IONOSPHERE/THERMOSPHERE/MAGNETOSPHERE: ITM ELECTRODYNAMIC COUPLING

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Image from H. Lühr
Penetration of solar wind electric field into the M-I system

Intense, long duration electric field event on April 17, 2002

Observations using ACE satellite and radar facilities (Jicamarca, Sondrestrom)

Strong temporal correlation
Magnetic storm of July 15, 2000

Large bite-outs of electron density in the equatorial region after sunset (e.g., enhanced fountain effect)

Strong scintillations at 250 MHz and L-band

Strong upward and southward drifts at 600 km (ROCSAT)
ESF IMPACT ON RF PROPAGATION
combined optical and propagation data: Jonathan Makela
Highly Enhanced Total Electron Content and GPS Phase Fluctuations During October 30, 2003 Storm

Intense GPS Phase Fluctuations (Delta TEC/MIN) Occur in the Auroral Region and along the Storm Enhanced Total Electron Content (TEC) Gradient. GPS outage caused WAAS to be non-operational for 11 hours

(Su Basu et al., GRL, 2005)
EVEN SLASHDOTTED!!!
June 19th, 2008

Can we trust our GPS devices?

In recent years, we have become increasingly dependent on applications using the Global Positioning System (GPS), such as railway control, highway traffic management, emergency response or commercial aviation. But in a very short news release, the American Geophysical Union (AGU) warns us that we can’t always trust our GPS gadgets because ‘electrical activity in the upper atmospheric zone called the ionosphere can tamper with signals from GPS satellites.’ However, some new research studies are underway and ‘may lead to regional predictions of reduced GPS reliability and accuracy.’ But read more...
Ion Velocity

\[ \frac{\partial \mathbf{V}_i}{\partial t} + \mathbf{V}_i \cdot \nabla \mathbf{V}_i = -\frac{1}{\rho_i} \nabla P_i + \frac{e}{m_i} \mathbf{E} + \frac{e}{m_i c} \mathbf{V}_i \times \mathbf{B} + \mathbf{g} \]

\[ -\nu_{in} (\mathbf{V}_i - \mathbf{V}_n) - \sum_j \nu_{ij} (\mathbf{V}_i - \mathbf{V}_j) \]

- Electric field: \( \mathbf{E} \)
- Neutral wind: \( \mathbf{V}_n \)
- Not independent drivers!
Ion Velocity

\[ \frac{\partial V_i}{\partial t} + V_i \cdot \nabla V_i = -\frac{1}{\rho_i} \nabla P_i + \frac{e}{m_i} E + \frac{e}{m_i c} V_i \times B + g \]

\[ -\nu_{in}(V_i - V_n) - \sum_j \nu_{ij} (V_i - V_j) \]

- Electric field: $E$
- Neutral wind: $V_n$
- Not independent drivers!
\[ \nabla \cdot \mathbf{J} = 0 \quad \mathbf{J} = \sigma \mathbf{E} \quad \rightarrow \quad \nabla \cdot \sigma \mathbf{E} = 0 \]

Field-line integration: \[ \int \nabla \cdot \sigma \mathbf{E} \, ds = 0 \]

\[ \nabla \cdot \Sigma \nabla \Phi = S(J_\parallel, V_n, ...) \]

\[ \mathbf{E} = -\nabla \Phi \]

- \( \Sigma \): Field-line integrated Hall and Pedersen conductivities
- \( J_\parallel \): Magnetosphere driven
- \( V_n \): Solar and magnetosphere driven
DERIVATION OF POTENTIAL EQUATION

some gory details 1: perpendicular current

- **Step 1:** calculate $J$

  \[ J = e(n_i V_i - n_e V_e) \]

- **Step 2:** calculate $V_\alpha$

  \[
  \frac{\partial V_\alpha}{\partial t} + V_\alpha \cdot \nabla V_\alpha = -\frac{1}{\rho_\alpha} \nabla P_\alpha + \frac{e_\alpha}{m_\alpha} E + \frac{e_\alpha}{m_\alpha} V_\alpha \times B + g
  \]

  \[
  -\nu_{\alpha n} (V_\alpha - V_n) - \sum_j \nu_{\alpha j} (V_\alpha - V_j)
  \]

- **Step 3:** simplify $V_\alpha$ equation

  \[ 0 = \frac{e_\alpha}{m_\alpha} E + \frac{e_\alpha}{m_\alpha c} V_\alpha \times B - \nu_{\alpha n} (V_\alpha - V_n) \]
Step 1: calculate $\mathbf{J}$

$$\mathbf{J} = e(n_i \mathbf{V}_i - n_e \mathbf{V}_e)$$

Step 2: calculate $\mathbf{V}_\alpha$

$$\frac{\partial \mathbf{V}_\alpha}{\partial t} + \mathbf{V}_\alpha \cdot \nabla \mathbf{V}_\alpha = -\frac{1}{\rho_\alpha} \nabla P_\alpha + \frac{e_\alpha}{m_\alpha} \mathbf{E} + \frac{e_\alpha}{m_\alpha c} \mathbf{V}_\alpha \times \mathbf{B} + \mathbf{g}$$

$$-\nu_{\alpha n} (\mathbf{V}_\alpha - \mathbf{V}_n) - \sum_j \nu_{\alpha j} (\mathbf{V}_\alpha - \mathbf{V}_j)$$

Step 3: simplify $\mathbf{V}_\alpha$ equation

$$0 = \frac{e_\alpha}{m_\alpha} \mathbf{E} + \frac{e_\alpha}{m_\alpha c} \mathbf{V}_\alpha \times \mathbf{B} - \nu_{\alpha n} (\mathbf{V}_\alpha - \mathbf{V}_n)$$
Step 1: calculate \( \mathbf{J} \)

\[
\mathbf{J} = e(n_i \mathbf{V}_i - n_e \mathbf{V}_e)
\]

Step 2: calculate \( \mathbf{V}_\alpha \)

\[
\frac{\partial \mathbf{V}_\alpha}{\partial t} + \mathbf{V}_\alpha \cdot \nabla \mathbf{V}_\alpha = -\frac{1}{\rho_\alpha} \nabla P_\alpha + \frac{e_\alpha}{m_\alpha} \mathbf{E} + \frac{e_\alpha}{m_\alpha c} \mathbf{V}_\alpha \times \mathbf{B} + \mathbf{g} - \nu_{\alpha n} (\mathbf{V}_\alpha - \mathbf{V}_n) - \sum_j \nu_{\alpha j} (\mathbf{V}_\alpha - \mathbf{V}_j)
\]

Step 3: simplify \( \mathbf{V}_\alpha \) equation

\[
0 = \frac{e_\alpha}{m_\alpha} \mathbf{E} + \frac{e_\alpha}{m_\alpha c} \mathbf{V}_\alpha \times \mathbf{B} - \nu_{\alpha n} (\mathbf{V}_\alpha - \mathbf{V}_n)
\]
Step 4: solve for $V_\alpha$ take $(B = B \, e_z)$

$$V_\alpha = \frac{1}{1 + \nu_{\alpha n}^2 / \Omega_{\alpha}^2} \left[ \left( \frac{cE}{B} + \frac{\nu_{\alpha n}}{\Omega_{\alpha}} V_n \right) \times \hat{e}_z + \frac{\nu_{\alpha n}}{\Omega_{\alpha}} \left( \frac{cE}{B} + \frac{\nu_{\alpha n}}{\Omega_{\alpha}} V_n \right) \right]$$

Step 5: solve for $J$ from definition

$$J = \sigma_P \left( E + \frac{B}{c} V_n \times \hat{e}_z \right) + \sigma_H \left( \frac{B}{c} V_n - E \times \hat{e}_z \right)$$

where

$$\sigma_P = \frac{ec}{B} \left[ \frac{n_i \nu_{in}/\Omega_i}{1 + \nu_{in}^2 / \Omega_i^2} + \frac{n_e \nu_{en}/\Omega_e}{1 + \nu_{en}^2 / \Omega_e^2} \right]$$

$$\sigma_H = \frac{ec}{B} \left[ -\frac{n_i}{1 + \nu_{in}^2 / \Omega_i^2} + \frac{n_e}{1 + \nu_{en}^2 / \Omega_e^2} \right]$$
Step 4: solve for $V_\alpha$ take ($B = B\, e_z$)

$$V_\alpha = \frac{1}{1 + \nu_{\alpha n}^2/\Omega_{\alpha}^2} \left[ \left( \frac{cE}{B} + \frac{\nu_{\alpha n}}{\Omega_{\alpha}} V_n \right) \times \hat{e}_z + \frac{\nu_{\alpha n}}{\Omega_{\alpha}} \left( \frac{cE}{B} + \frac{\nu_{\alpha n}}{\Omega_{\alpha}} V_n \right) \right]$$

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$$\sigma_H = \frac{ec}{B} \left[ -\frac{n_i}{1 + \nu_{in}^2/\Omega_i^2} + \frac{n_e}{1 + \nu_{en}^2/\Omega_e^2} \right]$$
CONDUCTIVITIES

typical values and spatial dependence
DERIVATION OF POTENTIAL EQUATION

gets uglier: dipole coordinates

\[ q = \frac{r_0^2 \cos \theta}{r^2} \quad p = \frac{r}{r_0 \sin^2 \theta} \quad \phi = \phi \]

\[
J_p = \sigma_P \left( E_p + \frac{B}{c} V_{np} \right) + \sigma_H \left( -E_\phi + \frac{B}{c} V_{np} \right)
\]

\[
J_\phi = \sigma_P \left( E_\phi - \frac{B}{c} V_{np} \right) + \sigma_H \left( E_p + \frac{B}{c} V_{n\phi} \right)
\]
\[ \nabla \cdot \mathbf{J} = 0 \]

in dipole coordinates

\[
\left[ \frac{\partial}{\partial p} (h_q h_\phi J_p) + \frac{\partial}{\partial q} (h_p h_\phi J_q) + \frac{\partial}{\partial \phi} (h_p h_q J_\phi) \right] = 0
\]

where

\[
h_p = \frac{r_0 \sin^3 \theta}{(1 + 3 \cos^2 \theta)^{1/2}}
\]

\[
h_q = \frac{r^3}{r_0^2} \frac{1}{(1 + 3 \cos^2 \theta)^{1/2}}
\]

\[
h_\phi = r \sin \theta
\]
POTENTIAL EQUATION

\[ \int \nabla \cdot \mathbf{J} \, dq = 0 \]

\[ \int \left[ \frac{\partial}{\partial p} (h_q h_\phi J_p) + \frac{\partial}{\partial q} (h_p h_\phi J_q) + \frac{\partial}{\partial \phi} (h_p h_q J_\phi) \right] \, dq = 0 \]

\[ \int \left[ \frac{\partial}{\partial p} (h_q h_\phi J_p) + \frac{\partial}{\partial \phi} (h_p h_q J_\phi) \right] \, dq = -h_p h_\phi J_q \quad (\propto J_\parallel) \]
Electric field in dipole coordinates: $\mathbf{E} = \nabla \Phi$

\[
E_p = -\frac{\Delta}{r_0 \sin^3 \theta} \frac{\partial \Phi}{\partial p} \quad E_\phi = -\frac{1}{r \sin \theta} \frac{\partial \Phi}{\partial \phi}
\]

Substitute $h'$s, $E'$s into potential equation

\[
\frac{\partial}{\partial p} p \Sigma_{pp} \frac{\partial \Phi}{\partial p} + \frac{\partial}{\partial \phi} \Sigma_{p\phi} \frac{\partial \Phi}{\partial \phi} - \frac{\partial}{\partial p} \Sigma_H \frac{\partial \Phi}{\partial \phi} + \frac{\partial}{\partial \phi} \Sigma_H \frac{\partial \Phi}{\partial p}
\]

\begin{align*}
\text{Pedersen} & \quad \text{Hall} \\
= \frac{\partial F_{pV}}{\partial p} + \frac{\partial F_{\phi V}}{\partial \phi} & + f(J_\parallel) \\
\text{Neutral winds} & \quad \text{High latitude currents}
\end{align*}
Electric field in dipole coordinates: \( \mathbf{E} = \nabla \Phi \)

\[
E_p = -\frac{\Delta}{r_0 \sin^3 \theta} \frac{\partial \Phi}{\partial p} \quad E_\phi = -\frac{1}{r \sin \theta} \frac{\partial \Phi}{\partial \phi}
\]

Substitute \( h' \)'s, \( \mathbf{E}' \)'s into potential equation

\[
\frac{\partial}{\partial p} p \Sigma_{pp} \frac{\partial \Phi}{\partial p} + \frac{\partial}{\partial \phi} \Sigma_{p\phi} \frac{\partial \Phi}{\partial \phi} - \frac{\partial}{\partial p} \Sigma_H \frac{\partial \Phi}{\partial \phi} + \frac{\partial}{\partial \phi} \Sigma_H \frac{\partial \Phi}{\partial p}
\]

\[
= \frac{\partial F_p V}{\partial p} + \frac{\partial F_\phi V}{\partial \phi} + f(J_\parallel)
\]

Pedersen \hspace{2cm} Hall

Neutral winds \hspace{2cm} High latitude currents
\[ \Sigma_{pp} = \int \sigma_P \frac{\Delta}{b_s} \, dq \quad \Sigma_{p\phi} = \int \sigma_P \frac{1}{b_s \Delta} \, dq \quad \Sigma_H = \int \sigma_H \frac{1}{b_s} \, dq \]

\[ F_{PV} = \int \frac{B_0}{c} r \sin \theta (\sigma_P V_{n\phi} + \sigma_H V_{np}) \, dq \]

\[ F_{\phi V} = \int \frac{B_0}{c} r_0 \sin^3 \theta \frac{\Delta}{\Delta} (-\sigma_P V_{np} + \sigma_H V_{n\phi}) \, dq \]

\[ \sigma_P = \sum_i \frac{n_i ec}{B} \frac{\nu_{in}/\Omega_i}{1 + \nu_{in}^2/\Omega_i^2} + \frac{n_e ec}{B} \frac{\nu_{en}/\Omega_e}{1 + \nu_{en}^2/\Omega_e^2} \]

\[ \sigma_H = -\sum_i \frac{n_i ec}{B} \frac{1}{1 + \nu_{in}^2/\Omega_i^2} + \frac{n_e ec}{B} \frac{1}{1 + \nu_{en}^2/\Omega_e^2} \]
CONDUCTANCES

typical values and spatial dependence
Derivation in \((p, \phi)\) space: solved in the magnetic equatorial plane (essentially \((r, \phi)\) space)

Can also be solved in \((\theta, \phi)\) space: map magnetic apex height \((p)\) to base of the field line to define associated latitude \(\theta\)

Richmond (magnetic apex model) and Heelis (Plan. Space Sci. 22, 743, 1974)
PUTTING IT ALL TOGETHER

pieces of the picture

Magnetosphere

\[ J_\parallel \]

Ionosphere

\[ n_n T_n V_n \]

Potential Solver

\[ \Phi \]

\[ \sum F_V \]

Thermosphere
THERMOSPHERIC WINDS

drives dynamo electric field (HWM07- Doug Drob)
MAGNETOSPHERIC CURRENTS

origin of $J_\parallel$: flow shear

Current Structure for $Bz=5\text{nT}$ with RCM coupling
- Region 1 Current
- Region 2 Current
- Tail Current
- Chapman-Ferraro Current

Center for Space Environment Modeling, University of Michigan
De Zeeuw, et. al. 2004

June 26, 2005
Sazykin--Ionospheric E-Fields--CEDAR Student Workshop
EXAMPLE OF MODELS

not all-inclusive

- Magnetosphere: LFM BATS-R-US GGCM (physics)
  AMIE (data driven)
  Weimer (empirical)

- Ionosphere: SAMI3 SUPIM IFM (physics)
  IRI (empirical)

- Thermosphere: TIMEGCM CTIPe (physics)
  NRLMSIS HWM07 (empirical)
SELF-CONSISTENT COUPLING: PRESENT

at NRL/RICE/ASTRA

LFM
Outer magnetosphere

RCM
Inner magnetosphere

\[ \Phi \]

\[ \Phi_{PCP} \]

\[ \Sigma \]

SAMII3
Ionosphere

\[ n_n T_n V_n \]

TIMEGCM
Thermosphere
The fundamental coupling of LFM/RCM and SAMI3 is through the solution of the potential equation

\[ \nabla \cdot \frac{\Sigma}{SAMI3} \cdot \nabla \Phi = \frac{J_{||}}{LFM/RCM} \]

→ SAMI3 provides the ionospheric conductance to LFM/RCM
→ LFM/RCM solves the potential equation to determine \( \Phi \)
→ LFM/RCM provides the \( \Phi \) to SAMI3
→ SAMI3 and RCM use \( \Phi \) to calculate the electric field
→ Transport the plasma
SAMI3/LFM RESULTS

17 April 2002 storm

17 Apr 2002

UT 09:09

North Pole

South Pole

TEC

0.0 50.0 100.0

Bx

By

Bz

rho
- Vertical $E \times B$ drift
- Time-dependence of $\Phi$ important: integrated effect
- Decay time $\sim 30 - 60$ min following impulse
DILEMMA: HIGH LATITUDE COUPLING

**LFM**
- Restricted to magnetic latitudes $\gtrsim 55^\circ$
- Potential $\Phi = 0$ on boundary
- Limited resolution of region 2 current system

**RCM**
- Restricted to magnetic latitudes $\lesssim 75^\circ$
- Potential $\Phi$ specified on boundary
- Limited resolution of region 1 current system
- Dipole field aligned with earth’s spin axis
- Interhemispheric symmetry ($B_y = 0$)

Resolution: blend/average currents from both codes and use resulting $\Phi$ in both codes?
Dynamo Currents & Electric fields

QUIET:
Sq current

STORM:
reverse Sq
ITM electrodynamic coupling can have a major impact on the low- to mid-latitude ionosphere during storms. Penetration electric fields can lead to large increases in the daytime mid-latitude TEC (storm enhanced densities) as well as large decreases in the post-sunset equatorial region. Dynamo electric field can be strongly modified by storm driven neutral winds (coupling to the thermosphere required).

Other coupling issues
- High-latitude Joule heating
- Ionospheric outflow