The Need for High Resolution Ionospheric Imaging: Magnetosphere-Ionosphere Coupling and the Electromagnetic Ionosphere

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Early models of M-I coupling assume height-integrated ionospheric conductivity and an electrostatic ionosphere, so electric field and field-aligned current related by $j_{\parallel} \sin i = -\nabla \cdot \hat{\Sigma} \cdot \nabla \Phi$

- Here conductivity can be dynamic, controlled by solar illumination and particle precipitation
- Thermospheric dynamics is usually ignored

Electrostatic approximation often used since Alfvén waves propagate quickly: ~ 500 km/s, vs. convection/wind speeds ~ 1 km/s.

However, the electrostatic approximation fails due to the presence of the Hall conductivity, which couples shear Alfvén waves to compressional fast mode waves with finite $\partial B_{\parallel}/\partial t$. 
Inductive Ionospheric Boundary Condition
(Yoshikawa and Itonaga, 1996; Lysak and Song, 2006)

Electrostatic boundary condition only deals with the shear Alfven mode that carries field-aligned current; it does not provide a boundary condition for the fast mode waves.

A more general boundary condition can be found by integrating Ampere’s Law over the ionosphere:

$$\mu_0 \mathbf{\hat{\Sigma}} \cdot \mathbf{E} = \mathbf{\hat{r}} \times \Delta \mathbf{B}$$

For vertical field lines and uniform $\mathbf{\hat{\Sigma}}$, taking the divergence yields the usual electrostatic condition, while taking the curl gives a second condition:

$$\Sigma_p \nabla \perp \cdot \mathbf{E} - \Sigma_H \mathbf{\hat{r}} \cdot (\nabla \times \mathbf{E} \perp) = -j\perp$$

$$\Sigma_H \nabla \perp \cdot \mathbf{E} \perp + \Sigma_p \mathbf{\hat{r}} \cdot (\nabla \times \mathbf{E} \perp) = (1/\mu_0)\Delta (\partial B_r / \partial r)$$

These equations illustrate the coupling of the shear mode (div E) and the fast mode (curl E) by the Hall conductivity.

Note that this equation requires knowledge of $\mathbf{B}$ in the atmosphere.
Many M-I coupling models also assume a constant Alfvén speed in the magnetosphere.

However, the Alfvén speed rises sharply above ionosphere due to exponential fall of plasma density.

Wave propagation speed goes back to the speed of light at altitudes below the ionosphere.

The minimum in Alfvén speed in ionosphere forms a resonant cavity for shear Alfvén waves (Ionospheric Alfvén Resonator) and a waveguide for fast mode waves in 1-10 s period range.
Small Spatial Scales: Phase Mixing

- Gradients in the Alfvén speed lead to phase mixing, producing smaller perpendicular scales (basic mechanism behind field line resonance.)

- Such gradients are always present, especially in boundary regions:
  - Plasma Sheet Boundary Layer: poleward boundary of aurora
  - Boundaries of aurora density cavities (e.g., Chaston et al., 2006, at right)

- Scale length estimated to be $\sim (\Sigma_A/\Sigma_P) L_0$, where $\Sigma_A = 1/\mu_0 V_A$ is Alfvén conductance and $L_0$ is gradient scale length.
Simulation of Phase Mixing in IAR

Simulations of linear wave propagation including electron inertia effect were made in a overall perpendicular density gradient.

**Density**

Density profile, Run 98, Max= 1.0e+005, Min= 1.65

**Alfvén speed**

Alfvén speed, Run 98, Max= 4.6e+004, Min= 941.05
Simulation initiated with uniform pulse across system oscillating at 1 Hz.
- Interference between up and downgoing waves leads to structuring of fields.
- Series of harmonics seen due to change of IAR eigenfrequencies.
- Waves phase mix to ~ 1 km scale waves.
Ionospheric Shielding Effect

- The sheet ionosphere assumption also fails at higher frequencies.
- Ionospheric Pedersen conductivity acts to shield higher frequency waves (collisional skin depth) $\delta = \sqrt{2/\mu_0 \omega \sigma_P}$
- Results are shown from a numerical model of Alfvén wave propagation including full ionosphere (Lysak et al., 2013)
- Model is driven with a broad-band “white noise” spectrum consisting of 100 waves from 0-2 Hz with equal amplitudes and random phases.
- It can be seen that the higher frequency components are attenuated at lower altitudes in the ionosphere
Horizontal Gradients

- Ionosphere is not only vertically stratified (as assumed in most M-I coupling models), but can have perpendicular gradients
  - Especially true in auroral ionosphere where localized electron precipitation can give columns of ionization
- Gradients in Alfvén speed can give rise to phase mixing, producing smaller-scale, intense field-aligned currents
- In presence of background convection, conductivity gradients can also lead to strong currents

(Semeter et al., 2005)
Ionospheric Feedback

In presence of background convection, fluctuations in conductivity can give rise to a feedback interaction

- Conductivity enhancement requires either polarization electric field or closure of enhanced currents by field-aligned currents
- Upward field-aligned current (downward electrons) can enhance conductivity
- Reflections in IAR or from conjugate ionosphere can lead to instability

Small-scale structures can form in large-scale downward current regions (blue and violet in lower figure)

Scale size limited by parallel resistivity, < 1 km

However:

- Theory has only been developed with height-integrated conductivity
- No convincing observations of this process have been made

(Lysak, 1990)

(Streltsov and Lotko, 2008)
Not to mention neutral winds…

And most magnetospheric physicists would prefer not to!

Or at least assume a single neutral wind rest frame in which Ohm’s Law is valid, \( \mathbf{j} = \mathbf{\sigma} \cdot (\mathbf{E} + \mathbf{V}_n \times \mathbf{B}) \)

However, Thayer (1998) derived neutral winds from radar data (assuming steady-state ion motion) and showed large vertical gradients in wind speed.
So what can be done?

Progress in understanding the details of the magnetosphere-ionosphere interaction requires a good knowledge of the state of the ionosphere

- Time resolutions ~ 1 sec to resolve IAR frequencies
- Spatial resolution ~ 1 km to resolve auroral arc scales

A system like EISCAT-3D would be a great advance in this regard

Is it possible to characterize neutral atmosphere at similar time and space scales?

- Or is it necessary given large inertia in thermosphere; how fast can thermospheric winds vary?