Issues in Magnetosphere-Ionosphere Coupling: The Need for a "Thick Ionosphere"

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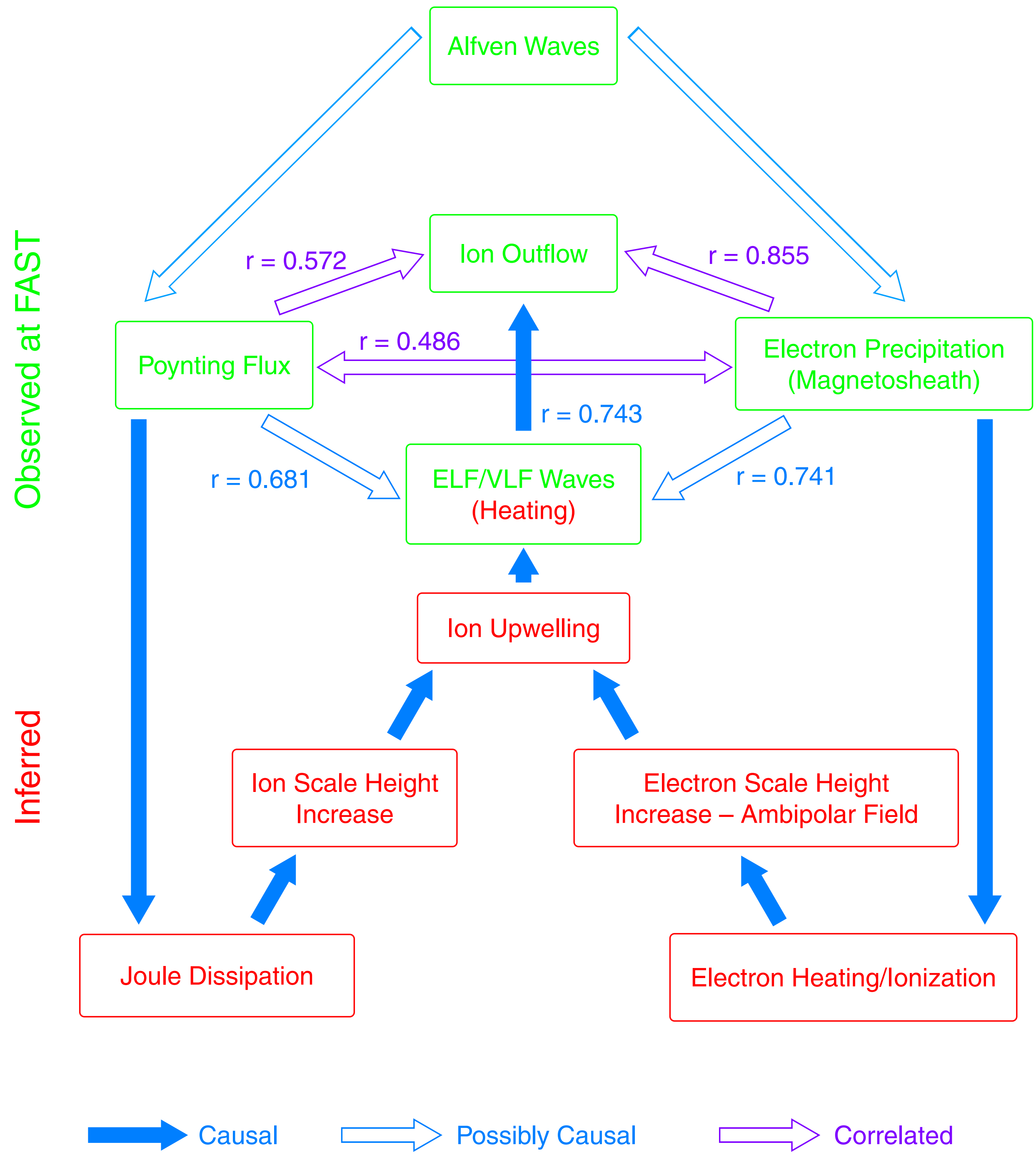
CCMC Workshop, Maui, 2001

Introduction

Two aspects of M-I coupling appear to require full ionospheric models (i.e., a "thick" ionosphere).

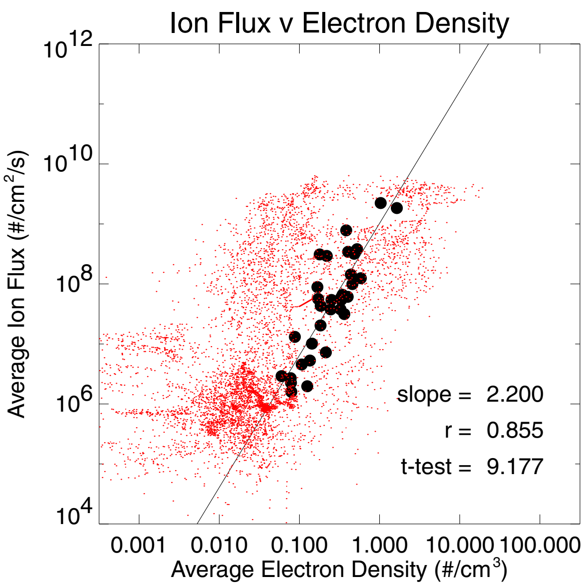
The first concerns the ionospheric outflows.

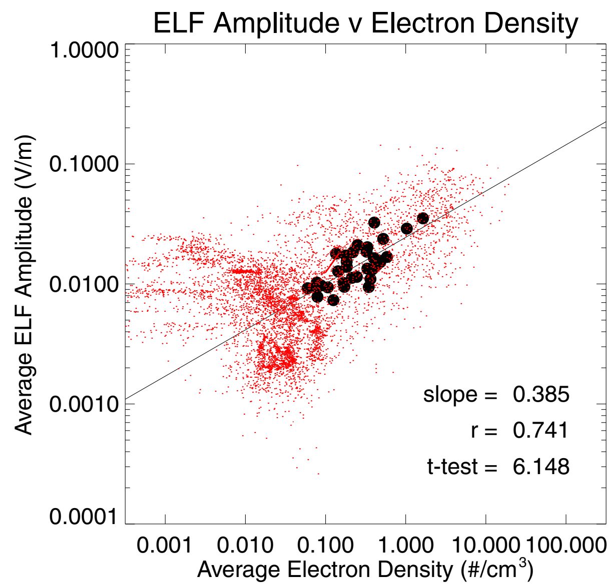
The second concerns the "prompt" response of the ionosphere to changes in magnetospheric convection.

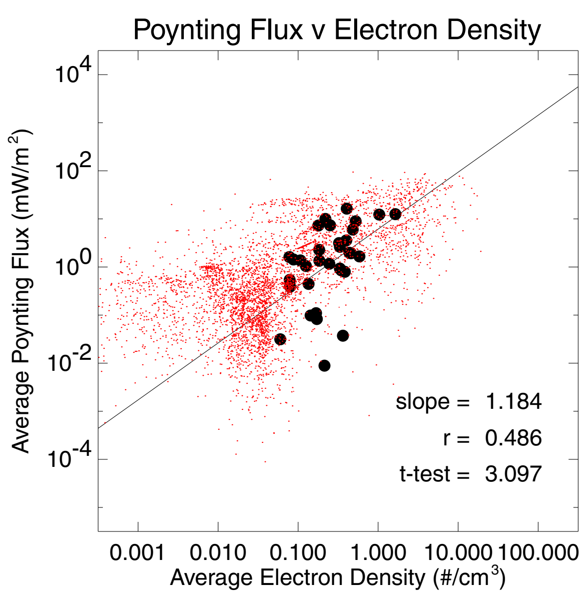


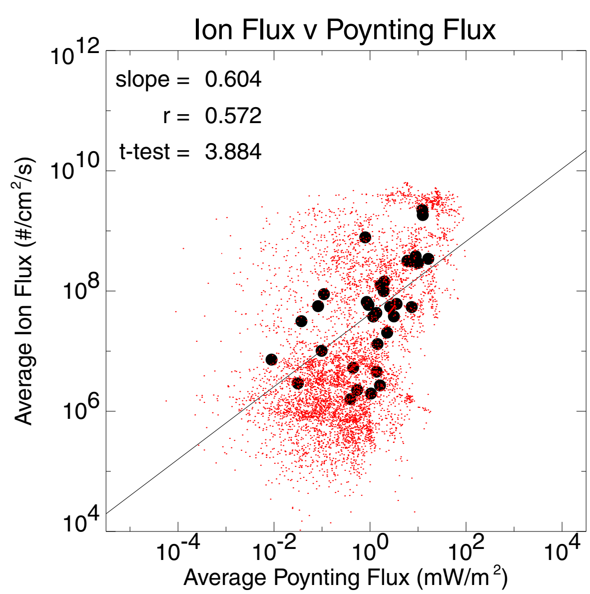
Alfven Waves
Observed at FAST
Inferred
Ion Outflow
r = 0.572
r = 0.855
Poynting Flux
r = 0.486
Electron Precipitation
(Magnetosheath)
r = 0.743
r = 0.681
ELF/VLF Waves
(Heating)
r = 0.741
Ion Upwelling
Ion Scale Height
Increase
Electron Scale Height
Increase – Ambipolar Field
Joule Dissipation
Electron Heating/Ionization
Causal
Possibly Causal
Correlated

Precipitating Electron Dependence









Correlation significant for t-test > 2.04 (95% Confidence)

Regression from orbit averages for orbits 8260 – 8292

Scatter points are 1-sec averages for orbits 8273 – 8279

Basics of Magnetosphere-Ionosphere Interactions

Strangeway and Raeder [JGR, 2001] present a detailed analysis of the electron and ion momentum equations governing M-I interactions, including all ion and electron collision frequencies. Their analysis shows that provided $_{en}/\;_{e} << 1$, the momentum equations can be rewritten as:

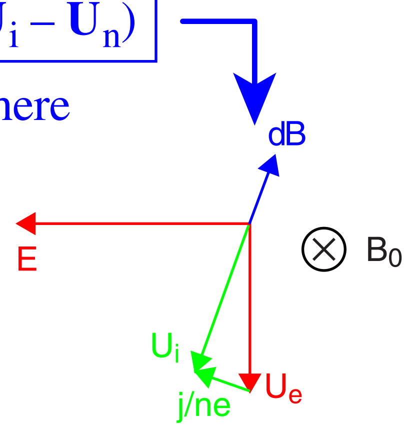
"Frozen-in" electron fluid:

$$\mathbf{E} + \left(\mathbf{U}_{\mathrm{i}} - \mathbf{j}/ne\right) \quad \mathbf{B} = 0$$

Momentum equation:

$$\frac{D\mathbf{U}_{\mathrm{i}}}{Dt} = - \quad P + \mathbf{j} \times \mathbf{B} - \nu_{in}(\mathbf{U}_{\mathrm{i}} - \mathbf{U}_{\mathrm{n}})$$

Magnetosphere   Ionosphere



Relationship Between Maxwell Stress and Poynting Flux

From the frozen-in condition for the electron fluid

$$\begin{aligned} & \qquad\qquad \text{Curvature} \qquad\qquad \text{Pressure} \\ \mathbf{j}_\perp \cdot \mathbf{E}_\perp &= \mathbf{U}_{i\perp} \cdot \frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{\mu_0} \quad - \mathbf{U}_{i\perp} \cdot \nabla \frac{B^2}{2\mu_0} \\ &= \quad -\nabla_\parallel \cdot \mathbf{S}_\parallel \quad - \nabla_\perp \cdot \mathbf{S}_\perp - \frac{\partial}{\partial t} \frac{B^2}{2\mu_0} \end{aligned}$$

$\nabla_\parallel \cdot \mathbf{S}_\parallel < 0$ when field-aligned Poynting flux flows into the ionosphere, as occurs when the magnetosphere is a generator.

For the ionosphere to appear as a generator Poynting flux must flow out of the ionosphere, requiring an excess of magnetic flux transported into the outflow region, i.e.,

$$\mathbf{U}_{i\perp} \cdot \nabla \frac{B^2}{2\mu_0} < 0$$

Note: this makes no assumptions concerning induction electric fields, but it does imply that the ionosphere must be “compressible” for there to be outward Poynting flux.

The “Prompt Ionosphere” Paradox

For the ionosphere to move the magnetosphere we require a magnetic pressure gradient. Yet the prompt response, which is assumed to be a signature of rapid fast-mode propagation, implies that magnetic pressure gradients are small.

Thus the very signature that is used to argue for an ionospheric driver of magnetospheric convection – “promptness” implies that the ionosphere moves first – suggests that there are no forces (magnetic pressure) to cause the motion.

This paradox requires that we investigate wave propagation in a dissipative medium.

Towards Resolving the Paradox

Need to investigate wave propagation (fast mode) in a dissipative medium.

First, linearize the equations.

Momentum equation

$$\rho \frac{\partial \mathbf{U}_i}{\partial t} = \mathbf{j} \times \mathbf{B} - \rho \nu_{in} \mathbf{U}_i$$

Wave Diffusion

Maxwell's relations

$$\nabla \times \mathbf{b} = \mu_0 \mathbf{j}$$

$$\nabla \times \mathbf{E} = - \partial \mathbf{b} / \partial t$$

(For simplicity displacement current is ignored.)

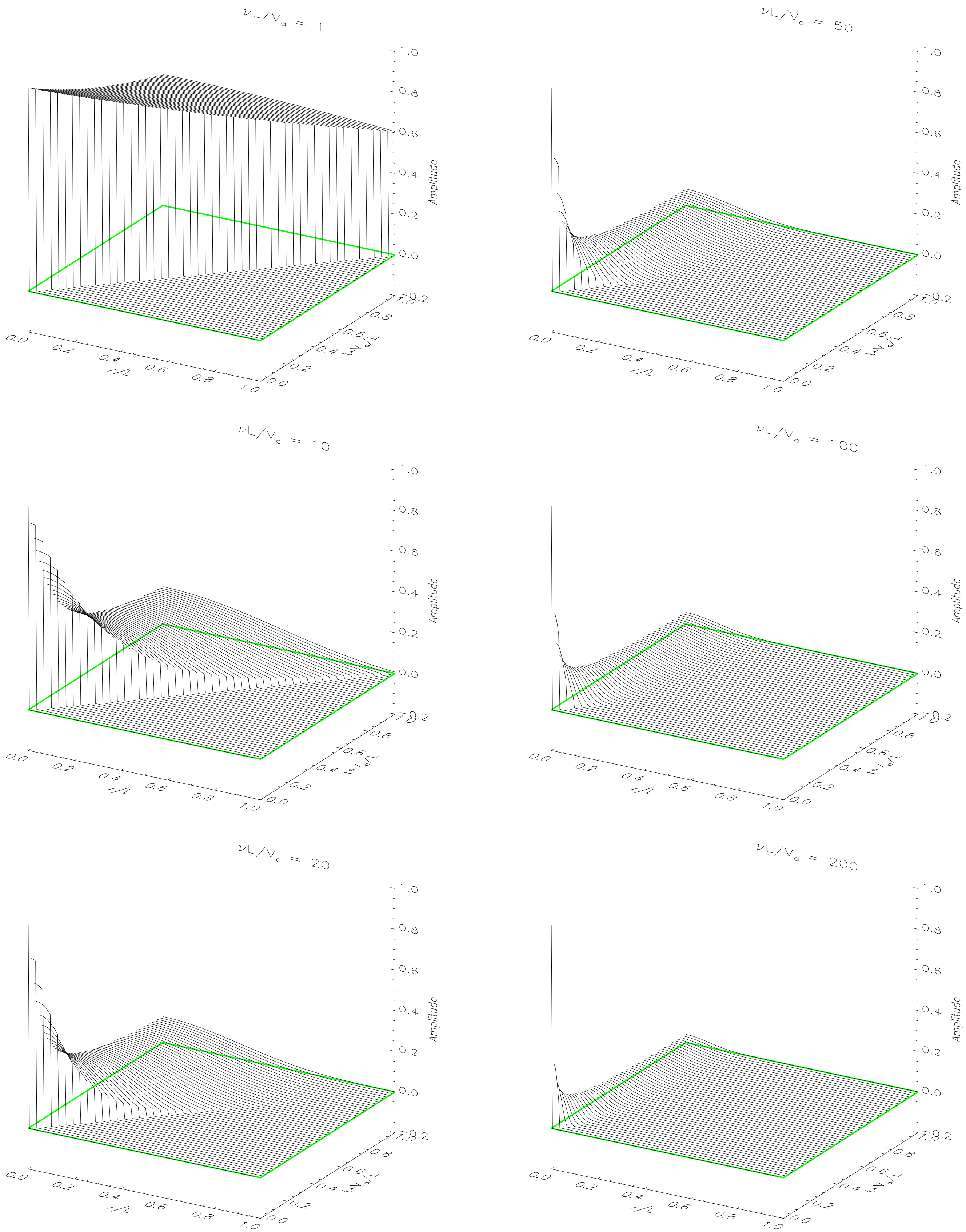
Frozen in ions (also for simplicity)

$$\mathbf{E} + \mathbf{U}_\mathrm{i} \times \mathbf{B} = 0$$

Gives the "Telegraphist's Equation" (e.g., Morse and Feshbach, Part 1 [1953])

$$\partial^2 \mathbf{U}_i / \partial t^2 = V_a^2 \nabla^2 \mathbf{U}_i - \nu_{in} \, \partial \mathbf{U}_i / \partial t$$

Green's Functions for Telegraphist's Equation



The Quandary Remains

First, a caution: The one-dimensional Green's function for the telegraphist's equation is a plane wave solution. This implies that the source function is not a 3-D delta-function, but an infinite plane of point sources. This further implies isotropic wave dispersion.

Second, even if the solutions are valid, the differential flow as a function of altitude again results in large induction electric fields. The magnetic field will change at a rate of ~ 100 nT/s.

As a consequence, currents will flow, generating forces to oppose the change in the magnetic field. This will effectively "lock" the higher altitude (wave-dominated) region to the lower altitude (diffusive) ionosphere.

Conclusions

- Understanding ionospheric outflows requires that the energetics of the ionosphere as a function of altitude be included in models.

- As an interim step, outflow rates could be parameterized as a function of input fluxes (Poynting flux, precipitating electron density), allowing for inclusion in global models.

- The prompt ionospheric response, used to argue for an ionospheric driver, also implies that pressure gradients are small. Where's the driver?

- We have begin to address this paradox by investigating wave propagation in a dissipative medium. Initial analysis suggests that the "driver" is at higher altitudes, but this still leads back to the original quandary. Moving the ionosphere requires strong currents to overcome the drag of the neutral atmosphere.

- The ultimate resolution of this paradox may require global simulations with a fully resolved ionosphere and surface-ionosphere waveguide.