GEM M-I Coupling Campaign Tutorials

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

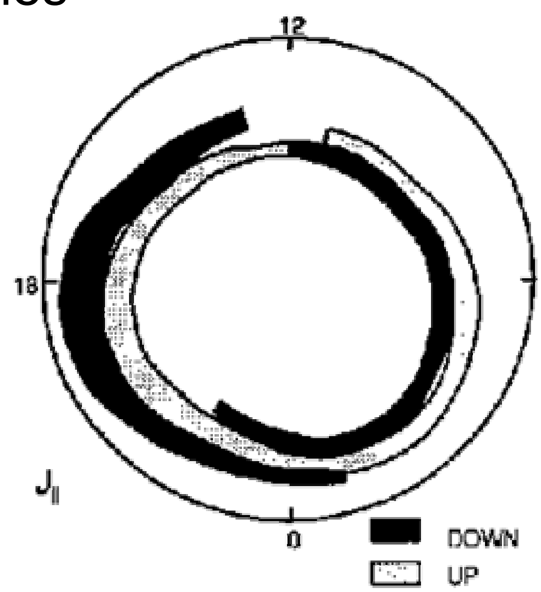
  - understanding how EM energy is transferred between the ionosphere and magnetosphere, and how several factors (e.g. field-aligned currents, electric fields, waves) affect this transfer at different scales

  - 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 $\nabla_{\perp} \cdot \mathbf{j}_{\perp} + \nabla_{||} \cdot \mathbf{j}_{||} = 0$

- 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 **E**-field:

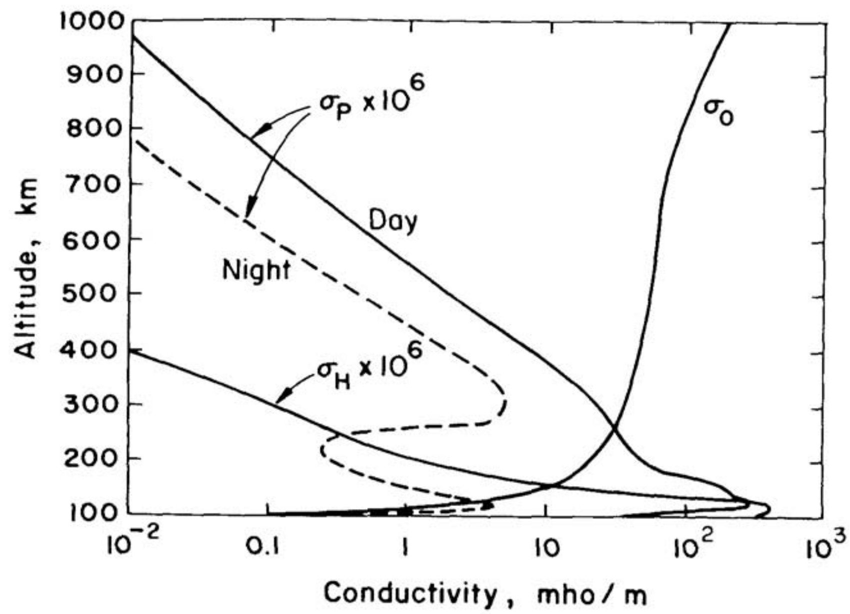
$$J_\perp = \sigma_P E_\perp - \sigma_H \frac{E_\perp \times B}{B}$$

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

σ_P = Pedersen conductivity

σ_H = Hall conductivity

σ_0 = parallel conductivity



- Particle precipitation can change σ, so feedback interaction with the magnetosphere

Steady-state Energy Transfer to the Ionosphere: Joule Heating

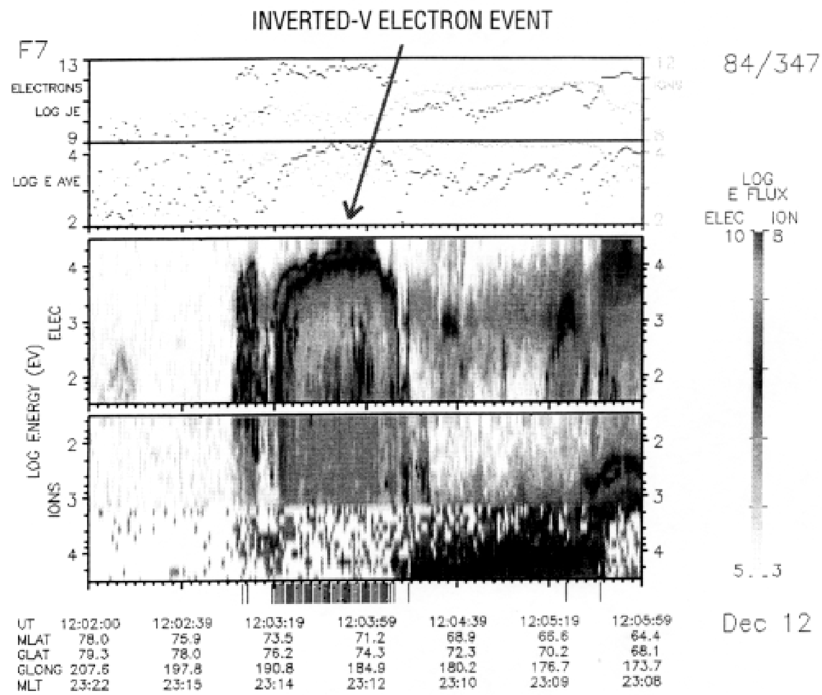
- Downward Poynting flux from the magnetosphere is dissipated in the ionosphere
- Joule heating rate: $\mathbf{J} \cdot \mathbf{E}$
- Energy dissipated by the current parallel to $\mathbf{E}_\perp$ – Pedersen current
- Joule heating dependence on characteristic energy; more energetic particles penetrate 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.

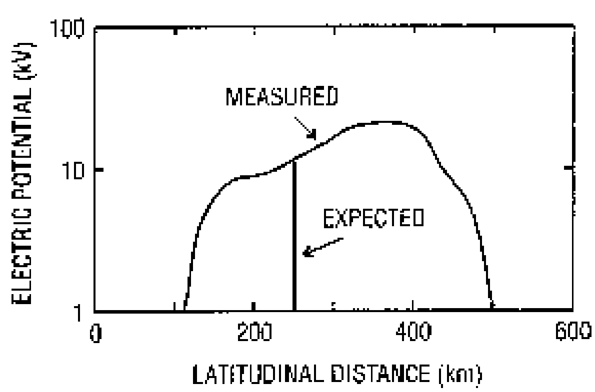
Auroral energization region; electron beams

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



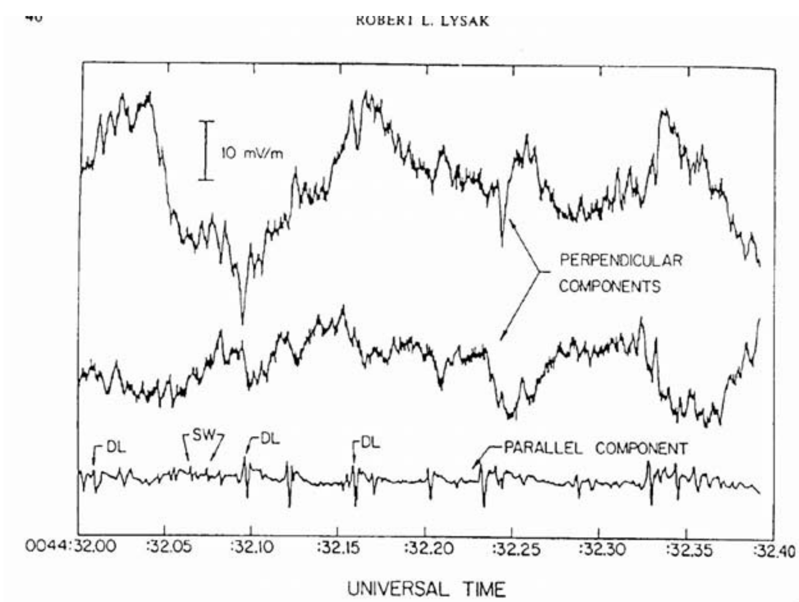
- Discrepancy between inverted-V events and discrete auroral arcs

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.



$E_{||}$ Formation

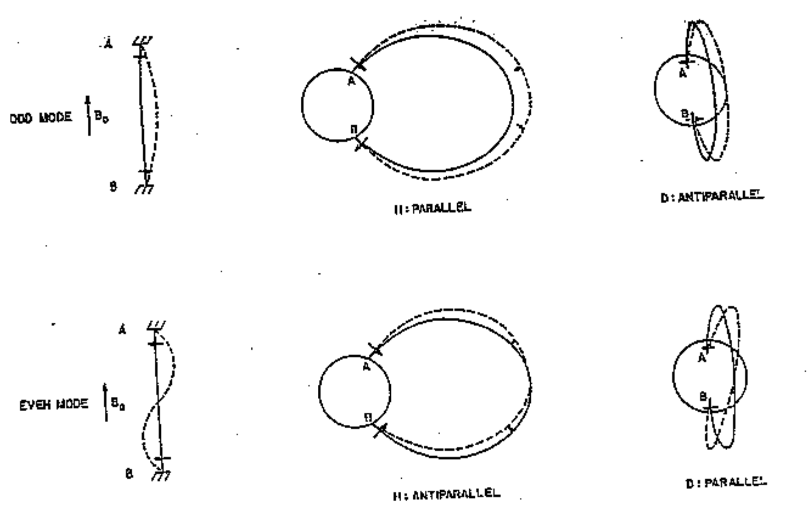
- Parallel electron beams (1-10 keV) energized by parallel potential drop
- They excite atoms in the neutral atmosphere – aurora
- $E_{||}$ theories:
  - Macroscopic: model the macroscopic current
  - Microscopic: how $E_{||}$ arises from microscopic effects (instabilities)
- Observations: $E_{||}$ not 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 β); Cold MHD plasma wave theory – 3 wave modes:
  - Fast (magnetosonic) wave
  - Slow wave
  - (shear) Alfvén wave, with $V_A = B_0/(4\pi\rho)^{1/2}$
- 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 Σ: $$I_\perp = \Sigma_P E_\perp$$
  - 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)

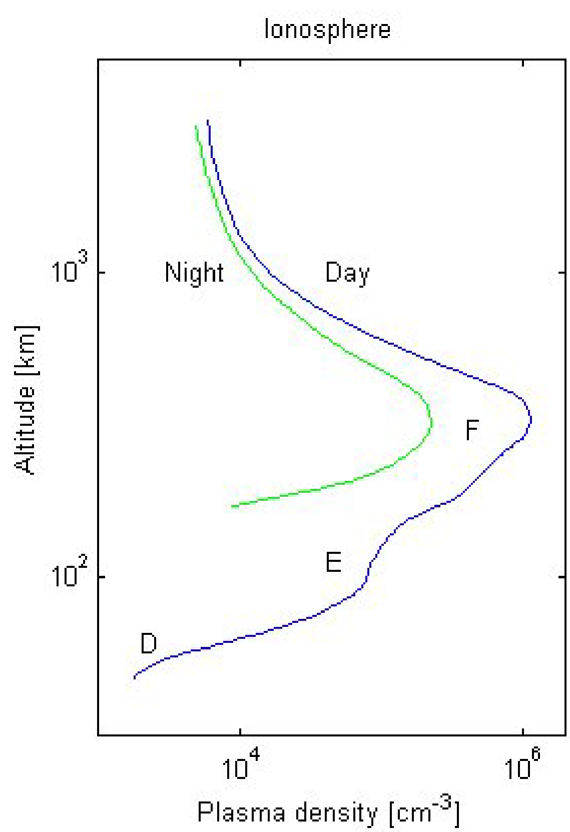
- Due to difference between Σ_A and $\Sigma_P \Rightarrow$ ionospheric reflection of Alfvén waves
- By matching currents of incident/reflected wave with ionospheric currents $\Rightarrow$ reflection coefficient

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

- V_A not constant $\Rightarrow$ waves can be trapped between two altitudes characterized by large VA : 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 ($v_e < V_A$)

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

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

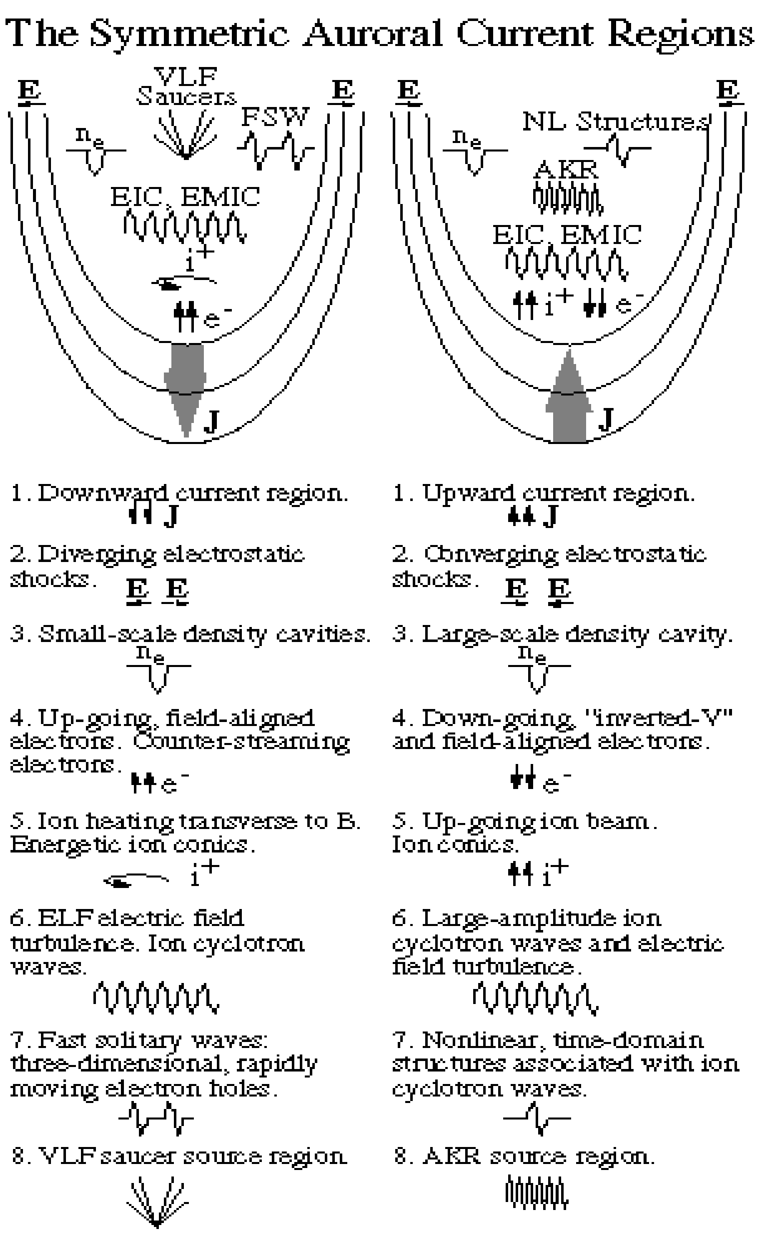
$$\omega = k_{\parallel} V_A \sqrt{1 + k_\perp^2 \rho^2}$$

- Both regimes called "kinetic Alfvén waves"

- Kinetic Alfvén waves have $E_{\parallel}$!
  - 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



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 ? $\langle \Sigma \rangle \langle E^2 \rangle \neq \langle \Sigma E^2 \rangle$ 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

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