Magnetosphere-Ionosphere-Thermosphere Coupling During Storms and Substorms

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Why (or when do we need to) worry about the complications of SW-M-I-T coupling?

• M, I and T are especially interactive for strong SW driving
• Model predictions don’t do well w/o coupling
• Utility depends on the fidelity of prediction: Space weather
• “Understanding” is demonstrated by prediction
• The coupled M-I-T system is equisitely complex and interesting
What might you learn from this tutorial?
(or be reassured you that what you once thought was true is still true)

• Coupling agents

• Pathways (coupled) and feedback
  – Electromagnetic
  – Material

• Insights into M-I-T coupling

• Coupling during storms
  (with data-model comparisons)
Agents of M-I-T Coupling

135° < θ_{MF} < 225°
Agents of M-I-T Coupling

Winter, high driving Conductance?
Pathways of M-I-T Interaction

1. Electromagnetic

Ionospheric Ohm’s law, electrostatic condition, current continuity ⇒

\[ j_{\parallel i} \cos \delta = \nabla \cdot \vec{\Sigma} \cdot \nabla \Phi_i \]

Find \( \Phi_i \)

\[ \downarrow \]

Spatial distribution of \( \vec{\Sigma} \) determines \( \Phi_i \) for given \( j_{\parallel i} \) and vice-versa

2. Material transport
Global M-I-T Interactions (active periods)

O\textsuperscript{+}

O\textsuperscript{+} loss

Tail reconnection

Magnetosphere inflation

SW-MIT interaction

Feedback?

Joule heating, upwelling, etc.

Enhanced convection & entrainment of dayside O\textsuperscript{+} into polar circulation

Regions of enhanced Poynting fluxes, soft electron precipitation, structured FACs

Needs attention in system context

Enhanced convection & entrainment of dayside O\textsuperscript{+} into polar circulation

Foster et al. 05

Liu et al. 05
Empirical convection: Increasing strength of SW driving

Stronger driving: Convection is faster and extends to lower latitudes

Empirical convection: Increasing strength of SW driving

Weimer model

Magnetopause location: $\rho v^2 |_{sw} = 4B(r)^2/2\mu_0$ (Better: Shue et al., 1998)

CW rotation of the convection pattern when viewed from above NP

Excess flux circulation in dusk cell

Harang region

Weimer-2005 model
Empirical convection: Effect of IMF $B_y$

No mirror symmetry with change in sign of $B_y$ (Heppner 1972)

NH cusp, PC pulled dawnward

Over flux circulation reverses: Now higher in dawn cell
Effect of season/dipole tilt

Weimer model

SUMMER: Rotation moderated, over flux circulation exacerbated

Weimer-2005 model

6/23/2015
CONCLUSION

Ionosphere polarizes so as to maintain

$$\nabla \cdot \vec{J}_H = \hat{b} \times \vec{E} \cdot \nabla \Sigma_H \approx 0$$
Effect of EUV Hall conductance gradient

Perpendicular Velocity in Equatorial Plane

Reconnection Rate Along the X-line

1-HOUR AVERAGE STATES

0 2 hr 4 nT –4 nT

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Effect of combined EUV and auroral Hall conductance gradient

LFM global simulation

One-hour average states for steady $N_{SW} = 5/\text{cm}^3$, $T_{SW} = 8.5 \text{ eV}$, $V_x = -300 \text{ km/s}$, $B_z = -4 \text{ nT}$, and $V_{yz} = B_{xy} = 0$
WIND, 17 Perigee Passes, 1995-97

Events selected for $\vec{V} > 250 \text{ km/s}$ and $\beta > 0.5$ (neutral sheet)
Asymmetries in poleward boundary intensifications and Alfvénic aurora

- 249 Poleward Boundary Intensifications (substorm expansion or pseudobreakup determined from THEMIS ASI)

  - MLAT of PBI
  - Number of Events vs. MLAT, deg

- Onset MLT
  - Number of Events vs. MLT, hr

- Downward Alfvénic Poynting Flux

- Broadband Electron Power

Nishimura et al. 2010
24 Aug 2005
CME Storm

**Initial phase:** 06:00 – 09:00 UT

- $B_z \approx \text{small}$
- $B_y \sim 20 \text{ nT}$
- $Kp \sim 3-6$

The $B_y$-dominant time period has been studied by Crowley et al. [2010] using TIME-GCM.

→ Results show Joule heating is important in enhancing the $F$-region neutral density.

**Main phase:** 09:00 – 16:00

- $B_z \rightarrow -40 \text{ nT}$
- $B_y \rightarrow -40 \text{ nT}$
- $Kp \approx 9$, $Dst = -184 \text{ nT}$ at 1200 UT
**Weimer disclaimer**: Model works best for $|B_y|$ and $|B_z|$ < 15 nT.
Coupled M-I-T (CMIT) model

\[ j_{||} \cos \delta = \nabla \cdot \hat{\Sigma} \cdot \nabla \Phi_i \]
Monoenergetic and Diffuse Electron Precipitation Algorithm

Low-altitude BCs for MHD

Add EUV, broadband contributions

Robinson et al. 1987

CONDUCTANCE

\[ \varepsilon = \frac{F_E}{F_N} \]
\[ \Sigma_p = \frac{40 \varepsilon}{16 + \varepsilon^2} F_E^{0.5} \]
\[ \Sigma_H = 0.45 \varepsilon^{0.85} \Sigma_p \]

Current-Voltage Relation

\[ \Delta \Phi_{||} = \eta |J_{||}| \]

\[ \eta = \frac{T_e^{05}}{n_e} \mathcal{H}(J_{||}) \quad [kV/\mu A/m^2] \]
\[ \mathcal{H}(J_{||}) = \begin{cases} \eta_{\uparrow} j_{||} \text{ upward} \\ \eta_{\downarrow} j_{||} \text{ downward} \end{cases} \]
\[ \eta_{\uparrow} = -5 \eta_{\downarrow} = 11.25 \]

Knight-Fridman-Lemaire

\[ \Rightarrow F_N, F_E \text{ using a mirror ratio of 8} \]
Broadband Electron Precipitation Algorithm

$$\nabla \cdot \Sigma \cdot \nabla \Phi_i = j_{i||} \cos \alpha$$

Low-altitude BCs for MHD

$$\Sigma_p = \frac{40E}{16 + \xi^2} F_E^{0.5}$$
$$\Sigma_H = 0.45E^{0.85} \Sigma_p$$

CONDUCTANCE
Robinson et al. 1987

Add EUV, mono/diffuse contributions

$$F_E = 2.0 S_{||}^{0.5}$$
$$F_N = 3 \times 10^9 S_{||}^{0.46}$$

Keiling et al. 2002
Strangeway, 2010

Map to 100 km

Bandpass 5 - 180 secs

$$\frac{1}{\mu_0} \delta E \times \delta B \cdot \frac{B}{B}$$

Zhang et al. 2012
Change in Thermospheric Density due to Soft Electron Precipitation

Difference between CMIT simulations w/ and w/o soft electron precipitation (BBE, cusp)

Difference between CHAMP accelerometer measurements and MSIS90 model results

Comparisons at 400 km altitude. CHAMP data are averages for 2002 for intervals of Kp = 0 – 2. CMIT results are a 1-hour averages for $V_{sw} = 400$ km/s, $n_{sw} = 5$ cm$^{-3}$, IMF $B_z = -5$ nT, $F_{10.7} = 150$.  

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“Standard” CMIT simulation for the storm

- CMIT tracks CHAMP reasonably well for weak driving (0600 – 0900 UT)
- CMIT overestimates ($\approx x2$) the CHAMP mass density during the main phase (0900 – 1600 UT)
- **Question:** What’s missing in the model during the main-phase simulation? Plasmaspheric effects? Ionospheric outflows? ...?
Effects of plasmaspheric plumes on dayside reconnection

- Plasma of plasmaspheric origin is observed in the dayside reconnection region [Borovsky and Denton, 2006; Walsh et al. 2014]
- To what extent does the plasmasphere influence dayside reconnection?

- The dayside reconnection rate is smaller in a multi-fluid global magnetosphere simulation when plasmaspheric H\(^+\) is included.

**Does plasmaspheric H\(^+\) influence the stormtime F-region neutral density?**
O\(^+\) Outflow Algorithm

\[ r = 3 R_e \text{ surface} \]

Apply Outflow BCs

\[ n_{O^+} = \frac{F_{O^+}}{V_{||O^+}} \]
\[ V_{||O^+} = 40 \text{ km/s} , T_{O^+} = 100 \text{ eV} \]

Map \( F_{O^+} \) / B = const

Empirical Relation

\[ F_{O^+} = 3 \times 10^{10} S_{||}^{1.2} \]

Brambles et al. 2011
Effects of ionospheric O$^+$ outflow on stormtime substorms

Observations and modeling studies show that outflows of ionospheric O$^+$ are important in stormtime solar wind-magnetosphere-ionosphere coupling, especially during CME-driven storms exhibiting “sawtooth oscillations.”

Note: Simulated onsets (with outflow) occur but are delayed $\approx 1.5$ hr relative to observed onsets.

Do O$^+$ outflows influence the stormtime F-region neutral density?
Controlled Simulation Experiments

CMIT with:

- Two types of O\(^+\) outflow
- Fixed outflow flux: No causal regulation
Simulated $F$-region Neutral Density Compared to CHAMP

Better agreement when auroral $O^+$ is included in CMIT

$10^{-12} \text{g/m}^3$

CHAMP
Baseline
Gallagher plasmasphere
Auroral $O^+$
PW $O^+$

UT (hour), Aug-24, 2005

Zhang et al. 2014
Orbit-Averaged Neutral Density Compared to CHAMP

Baseline
Gallagher plasmasphere
Auroral O⁺
PW O⁺
Auroral O⁺ x2
CHAMP

Zhang et al. 2014
Effects of $O^+$ on M-I Coupling

- **Plasmaspheric $H^+$**: Little effect on CPCP, field-aligned current
- **Polar wind $O^+$**: Reduces CPCP
- **Auroral $O^+$ outflow**: Reduces CPCP, increases ring current intensity (but not enough and not sustained in these simulations)
- Hemispheric power is similar in all four runs between 10-11 UT but with different polar cap distributions.

*Zhang et al. 2014*
**Effects cont’d**

- CPCP is smaller when O\(^+\) outflow is included in the simulation

- Region-2 currents are larger when auroral O\(^+\) outflow is included ⇒ higher integrated current

- Less Joule heating in polar cap with more R1-R2 current closure

- Neutral temperature and density at 400 km altitude are lower when auroral O\(^+\) outflow is included

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*Zhang et al. 2014*
Key Points: Auroral precipitation

• Increases meridional gradient in $E$-region conductivity
  – Ionosphere polarizes at the gradient
  – Exacerbates dawn-dusk asymmetry in ionospheric convection plasmasheet fast flows

Why does the M-I system maintain nearly divergence-free Hall currents?
Key Points: Soft electron precipitation

• Produced by direct-entry (cusp) and conversion of Alfvén wave power to field-aligned electrons (cusp and nightside convection throat)

• Enhances conductivity in the bottomside $F$-region

• Joule heating is enhanced there $\Rightarrow$ neutral mass density is elevated at CHAMP altitude (but it increases too much)
Key Points: \( \text{O}^+ \) ionospheric outflows

- Lowers reconnection rate (dayside and nightside)
  - Lower CPCP
  - Slower convection
  - Less Joule heating, esp. in polar cap

- Auroral outflows have greatest impact

Do ionospheric outflows directly affect the neutral gas and vice-versa?