The Geomagnetic Cusps: Magnetic Topology and Physical Processes

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http://pluto.space.swri.edu/IMAGE/glossary/cusp.html

Thanks to: Eric Adamson, Katariina Nykyri, Julia Pilchowski, Jason McDonald
The Geomagnetic Cusps

Structure:
Magnetic structure (topology) – Magnetic null point => B=0
Magnetic boundary maps to cusp point!
Identification

Topics:
Structure, Morphology
Location, size, formation
Geomagnetic significance
   Plasma entry
   Precipitation
   Ion outflow
   Waves and Turbulence
   Particle trapping
Physical processes
   Magnetic reconnection
   (Kelvin Helmholtz instability
    Turbulence)
Diamagnetic Cavities and Cusp Energetic Particles
Formation
Particle source and acceleration
Summary
The Geomagnetic Cusps

Chapman and Ferraro (1931)
Role of the cusps in magnetospheric physics

Interplanetary magnetic field

Magnetopause

Tail (magnetic) current

Tail lobe

Plasma sheet

Solar wind

A

B

c

d

V

V
The Geomagnetic Cusps - Structure

Structural Elements:
- Stagnation region
- Entry Layer (HLBL - High Latitude Boundary Layer)
- Midaltitude cusp
- LLBL (Low Latitude Boundary Layer)
- Plasma Mantle

Haerendel et al., 1978
Zong et al., 2005
Cusp Observations and Properties

Exterior Cusp
- Stagnant flow
- Weak magnetic field
- High plasma $\beta$
- Plasma properties different from magnetosheath
- Thin boundaries

Cluster Observations:
Lavraud et al., 2002
The Geomagnetic Cusps - Structure

Exterior Cusp: Region with strong magnetic field variation and depression!

Lavraud et al. (2004)
Exterior cusp:

- Boundaries: Lobes, dayside plasma sheet, and magnetosheath
- Stagnant plasma (particularly for $B_z > 0$)
- Total pressure balance
Cusp Precipitation:
Low energy, high number density flux (e.g. Burch, 1968; Heikkila and Winningham, 1971; Frank, 1971; Newell et al., 2004 …)
Ion precipitation (Proton aurora;

Newell et al. (2005)
The Geomagnetic Cusps - Boundaries

Zhang et al. (2006), also Dunlop (2005), Nykyri (2010)
The Geomagnetic Cusps – Precipitation + Ion outflow

Cusp aurora for changing IMF orientation

Fuselier et al. (2003)

Cusp aurora

Ion outflow distribution

Fuselier et al. (2008)

Also! Relation between upflow and poleward moving auroral transients (and intermittent reconnection) (e.g., Moen et al., 2004)
The Geomagnetic Cusps – Precipitation + Ion outflow

Net hemispheric outflow during quiet times (Peterson et al., 2008)

Ionosphere major plasma source for magnetosphere
(e.g. Chappell et al, ‘87, Lockwood et al., ’85; Horwitz and Moore, ’97)
• Local magnetic shear varies 360 degrees:
  • Antiparallel magnetic field => Magnetic Reconnection
  • Parallel and antiparallel field => Kelvin Helmholtz
  • Fast (superfast) flow past an obstacle => Turbulence
  • Low magnetic field strength
• Issue: Difficult in local models
Cusp Reconnection (Crooker, '79; Song and Russell, '92; ..)

Importance of magnetic null points?
Antiparallel vs. component reconnection?
Sash (White et al., 1998)
Cusp Reconnection

Dayside Hybrid Simulations (Lin and Wang, '06)
Cusp Reconnection - antiparallel vs component?

Fuselier et al.
Cusp Reconnection

Observations (Fuselier, Phan, Trattner, Wang, Lavraud, ..)
- Ground based (lobe reconnection cells, particle signatures)
- In-situ spacecraft observations
- Remote particle signatures

Trattner et al, 2004
Diamagnetic cavities:
- High level of magnetic and density fluctuations
- Frequently associated with strongly enhanced fluxes of energetic particles

(Also Chen et al., 1997, 1998; Sheldon et al., 1998; ...)

Fritz and Chen, 2001

Fritz and Chen, 2003
CEP’s - Cusp Energetic Particle Events:

- Regions of ‘turbulent’ weak magnetic field
- Enhanced energetic particle fluxes at/above 10 keV
- Particle energy proportional to charge
- Magnetic moment consistent with ring current/ radiation belt

Nykyri et al., 2008
Turbulence or structure

Nykyri et al. (2010)
Regions 1, 2, 3, 4

- Sharp Transitions between Regions with and without CEP's
- Regions with CEP's map to quasi-parallel bow shock.

Trattner et al. (2009)

<table>
<thead>
<tr>
<th>Region</th>
<th>Cusp</th>
<th>Closed Field Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Questions:

• Local Acceleration?
• Quasi-parallel bow shock source?
• Magnetospheric source (Aiskainen and Mursula, 2006)?
• What is the acceleration mechanism?
  - Turbulence, Betatron, Fermi, Potential, Other?
- Presence of energetic electron in cavities.
- Only small fraction of distribution in the loss cone (to the magnetosheath)
Local MHD + Test Particle Simulations

IMF-connected Magnetospheric field lines

Initial Configuration
3D Cusp-like Reconnection

\[ \nu_0 = 1090 \text{ km/s} \]
\[ B_0 = 50 \text{ nT} \]
\[ L_0 = 6400 \text{ km} \]
Typical Properties

- Enhanced Density and Pressure
- Thin Current sheet bounding exterior
- High Plasma Beta
- Flows into cusp from reconnection site
Diamagnetic Cavities

- Regions of strongly depressed magnetic field
- Scale: 4 to 6 $R_E$ parallel to boundary; 1 to 2 $R_E$ perpendicular to boundary
- Enhanced pressure and density
Cavity locations superposed for 3 IMF orientations.

Cavities increase in size due to reconnection in region with small guide field.
Test Particle Dynamics – Model:

\[
\frac{dr_i}{dt} = v_i
\]

\[
\frac{dv_i}{dt} = \frac{q_i}{m_i} (E + v_i \times B)_{r_i,t}
\]

Typical particle properties:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Protons</th>
<th>Electrons</th>
<th>He\textsuperscript{++}</th>
<th>O\textsuperscript{+}</th>
<th>O\textsuperscript{++}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gyro frequency</td>
<td>$\omega_{cs0}$</td>
<td>3.832 s\textsuperscript{-1}</td>
<td>7025 s\textsuperscript{-1}</td>
<td>1.916 s\textsuperscript{-1}</td>
<td>0.240 s\textsuperscript{-1}</td>
</tr>
<tr>
<td>Gyro time</td>
<td>$t_{cs0} = \omega_{cs0}^{-1}$</td>
<td>0.261 s</td>
<td>1.423 \times 10\textsuperscript{-4} s</td>
<td>0.522 s</td>
<td>4.18 s</td>
</tr>
<tr>
<td>Gyro period</td>
<td>$2\pi t_{cs0}$</td>
<td>1.640 s</td>
<td>8.94 \times 10\textsuperscript{-3} s</td>
<td>3.280 s</td>
<td>26.23 s</td>
</tr>
<tr>
<td>Time ratio</td>
<td>$t_{cs0}/t_A$</td>
<td>2.51 \times 10\textsuperscript{-2}</td>
<td>1.371 \times 10\textsuperscript{-5}</td>
<td>5.03 \times 10\textsuperscript{-2}</td>
<td>0.402</td>
</tr>
<tr>
<td>Gyroradius - $r_A$</td>
<td>$r_{cs} = v_A/\omega_{cs0}$</td>
<td>161 km</td>
<td>87.8 m</td>
<td>321 km</td>
<td>2575 km</td>
</tr>
<tr>
<td>Energy\textsuperscript{1} for $v_A$</td>
<td>$m_A v_A^2/2$</td>
<td>1.98 keV</td>
<td>1.081 eV</td>
<td>7.93 keV</td>
<td>31.7 keV</td>
</tr>
<tr>
<td>Thermal speed</td>
<td>$v_{ths} = \sqrt{\frac{m_A k_B T}{m_A}}$</td>
<td>309 km/s</td>
<td>13,200 km/s</td>
<td>154 km/s</td>
<td>77.2 km/s</td>
</tr>
<tr>
<td>Ther. gyrorad.</td>
<td>$v_{ths}/\omega_{cs0}$</td>
<td>80.6 km</td>
<td>1.88 km</td>
<td>80.4 km</td>
<td>322 km</td>
</tr>
</tbody>
</table>
Particle Dynamics: Initial conditions

- Shell distributions in velocity (e=500eV)
- Random distribution in space
- Color codes max energy (see next slide)
- Number of particles: here 20000
Particle Dynamics: Total/average energy

**Average Energies**
- Total
- Perpendicular
- Contrib. of energetic part
- Parallel

**En_par vs En_perp for Max energy**
- $E_{||}$ vs $E_{\perp}$
Particle Dynamics:
Evolution inside of simulation domain
Polar Observations: Pitchangle distribution

Chen and Fritz, 2004
Simulation: Particle Fluxes

**Protons**

- Triangles – flux constructed from test particles in the simulation domain (left) and particles leaving the domain (right)
- Dashed – flux corresponding to a Maxwellian with the initial thermal energy
- Solid – flux corresponding to a Maxwellian with the maximum thermal energy

**He^{++}**
Particle Dynamics:
Example 1

30keV

E_d vs x

B along x

Y vs X

Z vs X
Particle Dynamics: Example 1
Particle motion in Cusp ‘potential’

‘Potential’ isosurfaces
Mechanism:
• Highly efficient particle trapping.
• Particle motion: Combination of gradient curvature and ExB drift.
• Gradient curvature drift along the electric field component

Scaling of the acceleration process:

Drift velocity:

\[ v_{gd} = \frac{m v_{\perp}^2}{2qB^3} (B \times \nabla B) \propto \frac{v_{\perp} r_c}{L_g} \quad \text{with} \quad \frac{r_c}{L_g} \propto \frac{1}{B} \]

Electric field:

\[ E \propto v_A B = B^2 / \sqrt{n} \]

Energy:

\[ W \propto \int E \cdot ds \propto B^2 L_0 / \sqrt{n} \]
Particle Dynamics: Scaling laws

$B_0 = 40 \text{ nT}, \ L = 1 \ \text{RE}$

$B_0 = 80 \text{ nT}$

$L = 2 \ \text{RE}$

Particle drift paths:

Max. Energy: ~50 keV  ~200 keV  ~100 keV

Particle Distrib:
Model: Energy gain for duskward ion motion and $B_z < 0$
and dawnward ion motion and $B_z > 0$

Consistent with Cavity $E_y$ in Cluster event!
Summary on Particle Acceleration

Mechanism:
• Highly efficient particle trapping.
• Particle motion: Combination of gradient curvature and ExB drift.
• Gradient curvature drift along the electric field component

Scaling:
• Nonadiabaticity -> less spatially confined distributions, no contrib. to acceleration!
• Energy gain scales proportional to electric field \( \sim E \sim B^2 \) and length scale \( \sim L_0 \)
• Temporal scale \( \sim 1/B, \sim L_0, \) and \( \sim 1/m \)

Other:
• Energization not confined to inertial length scales!
• Primary energization in perpendicular direction.
• Parallel electric field = 0!
• Particle trapping + perpendicular electric field natural for high beta regions
  (magnetic neutral points, diamagnetic cavities, ..)
• Solar particle acceleration
• Particle dynamics and acceleration of key importance in many space plasma systems
Concluding remarks:

- Cusps are rich in physics and play an important role for the magnetosphere
- Important aspects:
  - Magnetic reconnection
  - Particle entry and precipitation
  - Ion outflow
  - Generation or storage of energetic particles
- Unresolved (but progress): Origin of CEP’s
  - Pitch angle distribution
  - Fluxes are higher then in adjacent magnetosheath
  - Presence of Oxygen
  - Presence of energetic electrons