Auroral Acceleration Processes and Their Role in Magnetosphere-Ionosphere Coupling

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Outline

Introduction – FAST observations

Primary auroral current

Knight relation

Precipitating electrons and ionospheric conductivity

Cowling conductivity

Return current – ion “pressure cooker”

Inertial Alfvén waves – boundary layer aurora

Ion outflows

Conclusions

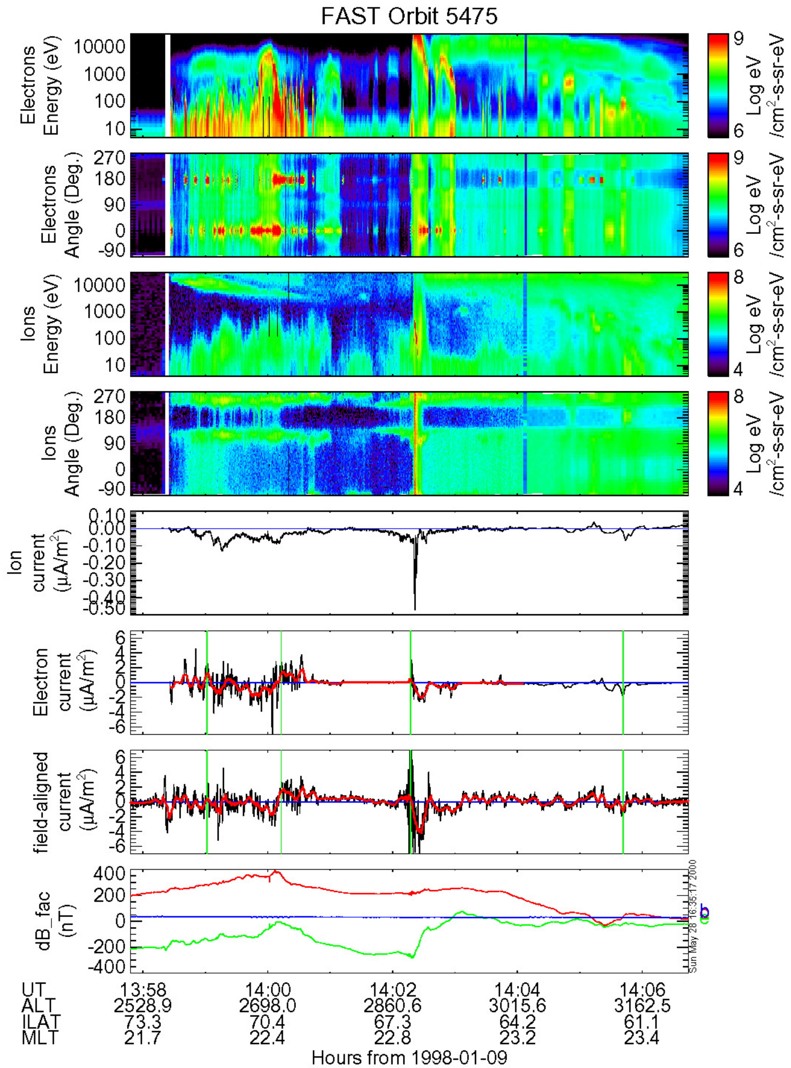
FAST Observations

Auroral zone crossing shows:

Boundary layer electrons

Inverted-V electrons

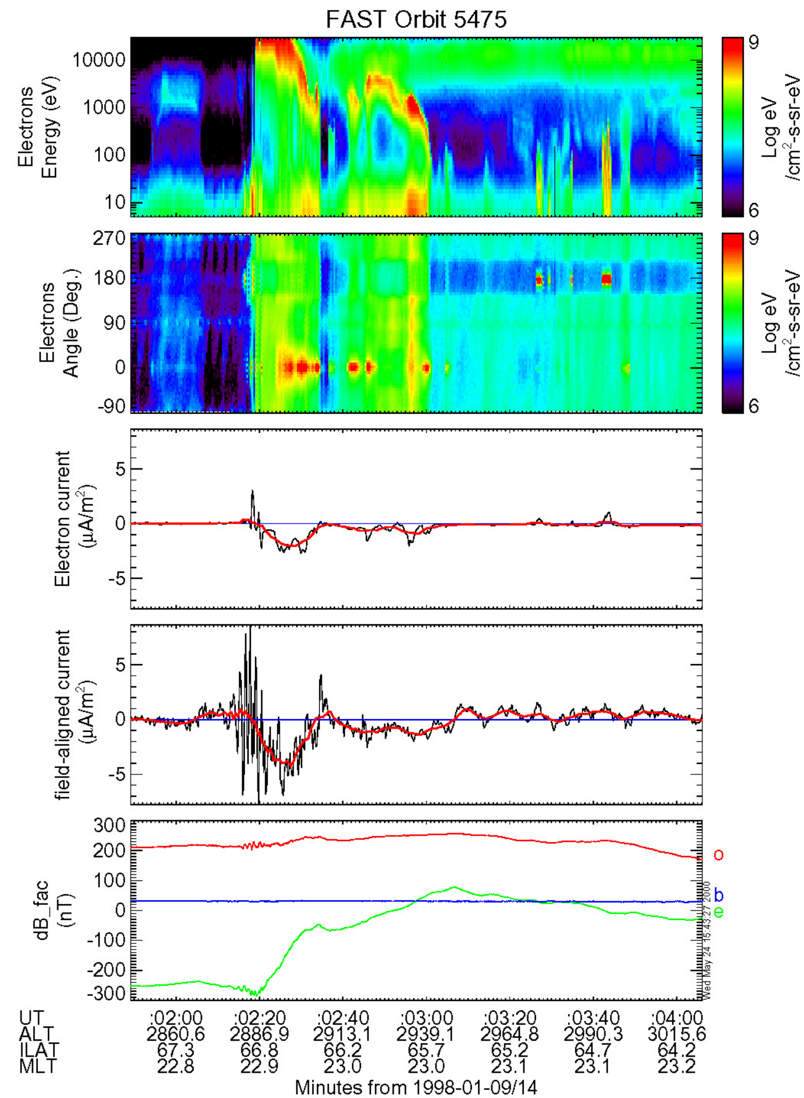
Return current



Primary Auroral Current

Inverted-V electrons appear to be primary (upward) auroral current carriers.

Inverted-V electrons most clearly related to large-scale parallel electric fields – the "Knight" relation.



Vlasov Equation

The Knight relation [Knight, PSS, 21, 741-750, 1973; Lyons, 1980] is based on the Vlasov equation:

$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\frac{\partial f}{\partial \mathbf{r}} + \mathbf{a}\cdot\frac{\partial f}{\partial \mathbf{v}} = 0$$

The Vlasov equation is an advective derivative in phase space – phase space density is constant along a particle trajectory [Liousville's theorem].

Consequence: Apart from the effect of the loss-cone, the density of an isotropic distribution is constant along a flux-tube.

Phase space mapping allows us to calculate effect of magnetic mirror force ($W_\perp = \mu B$) and electric field ($W + q\Phi$ = constant).

Current Density – Flux in the Loss-Cone

The auroral current is carried by the particles in the loss-cone.

Without any additional acceleration the current carried by the electrons is the precipitating flux at the atmosphere:

$$j_0 = nev_T/2\pi^{1/2} \approx 1\ \mu\text{A/m}^2 \text{ for } n = 1\ \text{cm}^{-3},\ T_e = 1\ \text{keV}.$$

A parallel electric field can increase this flux by increasing the flux in the loss-cone. Maximum flux is given by the flux at the top of the acceleration region (j_0) times the magnetic field ratio (flux conservation - with no particles reflected).

$$j_\text{m} = nev_T/2\pi^{1/2} \times (B_I/B_m).$$

Phase Space Boundaries

Trajectories in phase space defined by conservation of magnetic moment (μ) and conservation of total energy ($W + q\Phi$).

For downgoing electrons, $W_{||} = 0$ at the top of the acceleration region defines low energy limit – acceleration ellipse:

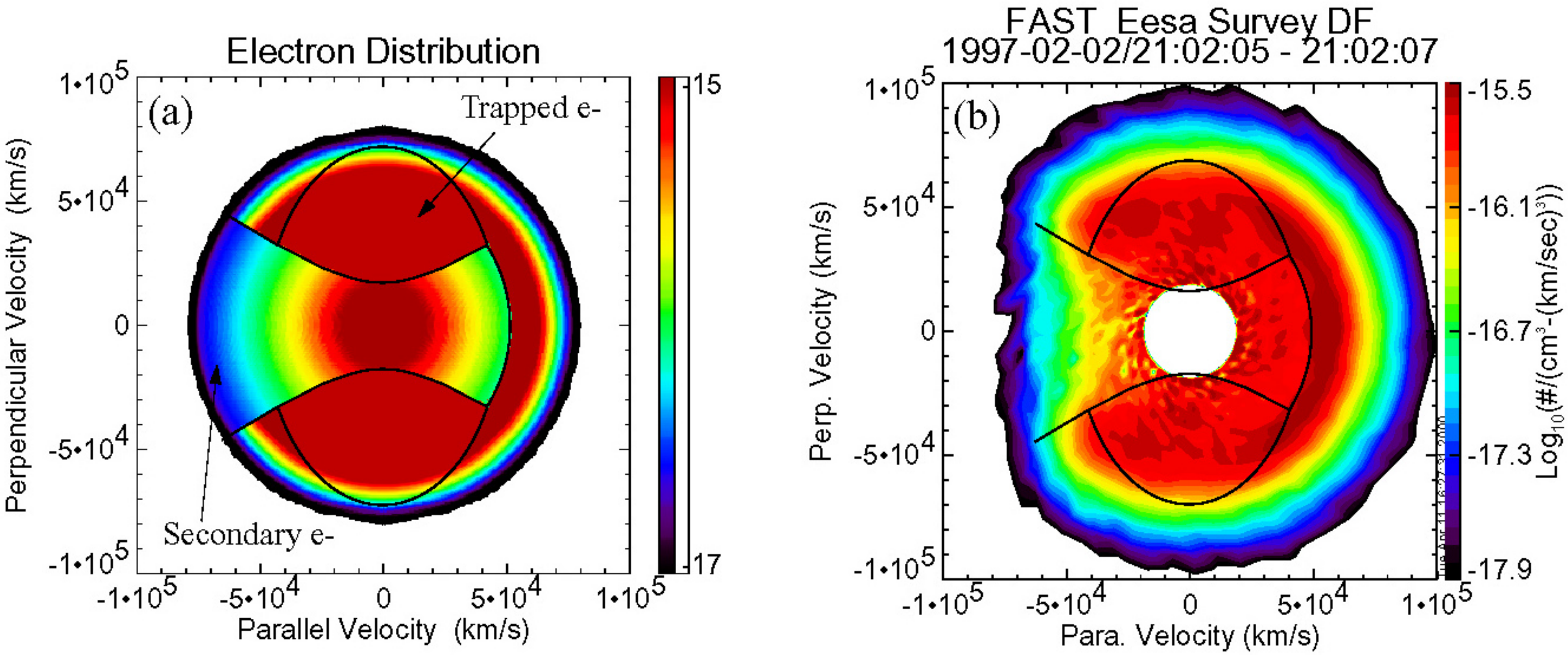
$$W_{\perp}(1 - B_m/B) + W_{||} = e\Phi$$

For upgoing electrons, $W_{||} = 0$ at the ionosphere defines loss cone – loss cone hyperbola:

$$W_{\perp}(B_I/B - 1) - W_{||} = e(\Phi_I - \Phi)$$

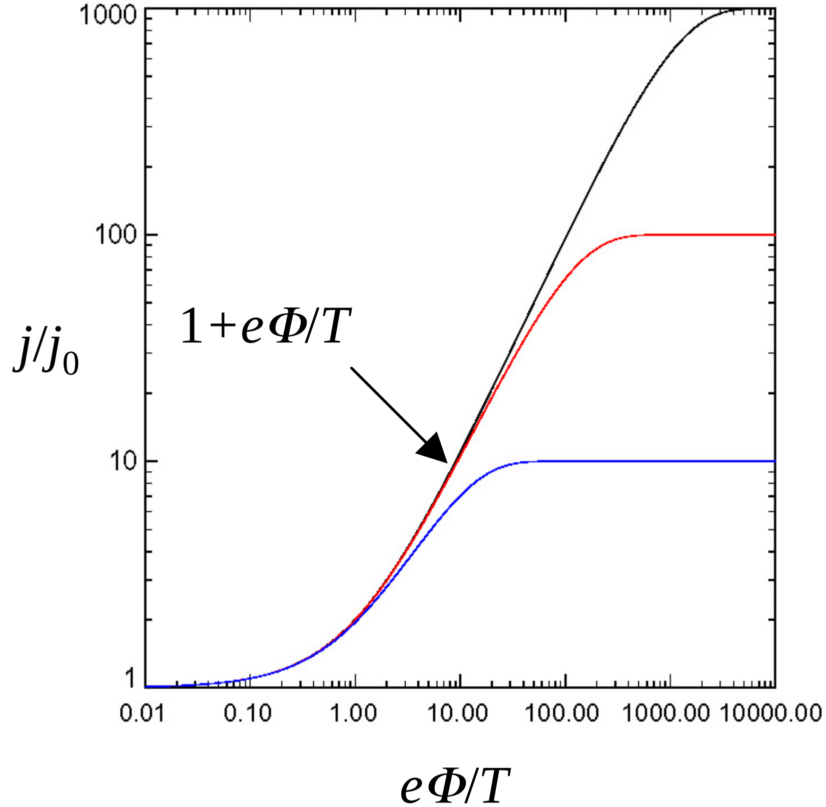
Phase Space Mapping

Theoretical and Observed Distributions
(Ergun et al., GRL, 27, 4053-4056, 2000)



Knight Relation

$$j = j_0 B_i / B_m \left\{ 1 - (1 - B_m / B_i) \exp\left[\frac{-e\Phi}{T(B_i/B_m - 1)} \right] \right\}$$



Asymptotic Value
$= B_I / B_m$

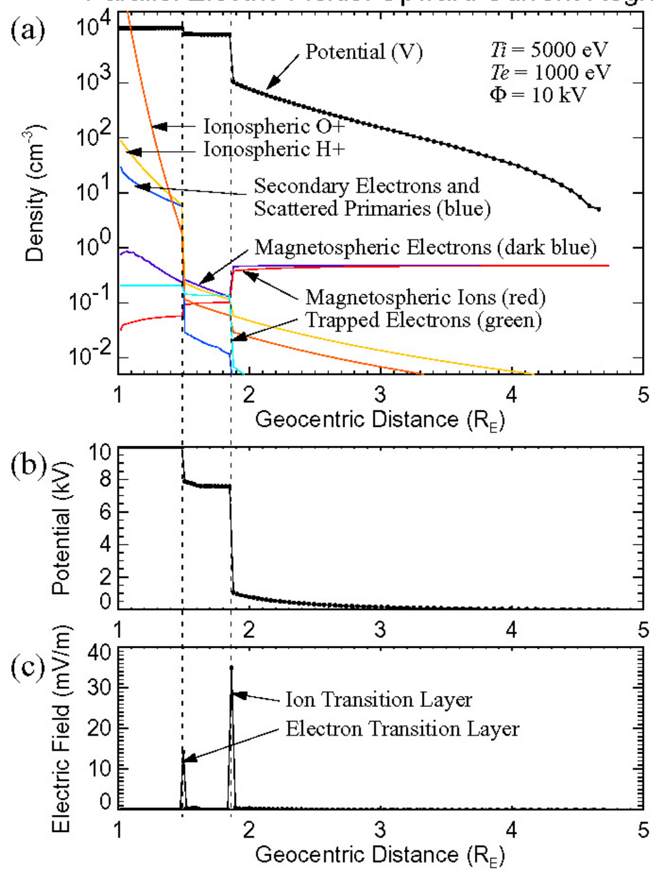
Numerical Results

Static Vlasov simulations (Ergun et al., GRL, 27, 4053-4056, 2000).

Two sheaths are present:
- Low altitude to retard secondaries;
- High altitude to reflect magnetospheric ions.

Disadvantage: No wave-particle interactions.

Parallel Electric Fields: Upward Current Region



Ionospheric Conductivity

Precipitating electrons modify the ionospheric conductivity.

Robinson et al. [JGR, 92, 2565-2569, 1987] provide formulas for Pedersen and Hall conductivities:

$$\Sigma_p = \frac{40\bar{E}}{16+\bar{E}^2}\Phi_E^{1/2}, \quad \frac{\Sigma_h}{\Sigma_p} = 0.45\ \bar{E}^{0.85}$$

where $\bar{E}$ is the average energy in keV

and Φ_E is the energy flux in mW/m^2

These are often used in MHD simulations to modify ionospheric conductivity, where the number flux is given by the upward field-aligned current density, *j*, the Knight relation gives the potential, $\approx \bar{E}$, and $\Phi_E \approx j\,\bar{E}$.

Cowling Conductivity

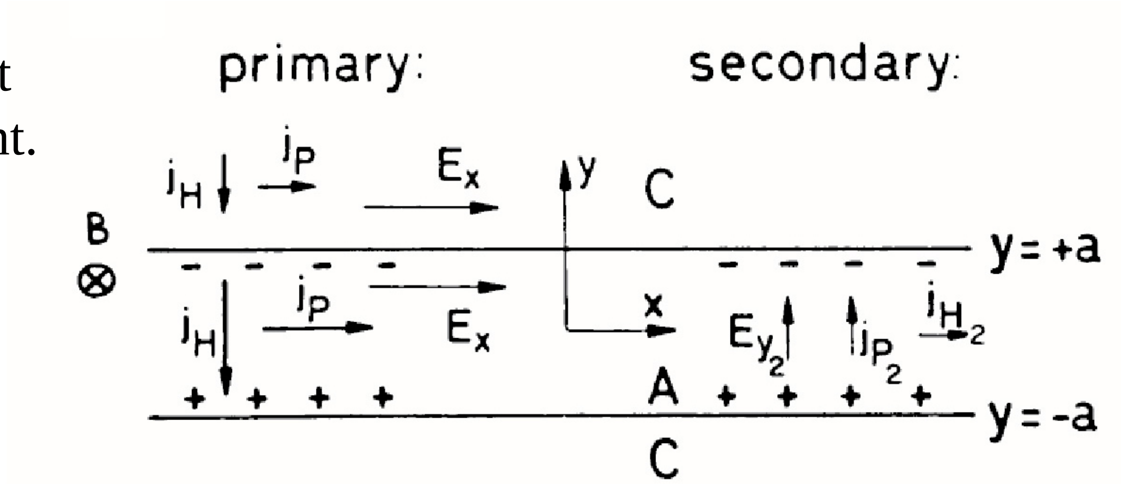
Gradients in the ionospheric conductivities can change the electric field and current structure within the ionosphere.

Often cited example is the Cowling conductivity (derived for equatorial magnetic field, but applied to the auroral ionosphere).

Secondary Pedersen current cancels primary Hall current.

Secondary Hall current enhances primary Pedersen current.

$$\Sigma_c = \Sigma_p + \Sigma_h^2/\Sigma_p$$



Cowling Conductivity Inconsistency

Although couched in terms of height integrated conductivity (Σ), the formalism also applies in terms of conductivity (σ).

Since $E_{y2} = \sigma_h E_x/\sigma_p$ and σ_h/σ_p depends on z (height), $\partial E_{y2}/\partial z \neq 0$, i.e., $\partial B_x/\partial t \neq 0$, implying a time-varying j_y.

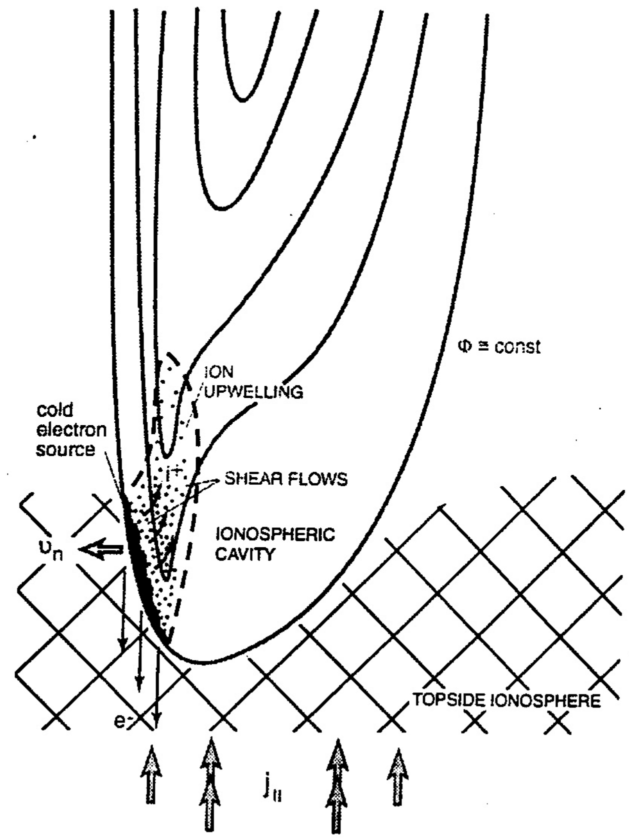
Alternatively, the primary Hall current could close via field-aligned currents, modifying the current system within the magnetosphere.

Thus a non-uniform Hall conductivity requires a new field-aligned current system orthogonal to the primary current system.

Ionospheric Modifications

Haerendel [Adv. Space Res., 23(10), 1637-1645, 1999] discusses the effect of proper arc motion on ionospheric cavity formation.

Specifically discusses thin arc formation.



Alfvén-Fälthammar

Alfvén and Fälthammar [1963] noted that distributions with different temperature anisotropies will mirror at different altitudes.

Phase space density mapping shows that an anisotropic distribution becomes more isotropic ($T_\perp$ –> $T_\|$) away from the equator. Thus a distribution with $T_\perp > T_\|$ will decrease in density, while $T_\perp < T_\|$ will increase. If ions and electrons have a different anisotropy, then an electric field will develop to ensure quasi-neutrality.

Investigated by Schriver [JGR, 104, 14,655-14,670, 1999] using a PIC code. [PIC codes include wave-particle interactions, unlike Vlasov codes, but it is difficult to set up a current boundary condition.]

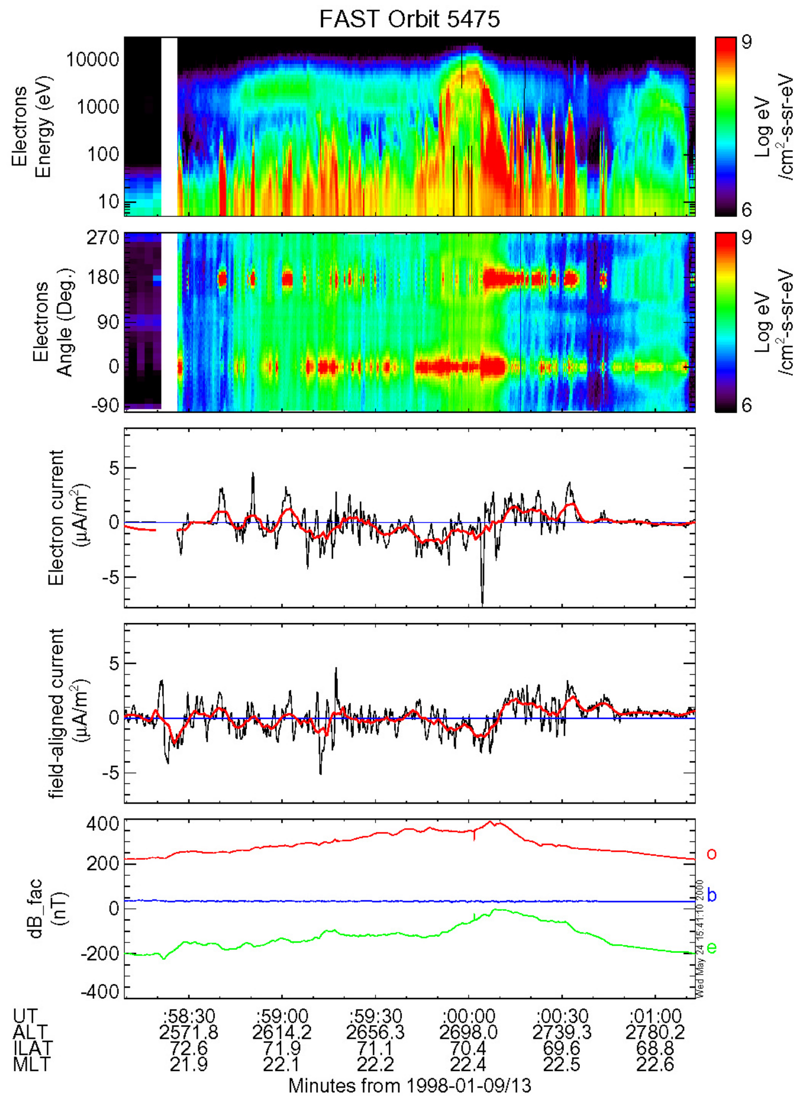
Does not explain why upward current is associated with inverted-V's.

Return Current

Return current carried by upgoing electrons.

Distributions heavily processed by wave-particle interactions.

Boundary layer distributions may be associated with Alfvén waves (see later).



Space-Charge Limited Flows

The return current is carried by upward electrons. However, the density profile is strongly controlled by the ions. The density should vary with a scale height given by $k(T_e + T_i)/m_i g$, but modified by a downward electric field that opposes the ambipolar electric field, so as to provide current continuity.

Thus, eventually the electron drift velocity will exceed the electron thermal speed. At this stage wave-particle interactions are likely to become significant. The return current region should therefore be turbulent, with considerable structure in the electron distribution.

Pressure Cooker

An additional consequence of the downward electric field in the return current region is the ion "pressure cooker" [Gorney et al., JGR, 90, 4205-4210, 1985].

The electric field holds the ions down until perpendicular wave heating has increased the magnetic moment so that the upward mirror force overcomes the electric field.

Ion conics are therefore a persistent feature of the return current region.

Ion conics are also observed in the primary current region below the acceleration region, but are folded into beams by the upward electric field.

Inertial Alfvén Waves

Wygant et al. have published several examples of large amplitude Alfvén waves observed by Polar at the plasma sheet boundary layer [e.g., JGR, 105, 18,675-18,692, 2000].

Poynting flux associated with these waves is 10's to 100's mW/m^2 at ionosphere – enough to power aurora.

Most of the Alfvén wave energy must be dissipated through electron acceleration, since impedance mismatch would reflect waves if not absorbed.

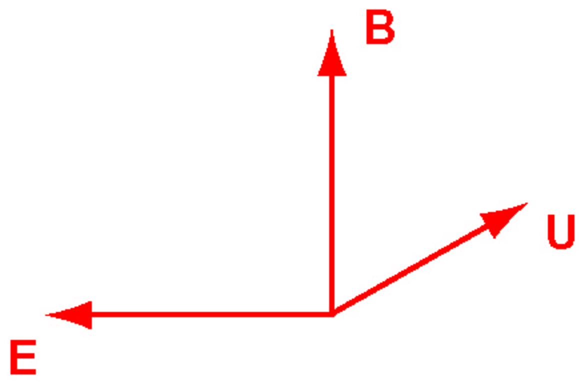
Chaston et al. [e.g., GRL, 26, 647-650, 1999] have published examples of "inertial" Alfvén waves, which could accelerate electrons.

Governing Equations

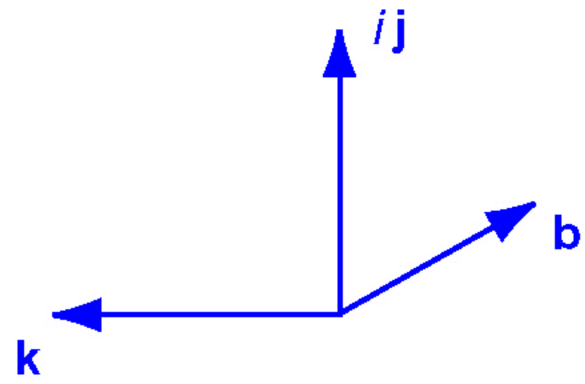
Faraday's Law:	$\mathbf{k} \times \mathbf{E} = \omega \mathbf{b}$
Ampere's Law:	$\mathbf{k} \times \mathbf{b} = -i\mu_0 \mathbf{j}$
Frozen in condition:	$\mathbf{E} + \mathbf{U}_i \times \mathbf{B} = 0$
Ion momentum:	$n m_i \omega \mathbf{U}_i = i\mathbf{j} \times \mathbf{B}$
Electron momentum:	$-i\omega j_{\parallel} = \omega_{pe}^2 \varepsilon_0 E_{\parallel}$

The electron momentum equation provides the "inertial" correction to the MHD modes. In particular electron inertia can allow the wave to carry a parallel electric field.

“Dungey Triads”



Frozen in Condition



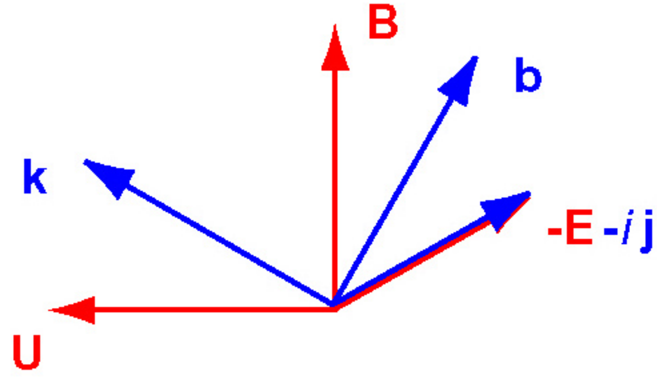
Ampere's Law

Rules for Triad Combination:

Faraday's Law: **b** perpendicular to **k**, **E**
(i.e., **b** in **U**, **B** plane)

Ion momentum: **U** perpendicular to **j**, **B**
(i.e., **j** in **E**, **B** plane)

Fast Mode



Fast Mode

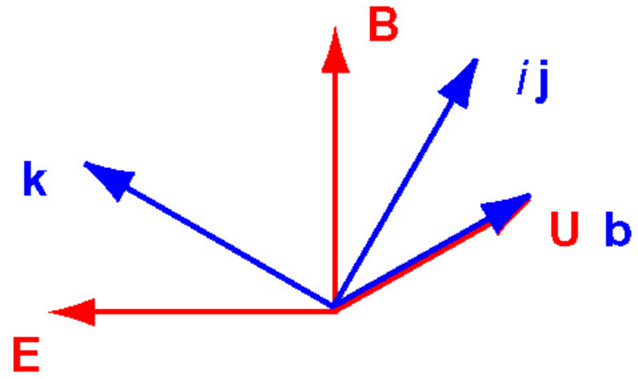
Fast mode properties

Perpendicular current

Compressible

Cannot have an E-parallel and still satisfy Faraday's Law

Shear (Alfvén) Mode



Shear Mode

Shear mode properties

Carries field-aligned current, Poynting flux

No compression

Can have an E-parallel and still satisfy Faraday's Law

Inertial Effect

Fast mode unaffected by electron inertia.

Alfvén mode modified by inertial effects, and

$$E_{\|}/E_{\perp} = k_{\|}/k_{\perp}\, k_{\perp}^2 c^2/\omega_{pe}^2 \,/(1 + k_{\perp}^2 c^2/\omega_{pe}^2\,)$$

At middle altitudes, c/ω_{pe} ~ 5 km, and $E_{\perp}$ ~ 10 mV/m, resulting in parallel potentials of ~ 50 V for $k_{\perp}c \approx \omega_{pe}$.

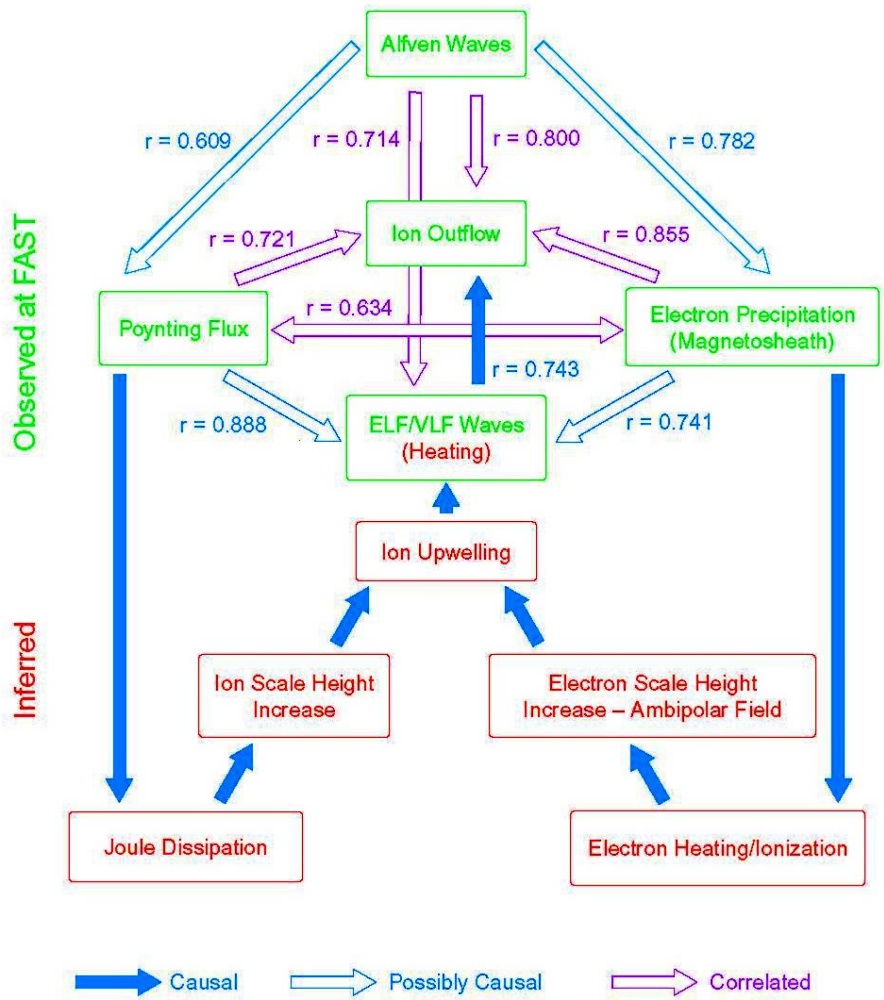
Ion Outflows

In addition to modifying ionospheric conductivities, auroral precipitation will also affect ion outflows.

Two processes are known to affect ion upwelling: collisional Joule dissipation (Poynting flux) and soft electron precipitation.

Both occur in the dayside cusp – correlative study using FAST data.

Outflow Correlations



Conclusions

Auroral acceleration processes manifest themselves in three ways:

- Primary auroral current – inverted-V
- Return current – ion pressure cooker
- Alfvén wave – boundary plasma sheet

Primary current affects ionospheric conductivity – feedback on magnetospheric generator, density depletions, ion beam outflows.

Return current – conic outflows, possible conductivity changes associated with bi-directional electrons.

Alfvén wave induced precipitation – soft electrons, similar to dayside cusp outflows.

Not discussed

- Decoupling implied by parallel electric fields (see Borovsky and Bonnell, JGR, 106, 28,967, 2001).
- Assumptions implicit in height integrated conductivity ("thin" ionosphere), in thick ionosphere current and ion flow vectors rotate.