**Magnetotail-Ionosphere-Thermosphere Coupling in Geospace Dynamics**

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**Collaborators**

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**EM Power Flows**

**Observation, Theory**

Alfvén wave energy flowing to low altitude powers “broadband” electron precipitation and ionospheric O+ outflows.

**Model Strategy**

Use satellite-derived empirical relations to causally regulate broadband electron precipitation and ionospheric O+ outflows in LFM global simulations.

**Science**

What is the genesis of the simulated Alfvénic Poynting flux?  
What regulates its features and patterns?

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**Agents of M-I-T Coupling**

**Electromagnetic power flows**

- convection, currents

**Charged-particle precipitation**

- ionization, energy deposition

**Ionospheric outflows**

- mass, energy redistribution

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**Mapping**

**Alfvénic Power**

**Steady conditions**

- $v_{sw} = 400$ km/s  
- $B_z = -5$ nT  
- $n_{sw} = 5$/cm$^3$

**LFM simulations**

- with precipitation-enhanced conductance  
- without precipitation-enhanced conductance
Effect of Precipitation on Plasmasheet State

SW: \( V_x = -400 \text{ km/s}, n = 5 \text{ cm}^3, C_s = 40 \text{ km/s} \)
IMF: \( B_z = -10 \text{ nT} \)

Full precipitation \( \Sigma_H = 5 \text{ mho} \)

\( \Sigma_H = \Sigma_p = 5 \text{ mho} \)

\( j \cdot E, \mu \text{W/m}^2 \)

-0.5 0 0.5

\( -1.5 \) \( -1.5 \) \( -1.5 \)

\( 0 \) \( 0 \) \( 0 \)

\( 1.5 \) \( 1.5 \) \( 1.5 \)

Effect of Precipitation on Ionospheric State

SW: \( V_x = -400 \text{ km/s}, n = 5 \text{ cm}^3, C_s = 40 \text{ km/s} \)
IMF: \( B_z = -10 \text{ nT} \)

Full precipitation \( \Sigma_H = 5 \text{ mho} \)

\( \Sigma_H = \Sigma_p = 5 \text{ mho} \)

\( J_{||}, \mu \text{A/m}^2 \)

-1.5 0 1.5

Effect of Precipitation on Plasmasheet State

Full precipitation \( \Sigma_H = 5 \text{ mho} \)

\( \Sigma_H = \Sigma_p = 5 \text{ mho} \)

WIND, 17 perigee passes, 1995-97

\( V > 250 \text{ km/s} \)

Duration = Time spent observing flows in given velocity range relative to flows with \( \beta > 0.5, V_x > 0 \), and \( 0 \leq V < 1000 \text{ km/s} \).

Raj et al. 2002

Bursty Bulk Flow and Plasmasheet Flow Statistics


Juusola et al. 2010

Effects of Soft Electron Precipitation on the Ionosphere-Thermosphere

CMT Simulations: LFM-regulated electron precipitation
One-hour averages, equinox conditions, \( \tilde{F}_{10.7} = 100 \)

Interplanetary Conditions

Zhang et al. 2011

IMF \( B_z = -5 \text{ nT}, B_x,y = 0, n = 5 \text{ cm}^3, V_x = -400 \text{ km/s}, V_y,z = 0, C_s = 40 \text{ km/s} \)
Effects of Soft Electron Precipitation on Neutral Gas Density @ 400 km

CMIT Simulations: One-hour averages, equinox conditions, $F_{10.7} = 100$
- IMF $B_z = -5$ nT, $B_{x,y} = 0$
- $V_e = -400$ km/s, $V_o = 0$, $n_e = 5$ cm$^{-3}$, $C_s = 40$ km/s

CHAMP measurements: One-year average (2002)
- $Kp = 0 - 2$, $F_{10.7} = 180$ (mean)

CMIT simulations show
- When soft electron precipitation is included, neutral density at 400 km is enhanced up to 20%.
- Soft electron precipitation changes the neutral density by increasing the Joule Heating

| % difference in CMIT simulations with and without soft electrons | Zhang et al. 2011 |
| CMIT | CHAMP |
| % difference between CHAMP measurements and MSIS90 | Liu et al. 2005 |

Thermospheric Regulation of Outflows (Cannata and Gombosi 1989)

- Accidentally resonant charge exchange chemistry couples H$^+$, O$^+$ flows to the neutral density profiles of atomic H and O.
- Larger O$^+$ outflows arise at solar max based solely on thermospheric changes
- Higher neutral O scale heights at solar max shifts maximum production level of O$^+$ to higher altitudes where loss by reaction with O$_2$ and N$_2$ is less frequent

Correlations with outflow flux (FAST)

- 1-hour average
- Growth phase

Causal regulation
- $F_{||O} = 3 \times 10^{10} (\alpha S_{||A})^{1.2}$
- $v_{||O} = 44$ km/s
- $T_O = 40$ eV
- $\alpha = 3.8$

Steady Driving
- $V_{sw} = 400$ km/s
- $n_{sw} = 5$ cm$^{-3}$
- $B_z = -10$ nT

Brambles et al. Science, 2011

O$^+$ outflow at 2.2 $R_E$, mapped to ionosphere

Feldstein auroral oval superposed

Are Alfvén waves direct or indirect drivers?

Strangeway, 2009

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Hemispheric Outflow Rate \( \langle F_{\text{TOT}} \rangle \) vs. SW Driving \( \varepsilon \)

\[
\varepsilon = V_{\text{SW}} B_{\text{IMF}} \sin(\theta/2) P_{\text{dyn}}^{1/6}, \text{mV/m(nPa)}^{1/6}
\]

No Outflow vs. Outflow \( \Rightarrow \) “Sawtooth” Substorms

Brambles et al. 2011

Sawtooth Oscillation Period vs. Outflow Rate

\[
T = 8.5 \langle F_{\text{TOT}} \rangle^{1} + 0.5
\]

\begin{array}{|c|c|c|c|c|c|}
\hline
\text{Run} & V_{\text{SW}} \text{ km/s} & B_{z} \text{ nT} & \alpha & \langle F_{\text{TOT}} \rangle \text{ 10^6/s} & T \text{ hrs} \\
\hline
A & 400 & -10 & 2.14 & 3.7 & 1.18 & 8.9 \\
B & 400 & -10 & 3.80 & 3.7 & 2.36 & 4.4 \\
C & 400 & -10 & 5.32 & 3.7 & 3.55 & 2.8 \\
D & 400 & -10 & 6.76 & 3.7 & 4.80 & 2.6 \\
E & 400 & -10 & 12.0 & 3.7 & 9.59 & 1.7 \\
F & 400 & -10 & 12.0 & 3.7 & 4.80 & 2.6 \\
G & 400 & -10 & 3.80 & 6.4 & 4.02 & 2.0 \\
H & 600 & -10 & 3.80 & 1.9 & 1.36 & 5.3 \\
I & 400 & -5 & 3.80 & 1.9 & 1.36 & 5.3 \\
\hline
\end{array}

\text{Brambles et al. Science, 2011}

Ring Current Enhancement \( \Rightarrow \) Magnetospheric Inflation
Conclusions

Coupled models:

- Capture statistical distributions and amplitudes of auroral and cusp-region Alfvénic Poynting fluxes
  - Dispersive Alfvén waves are subgrid; extrapolate from Alfvénic continuum

- Provide insights into the role of precipitation-enhanced conductance in regulating nightside reconnection and fast flows in the plasmasheet
  - Physics of the M-I interaction is still a somewhat murky

- Produce thermospheric upwelling in regions of soft electron precipitation

- Show that ionospheric O⁺ outflows regulate the SW-M interaction (and CPCP) and induce ~3-hour periodic substorms (“sawtooth oscillations”)
  - We need better transport relations for ionospheric outflows

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Ionospheric Cavitation

a) Density from the calibrated Langmuir probe (black), electrostatic analyzer for electrons (red), and electrostatic analyzer for ions (green).
b) Perpendicular to \( B_0 \) electric field pointing roughly northward (\( E_x \) or \( E_y \)).
c) Approximate parallel to \( B_0 \) electric field (\( E_z \) or \( E_y \)).
d) Magnetic field measurements perpendicular to \( B_0 \) and pointing roughly eastward (\( B_y \) or \( B_z \)). The red trace is from the fluxgate magnetometer and the black trace from the fluxgate magnetometer plus the search coil magnetometer.
e) Ion energy spectrogram for the hemisphere opposite to the spacecraft velocity vector.
f) Ion pitch angle spectrogram for the hemisphere opposite to the spacecraft velocity vector.
g) Integrated ion flux for the hemisphere opposite to the spacecraft velocity vector.
h) Electron energy spectrogram.
i) Electron pitch angle spectrogram.

Chaston et al 2006
Ion Exobase Cavitation

Lundin et al. 1994

Electrons, 0°–20° p.a.
O⁺ ions, 45°–135° p.a.

Langmuir Probe Data

Plasma Density

Substorm Onsets

Rankin & Gillam MPA

557.7 nm
VIS Low-Resolution Camera, 557.7 nm

Lyons et al. 2002

Auroral Signatures: Poleward boundary intensifications, streamers

Aikio and Selkälä 2009

Conductance – Electric Field Correlation

€\langle \Sigma \rangle = \langle \Sigma \rangle \langle \mathcal{E} \rangle^2 > 0
+ \sigma_x \sigma_{E_x} \, \mathcal{E}_x^2 + \langle \Sigma \mathcal{E}_x \rangle \langle \Sigma \rangle
-1 \leq \sigma_x \leq 1

Cosgrove et al. 2009, 2011

Aikio and Selkälä 2009
Conductance – Electric Field Correlation

GUMICS - 4
28-29 Mar 1998, 2330 – 0600 UT

Correlation Coefficient = 0.66

\[
\frac{\langle E \times (\delta B) \rangle}{\mu_0} \cdot \hat{b}_{dp} = \left( \frac{\langle \delta E \delta B \rangle}{\mu_0} \cdot \hat{b}_{dp} \right)
\]

LFM
23 Nov 1999, 1400-1500 UT

Palmroth et al 2005

Melanson et al 2007