Formation of the high-altitude cusps and dayside boundary layers: CLUSTER results

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Outline

• Introduction to the magnetospheric cusps

• Results from case studies:
  → Northward IMF
  → Southward IMF

• Results from statistical studies:
  → Global properties for all IMF conditions
  → Flows characteristics for selected IMF

• Conclusions: structure and role of the cusps
Introduction: the magnetospheric cusps

• The exterior cusp region may be characterized by large-scale turbulence and flow eddies [e.g. Haerendel et al., 1978]

• The exterior cusp / magnetosheath boundary may be a shock [e.g. Walters, 1966; Cargill, 1999]

• Original picture from Cluster mission proposal

• Cluster orbit was designed to encounter the high-altitude cusp
Introduction: reconnection and the magnetospheric cusps

- Reconnection may occur at the low-latitude magnetopause for southward IMF, but in the lobes for northward IMF.
- The outer cusp boundary may be a rotational discontinuity (RD).
- Presence/absence of a plasma mantle for southward/northward IMF.
- Super-Alfvenic flows in the magnetosheath would prevent sunward convection in the cusps under northward IMF.
Case studies of the exterior cusp structure: Northward and Southward IMF
Northward IMF case: February 04, 2001
The exterior cusp is stagnant and surrounded by:
- High-speed downward flows but no plasma mantle
- Two distinct boundaries with the plasma sheet and sheath

→ The exterior cusp is bounded by three distinct boundaries
Minimum variance and planar discontinuity analyses yield:

- **Outward** boundary normal
- **Inward normal** magnetic component
- **Inward** boundary speed
- **Inward, additional** plasma flow

→ Magnetosheath plasma flows through an “open” boundary
Boundary with the magnetosheath (2)

• Slow deHoffmann – Teller velocity, directed sunward and downward
• Walén test satisfied consistent with $B_n \neq 0$

$V_{\text{SHEATH}} - V_{\text{HT}} = V_A$

$V_{\text{HT}} = 10.39, 41.29, -18.41$

The boundary is possibly a rotational discontinuity (RD) originating from lobe reconnection

Walén

Walén slope: 0.74383325
Walén c.c.: 0.97782188
Sub-Alfvénic plasma depletion layer

- Magnetic field pile-up at the dayside magnetopause → Plasma depletion layer (PDL)
- Density decreases and magnetic field increases → Alfvén speed increases → Sub-Alfvénic flows close to the magnetopause

→ The sub-Alfvénic PDL allows the sunward convection ($V_{HT}$) and propagation of the reconnected field lines
→ It may allow the stability of the lobe reconnection site
The exterior cusp under northward IMF: Overall structure

The exterior cusp structure is consistent, at large scales, with the occurrence of lobe reconnection
Southward IMF case: April 01, 2003
Large plasma flows in the high-altitude cusp

- Presence of a plasma mantle
- Low magnetic field and large flows in the exterior cusp simultaneously at two S/C
- S/C 1 monitors a southward IMF when S/C 3 crosses MP
Boundary with the magnetosheath

• Large deHoffmann – Teller velocity, directed upward
• Normal magnetic component $B_n \neq 0$
• Walén test satisfactory

$\Rightarrow$ The boundary is possibly a rotational discontinuity (RD) originating from low-latitude reconnection
The exterior cusp under southward IMF:
Overall structure

The exterior cusp structure is consistent, at large scales, with the occurrence of low-latitude reconnection.
Statistical study of the exterior cusp structure: Three years of Cluster data
Solar wind conditions are sampled at intervals of 10 minutes (ACE) and Cluster data every 2 minutes (163 crossings).

We make use of SC3 data on 2001 and 2002 (~600 and 100 km separation), data from satellites 1 and 3 are used for 2003 (~1Re).
The orbit points are brought back to the \((X,Z)_{SM}\) plane.

The variations in cusp latitudinal location are taken into account by use of a model field [Tsyganenko, 1996].

The variations in radial magnetopause location are taken into account by use of a model magnetopause [Shue et al., 1997].
Superposed epoch analysis: methodology

- The orbit points are brought back to the (X,Z)\textsubscript{SM} plane
- The variations in cusp latitudinal location are taken into account by use of a model field [Tsyganenko, 1996]
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Global properties for all IMF conditions
Magnetic configuration

• The magnetic configuration follows that expected in the lobes and dayside plasma sheet
• The variations in $\langle |B_{\text{meas}} - B_{T96}| \rangle$ shows the existence of a transition region:
  “The Exterior Cusp”
The exterior cusp: a diamagnetic cavity

- The magnetic pressure difference observed with the T96 model field shows the diamagnetic nature of the exterior cusp
- Three distinct boundaries are found with the lobes, the dayside plasma sheet and the magnetosheath
Flow characteristics for selected IMF directions
IMF restrictions

- Clock angle (CA) = arctan (IMF By / IMF Bz)
- Northward IMF defined as $|CA| < 60^\circ$
- Southward IMF defined as $|CA| > 120^\circ$
Parallel flows: precipitation location

- Precipitation occurs at the equatorward edge of the cusp for southward IMF, at the boundary with the dayside plasma sheet.
- It occurs at higher latitudes for northward IMF, at the boundary with the lobes.
Perpendicular flows: plasma convection (X direction)

- Plasma convection is clearly tailward at the equatorward edge, and throughout, the cusp for southward IMF.
- The exterior cusp is rather stagnant for northward IMF, slight sunward convection is observed near the boundary with the lobes.
Conclusions: the structure of the cusp

• The **Exterior Cusp** is a diamagnetic cavity forming a **transition region** between the magnetosheath and the magnetosphere

• **Three distinct boundaries** surround the exterior cusp with the lobes, the dayside plasma sheet and the magnetosheath

• The **outer boundary** may be defined as the magnetopause

• It is seen as a **sharp transition** in most parameters, may be **rotational in nature**, and allows for **permanent plasma entry** into the cusps
Conclusions: the role of reconnection

- Plasma precipitation occurs at low (high) latitudes for southward (northward) IMF
- Plasma convection is tailward for southward IMF, the exterior cusp is stagnant for northward IMF
- Sunward convection is observed near the boundary with lobes under northward IMF
- Under northward IMF, the presence of a PDL renders the magnetosheath flow sub-Alfvénic, possibly allowing lobe reconnection to be stable
- Such findings are consistent with the high-altitude cusp being structured, at large scales, by reconnection
• What are the mechanisms leading to the formation of the low-latitude boundary layers and plasma sheet (cold and dense) under northward IMF?

• Candidate mechanisms:
  - Diffusion by wave particle interactions
  - Transport through Kelvin-Helmholtz instability
  - Double high-latitude reconnection (see next talk by J. McFadden)