Ionospheric Plasma in the Earth's Magnetotail

**A Tutorial:**
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**Credit:** M-C Fok, D C Delcourt, J A Fedder, S P Slinker

21st Century Outflow Observations:
- Andersson '06; Chaston '06;
- Chen '04 '06; Cully '03a,b;
- Dandouras '04;
- Elliott, '01, '02;
- Fuselier, '03, '06;
- Gardner, '04 '05;
- Huddleston '05;
- Liemohn '05; Lund '00;
- Mouikis, '06; Moore, '01, '03, '05a,b;
- Peterson '01, '02, '06; Sauvaud '02;
- Strangeway '05; Tu, '05;
- Tung, '01; Valek, '02; Wilson, '03, '04;
- Wu '02; Zeng, '04, Zheng '05;
The Central Problem

- Consider a conical tank standing in a river, creating a wake flow.
- At times, tank gets filled and pressurized to 20x dynamic pressure.
- Q. How can a fluid flow pressurize itself into an embedded tank?

Perhaps fluid pumped by latent electromagnetic energy?
Perhaps steady pumping with stretch/relax-compression cycles?
What role might an abundant cold internal fluid play in this?
How does this work in real heliophysical situation?
Why a Magnetosphere?

- Stagnant solar breeze ~ 1 nPa
  - spherical magnetopause, polar cusps
- Magnetized plasma cell constrained by fibrous connective tissue of flux tubes
  - Like surface tension but distributed
- 1. Cell collisions yield linkage of fibres, possibly merging cells
- 2. High relative speed parcels within a cell distend and may split the cell
- 1a. Small cells embedded in larger cells tend to be eroded and-or assimilated
Why a Magnetotail?

- Solar wind -> pressure asymmetry -> tail and viscous BL
- Embedded in larger cell
- Reconnection for NBz:
  - LLBLs circulate into lobes, PS fattens; yields Cold dense plasma sheet
  - LLBL as upstream source
- Reconnection for SBz:
  - Lobes circulate into Hot PS, NENLs, plasmoids
  - Polar cap as upstream source
- To balance plasma pressure with Maxwell stresses
Why Plasma Flow?

On the question: does $E$ cause $V$ or does $V$ cause $E$?

My take:
- Moving plasmas are electrodynamically coupled, so...
- No $V$ without $E$, BUT
- $M - \nabla P \Rightarrow V \& E$

Pressure gradients unbalanced by Maxwell stresses move plasmas, generate $V$, $E$, EMF of generator
Why a Distant X Line?

1. Disconnection of IMF hung up on magnetopause
   - As for comet tails
2. Disconnection of solar wind plasma trapped on closed flux tubes
   - Nearer/farther from Earth for stronger/weaker solar wind

Beyond some distance, wind too strong, field too weak, to be confined/closed

Treumann in Hultqvist et al. 1999
Why a Near Earth X line?

- Same as distant X line except much deeper
- Greater pressure req.
- When plasma pressure cannot be contained, in a region of stronger field than for distant X line...

- Excess plasma trapped on closed flux tubes
Why a Ring Current?

- Typ' solar wind Pd ~ 1 nPa ~ 6 keV/cc
  held off at 10Re by ~100 nT field
- Q. What pressure to penetrate to 3-4 Re?
  A. ~20 nPa ~ 130 keV/cc
- [DPS: 2.5e29 keV = -1 nT Dst ring current]
- How can a fluid flow pressurize itself x20?
- Consider pumps/compressors:
  - Some use cyclical motion; some store-release cycle:
  - Venturi pump uses one fluid to pump another:
    - Magnetospheric bicycle tire gets topped up with pressure just by riding real fast!
- Something in the magnetosphere wants out...
  - External or internal plasma, how pressurized?
Why Geopause vs Plasmapause?

The question: How much does the ionosphere contribute to hot plasma? Answer: Depends on where and when; magnetosphere is inhomogeneous.

Inner region clearly geogenic = geosphere, expands with activity.

Geopause region is hot O+ dominated, unlike plasmasphere.

Ring Current growth involves an exponential O+ increase.
Why Test Particles in LFM?

Strengths:
- Pathways can be traced
- Drifts and non-adiabatic behavior can be computed
- Dynamic importance of ionosphere can be assessed

Weaknesses:
- Problematic to do plasmaspheric ions
- Inner magnetospheric convection strength lacking
- Not self consistent since no $O^+$ load on system

Opportunities:
- Embed inner magnetosphere model, e.g. CRCM
- Integrate dynamic auroral wind into global simulation

Threats:
- Improved understanding and predictions
Role of IMF $\partial B_z$: Solar Wind

Solar wind behavior is familiar response to $SB_z$
Solar Wind Pathways to PS

Solar wind paths arrive in CPS mainly for NBz, from LLBL
Interactive Ionosphere Outflows

Table 1. Local empirical scalings used to initialize ionospheric particles
* Indicates parameters that remain poorly determined from empirical studies

<table>
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<tr>
<th>Parameter</th>
<th>Scaling</th>
<th>Notes</th>
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| **Auroral wind O+ flux** | NVprecip = 2.8e9*(N/10)^2/2 [cm^-2s^-1] 
NVpoynt = 5.6e7*(0.245*S_{120})^{1.26} [cm^-2s^-1] 
NV = NVprecip + NV poynt 
Strangeway et al. [2005 JGR] 
Zheng [2005 JGR]. | N is LFM density in cm^-3; 
* N/10 is assumed fraction of density above instrumental Emin 
S_{120} is LFM Poynting flux in mW/m^2 at 120 km altitude; 0.245 maps from 120 to 4000 km alt. Fluxes mapped to 1000 km. |
| **Auroral wind O+ temperature** | 0.1 + 9.2*(0.24*S_{120})^{0.35} [eV] | Strangeway [private communication] |
| Parallel energy   | E_// [eV] = E_{th} + e\Phi[V] where 
\Phi[V] = 1500[V/\mu A m^-2] *(J_// - 0.33)^2 [\mu A m^-2] | Moore et al., 1999 SSR 
Lyons [1981 Geo.Mono. 25] 
* Threshold current 0.33 \mu A/m^2 |
| **Polar Wind H+ flux** | 0 < SZA < 90: F_{1000} = 2x10^8 cm^-2s^-1 
90 < SZA < 110: 
NV_{1000} = 2 \times 10^8(8-(SZA-90)/20*2.5) 
110 < SZA < 180: F_{1000} = 2 \times 10^{5.5} | Su et al., [1998 JGR] solar zenith angle (SZA) dependence 
All fluxes at 1000 km altitude |

**Detailed specifications for local response to MHD b.c.**
IMF $dB_z$: Auroral B.C.

Poynting Flux, soft electrons, and $J_{\parallel}$ drive outflows
Role of IMF $\partial B_z$: Auroral Wind

Initial void is filled with O+ outflows as SBz takes effect
Auroral wind paths arrive at CPS from caps through the lobes.
Global Ionospheric Outflow

Upper trace:
Pd increase 2 hrs
0.45 to 4.5 nPa
from:
Bz = 0, By = 5nT

Lower trace:
SBz for 2 hrs
from: NBz 5 nT
Pd = 0.8 nPa

SBz and Pd both enhance outflow, only NBz suppresses

Yau et al. 1988 global average range
Actual fluences are
1/3-1/2 this when Poynting
flux and ion temperature
are low, begin and end.
Energy of Ring Current

- Total Energy developed inside 15 Re or Magnetopause

As we know, MHD alone does not produce much ring current.
Modeling Inner Magnetosphere
Fok, Wolf et al. Comprehensive Ring Current Model

- Driven by $V_{TP}$
- MHD imposed
- Supplied by b.c. @ 8 $R_E$ from test particles
- Flow/E loaded by coupled ionosph. conductivity
- Losses accounted
- Self consistent $V$, $E$ in inner mag'
LFM-CRCM Combined Global Pressure Response

Right: O+ pressure and anisotropy distributions

Below: driver potential

Potential Drop Across the CRCM Poleward Boundary

SBz

Substorm

NBz

1. a. b. c.
With outer b.c. for SW, PW, AW from test particle results above

~60 nT from O⁺
~20 nT from H⁺ (SW+PW)

SW H⁺: ~18 nT

What features of CRCM are responsible for this?
- Anisotropic drift physics, plasma sources, conductance, composition?

Ionospheric O⁺ dominates when supplied per this prescription
What about Conductance?

- Ebihara, 2005 JGR stressed importance
- Simple generator-load result:
  - If draw excess power, drive gen. into current source mode, reduce load pot. & power:
  - Max energy transfer for matched conductances
  - “Brownout” makes generator take over as the load
- More conductance makes more ring current: $O^+$ becomes the generator-load for inner magnetosphere
Why is Ionosphere So Important?

- Ionosphere starts out “inside the tank”
- Heavy and slow enough to remain “in the tank” for multiple passes through “the pump”
- Lower energy particles respond more radially to given size $\nabla P$-driven $E$ field
- Ionospheric plasmas become load on the generator for the inner magnetosphere in brownout (current supply) mode

“Ionospheric plasma is heated, pumped, and compressed by the solar wind, causing it to expand into and inflate the magnetosphere, until it escapes into the solar wind.”
The Self-Pumping Bicycle Tire

Auroral Acceleration

Cleft Fountain Production

Magnetotail Reconnection, Dipolarization

Atmosphere Ionosphere Ablation

Plasmaspheric Erosion

Magnetopause Reconnection

Geospheric Pressurization

Magnetospheric Inflation

Flank BL Interaction

Dayside BL Interaction

Solar Wind Interaction

SBz - NBz

Energy

Mass
The Self-Pumping Bicycle Tire

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