring surrounding the Earth.

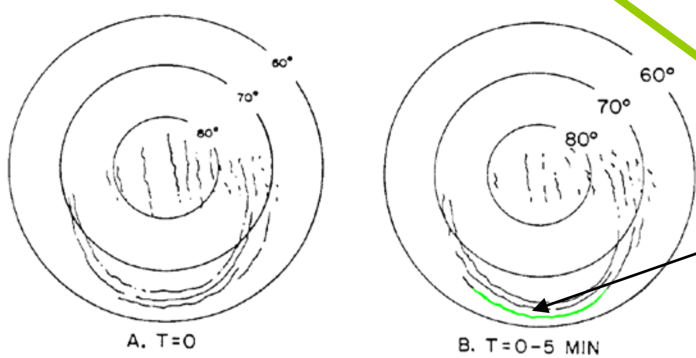
Location of isolated substorm expansion phase onset

http://pgia.ru/lang/en/webapps/

Antonova et al. [2014]

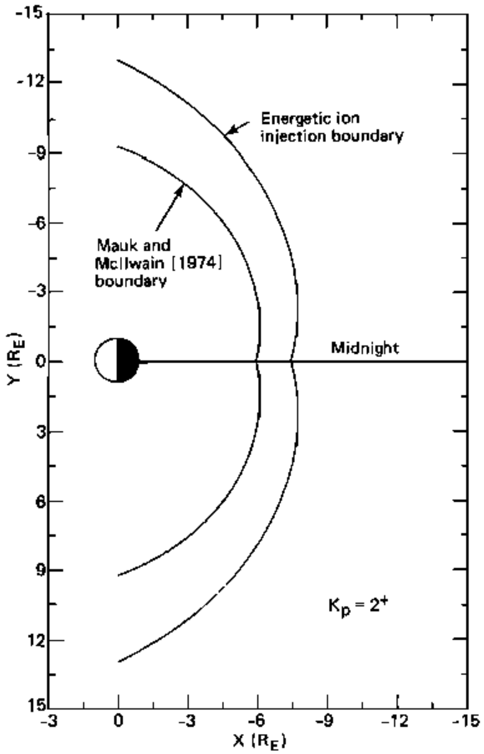




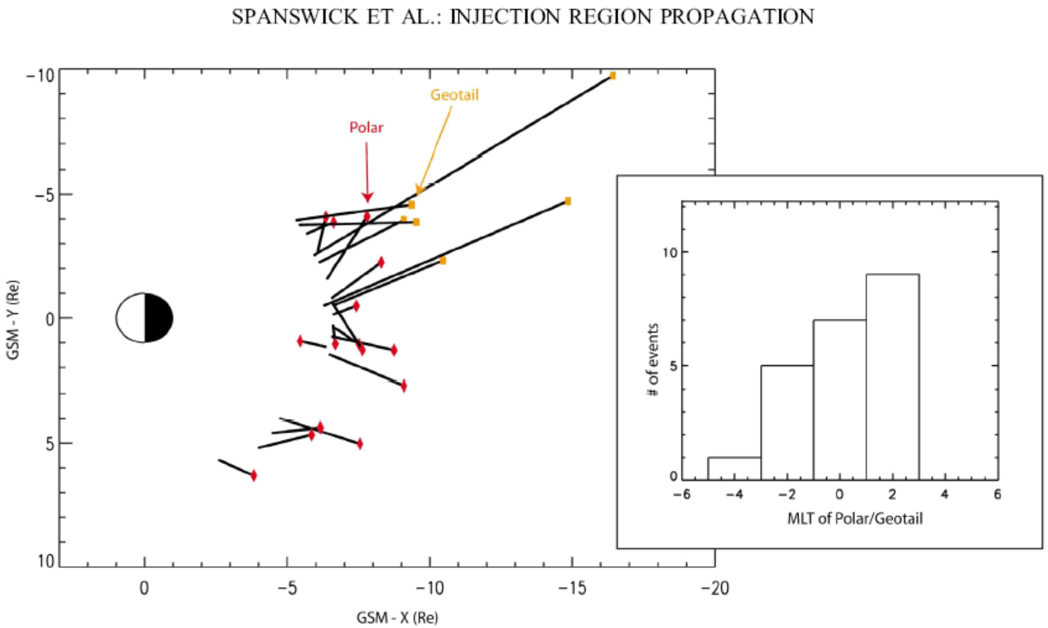


According to Akasofu [1964], first auroral arc brightening is located at the equatorial boundary of the auroral oval where *p*~1 nPa inside the surrounding the Earth plasma ring

Location of injection boundary



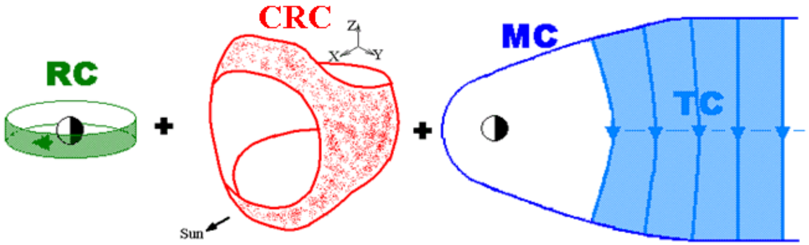
Lopez et al. [1990, doi:10.1029/JA095iA01p00109]



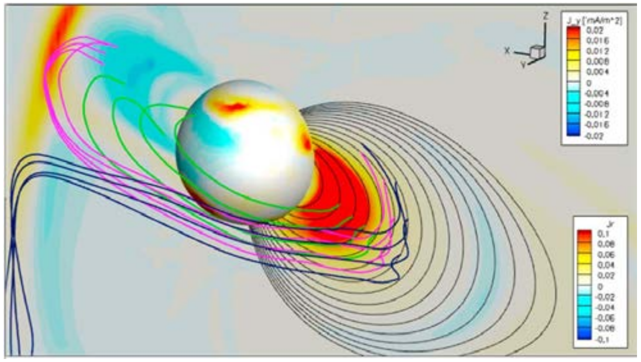
Spanswick et al. [2010, doi:10.1029/2009JA015066]

Location of the injection boundary coincides with the position of first auroral arc brightening inside the surrounding the Earth plasma ring.

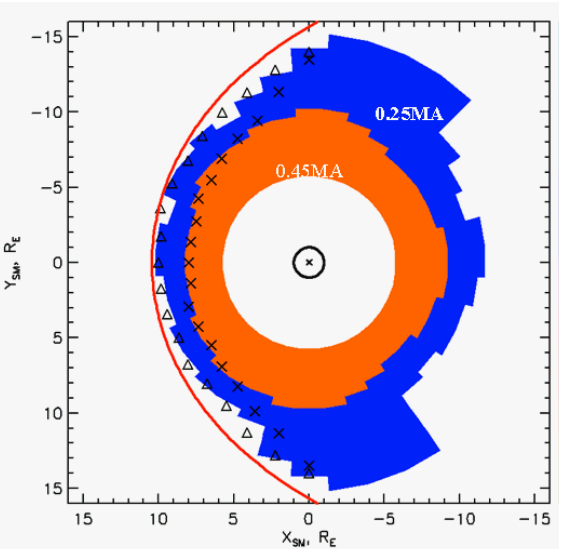
Transverse currents in the surrounding the Earth plasma ring were not included in the magnetic field models with predetermind geometry of current systems



Ring current has the high latitude continuation till the dayside magnetopause – cut ring current (CRC) [Antonova and Ganushkina, 2000, doi:10.1016/ S0273-1177(02)00434-9; Antonova, 2000, doi:10.1016/S0273-1177(99)00669-9]



CRC-type current lines appears in the magnetohydrodynamic (MHD) models of high latitude transverse currents [Liemohn et al., 2011, doi:10.1029/2011GL049611]



Integral current calculated using obtained distribution of plasma pressure and taking into account the shift of *Bmin* from the equatorial plane and obtained gradients of plasma pressure. Tsyganenko- 2001 model is used for *Bmin* calculations [Kirpichev and Antonova, 2014, doi:10.1134/S0010952514010043].

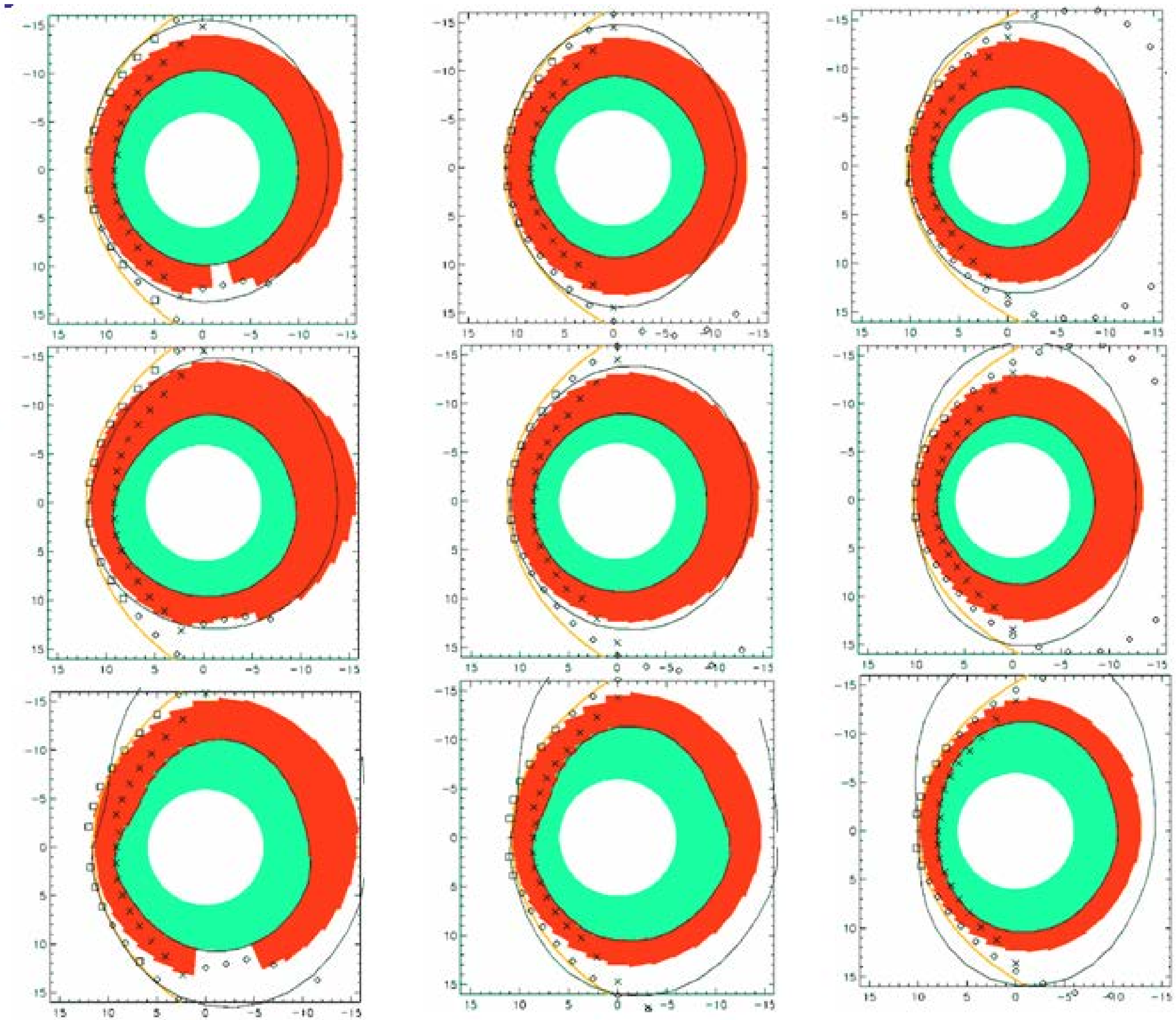
Latest results of CRC calculation at different solar wind P_{dyn} and IMF Bz

P_{dyn} =0.7 nPa | 1.1 nPa | 1.9 nPa

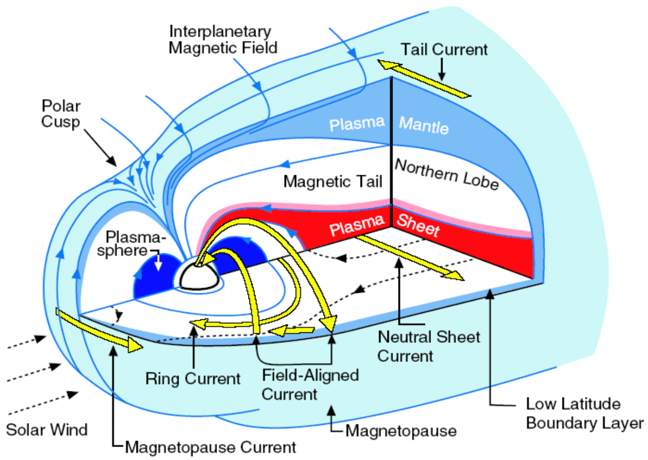
Bz =3 nT

0 nT

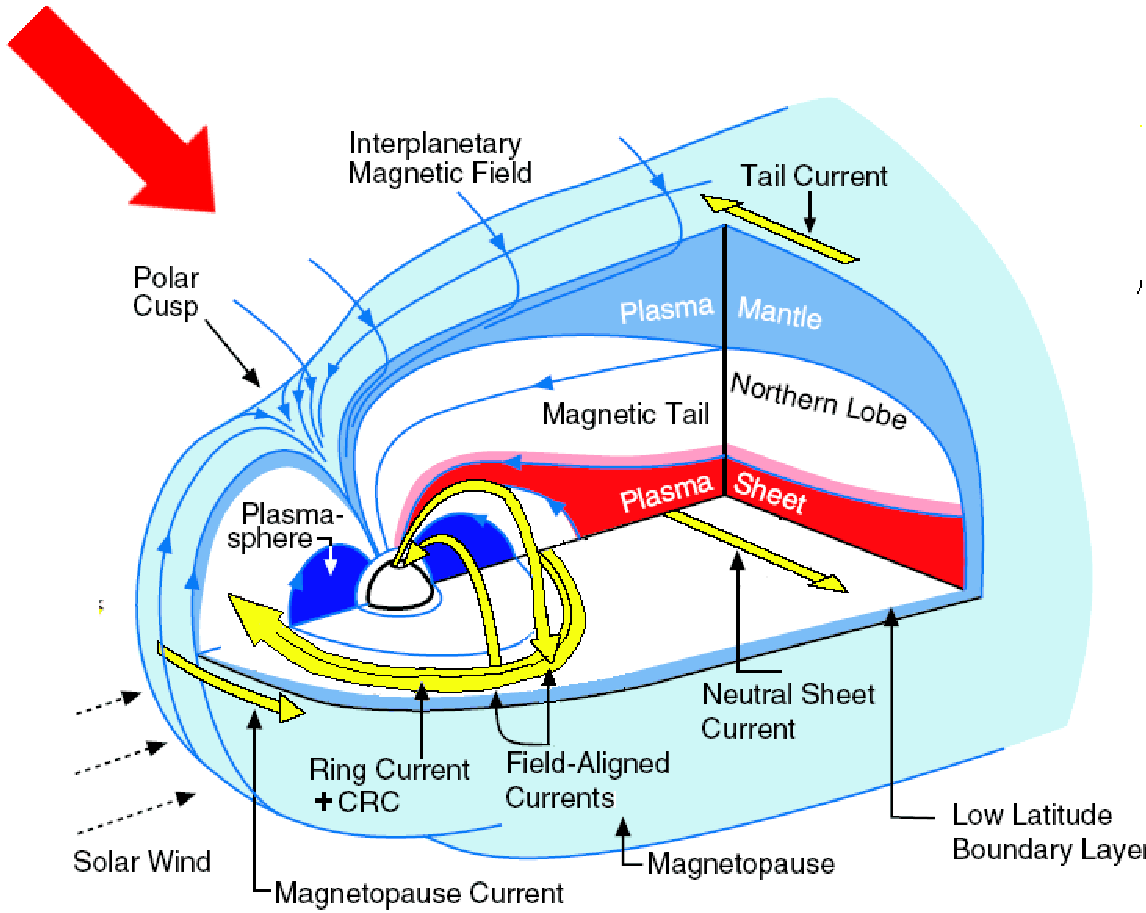
-3 nT



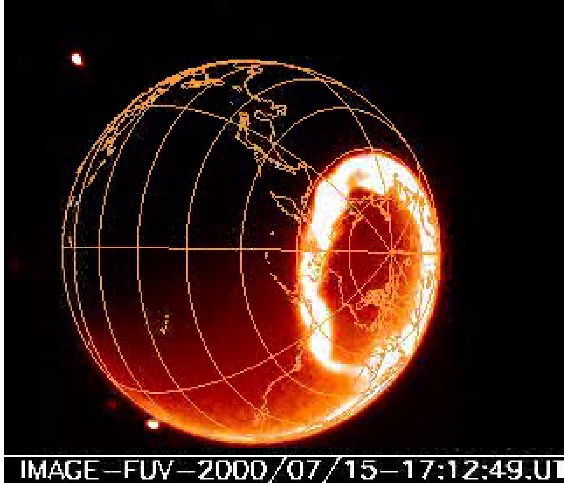
Picture of magnetospheric currents requires the modification:
a. it is necessary to add CRC,
b. it is necessary to modify the location of sources of the Region 1 field-aligned currents



Kivelson and Russell (1995)



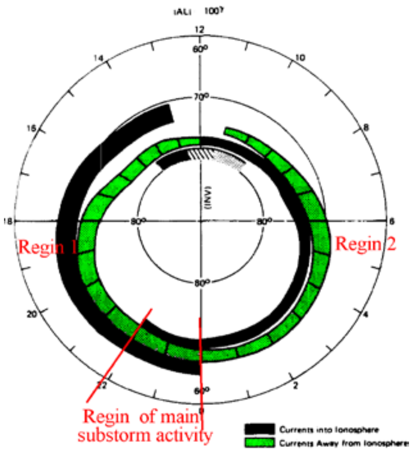
The results of mapping using the pressure as a tracer explain the ring-like shape of the auroral oval This shape is easily observed during magnetic storm when auroral oval becomes very bright and moves toward the equator.

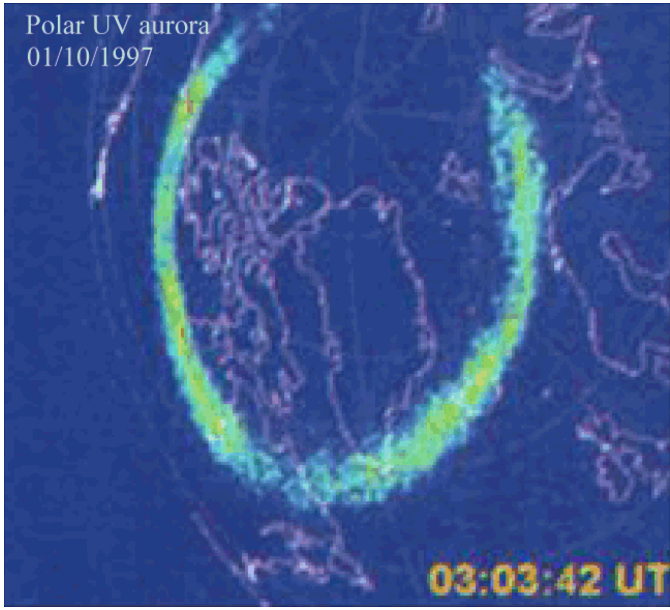


Why the point of view of the auroral oval mapping to the plasma sheet is so popular?

Energy fluxes of ordinary auroral precipitations are below the thresholds of ground-based and auroral imager observations. These observations provide the distribution of the upward field-aligned currents.

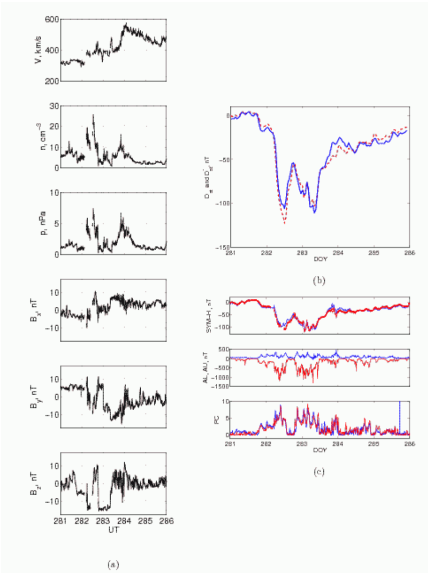
The commonly observed horseshoe form of bright aurora is a manifestation of the picture of upward field-aligned currents of Iijima and Potemra [1976]



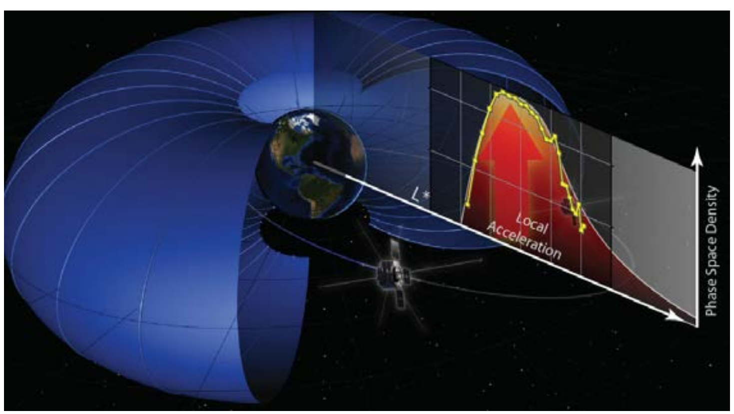


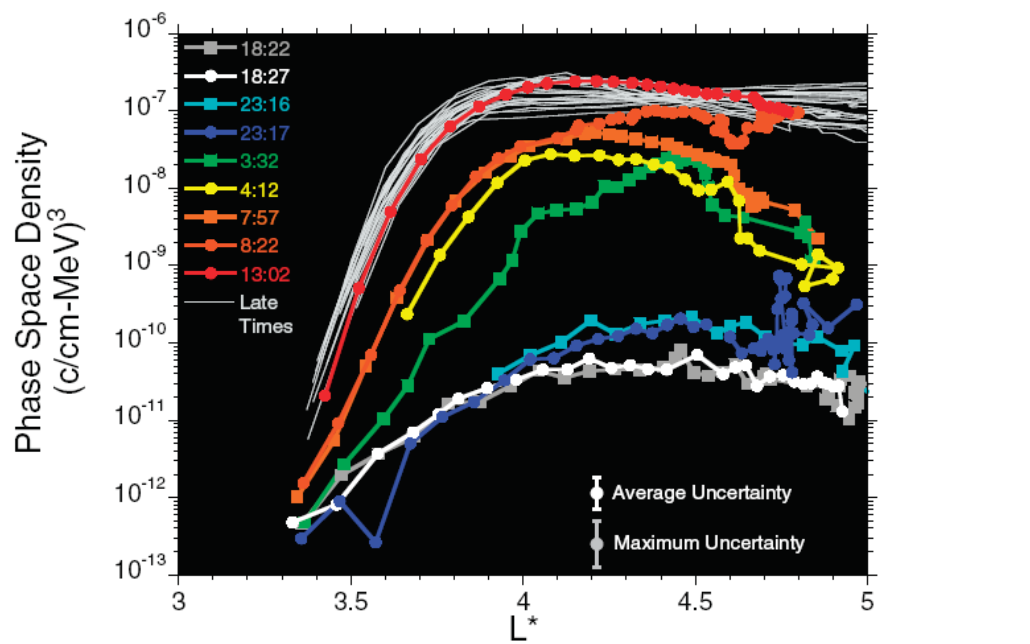
Auroral oval and outer electron radiation belt

for magnetic storm 8–9 October 2012 with minimal Dst=-105 nT

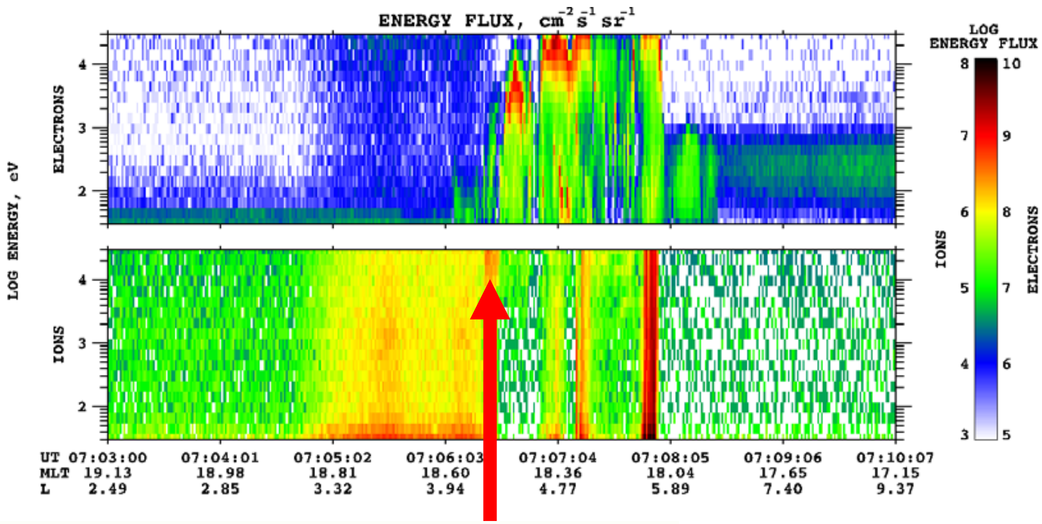


Reeves et al. [2013, doi:10.1126/science.1237743] studied the phase space density evolution of relativistic electrons and found that the phase space density (PSD) maximum is located at L=4.2.

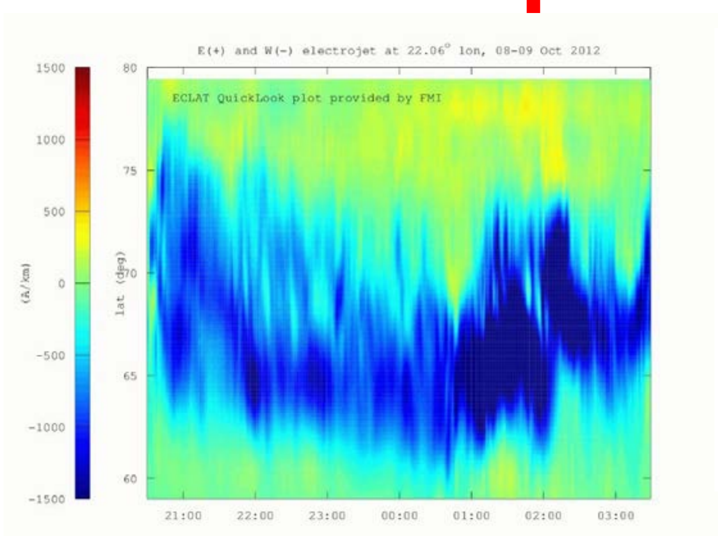




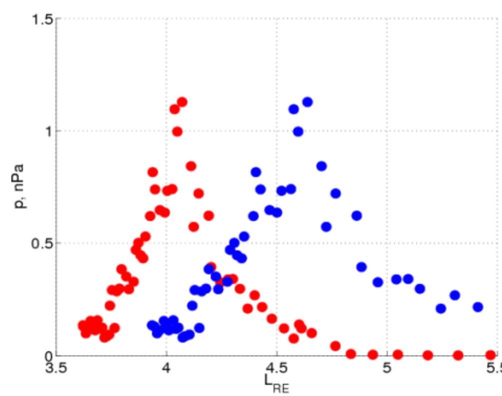
Antonova and Stepanova [2015, doi:10.1186/s40623-015-0319-7] produced the additional analysis of the magnetic storm 8–9 October 2012 and show that it is possible to predict the position of a new radiation belt using the data of low orbiting and ground based observations.



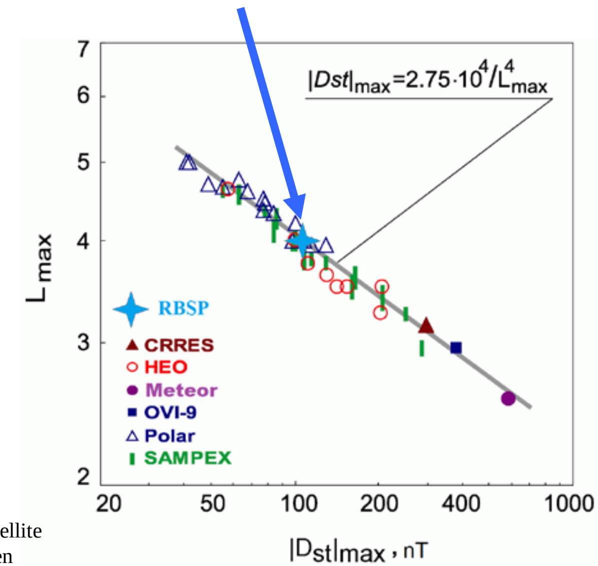
The Tverskaya relation predicts for the minimal Dst=-105 nT the location of PSD maximum at Lmin=4.02 in a very good agreement with the results of Reeves et al. [2013].



Intensity of the westward auroral electrojet, obtained using the IMAGE magnetometer network near the Dst minimum. The 1D equivalent current system obtained using the data of the IMAGE magnetometer network on 8–9 October 2012

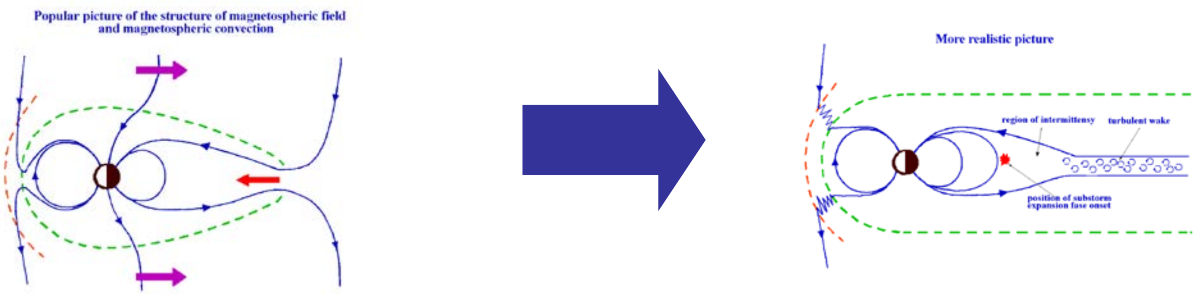


Plasma pressure profiles obtained from the DMSP F17 satellite data during the auroral crossing on 8 October 2012 between 21:47:40 and 21:52:50 UT mapped to the equatorial plane by IGRF (red) and Tsyganenko 2004 (blue) models, we used the methodology proposed by Stepanova et al. (2004, 2006, 2008)



Conclusions:

•High level of plasma turbulence in the magnetosheth and in the plasma sheet is an obstacle for the traditional picture of the magnetospheric dynamics.



•There is a plasma ring surrounding the Earth. Its plasma has characteristics similar to ones in the plasma sheet. Distribution of plasma pressure at geocentric distances R<10-12R_E obtained using the THEMIS data is near to isotropic at geocentric distances >5-6R_E.

•The dayside part of the inner magnetosphere transverse currents flows at high latitudes. Such currents are closed inside the magnetosphere by nighttime transverse currents and constitute cut ring current CRC - high latitude continuation of the ordinary ring current

•Plasma pressure at geocentric distances >5-6R_E can be considered as natural tracer of the magnetic field line.

•Most part of the auroral oval is mapped to the surrounding the Earh plasma ring. Such feature helps to explain the observed near circular form of the auroral oval and is important for the analysis of magnetic storms.

Thank you for your attention