Electrodynamics of M-I Coupling

by

Sorin Zaharia

Princeton Plasma Physics Laboratory
Princeton University

Presented at GEM Workshop
Telluride, CO, June 2002
Outline

- Introduction: M-I Coupling Campaign WG2 (Electrodynamics of M-I Coupling)

- Magnetosphere – main electrodynamic driver of ionosphere, via **field-aligned currents**

- Magnetosphere-ionosphere link
  - Parallel electric fields
  - Particle energization; parallel electron beams; **aurora**
  - Ionospheric conductivity; Joule heating

- Time-dependent picture
  - **Alfvén waves**; ionospheric Alfvén resonator
  - Non-MHD effects; Wave-particle interactions

- Observations; FAST mission

- Issues in M-I Coupling Campaign WG2
GEM M-I Coupling Campaign – WG2

- WG1 – Ionospheric Plasma in the Magnetosphere
- WG2 – Electrodynamics of M-I Coupling
  - understanding how EM energy is transferred between the ionosphere and magnetosphere, and how several factors (e.g. field-aligned currents, electric fields, waves) affect this transfer at different scales
  - Connections with other campaigns (IM-Storms, GGCM) – M-I coupling is just a part in the overall solar-wind-magnetosphere-ionosphere system
Driver: Field-aligned currents

- Linkage between solar wind-magnetosphere system and ionosphere – act as a dynamo
- Region 1 and region 2 currents; Mantle/NBZ currents at the ionosphere
- Magnetospheric formation: due to pressure gradients $\nabla_\perp \cdot j_\perp + \nabla_\parallel \cdot j_\parallel = 0$
- FACs close through the ionosphere, in the auroral zones

Ionosphere is collisional, so EM energy is dissipated there; $E_\perp$ electric fields must exist, and so the ionosphere is a load for the current system
Ionospheric conductivity: Hall and Pedersen currents

- Ionosphere – one-fluid model not applicable, need to use three (or more)-fluid model
- Relation between current and $\mathbf{E}$-field:

$$J_\perp = \sigma_P E_\perp - \sigma_H \frac{E_\perp \times B}{B}$$

$$J_\parallel = \sigma_0 E_\parallel$$

$\sigma_P$ = Pedersen conductivity
$\sigma_H$ = Hall conductivity
$\sigma_0$ = parallel conductivity

- Particle precipitation can change $\sigma$, so feedback interaction with the magnetosphere
Steady-state Energy Transfer to the Ionosphere: Joule Heating

- Downward Poynting flux from the magnetosphere is dissipated in the ionosphere

- Joule heating rate: $\mathbf{J} \cdot \mathbf{E}$

- Energy dissipated by the current parallel to $\mathbf{E}_\perp$ – Pedersen current

- Joule heating dependence on characteristic energy; more energetic particles penetrate more deeply into the ionosphere, where $\sigma_H > \sigma_P$, therefore Joule heating is less important for them

  ↓

  Vertical structure of conductivity also important

- Aside: Joule heating can also lead to ionospheric thermal ion outflow events.
Auroral energization region; electron beams

- “Inverted-V” electron events in auroral acceleration region (2000 - 4000 km): energy of electrons indicates the electric potential

- Discrepancy between inverted-V events and discrete auroral arcs

The latitudinal width of an inverted-V electron event is often nearly two orders of magnitude larger than the apparent thickness of a thin discrete arc.
**E\(_{\parallel}\) Formation**

- Parallel electron beams (1-10 keV) energized by parallel potential drop
- They excite atoms in the neutral atmosphere – aurora
- \(E_{\parallel}\) theories:
  - Macroscopic: model the macroscopic current
  - Microscopic: how \(E_{\parallel}\) arises from microscopic effects (instabilities)
- Observations: \(E_{\parallel}\) not continuous, but series of localized potential steps: double layers

- Double layer formation – plasma turbulence effects (nonlinear effects due to trapping of ions and electrons in localized potential bumps)
Time-dependency: Role of Alfvén Waves

- System not in steady-state – inclusion of temporal variation required
- Ionosphere “cold” (low $\beta$); Cold MHD plasma wave theory – 3 wave modes:
  - Fast (magnetosonic) wave
  - Slow wave
  - (shear) Alfvén wave, with $V_A = \frac{B_0}{4\pi\rho}^{1/2}$
- Shear waves exists in the magnetosphere ("natural modes" - field-line resonances – FLR) and couple to the ionosphere
Similarity between static Pedersen current and Alfvén waves

- Physical quantities in the Alfvén wave:
  - Fluid velocity: \( v = \pm \frac{b}{\sqrt{4\pi\rho}} \)
  - Perpendicular electric field: \( E_\perp = \pm \frac{B_0 \times b}{c \sqrt{4\pi\rho}} \)
  - Perpendicular current: \( I_\perp = \pm \frac{c^2}{4\pi V_A} E_\perp \)
    (currents defined as \( I_\perp = \int dz j_\perp \))

- Analogy:
  - Ohm’s law with Pedersen \( \Sigma \): \( I_\perp = \Sigma_p E_\perp \)
  - Alfvén “conductivity”: \( \Sigma_A = \frac{c^2}{4\pi V_A} \)

- Difficult (but possible) to distinguish between static current patterns (Pedersen) and propagating Alfvén waves

- Conductivities different: \( \Sigma_p > 1 \text{ mho} \)
  \( \Sigma_A \leq 0.1 \text{ mho} \)
Alfvén Wave Reflection; Ionospheric Alfvén Resonator (IAR)

- Due to difference between $\Sigma_A$ and $\Sigma_P \Rightarrow$ ionospheric reflection of Alfvén waves
- By matching currents of incident/reflected wave with ionospheric currents $\Rightarrow$ reflection coefficient

$$R = \frac{\Sigma_A - \Sigma_P}{\Sigma_A + \Sigma_P}$$

- $V_A$ not constant $\Rightarrow$ waves can be trapped between two altitudes characterized by large $V_A$: the lower limit at F-layer, the upper limit at about 3000 km
- Formation of resonant cavity modes – Alfvén resonator
  - Frequencies of 0.1 – 1 Hz and higher
  - Can have growing modes - ionospheric feedback instability (beam instability)
Ionospheric waveguide

High electron density at lower altitudes compressional (magnetosonic) waves also propagate or resonate – ionospheric waveguide in F region of the ionosphere for magnetosonic waves
Wave-particle interactions

- MHD picture breaks down for large $k_\perp$
- Inertial term important at low altitudes ($v_e < V_A$)

$$\omega = \frac{k || V_A}{\sqrt{1 + k_\perp^2 c^2 / \omega_{pe}^2}}$$

- Kinetic effects (finite Larmor radius) important at higher altitudes ($v_e > V_A$)

$$\omega = k || V_A \sqrt{1 + k_\perp^2 \rho^2}$$

- Both regimes called “kinetic Alfvén waves”

- Kinetic Alfvén waves have $E_{||}$!
  - Electron population accelerated in bulk – current-driven instabilities may appear
  - Excitation of instabilities by the current in the waves – formation of steady electric field through the formation of double layers or anomalous resistivity
Recent Observations of Auroral Energization Region

- FAST mission (Fast Auroral SnapshoT) – launched in 1996

The Symmetric Auroral Current Regions

1. Downward current region.
2. Diverging electrostatic shocks.
3. Small-scale density cavities.
5. Ion heating transverse to B. Energetic ion conics.
6. ELF electric field turbulence. Ion cyclotron waves.
8. VLF saucer source region.

- Upward and downward currents
- Parallel electric fields
- Particle beams
- Plasma heating
- Host of wave-particle interactions
- Higher-frequency waves (ion-cyclotron)
Summary

- **Auroral zone** – “transmission line”, carrying EM energy from a magnetospheric generator region to a load region (ionosphere)
  - Joule dissipation in the ionosphere
  - Non-linear losses (plasma turbulence)

- **Auroral particle energization**
  - Particle acceleration region (2000-4000 km)
  - Parallel potential drop

- **Time-dependent picture**
  - Alfvén waves
  - Wave-particle interactions:

- **M-I system** – dynamical system; challenging object of study – rich physics
  - Plasma kinetic theory
  - More global aspects – fluid models
  - Similar current systems and particle energization processes are likely to be present in other astrophysical processes (e.g. solar flares, accretion disks)
Issues in M-I Coupling Campaign WG2

- **Ionospheric conductance**
  - global distribution?
  - temporal and spatial variability

- **Auroral Plasma Energization**
  - Relationship between precipitating electron flux and field aligned currents
  - To what extent is MI coupling hemispherically conjugate and synchronous?
  - What processes determine the formation and structure, including length scales, time scales and altitude, of auroral acceleration regions?

- **Multi-scale Processes**
  - Manifestations: discrete aurora, filamentary and layered auroral structures, polar cap arcs
  - how do the different scale sizes interact?
  - Are averages of energy dissipation meaningful? \[ \left\langle \sum \right\rangle \left\langle E^2 \right\rangle \neq \left\langle \sum E^2 \right\rangle \] How far off are they?
  - What scales contribute most to energy dissipation?)

- **More general question**: Does MI coupling regulate (or how does it regulate) magnetospheric convection, magnetotail dynamics, and solar wind-magnetosphere coupling?

- **Energy Budget Challenge** — the energy flow from the magnetosphere to low altitudes and its myriad pathways for deposition in the ionosphere and lower magnetosphere
References


3. Alfvén waves in the auroral ionosphere: A numerical model compared with measurements, by D.J. Knudsen et al., *JGR* 97, pp.77-90, 1992

4. Introduction to Space Physics, by M. Kivelson and C. T. Russell

5. Space Physics, by C-G. Fälthammar

6. Introduction to magnetospheric and space plasmas, by Jay R. Johnson, Graduate Seminar, 2000


8. Outstanding issues in M-I coupling: the three-dimensional ionosphere, by R. J. Strangeway, GEM 2000 Workshop
