Energy and momentum transfer from waves to particles

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Outline

- Motivation
- Multimoment fluid theory
- Wave-particle interaction terms
- Application to auroral ion heating
- Future work and concluding remarks

Motivation

- Perpendicular ion heating is a common feature in astrophysical plasmas
- Many types of waves can produce some heating
- However, what waves actually produce the observed heating is a key question
- Needed: a self-consistent model to answer this question

Anomalous resistivity is not enough!

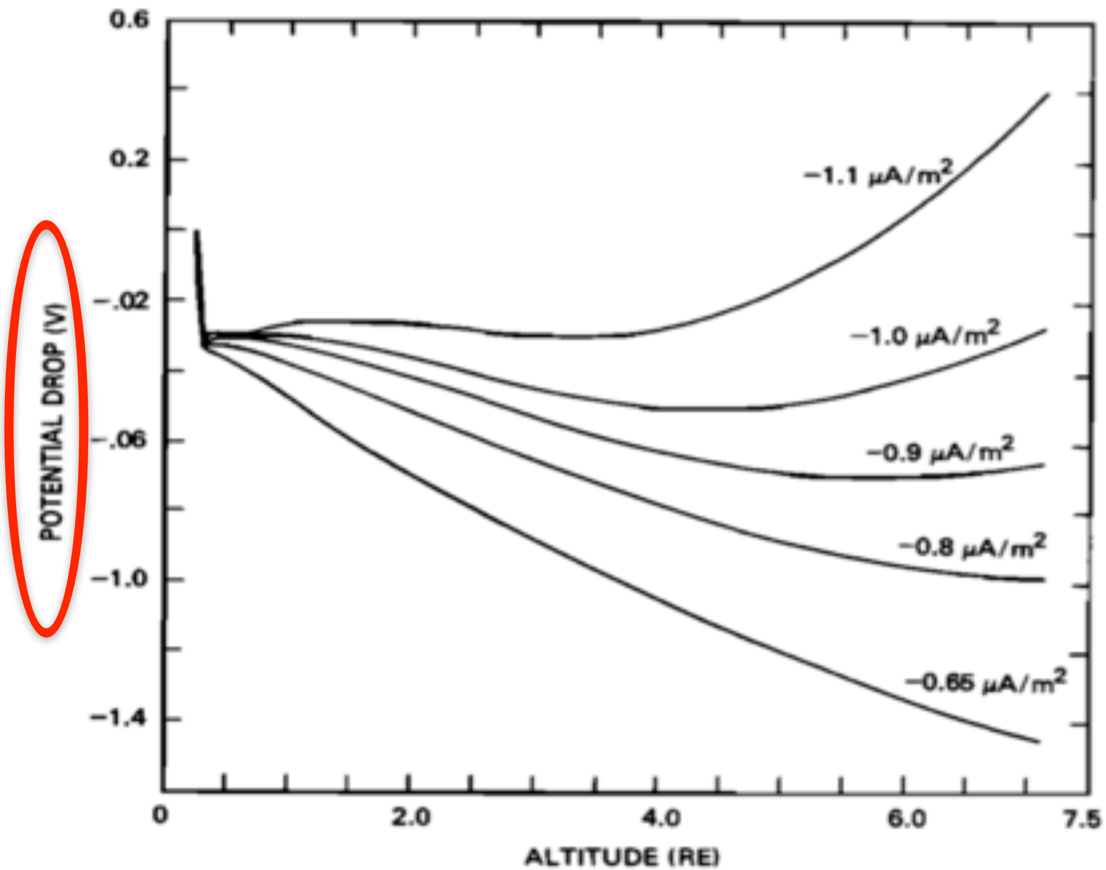

Fig. 15. Potential drop along the tube for all currents.

Ganguli and Palmadesso (1987), JGR 92, 9673

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Approximations

- Guiding center
- Gyrotropic particles
- Fluid description (take moments)
- $E/B > c$ (often true in auroral region)

On the quasisteady state

- No true steady state solution of these equations exists in the downward current region
- However, there is an average “state” about which the instantaneous state fluctuates
- Electron time scales << ion time scales ⇒ can compute quasisteady state as average over electron time

Multi-moment fluid equations

$$
\begin{aligned}
\frac{\partial n_\alpha}{\partial t} + B\frac{\partial}{\partial s}(n_\alpha u_\alpha/B) &= 0 \\
\frac{\partial}{\partial t}(m_\alpha n_\alpha u_\alpha) + \frac{\partial}{\partial s}[n_\alpha(T_{\alpha\parallel} + m_\alpha u_\alpha^2)] - \frac{1}{B}\frac{dB}{ds}n_\alpha(T_{\alpha\parallel} + m_\alpha u_\alpha^2 - T_{\alpha\perp}) + q_\alpha n_\alpha\frac{\partial\phi}{\partial s} &= \dot{M}_{\alpha\parallel} \\
\frac{1}{2}\frac{\partial}{\partial t}[n_\alpha(T_{\alpha\parallel} + m_\alpha u_\alpha^2)] + \frac{\partial}{\partial s}(n_\alpha q_{\alpha\parallel}) - \frac{1}{B}\frac{dB}{ds}n_\alpha(q_{\alpha\parallel} - q_{\alpha\perp}) + q_\alpha n_\alpha u_\alpha\frac{\partial\phi}{\partial s} &= \dot{W}_{\alpha\parallel} \\
\frac{\partial}{\partial t}(n_\alpha T_{\alpha\perp}) + B^2\frac{\partial}{\partial s}(n_\alpha q_{\alpha\perp}/B^2) &= \dot{W}_{\alpha\perp} \\
\frac{\partial^2\phi}{\partial s^2} + 4\pi\sum_\alpha q_\alpha n_\alpha &= 0
\end{aligned}
$$

- Right-hand side represents wave-particle interactions (anomalous resistivity and anomalous heating/cooling)

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Formal derivation

- Wave-particle interactions are treated via a Fokker-Planck formalism

$$\begin{bmatrix} 0 \\ \dot{M}_{\alpha\|} \\ \dot{W}_{\alpha\|} \\ \dot{W}_{\alpha\perp} \end{bmatrix} = \int d^3v \begin{bmatrix} 1 \\ m_\alpha v_\| \\ m_\alpha v_\|^2/2 \\ m_\alpha v_\perp^2/2 \end{bmatrix} \bar{C}_\alpha$$

$$C_\alpha = -\frac{\partial}{\partial \mathbf{v}} \cdot (\mathbf{F}_\alpha^f + \mathbf{F}_\alpha^p) f_\alpha + \frac{1}{2}\frac{\partial}{\partial \mathbf{v}}\frac{\partial}{\partial \mathbf{v}} \cdot \cdot \mathsf{D}_\alpha^f f_\alpha$$

Wave-particle interaction terms

$$\dot{M}_{\alpha\|} = \frac{\pi q_\alpha^2}{m_\alpha}\int d^3v f_\alpha \sum_n \int \frac{d^3k}{(2\pi)^3}\int_{-\infty}^{\infty} d\omega \left\{ \frac{k_\perp^2}{2k^2}\frac{k_\|}{\Omega_\alpha}[J_{n-1}^2(\xi_\alpha) - J_{n+1}^2(\xi_\alpha)]\langle|\delta\tilde{E}^2|(\mathbf{k},\omega)\rangle + \frac{k_\|^2}{k^2}k_\| J_n^2(\xi_\alpha)\left(\frac{\partial}{\partial\omega}\langle|\delta\tilde{E}^2|(\mathbf{k},\omega)\rangle\right) + 4m_\alpha\frac{k_\|}{k^2}J_n^2(\xi_\alpha)\,\mathrm{Im}\,\tilde{\epsilon}(\mathbf{k},\omega)^{-1}\right\} \times \delta(n\Omega_\alpha + k_\| v_\| - \omega)$$

- Similar expressions can be obtained for $\dot{W}_{\alpha\|}$ and $\dot{W}_{\alpha\perp}$

Characteristic **k** method

$$I(s,t)_m^{(1)} = (2\pi)^{-2}\int_0^\infty dk_\perp\, k_\perp \int_0^\infty dk_\parallel \int_0^\infty d\omega\, h(s,t;\mathbf{k},\omega) \times\langle|\delta\tilde{E}^2|(s,t;\mathbf{k},\omega)\rangle_m$$
$$= \delta\tilde{E}^2(s,t)(2\pi)^{-2}\int_0^\infty dk_\perp\, k_\perp \int_0^\infty dk_\parallel \times\int_0^\infty d\omega\, h(s,t;\mathbf{k},\omega) g(s;\mathbf{k})_m^{(1)} R(s;\mathbf{k},\omega)_m^{(1)}$$

- *h* and *R* vary slowly with **k**
- *g* is sharply peaked about a characteristic $\mathbf{k}_{0m}^{(1)}$
- Can approximate above integral for quadrant (1) and resonance *m* as

$$I(s,t)_m^{(1)} \approx \delta\tilde{E}^2(s,t)_m^{(1)}\int_0^\infty d\omega\, h(s,t;\mathbf{k}_{0m}^{(1)},\omega) R(s;\mathbf{k}_{0m}^{(1)},\omega)_m^{(1)}$$

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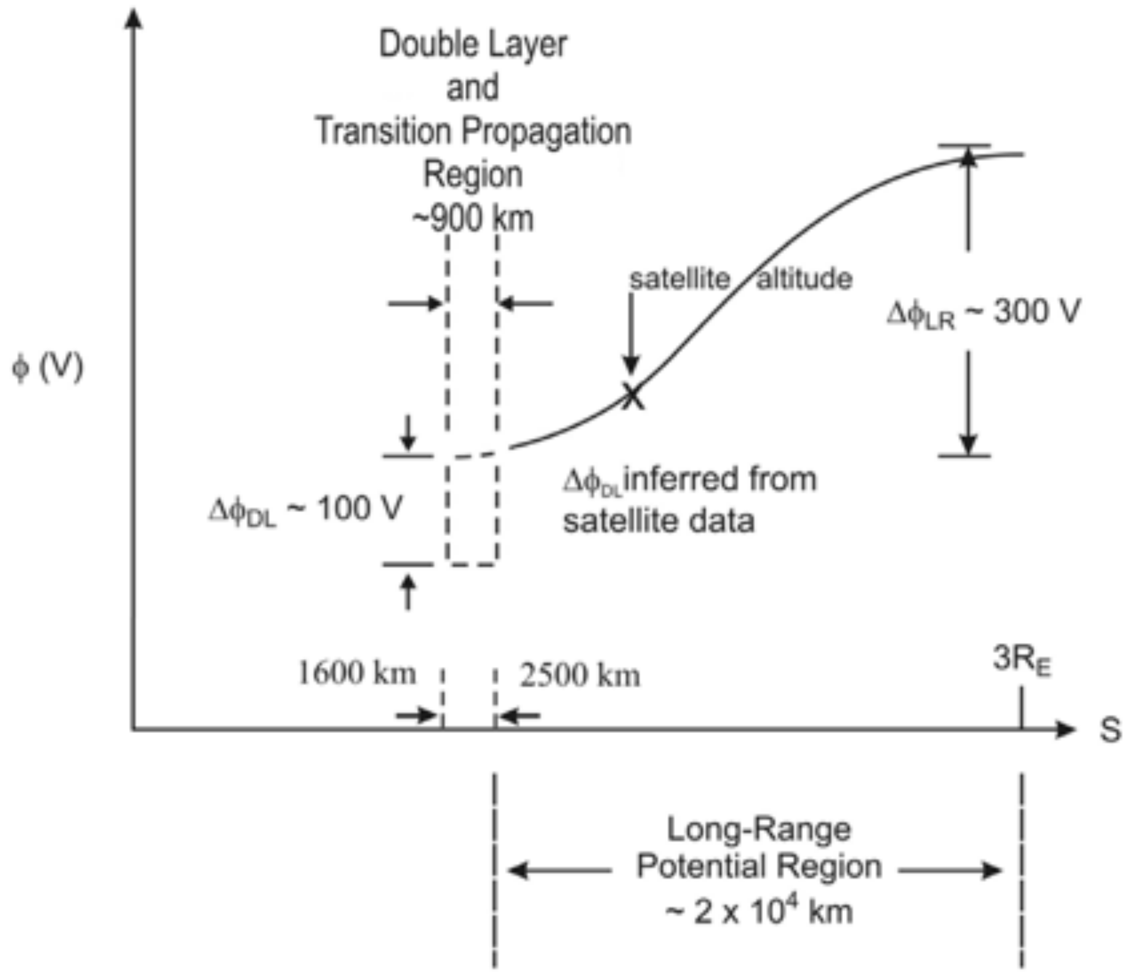
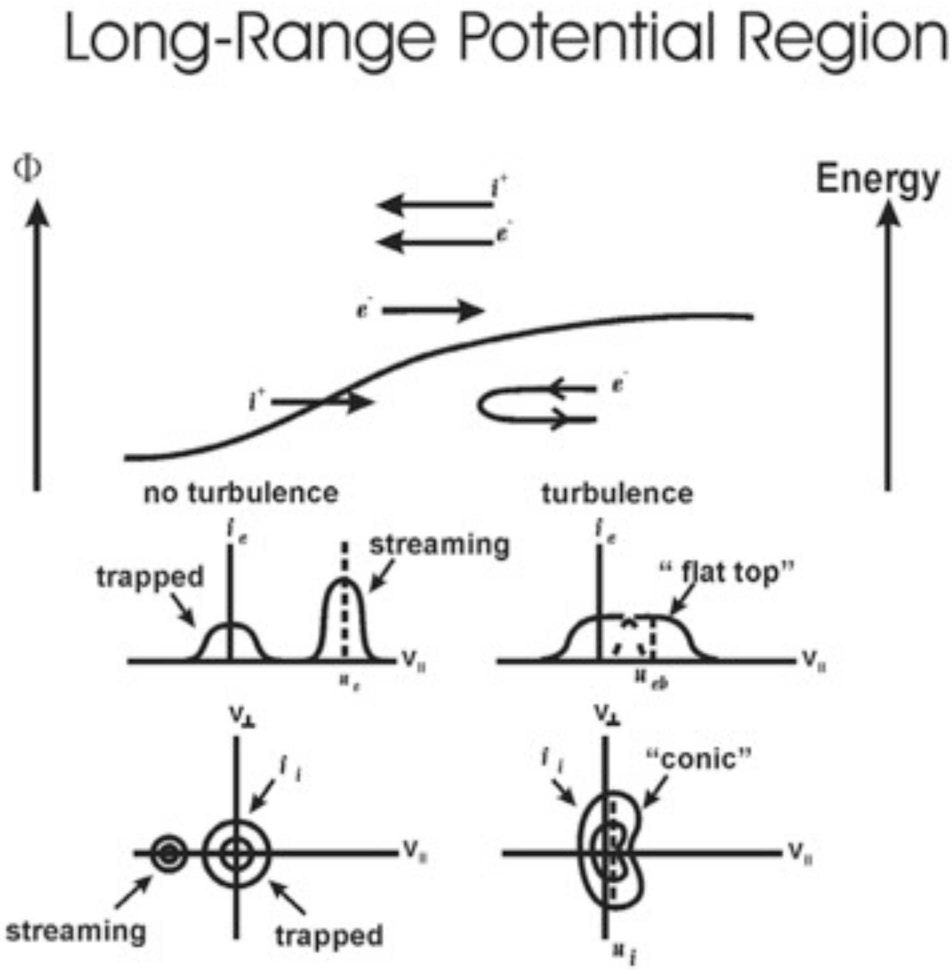
Auroral basics

- Electrons carry field-aligned currents upward and downward
- Charge carrier number flux limited, so electric field needed
  - Double layers (short-range $E_{||}$) form at interface with ionosphere
  - Different anisotropy of electrons, ions leads to charge separation $\Rightarrow$long-range $E_{||}$

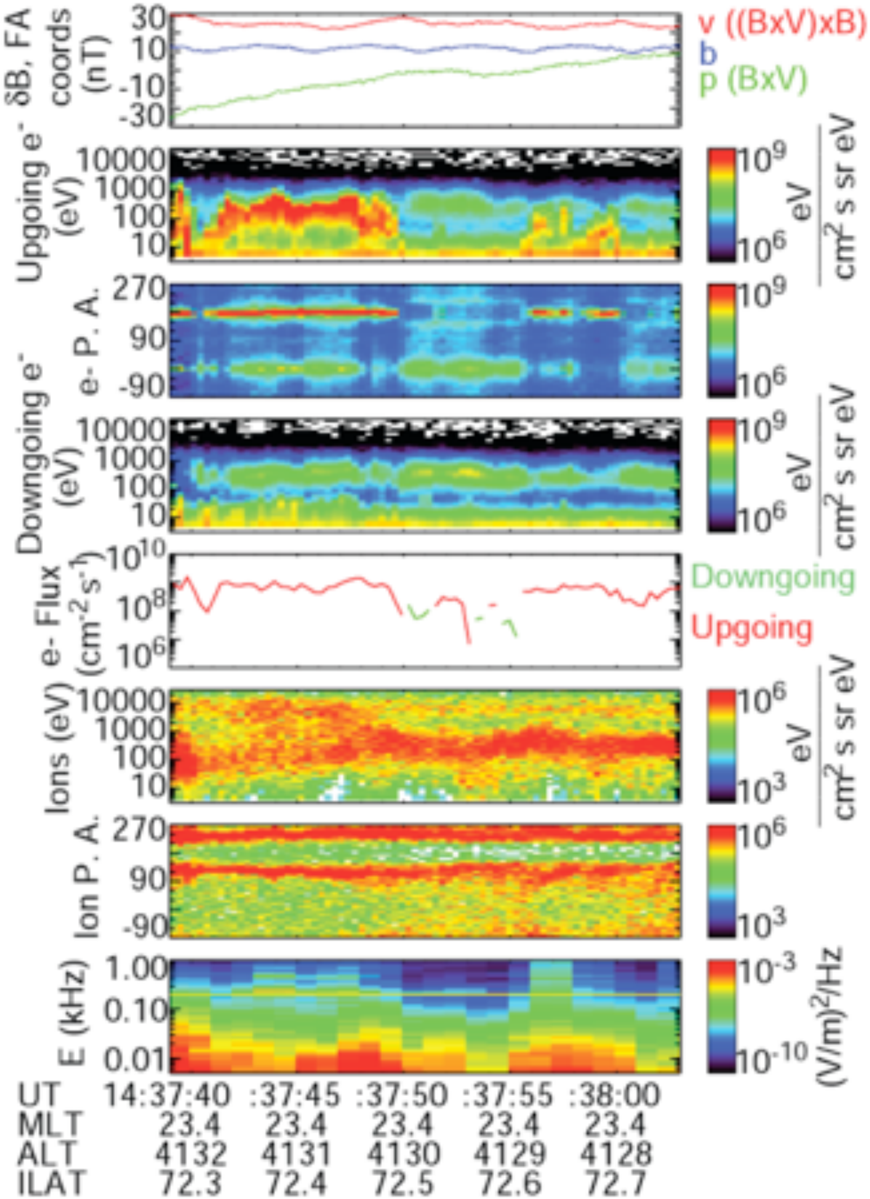
Picture of field-aligned potential difference (downward $J_{\|}$)



Typical particle distributions

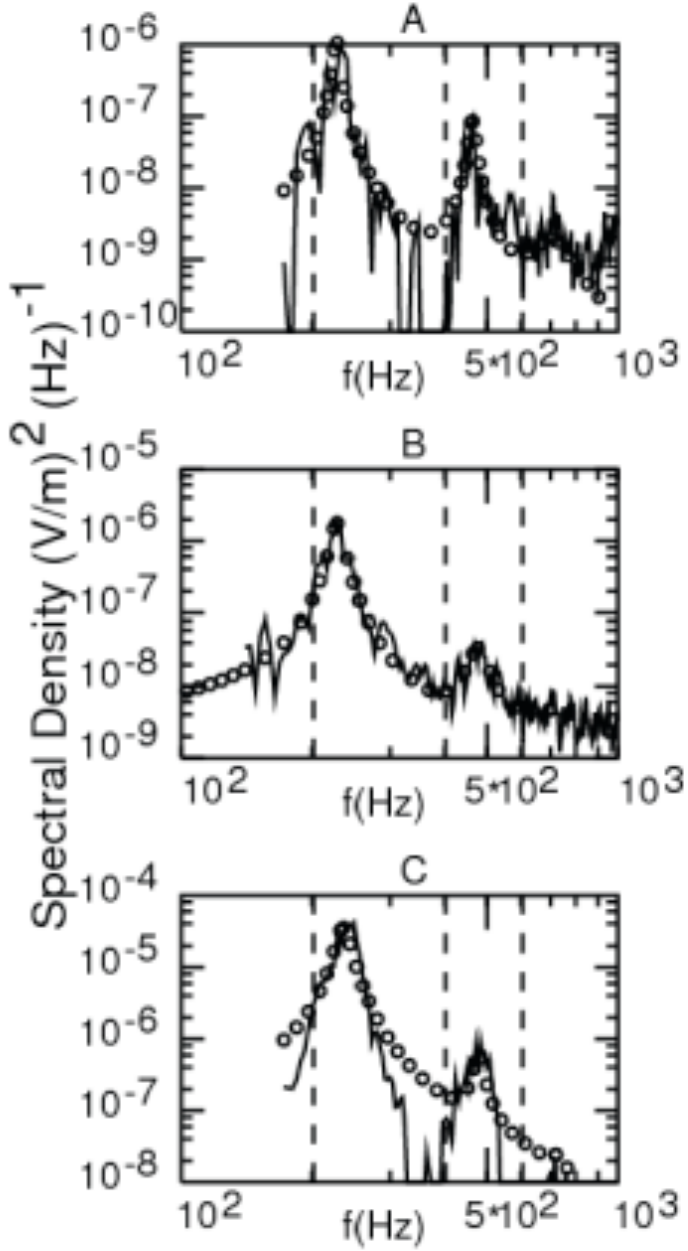


Example FAST data



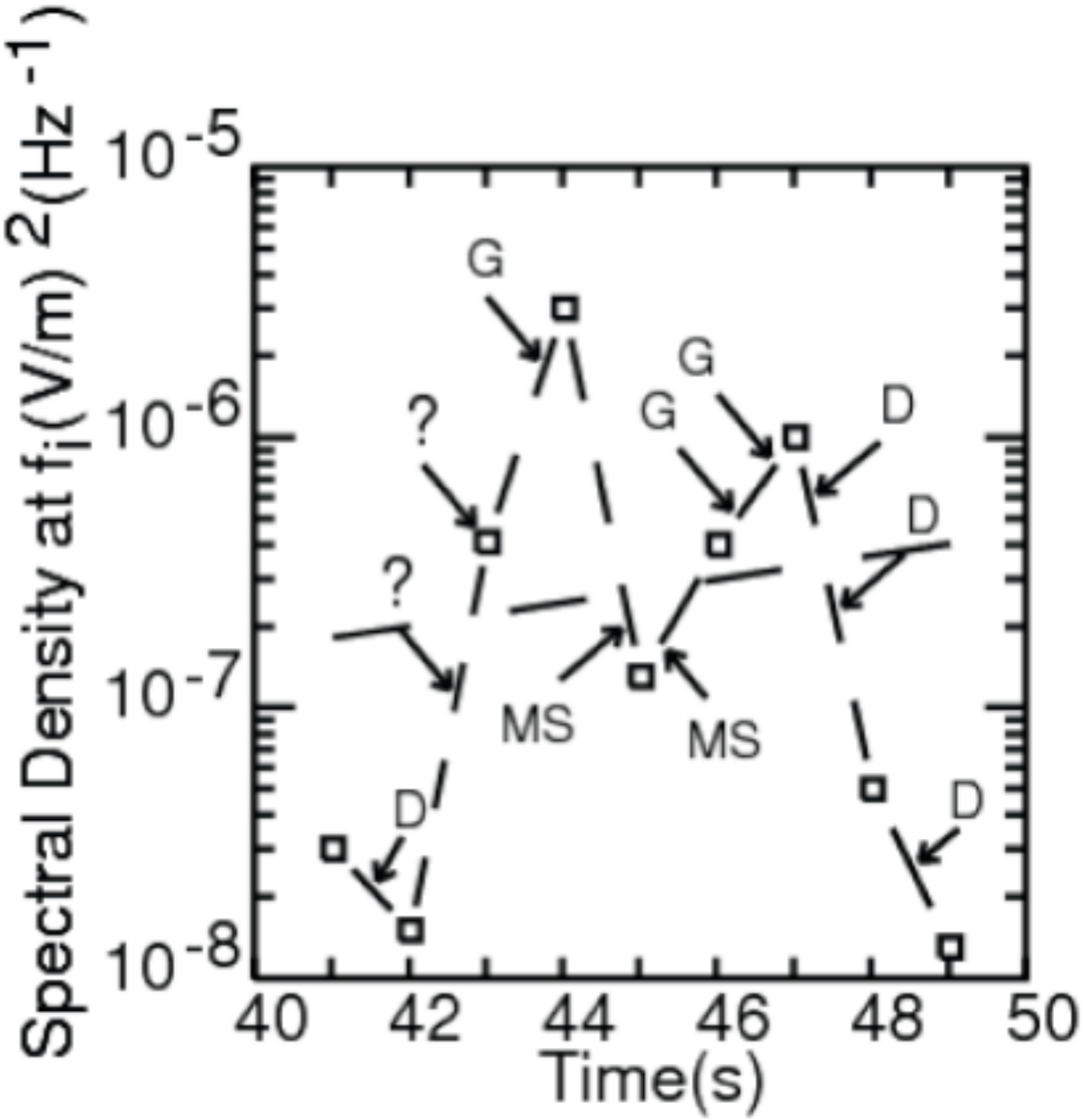
- Portion of a nightside pass
- Predominantly downward current (upward field-aligned electrons)
- Ion conic present throughout
- EIC and BBELF waves present

EIC wave spectra



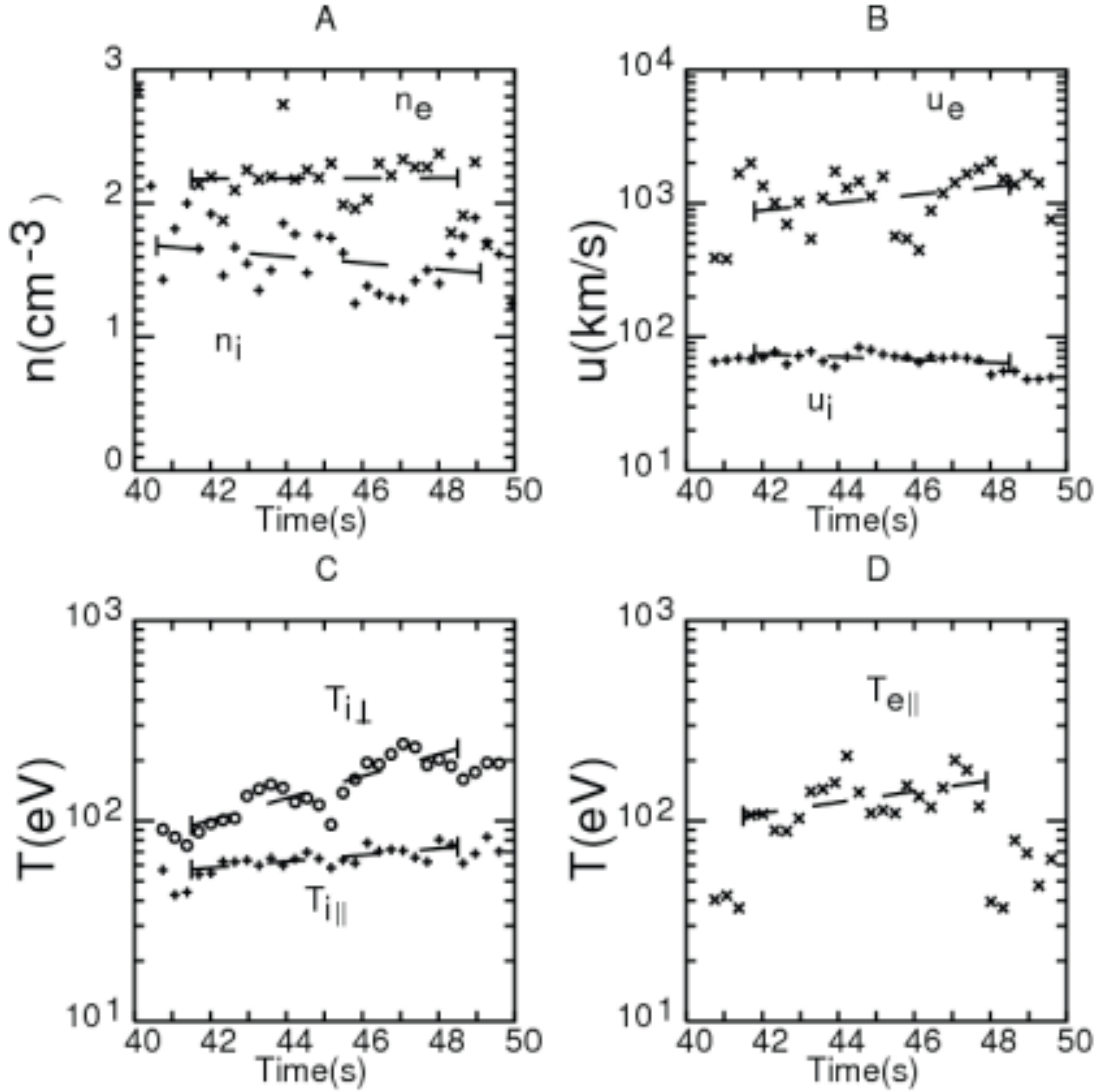
- Three emission levels (low, medium, high) depicted
- Fundamental, 2nd harmonic, and sometimes 3rd harmonic visible
- Fits shown to Lorentz resonance functions

Wave growth and damping

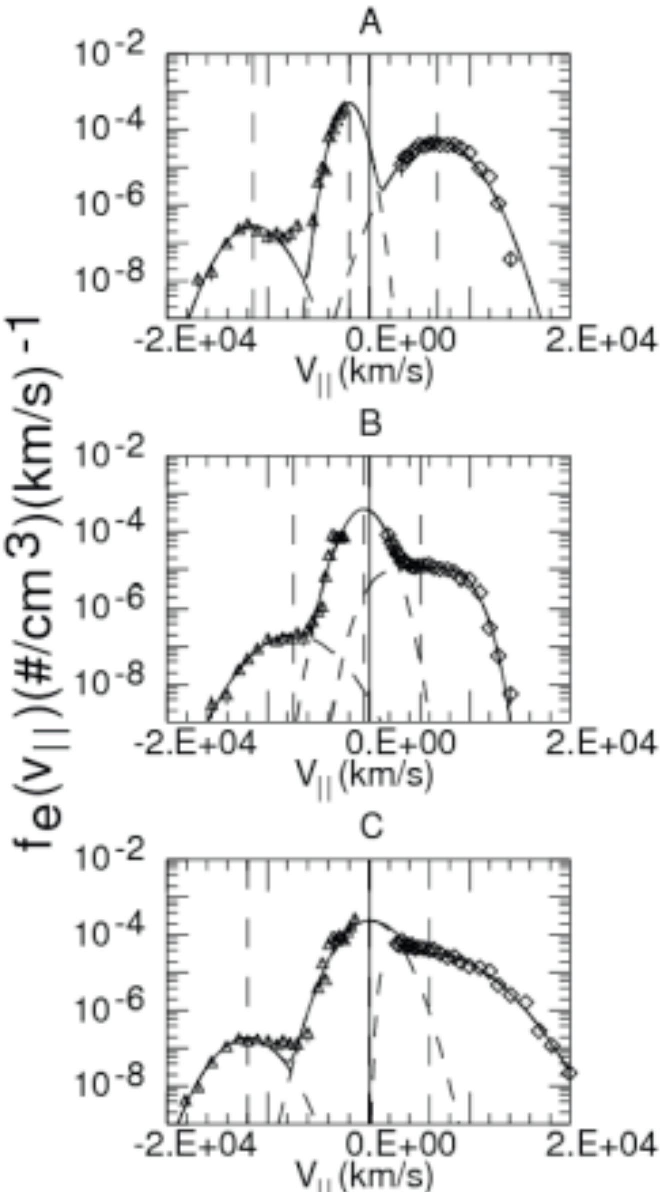


- PSD measured at 201 Hz (f_{cH})
- Electron distributions suggest:
  - G—growth
  - MS—metastable
  - D—damping

Electron and ion moments

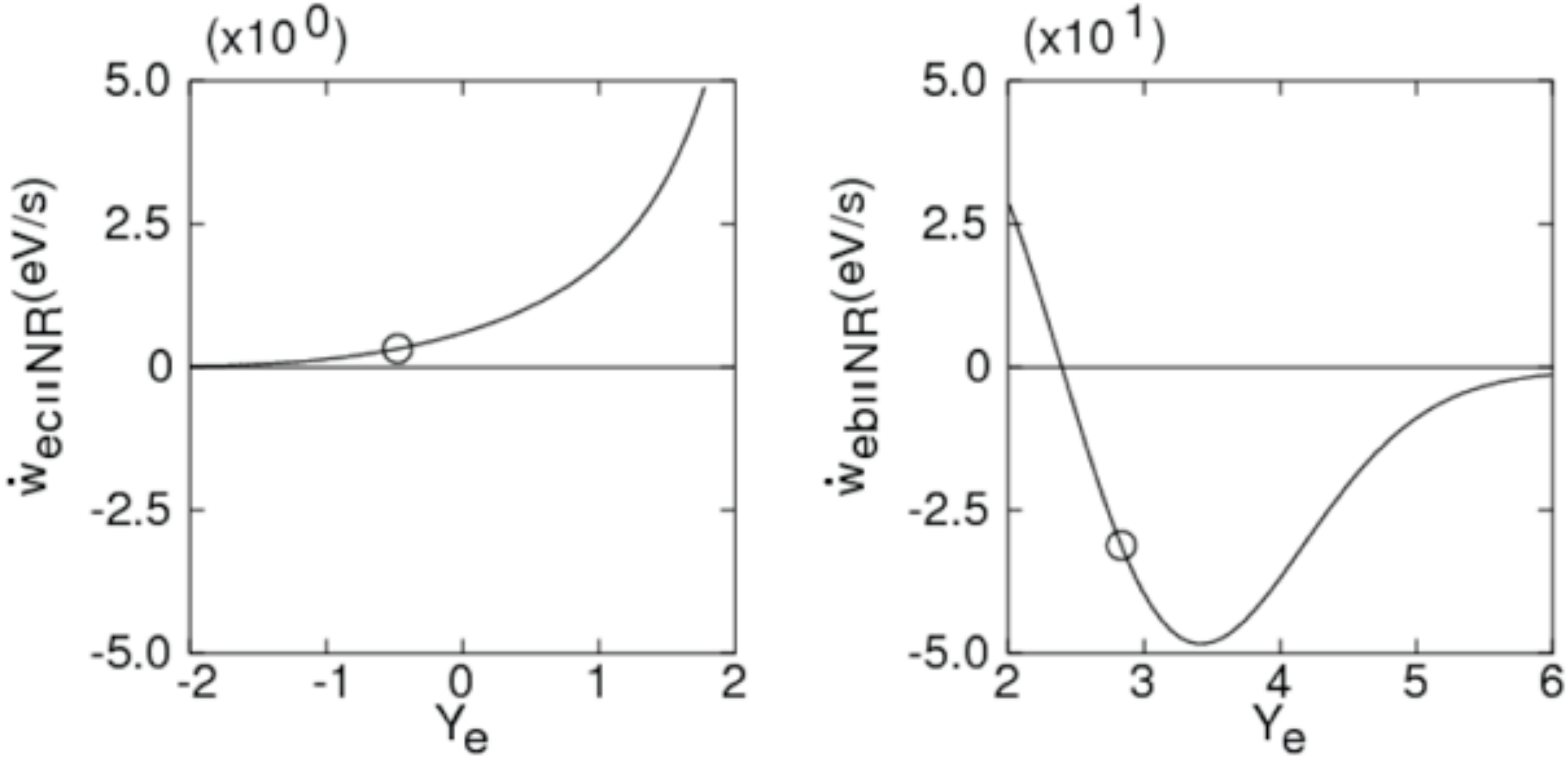


Sample electron distributions



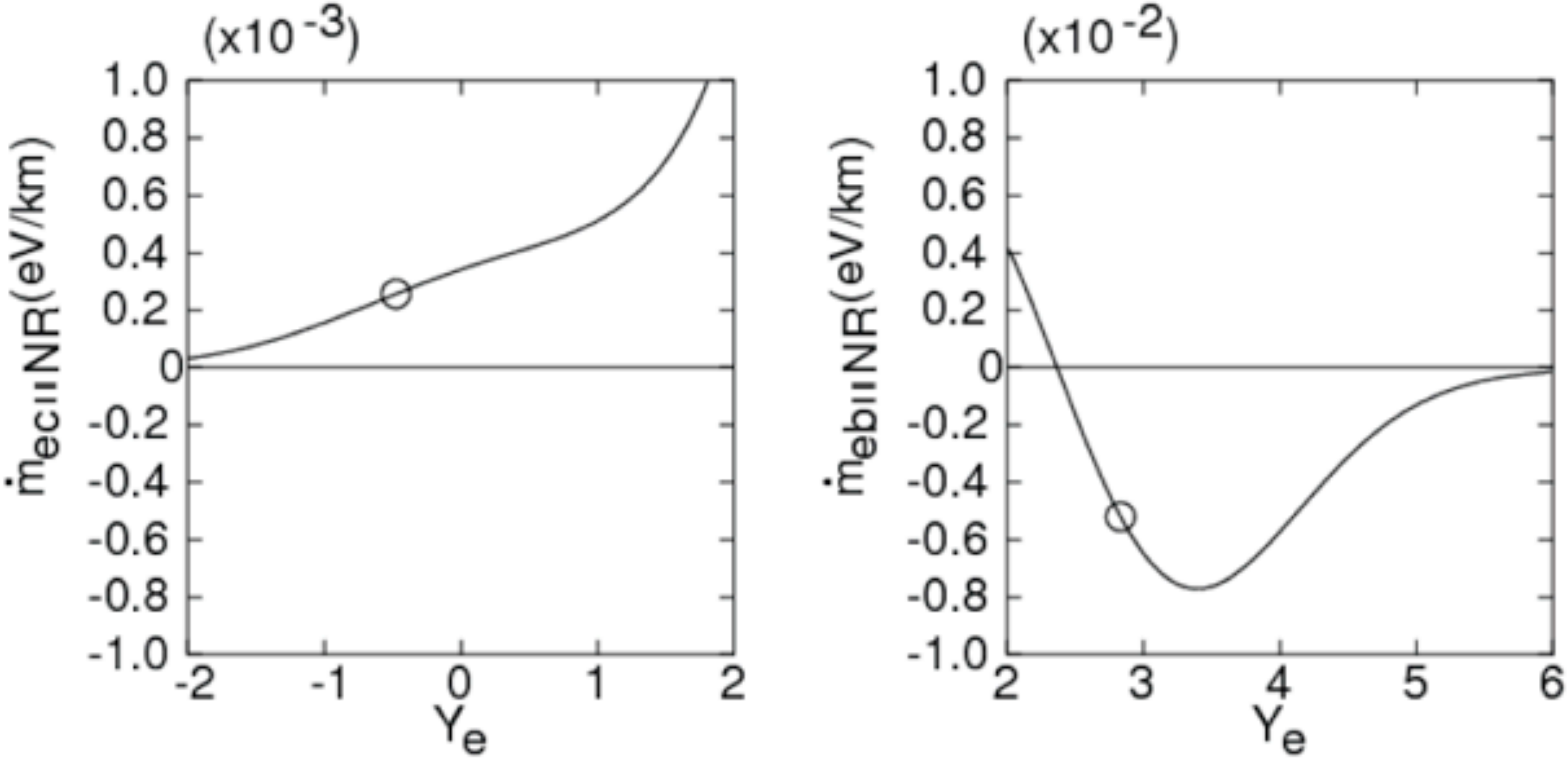
- Three populations in fit
  - Core
  - Upgoing
  - Downgoing
- Potentially unstable, marginally stable, and stable distributions seen
- Instability is bump-on-tail-driven, not current-driven

Core and beam energy transfer rates per particle (marginally stable case)



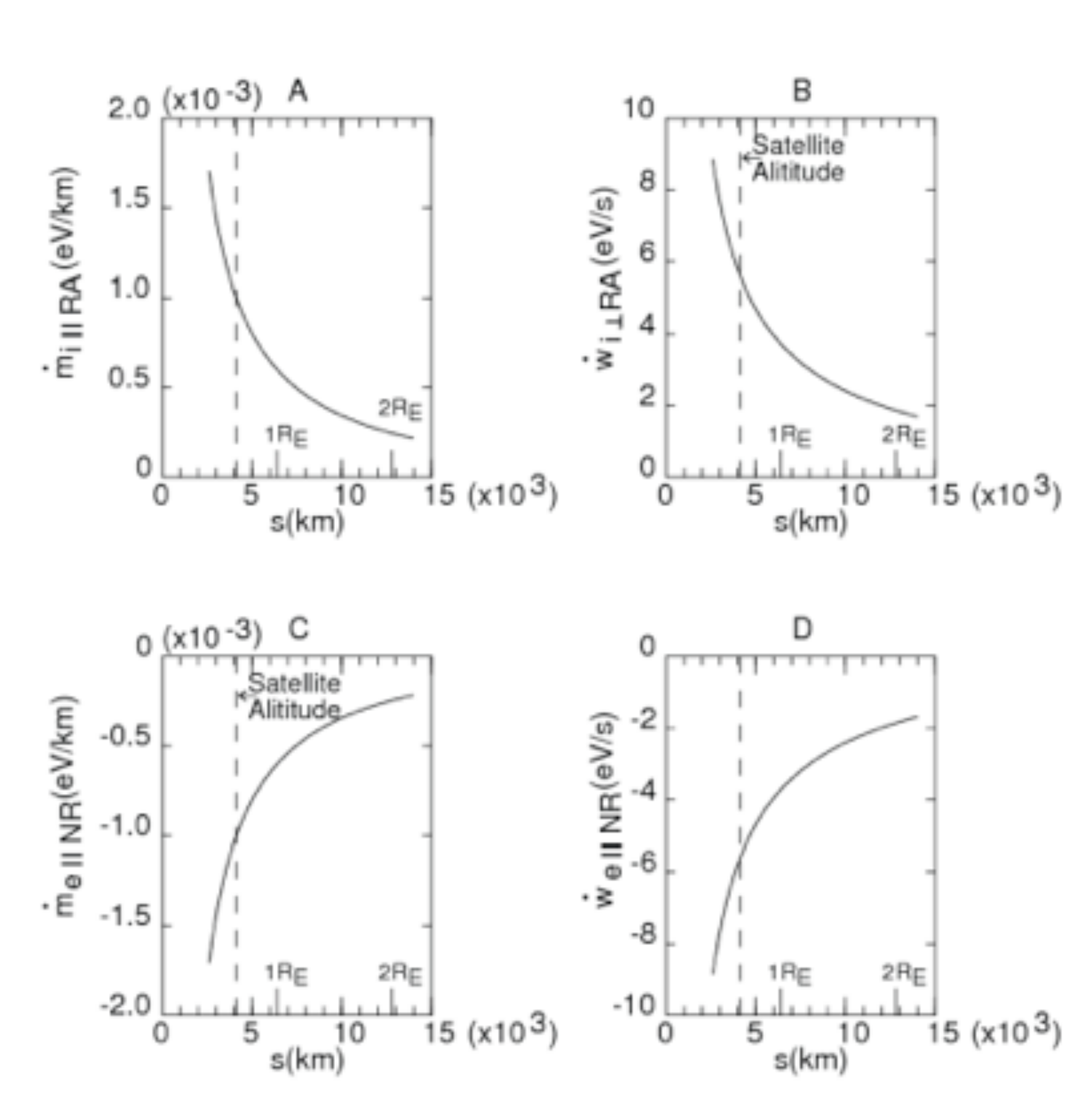
$$Y_e = u_e / v_{e\|}$$

Core and beam momentum transfer rates per particle (marginally stable case)

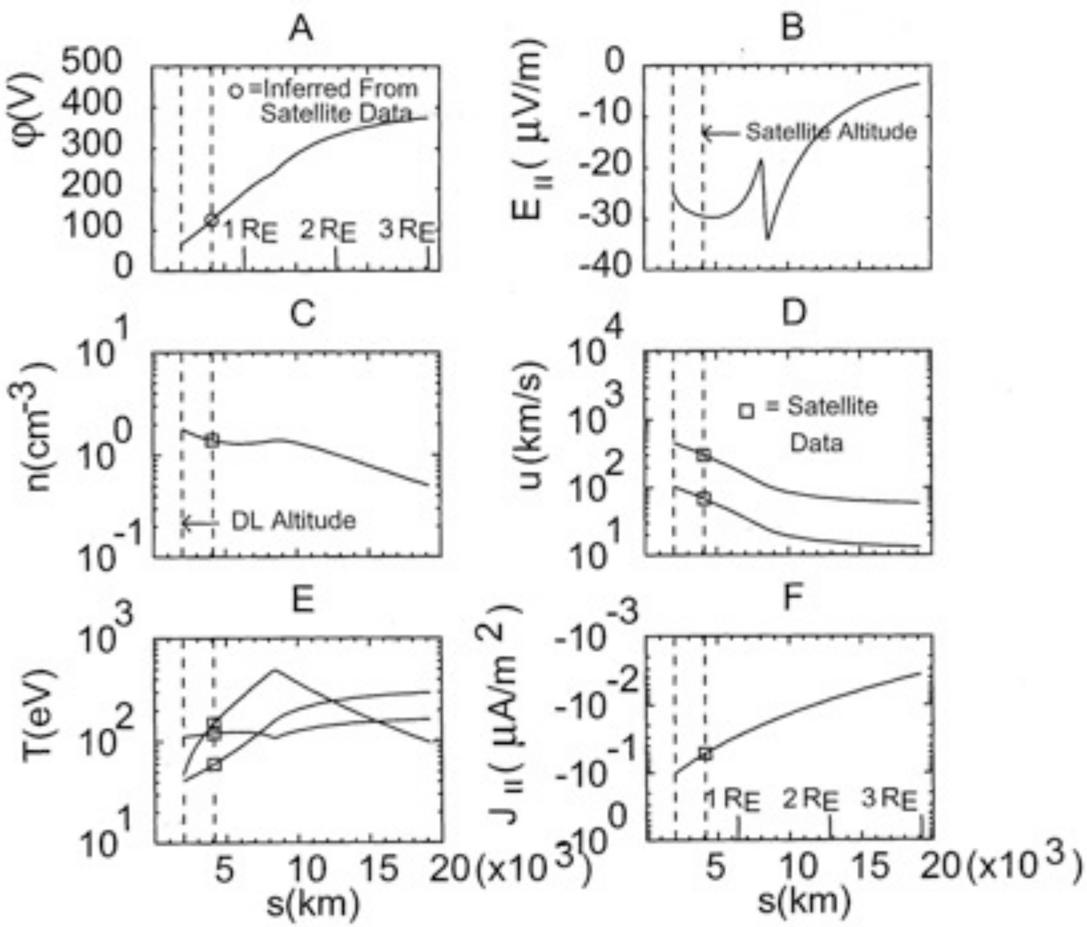


$$Y_e = u_e / v_{e\|}$$

Total anomalous transfer rates per particle (marginally stable case)

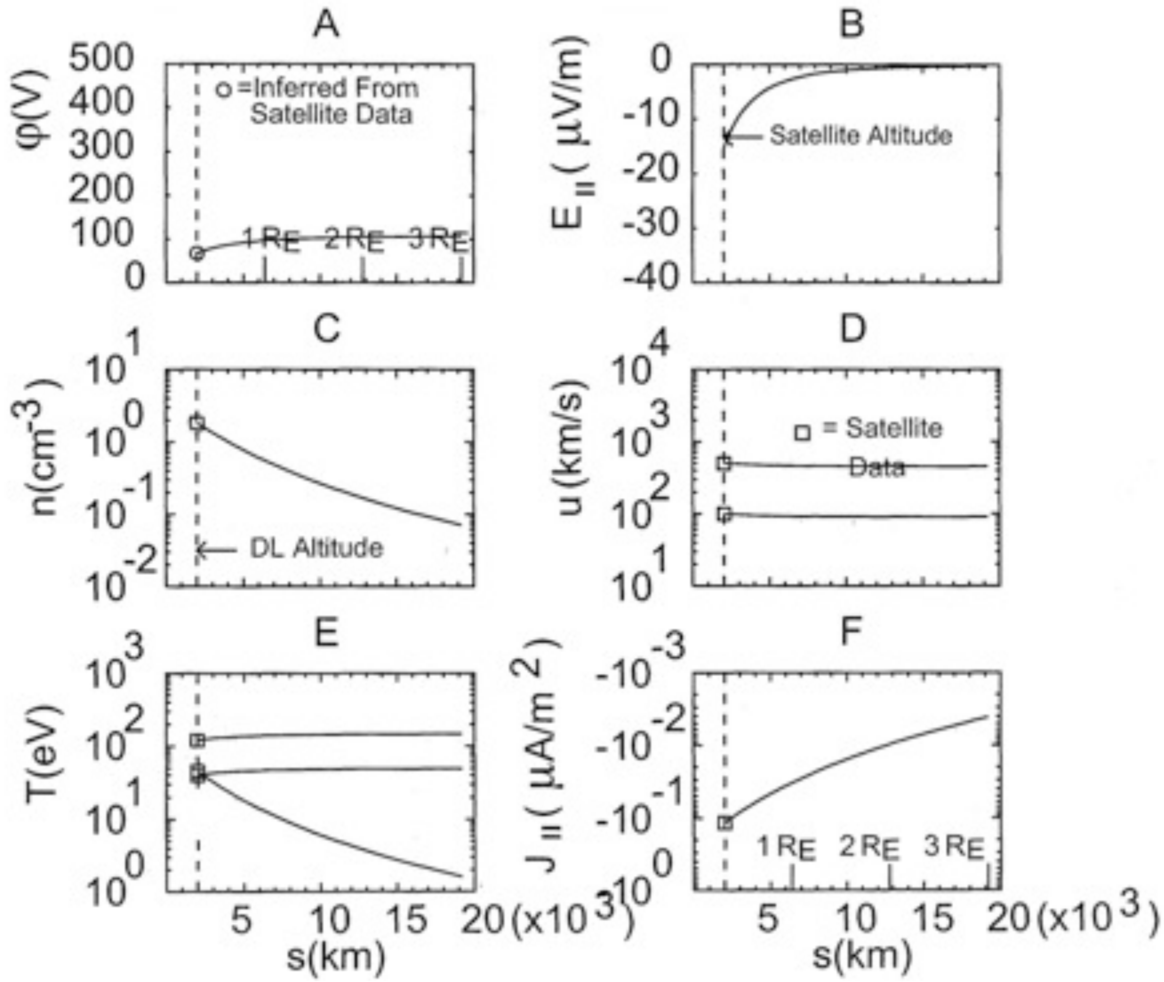


Ion heating with EIC turbulence



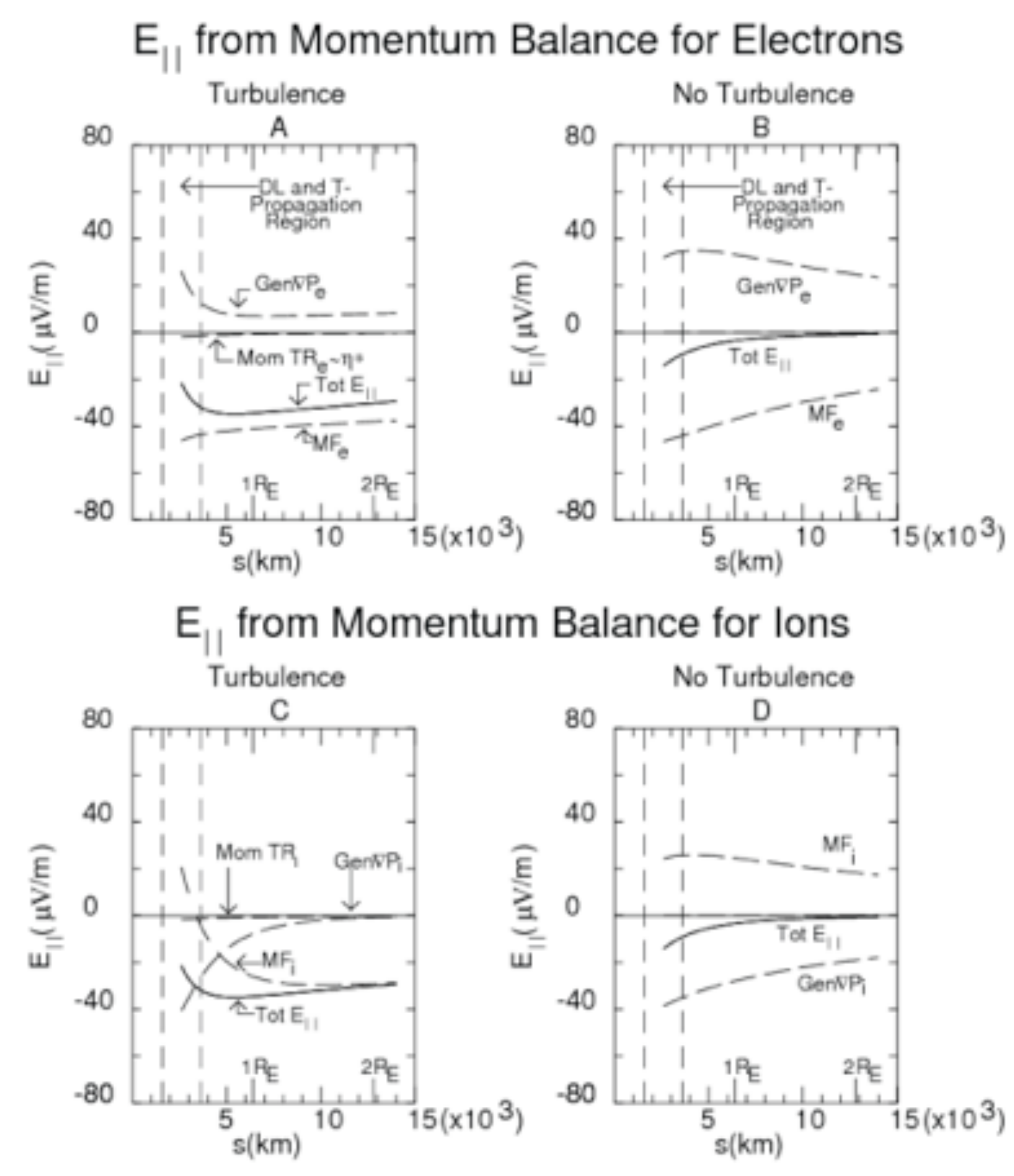
- Modified Drummond-Rosenbluth instability
- Turns off when $J_{||}$ drops below threshold
- Sufficient to account for observed heating

Without EIC turbulence



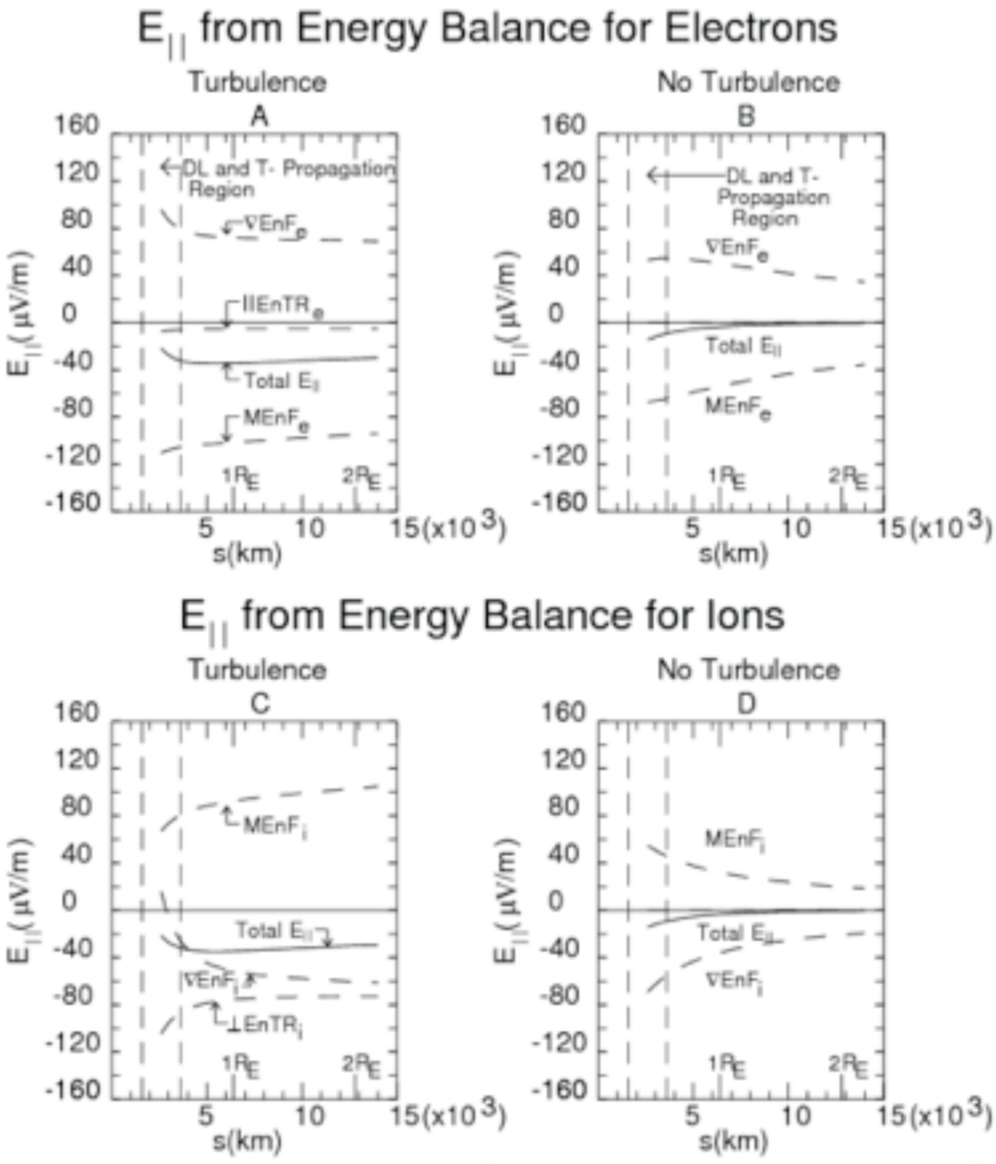
- No heating occurs
- $T_{i\perp}$ cools adiabatically
- Inconsistent with observations

$E_{\|}$ from momentum balance



- Anomalous resistivity only a minor contributor ($E \neq \boldsymbol{\eta}^{*}J$)
- Turbulence changes contributions of ∇p, mirror force terms

$E_{||}$ from energy balance



- Energy transfer to ions a significant contributor
- Gradient and mirror terms dominate for electrons

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Future Work

- Extend to other wave modes (ESWs, electromagnetic modes, etc.)
- Extend to upward current region
- Time dependence

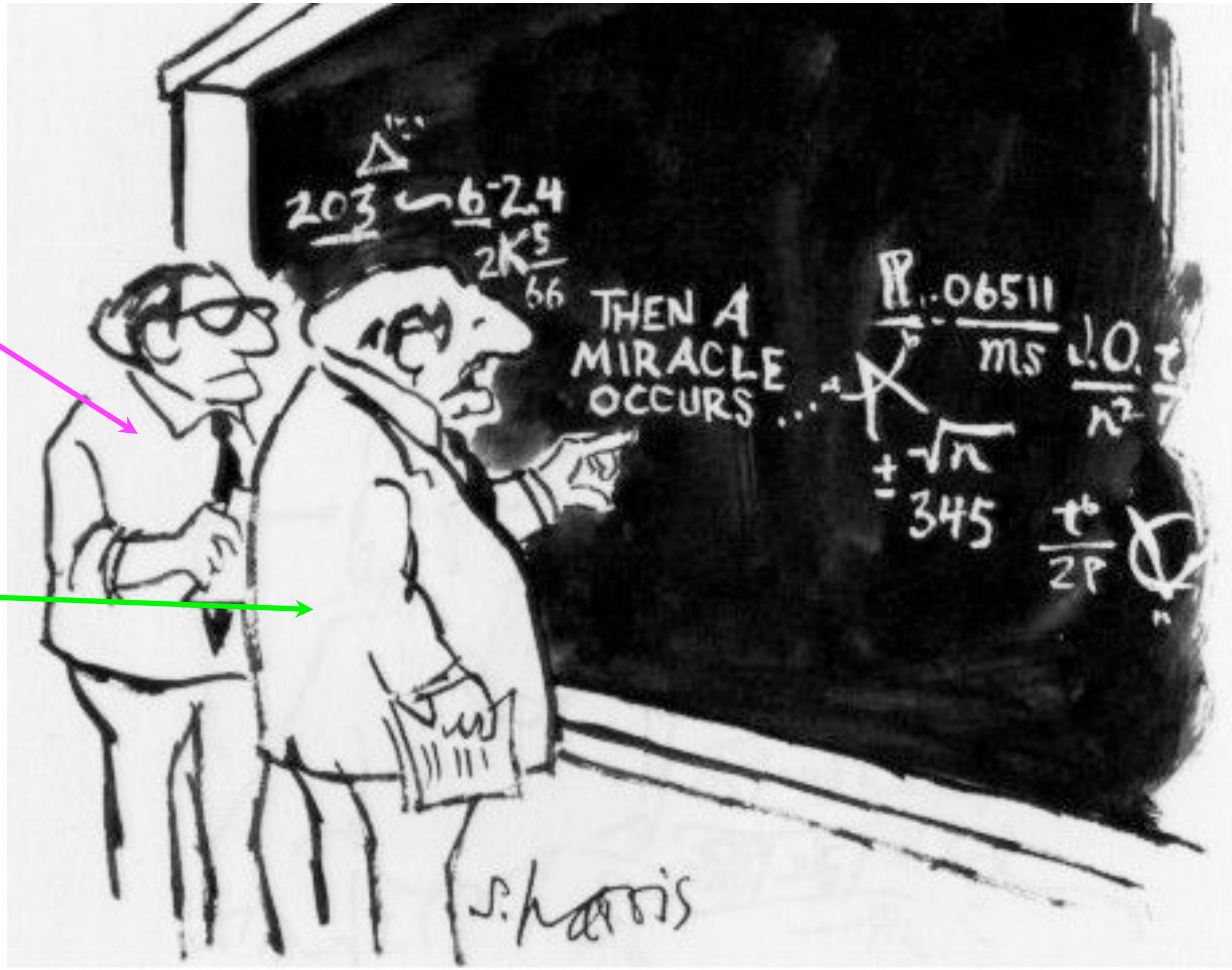
Summary

- Self-consistent fluid theory for perpendicular ion heating in auroral (and other astrophysical) plasma
- Theory includes effects of wave turbulence
- Predicted ion heating rate consistent with observations if turbulence is included
- $E_{||}$ supported by anomalous heating, not anomalous resistivity

Cutting room floor

Global modelers

Auroral physics community



"I think you should be more explicit here in step two."

from *What's so Funny about Science?* by Sidney Harris (1977)

Self-consistent solutions