SM21A-0454

Electromagnetic Ion Cyclotron Waves as a Diagnostic for Heavy Ion Mass Density

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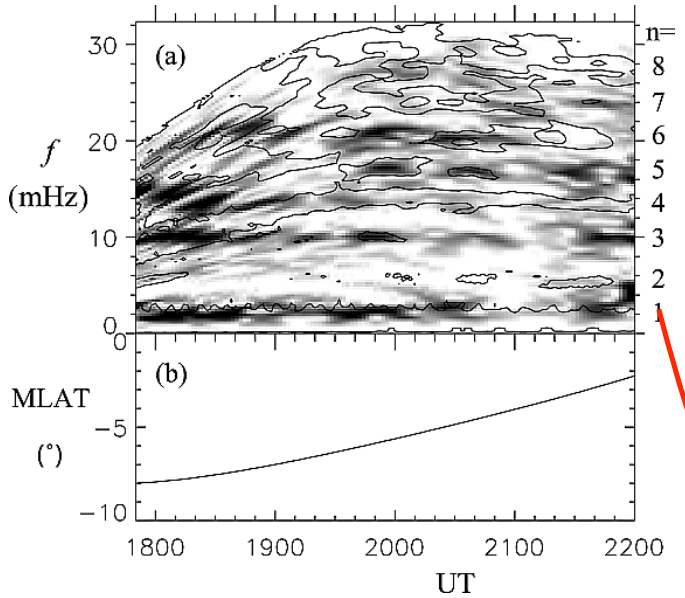
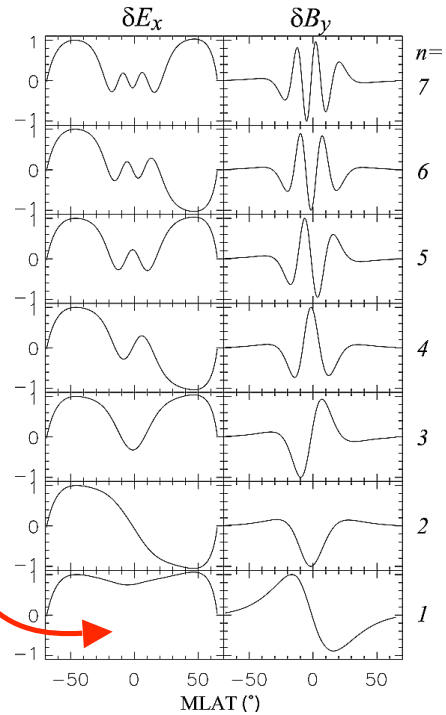
Outline

- Brief review: methods for probing mass density
  - Toriodal/Shear Alfven eigenmodes
  - Plasma waves
  - Ion cyclotron waves are complimentary to other techniques
- Proposed observational techniques
  - Satellite conjunctions
  - Wave emissions from satellites
- Ion cyclotron wave solutions and heavy ion density
  - Wave solutions
    - Ion cyclotron resonance
    - Ionospheric absorption
    - Poynting flux
  - Probing mass concentrations using tomography
    - ICW absorption removes Poynting flux
    - Reflection of emitted wave off resonance
  - Self consistency and heavy ion outflows

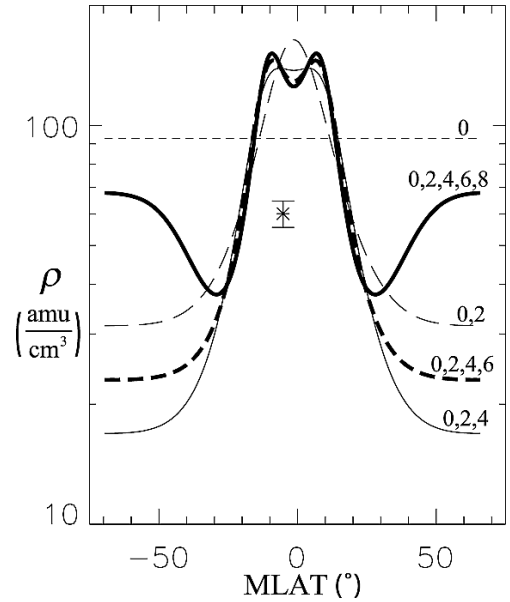
Toroidal Alfvèn Waves and Mass Density



Power spectrum $|\omega\delta E_x|^2$ and $|\omega\delta B_y|^2$ from CRESS show harmonic structure



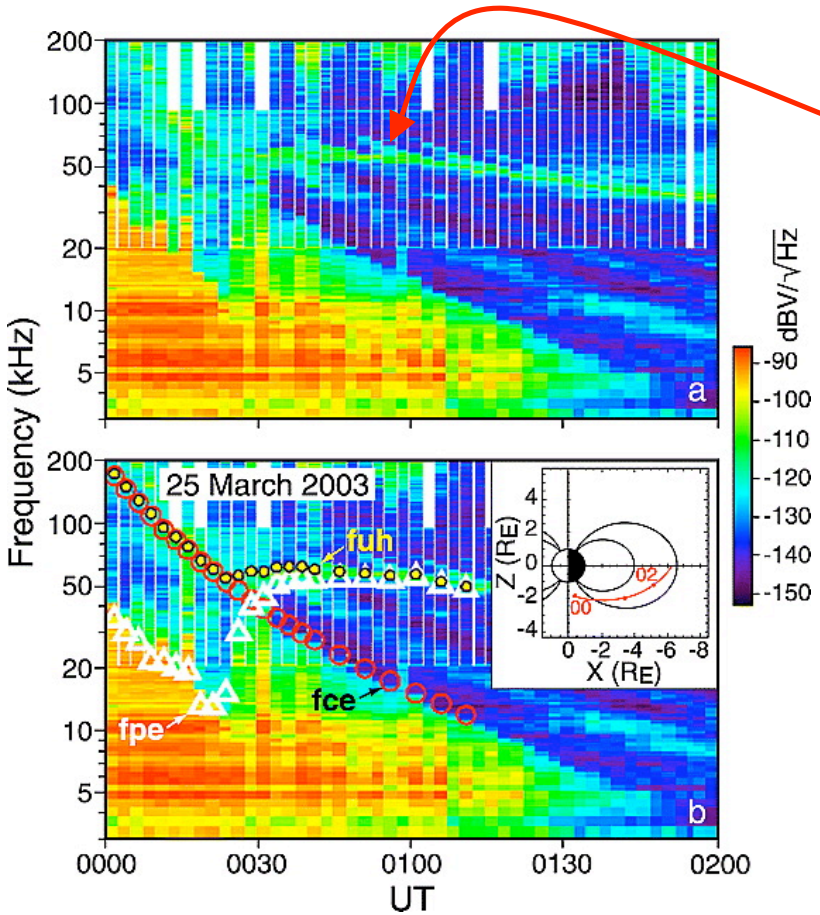
Theoretical eigenmode solutions.



Inferred mass density and error estimate based on toroidal Alfvèn wave solutions

[Denton et al., 2004] (see SM 21A-0458)

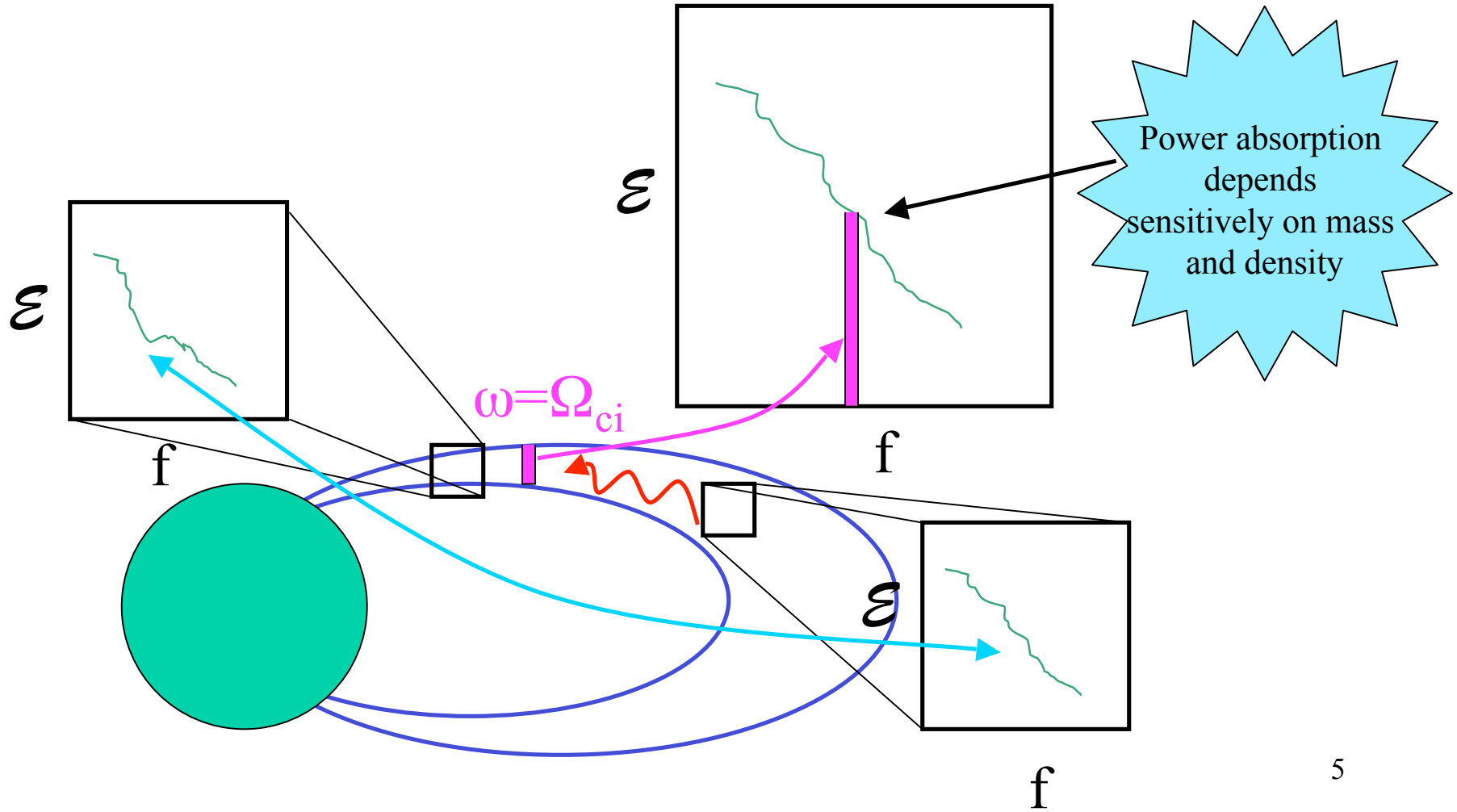
Plasma Waves and Electron Density



- The Passive Radio Plasma Instrument on IMAGE can be used to identify the electron density from intense narrowband emission known as the upper hybrid band which is bounded by $f_{pe} \sim n_e e^2/m_e$ and $f_{uh}=(f_{pe}^2 + f_{ce}^2)^{1/2}$

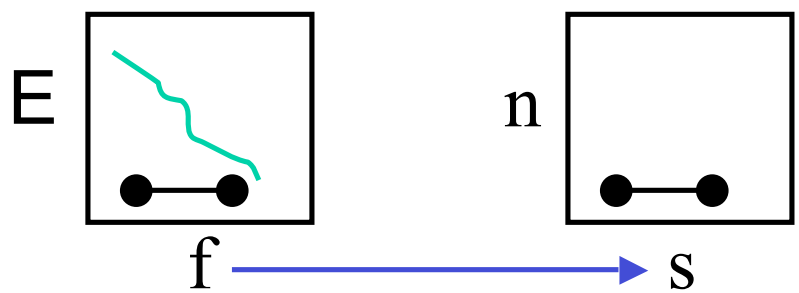
[Benson et al, 2004]

Ion Cyclotron Waves and Mass Density



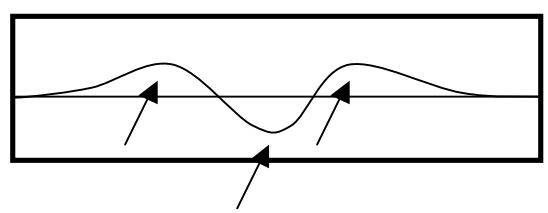
Advantages of ICW

- Provides continuous information along a field line



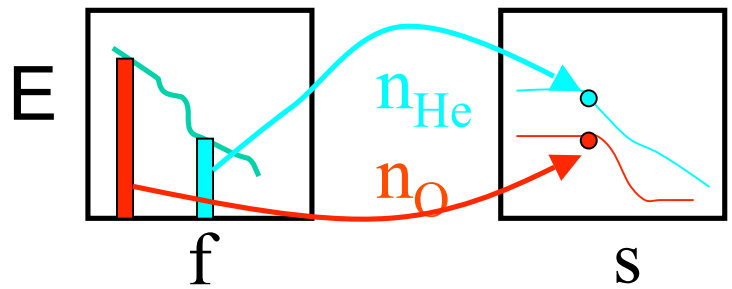
Frequency maps along field line distance, s

- Alfven wave measure provides density information only where amplitudes are large



Advantages of ICW

- Provides information about concentration of individual ions



- Alfven wave methods can be used to infer the total mass density. When compared with accurate electron density, the constituent mass concentrations can be potentially bounded.

Disadvantages of ICW

- Relies on conjugate observations if a natural generator is used
- Not observed as regularly as low frequency global eigenmodes
- Perpendicular wave vector may not be well constrained
- May propagate off field lines after mode conversion and not be field aligned

Ion Cyclotron Waves as a Diagnoistic Tool

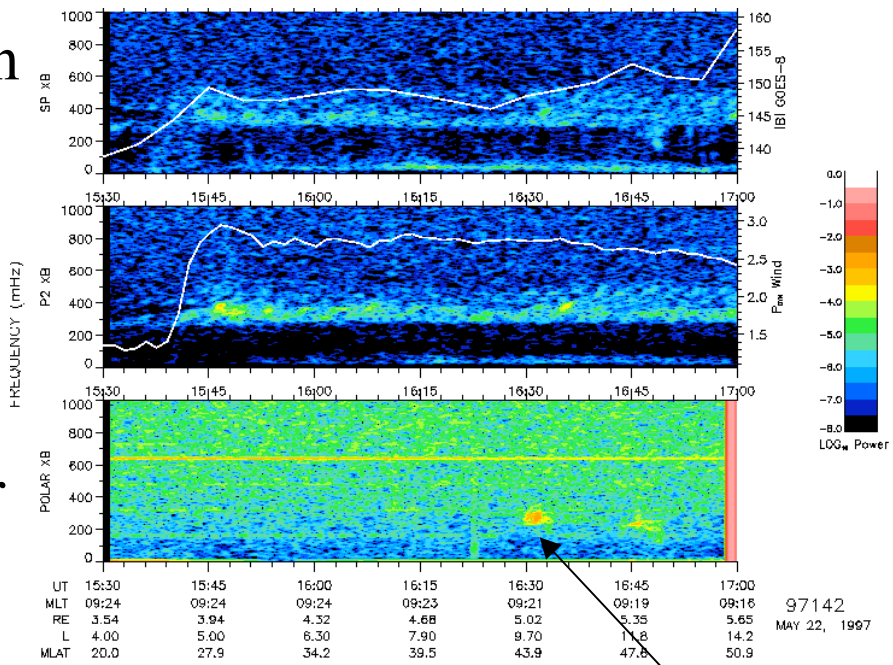
- Wave-ground conjunctions can be used to compare difference in wave amplitudes and attenuation of frequencies
- Waves can also be a source for ion outflows and can be used to probe the outflow density
- Waves can be generated by satellites and used to probe density by reflection
- Examples---
  - Polar, AMPTE and South pole conjunctions
  - FAST observations of auroral waves
  - Ion outflow measurements

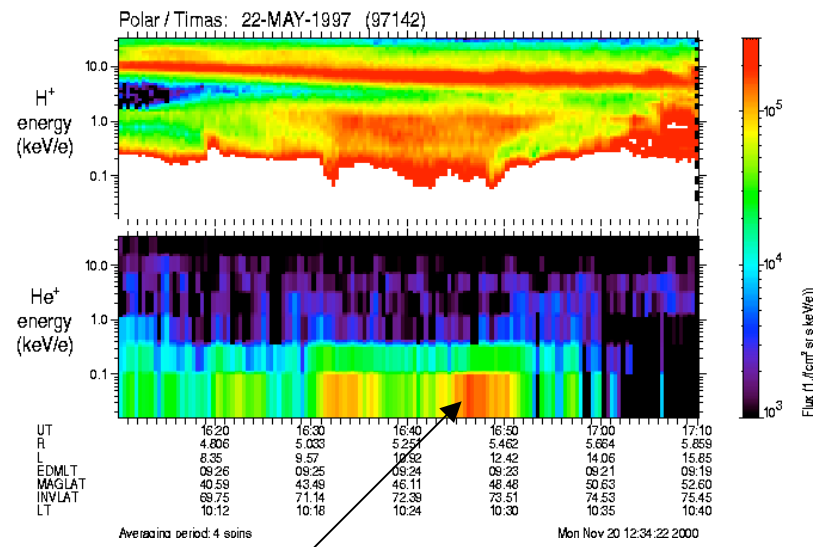
Polar/Ground Conjunctions

South Pole

P2

Polar

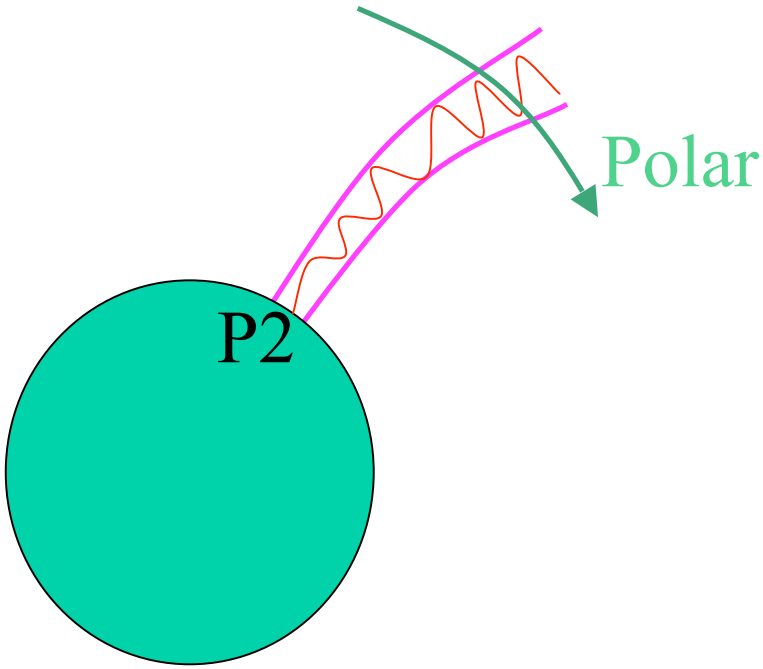




Heated Helium and EMIC Waves

Courtesy Mark Engebretson

Ground Satellite Conjunctions



- Continuous pulsations seen at the ground (P2)
- Satellite briefly detects localized wave conjugate to the magnetometer location with the same frequency
- Steady spatially localized pulsations are observed

Similar for Low Frequency Waves in Central Plasma Sheet

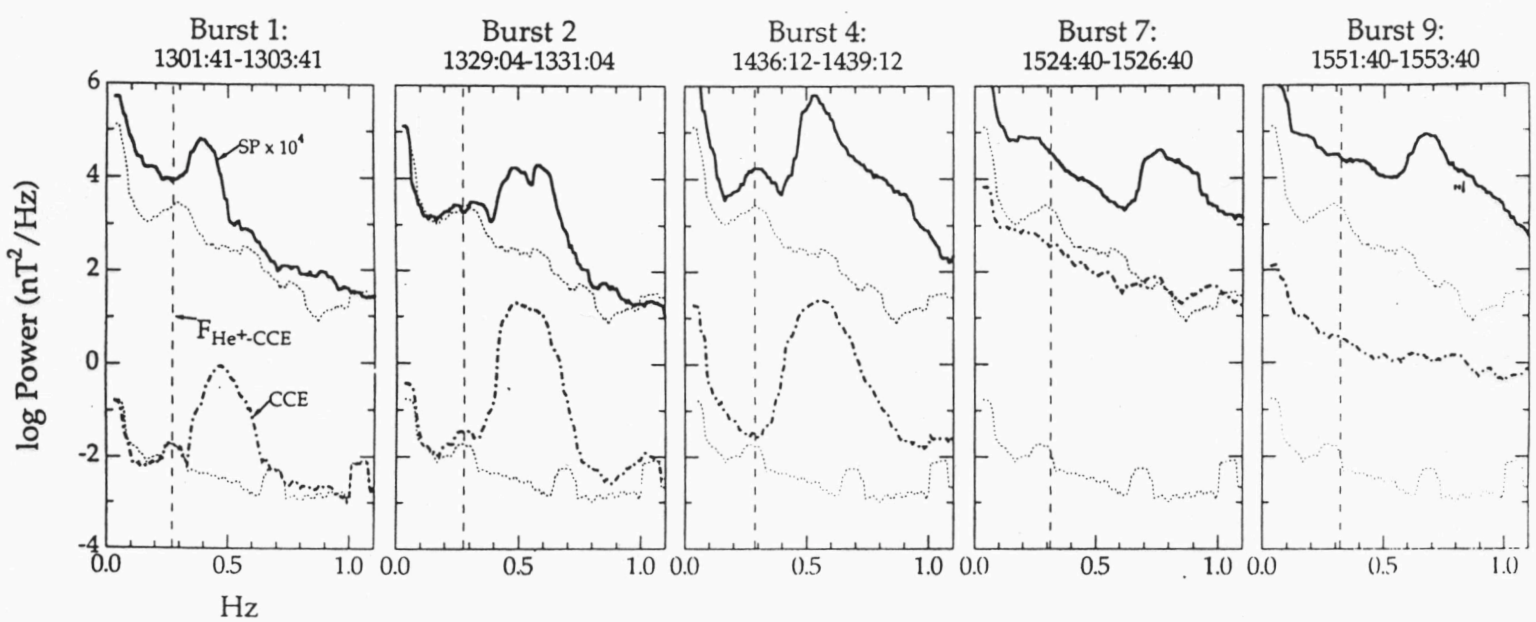


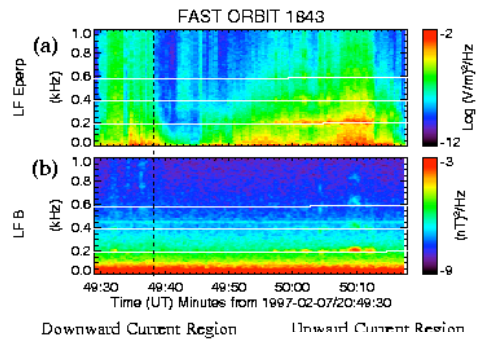
Figure 4. Power spectra of South Pole and CCE magnetic field fluctuations during five Pc 1 bursts. Thick traces are spectra observed during times indicated. Thin dotted traces show spectra from 1355 to 1357 UT. Vertical dashed lines indicate the average F_{He^+} at CCE.

Pc1 Waves Observed at AMPTE and South Pole

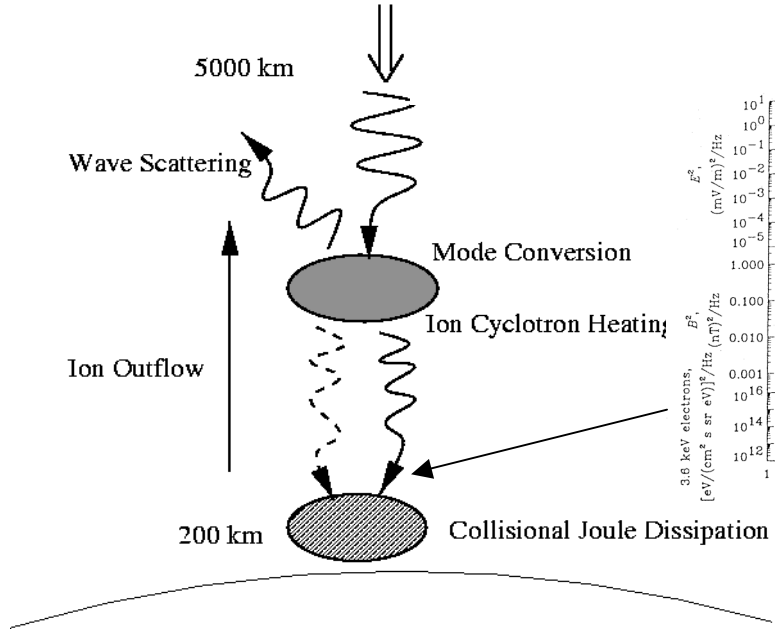
[Anderson et al., 1996]

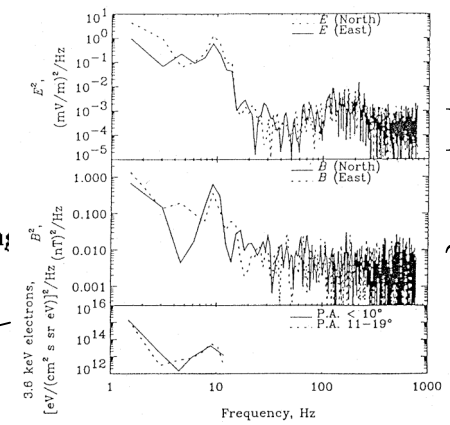
Waves Reach Rocket Altitudes

Poynting Flux
~3×10^{-5} W/m^2



Fast Satellite
[Ergun, 1998]

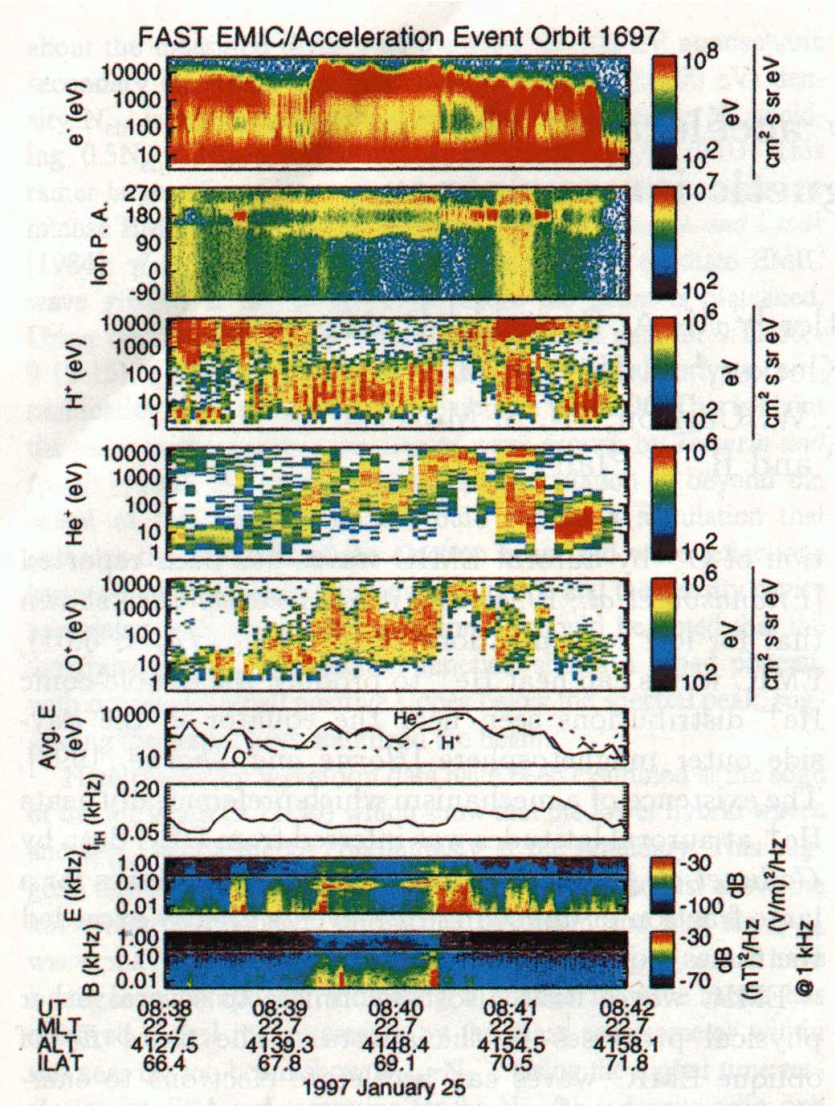




Poynting Flux
~10^{-5} W/m^2

Rocket Observation
[Lund, 1997]

FAST Observation



- Lund et al., 1998
- Fast satellite pass through Auroral zone at 4000km
- Heated Ion Conics
- Preferential Heating of He^+
- Electromagnetic Waves f~80-100Hz

Possible Sources of ICWs

- Field Aligned Currents/ Electron Beams
  - Kindel and Kennel, 1971, Bergmann, 1984, Temerin and Lysak, 1984
- Upflowing Ion Beams
  - Bergmann, 1984, Catell et al., 1998,
- Velocity Shear
  - Ganguli, 1996, Amatucci et al., 1998, Ganguli, PRL, 2000
- Temperature Anisotropy/Loss Cones
  - Oscarsson and Andre, 1986

Ray Tracing Approach is Inadequate

- Ray Tracing Theory Cannot Explain Observations
- Waves reflect at the ion-ion hybrid resonance

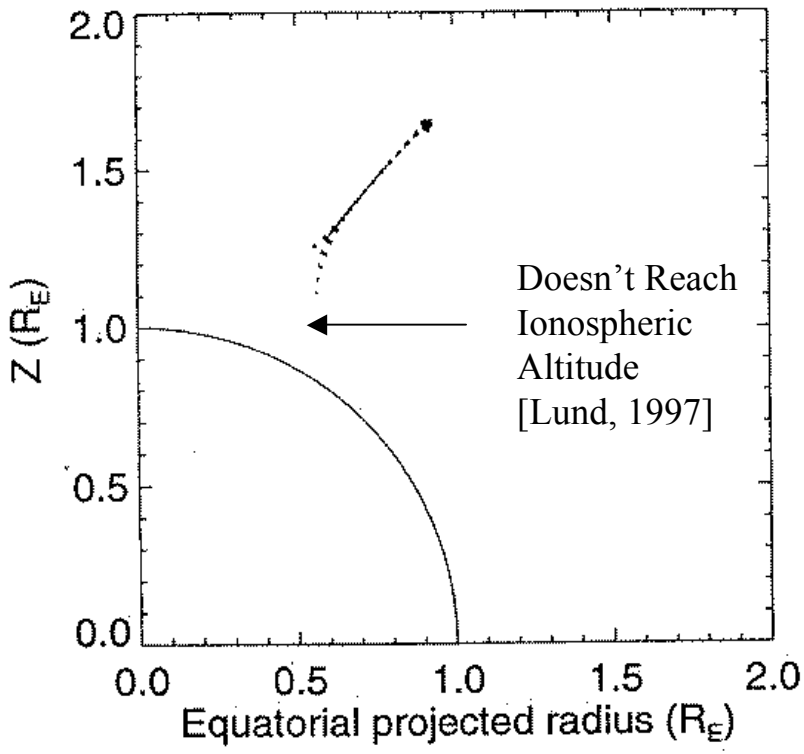


Figure 8. Ray paths of 128-Hz H^+ EMIC waves originating on the $L = 8$ field line at 4460 km ($\sim 0.01 R_E$ below the resonant altitude).

Wave Equation

Equations for collisional fluid plasma with 1-D solution for propagation along B.

$$\nabla^2 \mathbf{E} - \nabla(\nabla \cdot \mathbf{E}) + \frac{\omega^2}{c^2} \mathbf{å}(s) \cdot E = 0$$

$$\mathbf{å}(s) = S(\mathbf{I} - \mathbf{bb}) - iD(\mathbf{e}_1 \mathbf{b} \times \mathbf{e}_2 - \mathbf{b} \times \mathbf{e}_1 \mathbf{e}_1) + P\mathbf{bb}$$

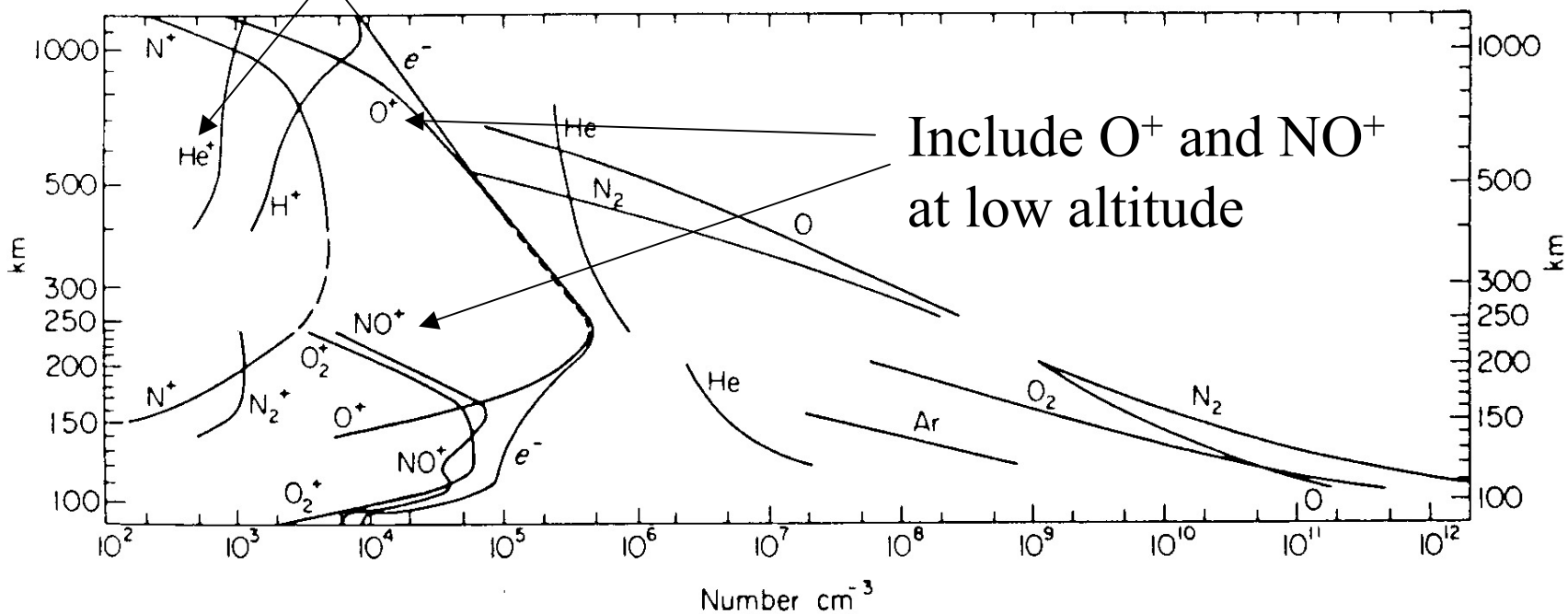
$$S = 1 - \sum_j \frac{\omega_{pj}^2 (\omega + i\nu_j)}{\omega[(\omega + i\nu_j)^2 - \Omega_j^2]}$$

$$D = 1 - \sum_j \frac{\omega_{pj}^2 \Omega_j}{\omega[(\omega + i\nu_j)^2 - \Omega_j^2]}$$

$$P = 1 - \sum_j \frac{\omega_{pj}^2}{\omega(\omega + i\nu_j)}$$

Model Ionosphere

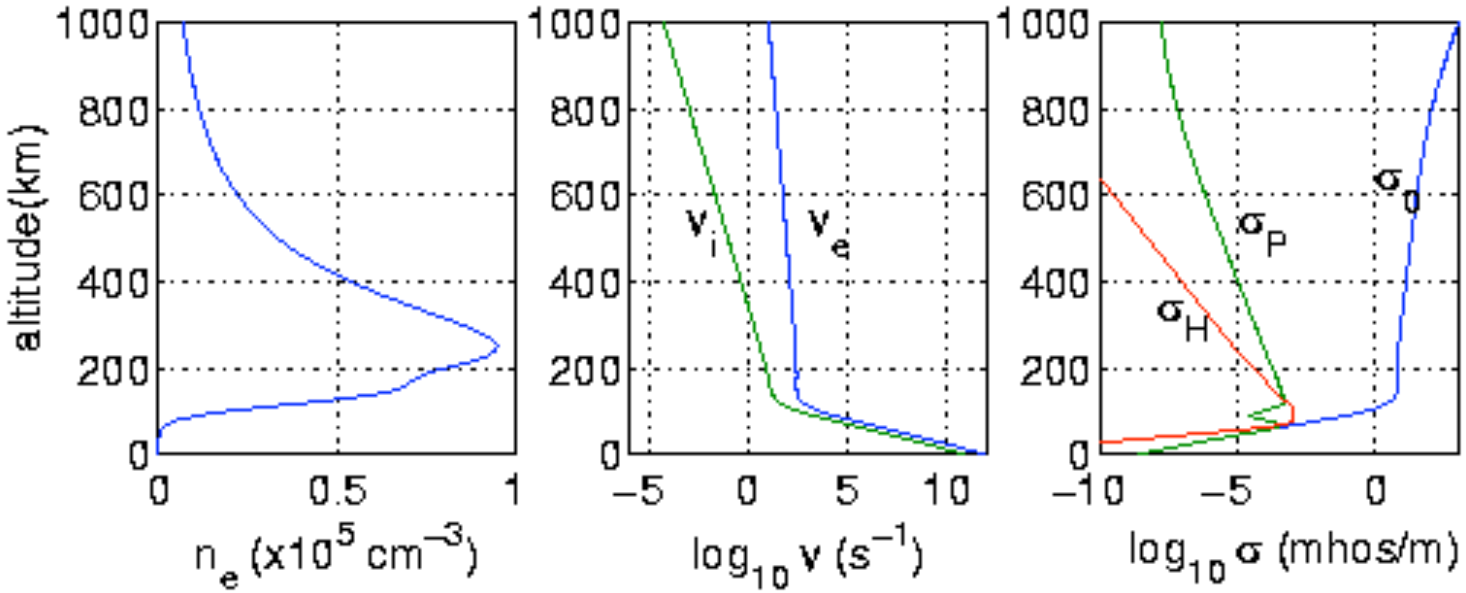
Exponential Falloff to $n=10cm^{-3}$
Fraction of H^+, He^+ and O^+ varies



[Banks and Kockarts, 1973]

Ionospheric Collisions

- Electron and Ion Collisions [Banks and Kockarts, 1973]
- Include NO^+ and O^+ [Kelley, 1989]
- Electron/Ion Density includes E and F region peaks



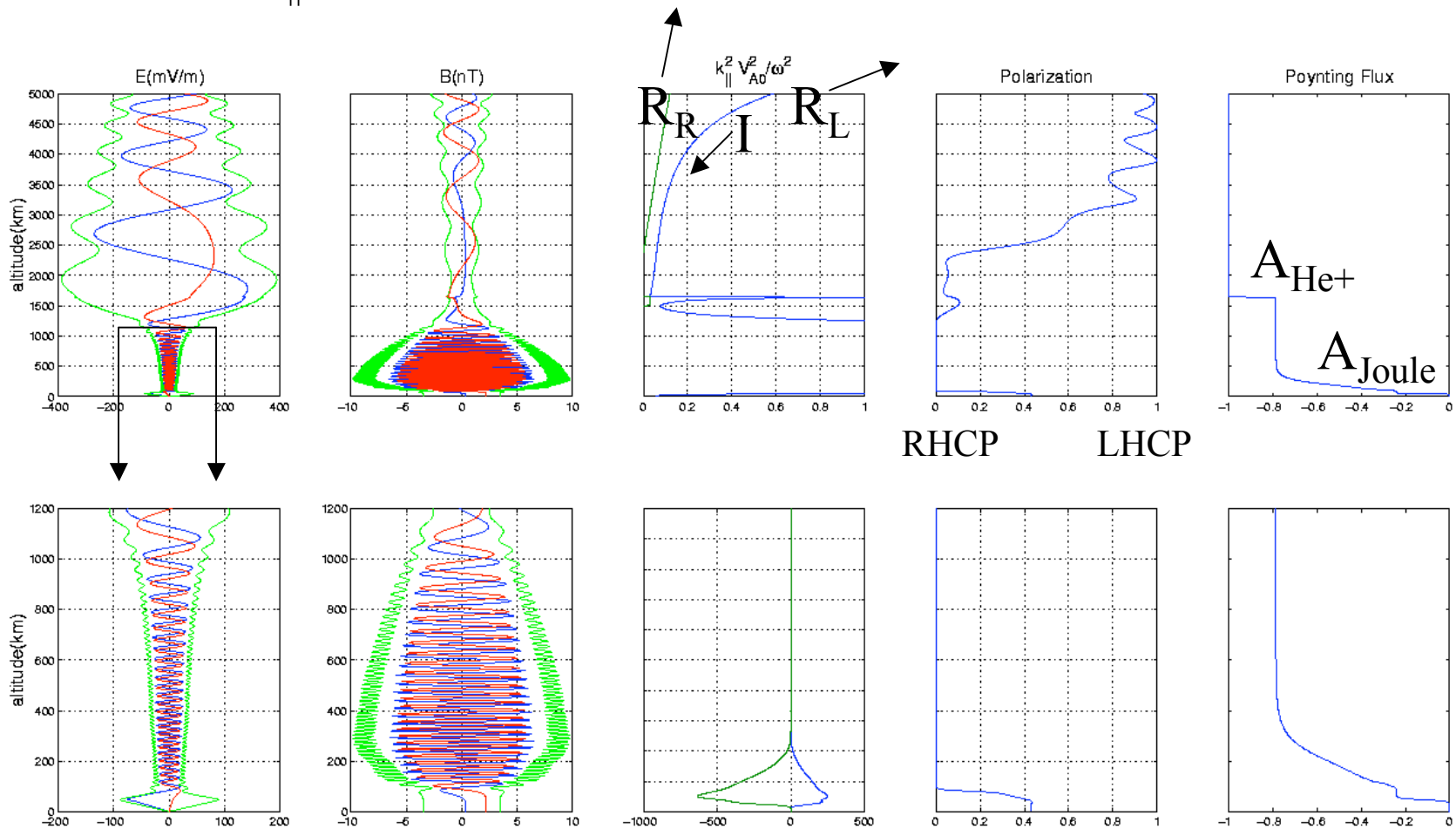
Observations + Model = Predictability

- Observations
  - Need conjugate measurements
  - Useful to have a continuous wave train
  - Useful to compare Poynting fluxes
- Model
  - Needs to have an ionosphere (because waves are observed at the ground)
    - Collisions
    - Include heavy ion species of ionospheric origin
  - Needs to solve full wave equations (ray tracing inadequate)
  - Needs to include absorption at the ion cyclotron resonance

Wave Solutions (f=128Hz, θ=15)

$\theta = \tan^{-1}(k_{||}/k_{\perp})$

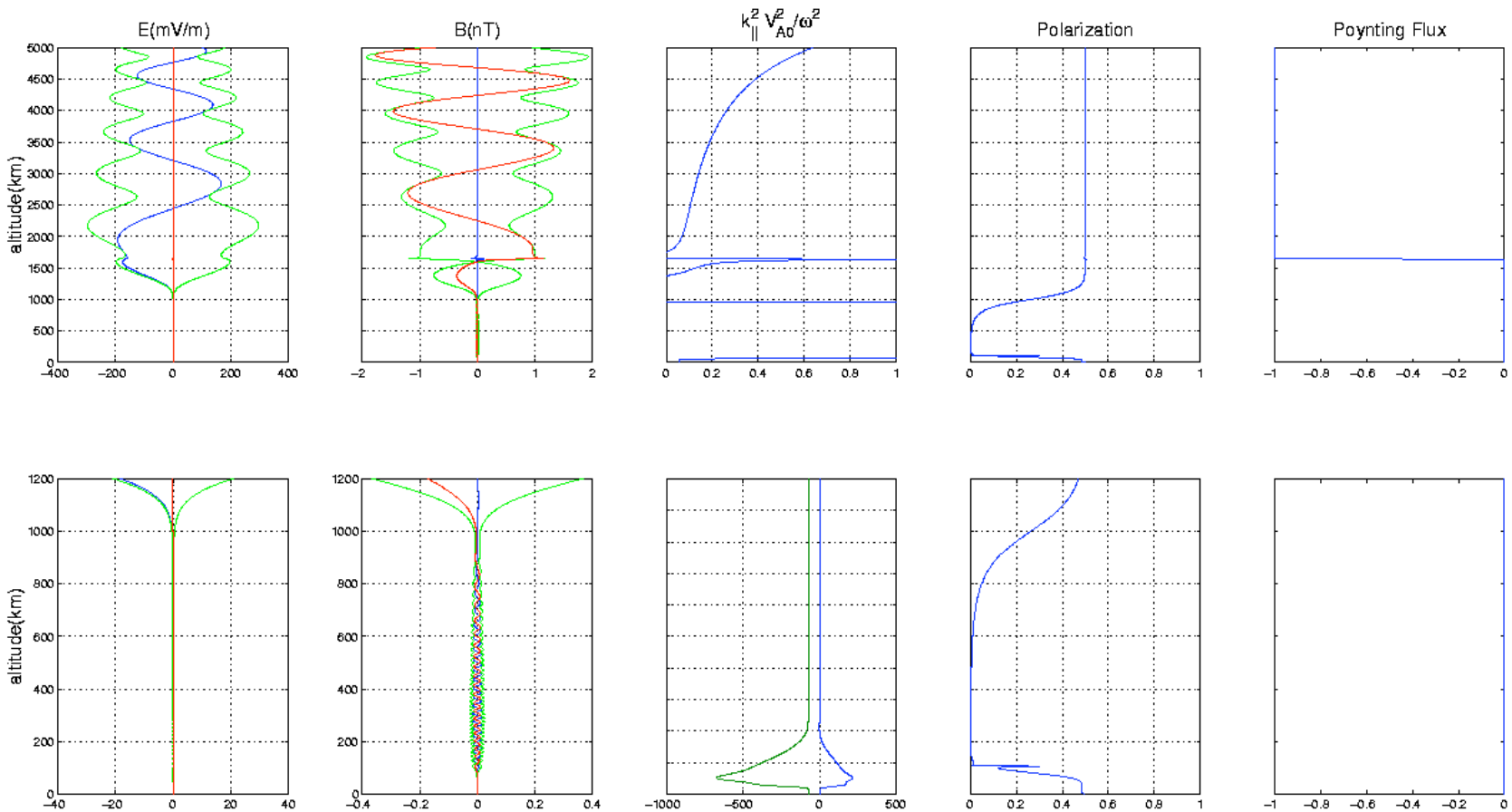
$\eta_{He+} = \eta_{O+} = 5\%$



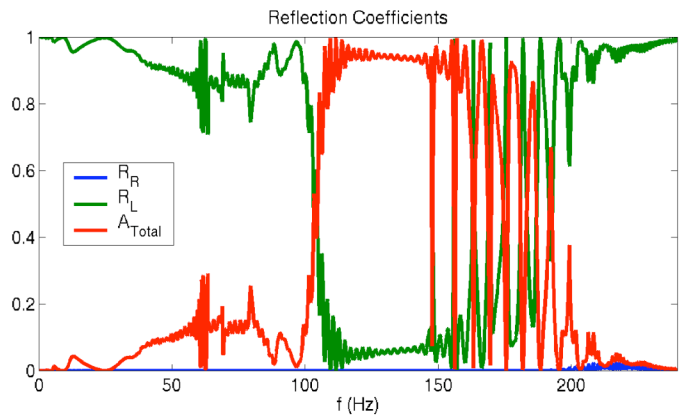
Expanded View in the Ionosphere

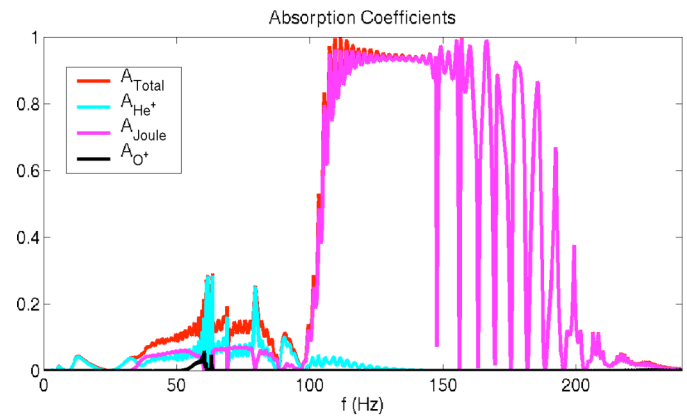
Wave Solutions (f=128Hz, θ=85)

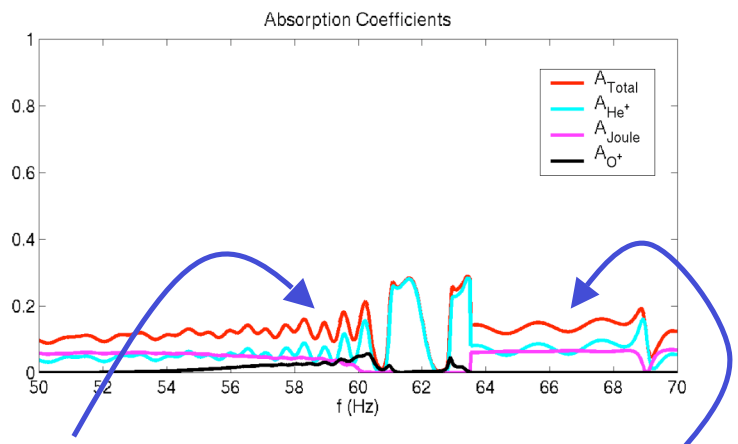
$\eta_{He+}=\eta_{O+}=5\%$

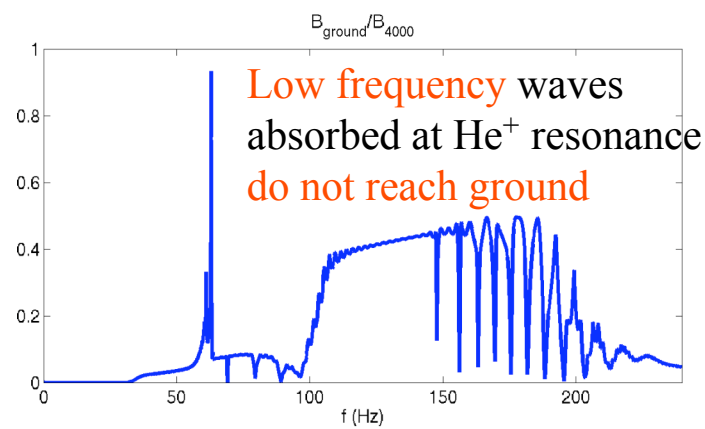


Frequency Dependence of Coefficients (θ=60)









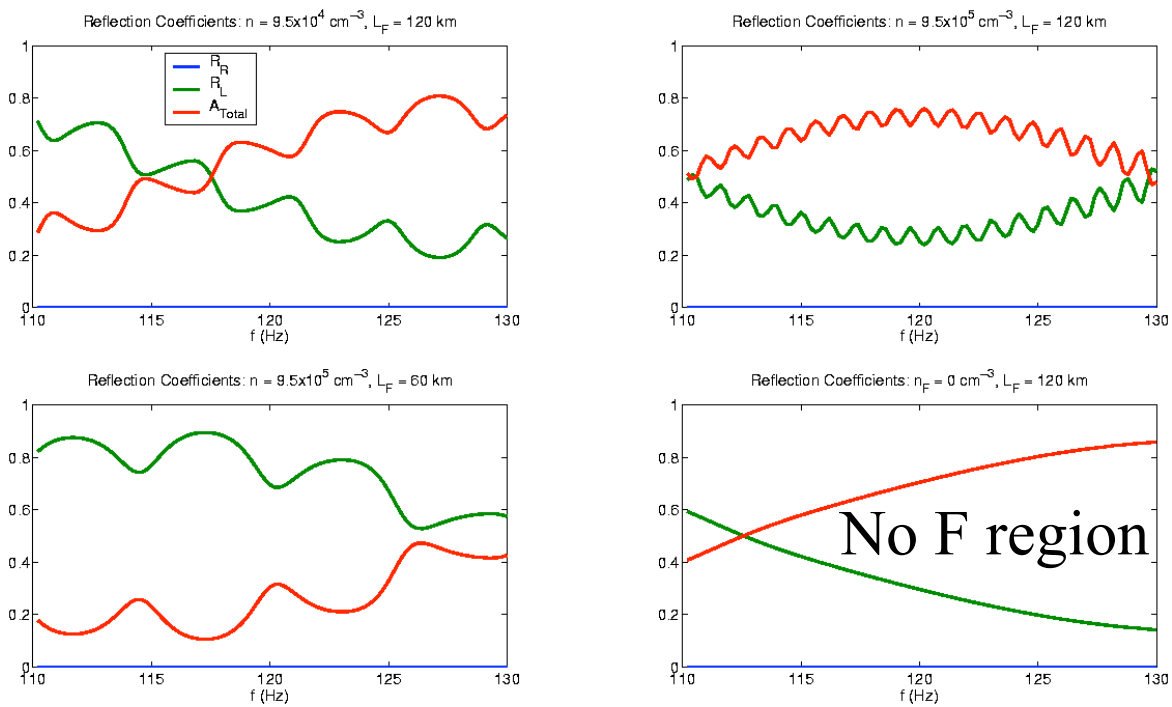
Frequency Modulation

F-region Produces Modulations

- Compressional Wave in F-region $k_{\parallel} = 2\pi m/L_F \approx \sqrt{(2\pi f_m/V_A)^2 - k_{\perp}^2}$
- $\Delta f = f_{m+1} - f_m \approx V_A/L_F$

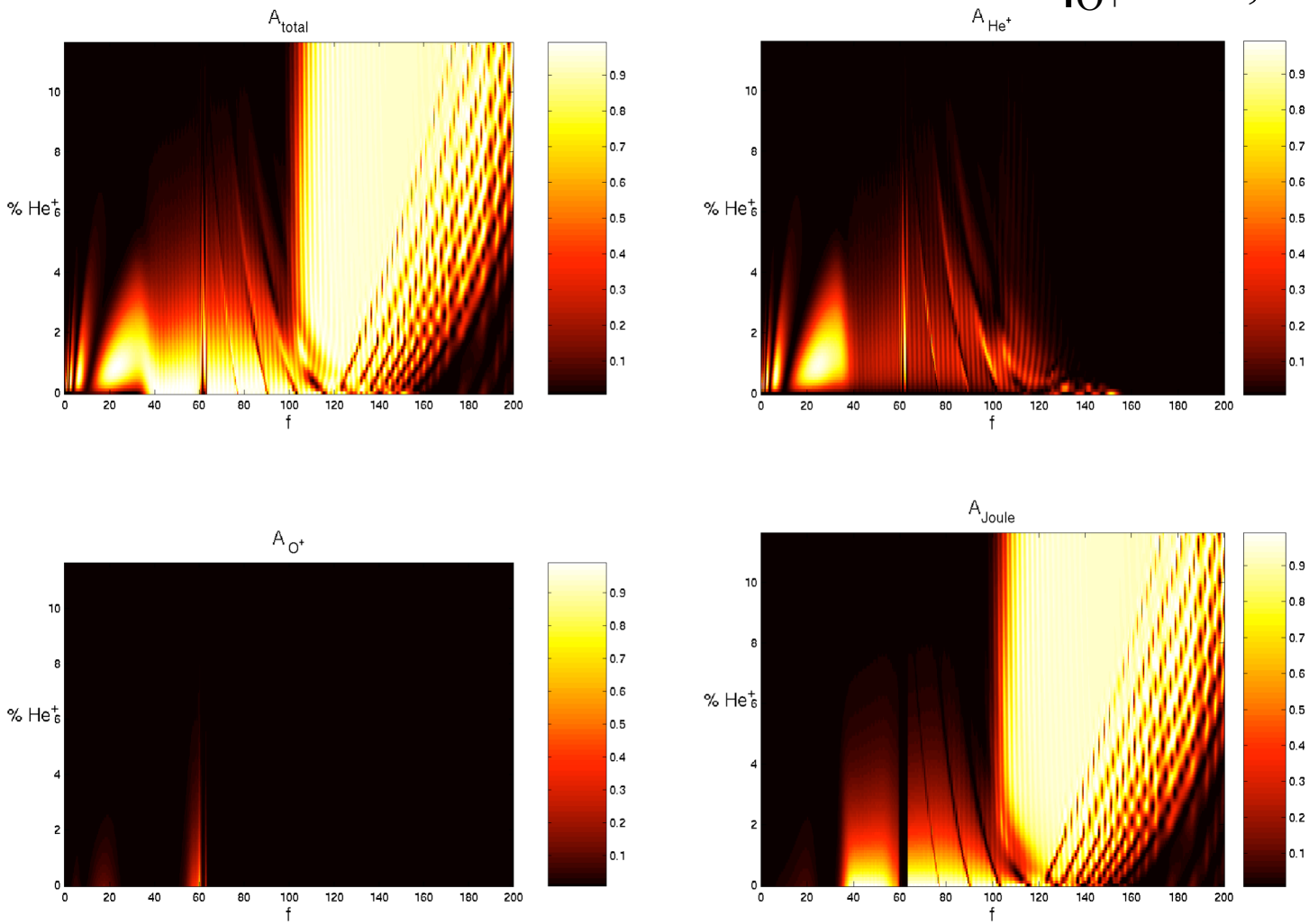
$n_F \uparrow 10 \Rightarrow \Delta f \downarrow 3$

$L_F \downarrow 2 \Rightarrow \Delta f \uparrow 2$



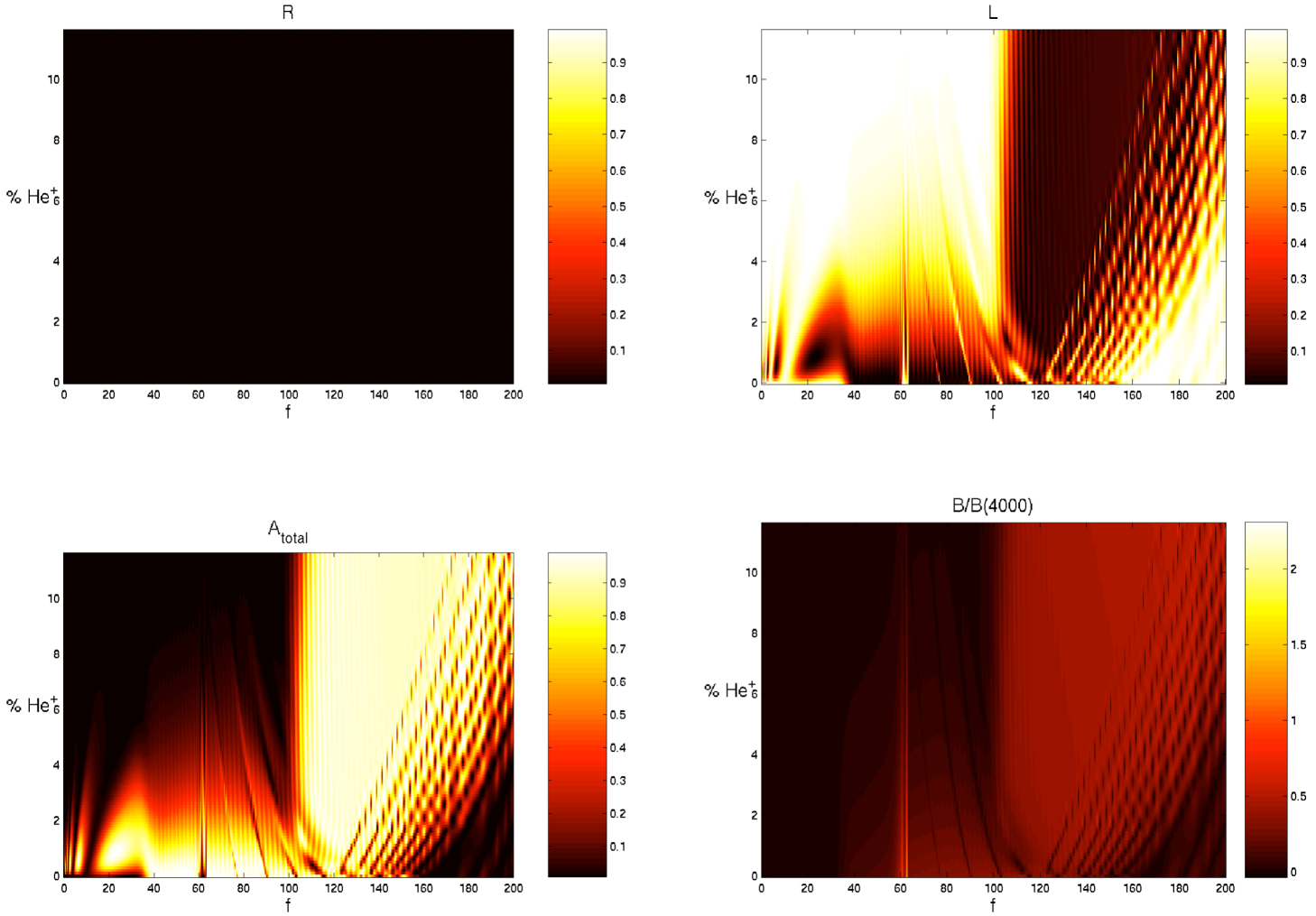
Absorption He^+ Concentration

η_{O+} =5%; θ=60



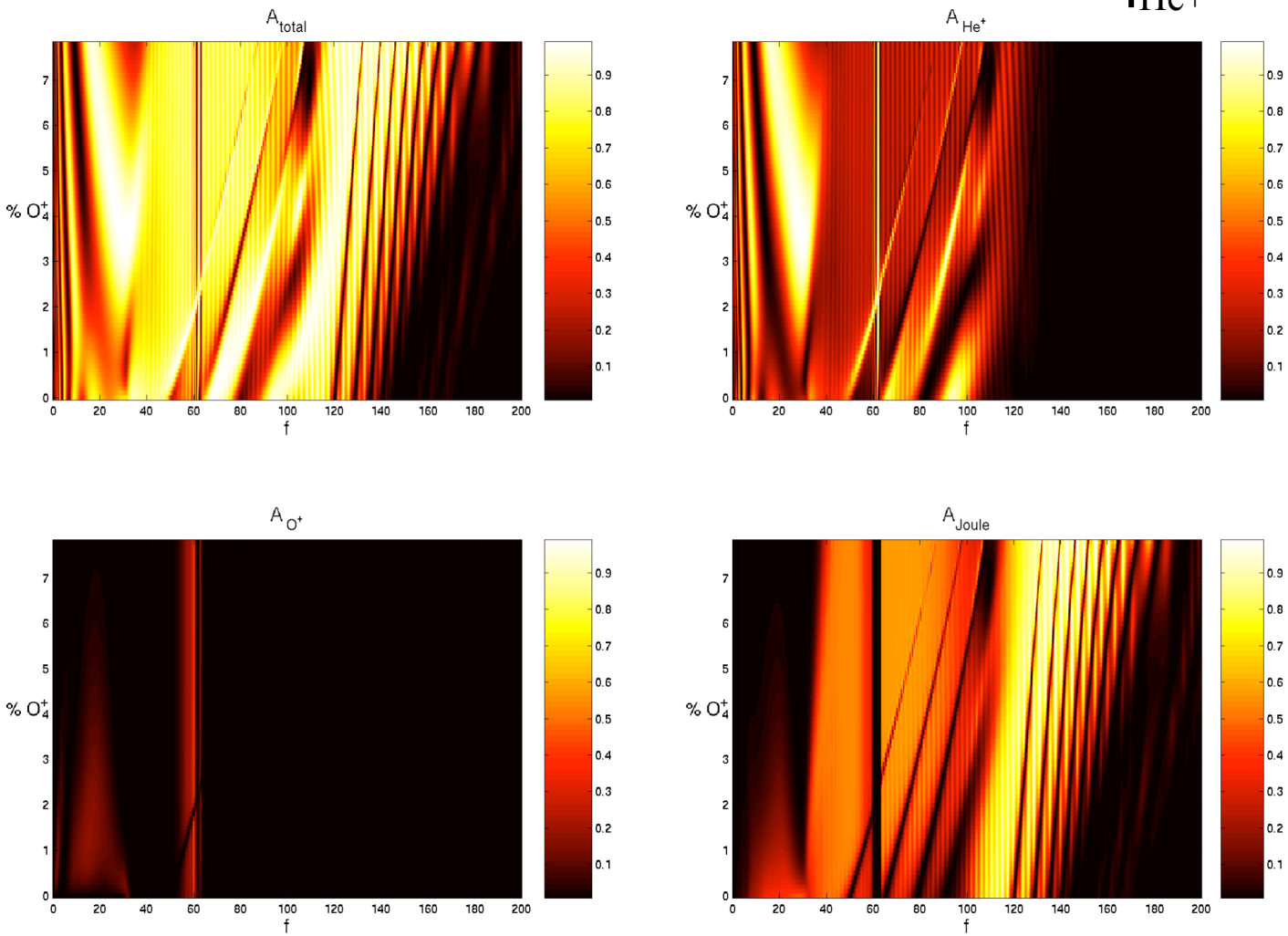
Coefficients and He^+ Concentration

η_{O+} =5%; θ=60



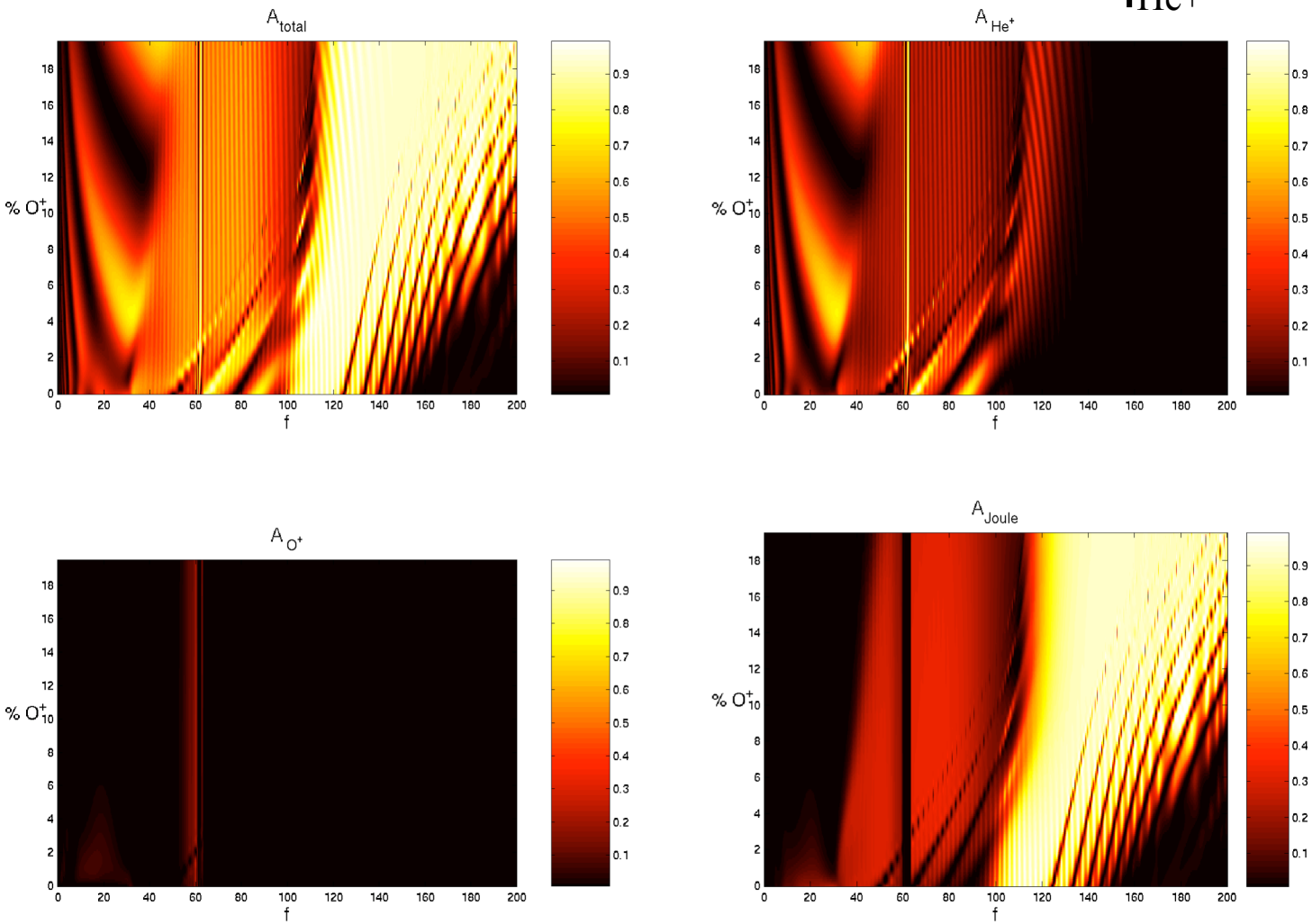
Absorption and O^+ Concentration

η_{He+} =1%; θ=60



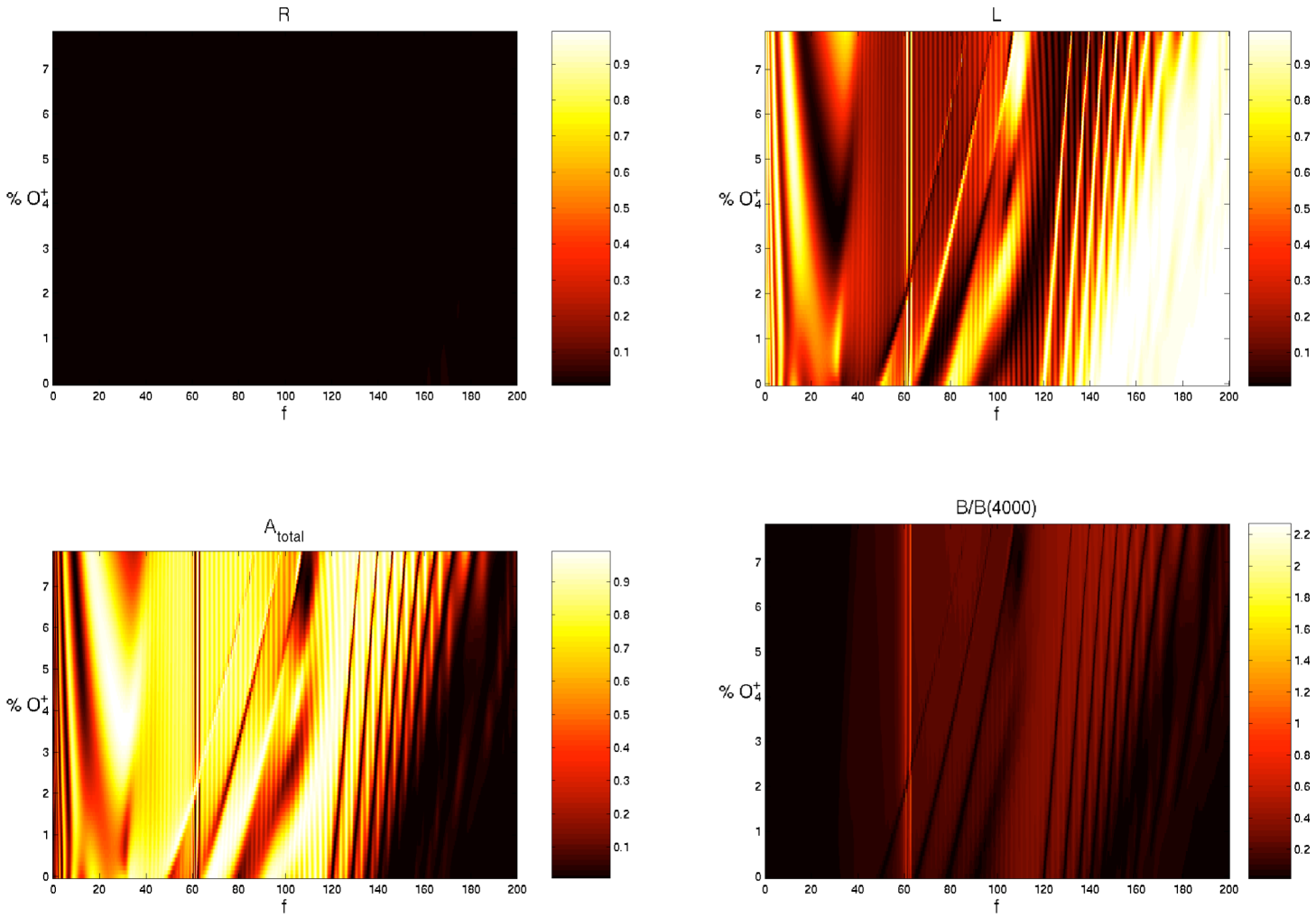
Absorption and O^+ Concentration

η_{He+} =2%; θ=60



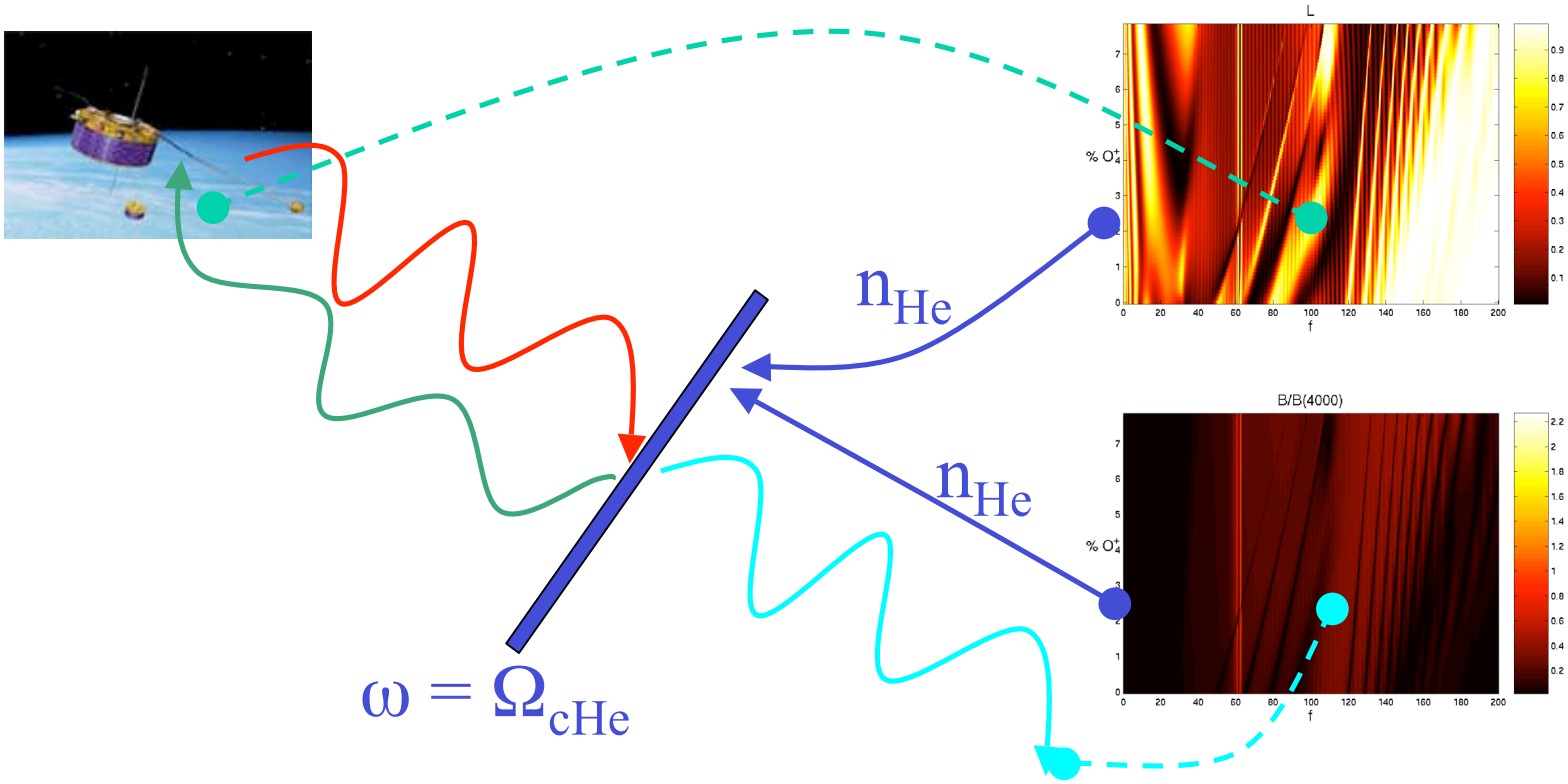
Coefficients and O^+ Concentration

η_{He+} =1%; θ=60



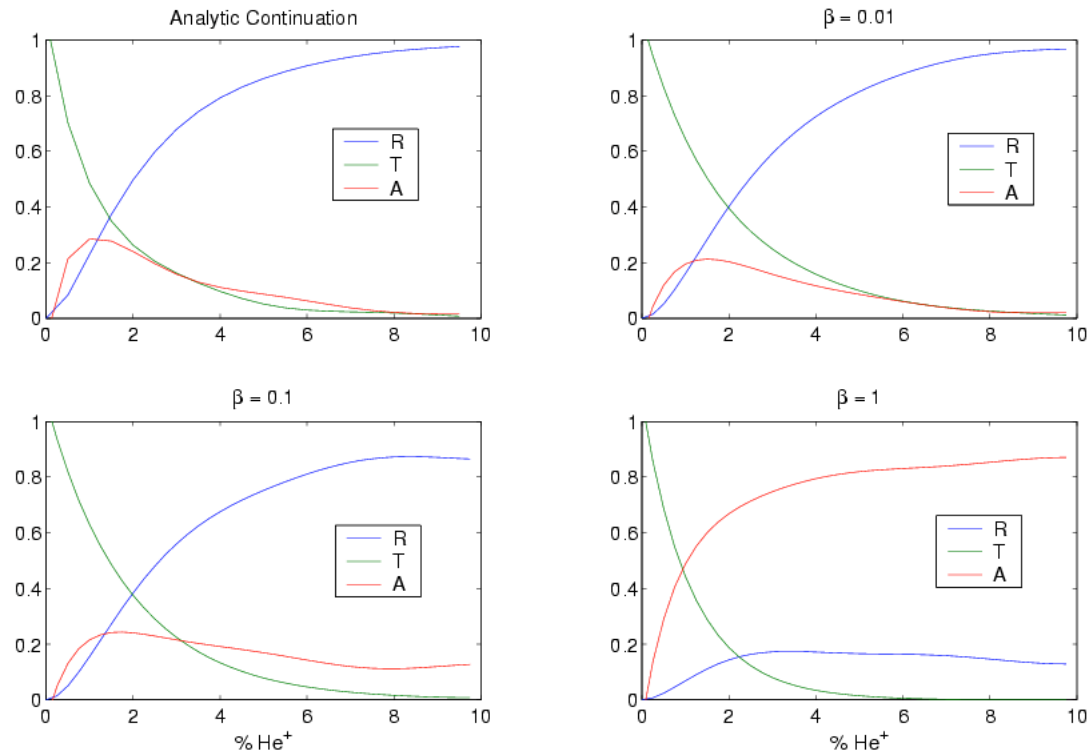
Experiment

- Tomography



Hot Plasma Effects Near Resonance

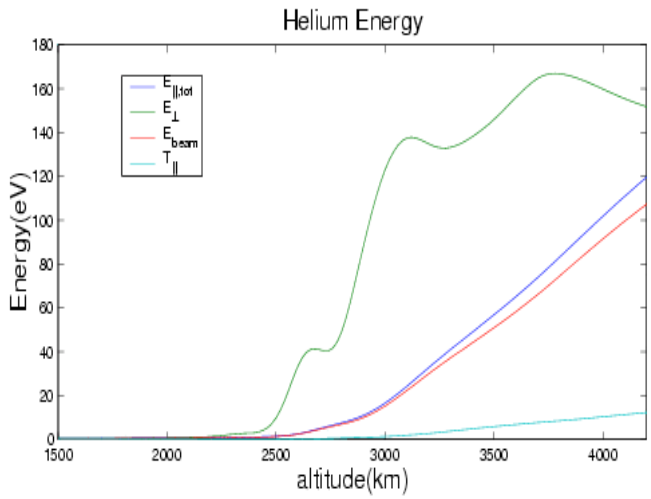
- Two minor ion species plasma
- Solve integral equation for ion response near resonance
- Evaluate mode conversion for incident ICW from low field side
- Note that cold plasma result is very similar to warm plasma result for $\beta < 0.1$---in ionosphere, $\beta < m_e/m_i$

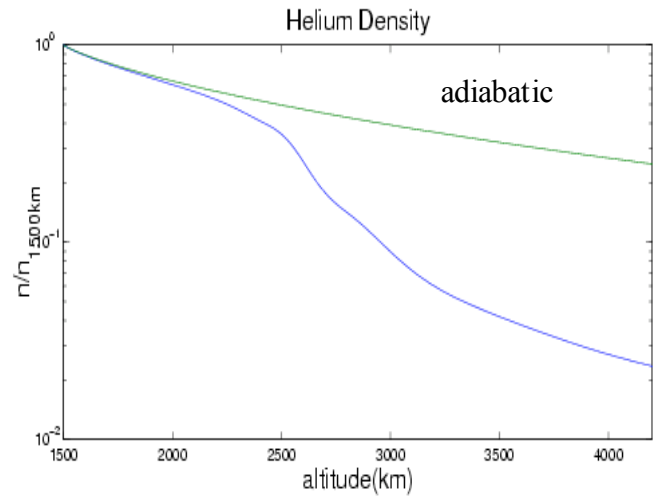


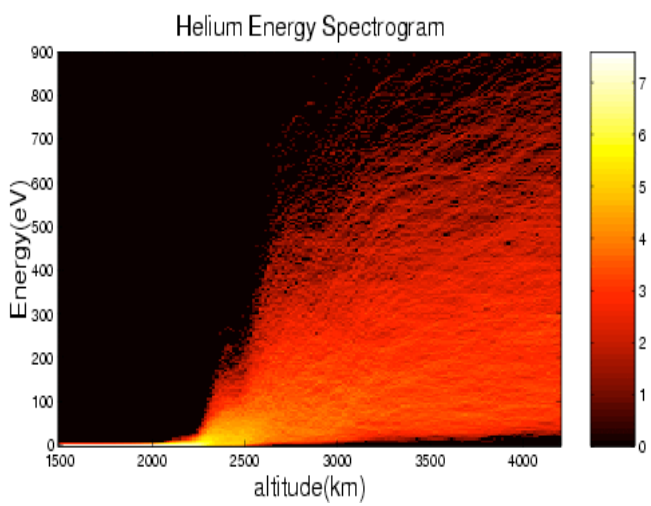
Feedback Between Waves and Outflows

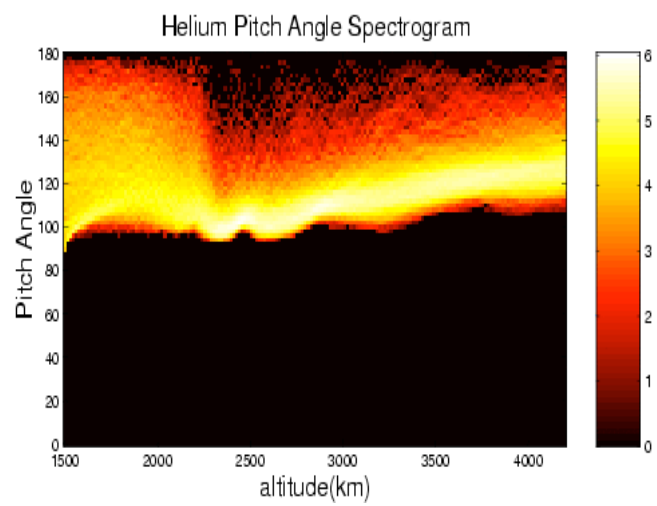
- Background ion profiles determine wave absorption (and generation)
  - Minor ion concentrations and density
  - Local Alfven velocity (which determines wavelength)
  - Spectrum of incident waves (not considered here)
- Wave absorption determines ion heating
  - Heating computed from electromagnetic fields near the resonance which heats ions
- Ion heating determines background ion profiles
  - Heating rate (eV/s) heats heavy ions which modifies the ion density as a function of altitude

Steady State Helium Profiles
$\theta=60, \eta_{He}=5\%, \eta_O=1\%$



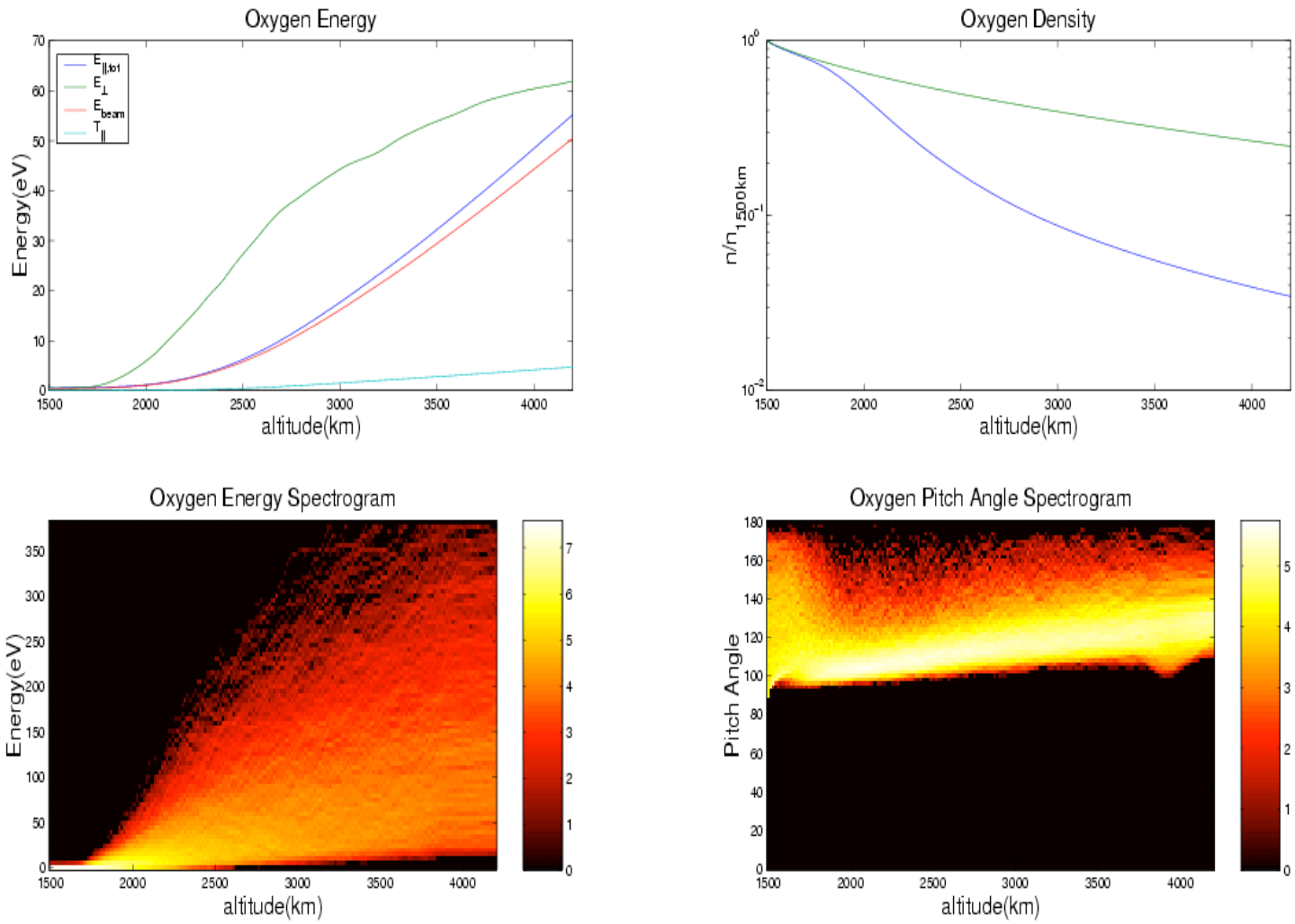




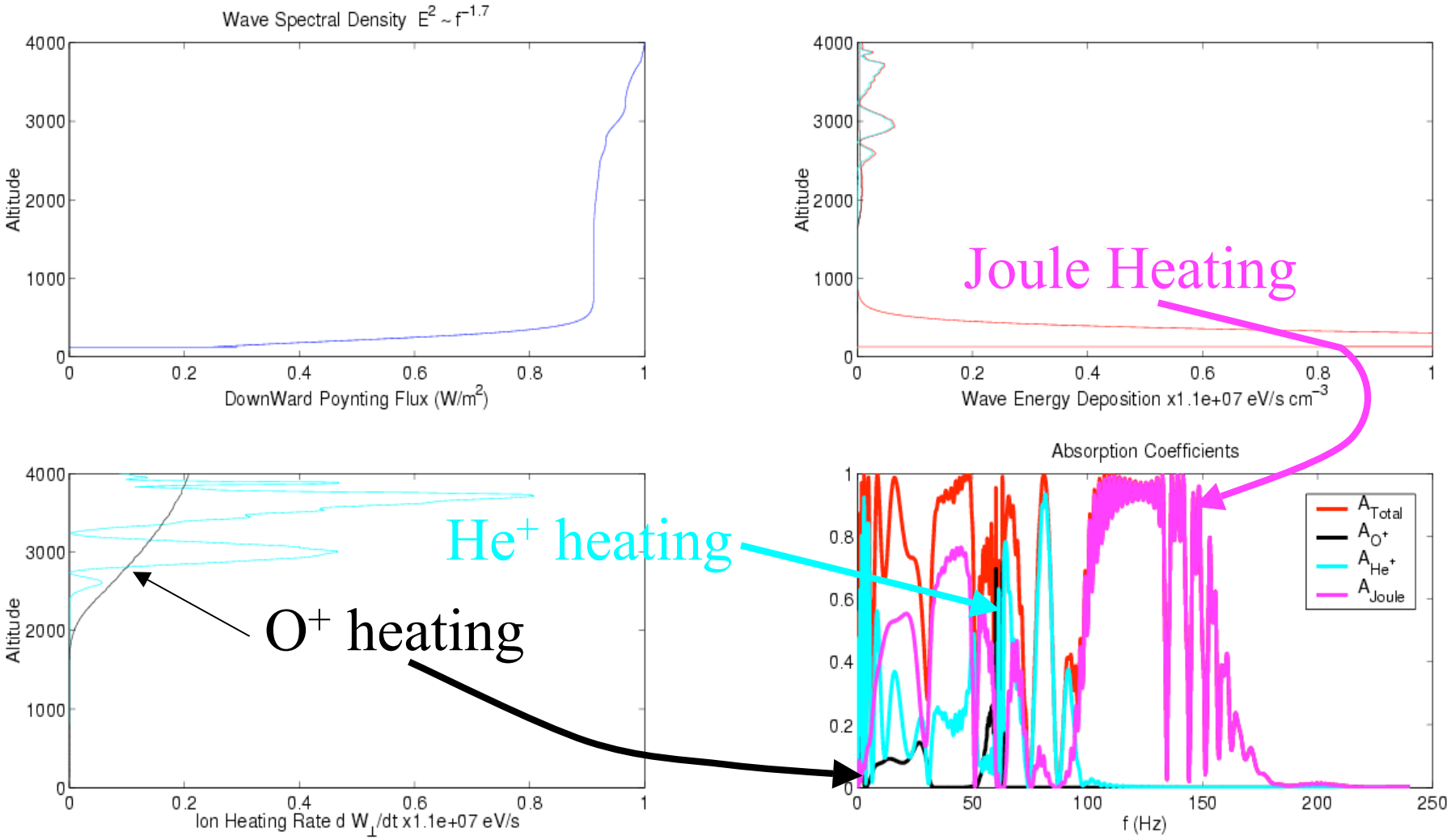


Steady State Oxygen Profiles

$\theta=60, \eta_{He}=5\%, \eta_O=1\%$



Steady State Heating Rate
$\theta=60, \eta_{He}=5\%, \eta_O=1\%$



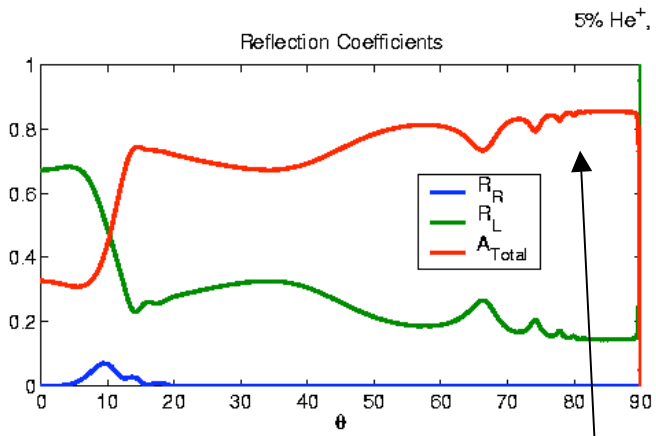
Conclusions

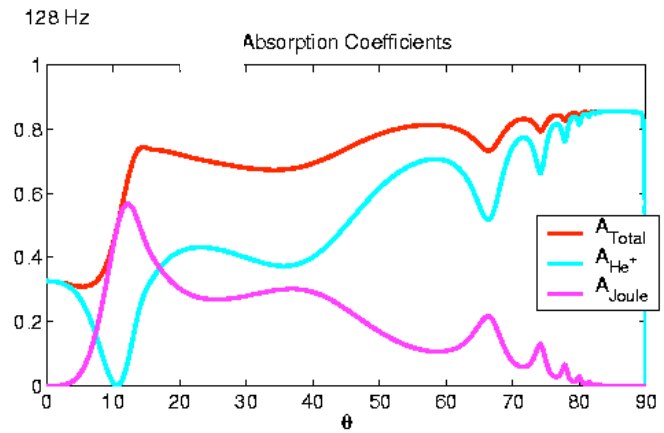
- Ion cyclotron waves are complimentary to other techniques for probing mass density
- They can potentially provide precise altitude information about heavy ion concentrations
- We propose using
  - Naturally generated waves that are frequently detected by satellites and ground based magnetomenters
  - Wave emissions from satellites which will reflect off heavy ion resonance layers
- We have presented wave solutions, Poynting flux, reflection, and absorption coefficients for ion cyclotron waves propagating along magnetic field lines
- It is possible to construct model ion concentrations along the field using the observed wave spectrum combined with the wave analysis iteratively
- We have incorporated feedback between waves and particles to give a steady state ion outflow which predicts energy and density based on observed wave spectra

Reprint Request

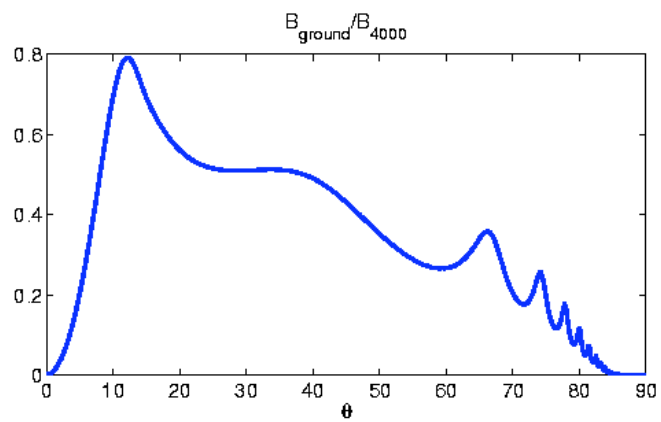
Name Address

Reflection/Absorption Coefficients



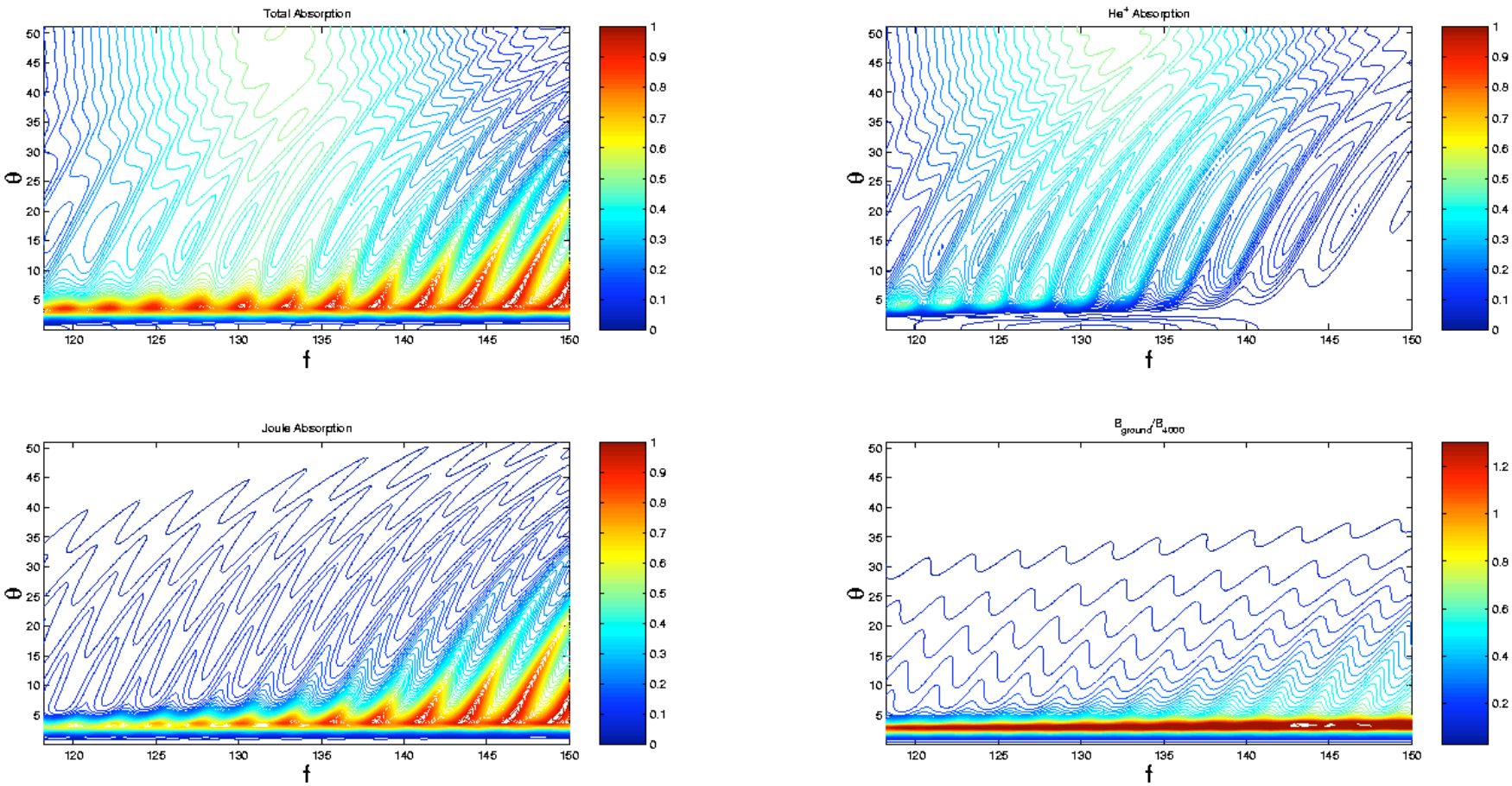


Most Wave Energy is Absorbed by He^+ or by Joule Dissipation in the Ionopshere



The Waves Reach the Ground as Observed!

Frequency-Wavevector Relation

Note: Compressional Wave Coupling in Ionosphere

$k_{||}$ fixed $\Rightarrow w^2 \sim const + k_{\perp}^2$