Toward a Self-Consistent Model for Ion Outflows Associated with Electromagnetic Ion Cyclotron Waves

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Why are Ion Outflows Important?

•The ionosphere is a fully adequate source of magnetospheric plasma [Chappel et al., 1987]

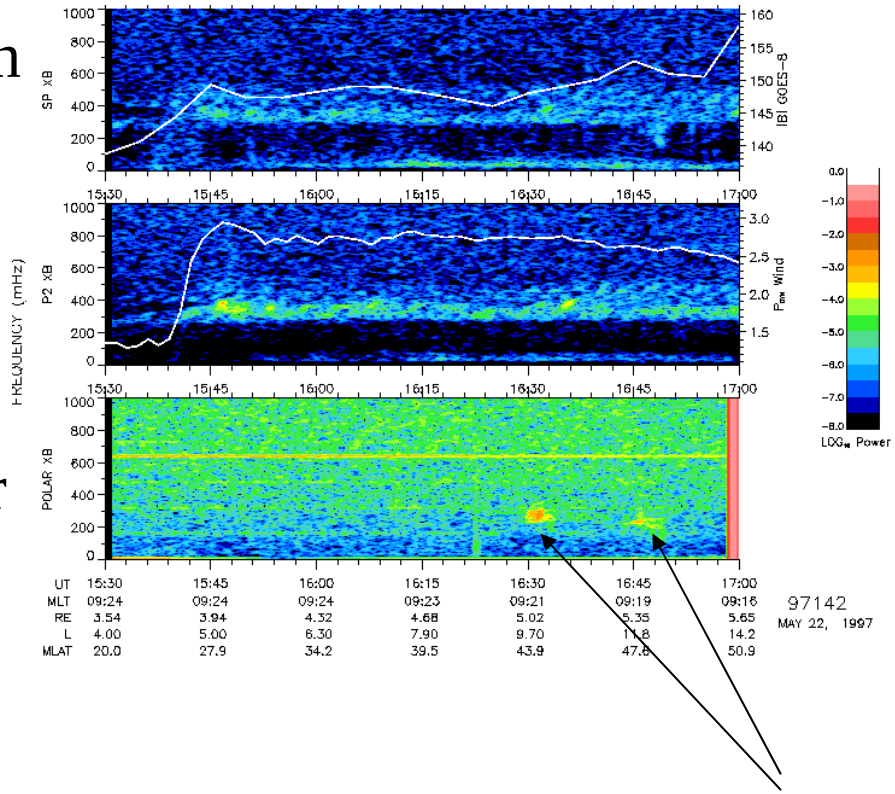
•During active magnetospheric conditions heavy ions of ionospheric origin can dominate the energetic ion density

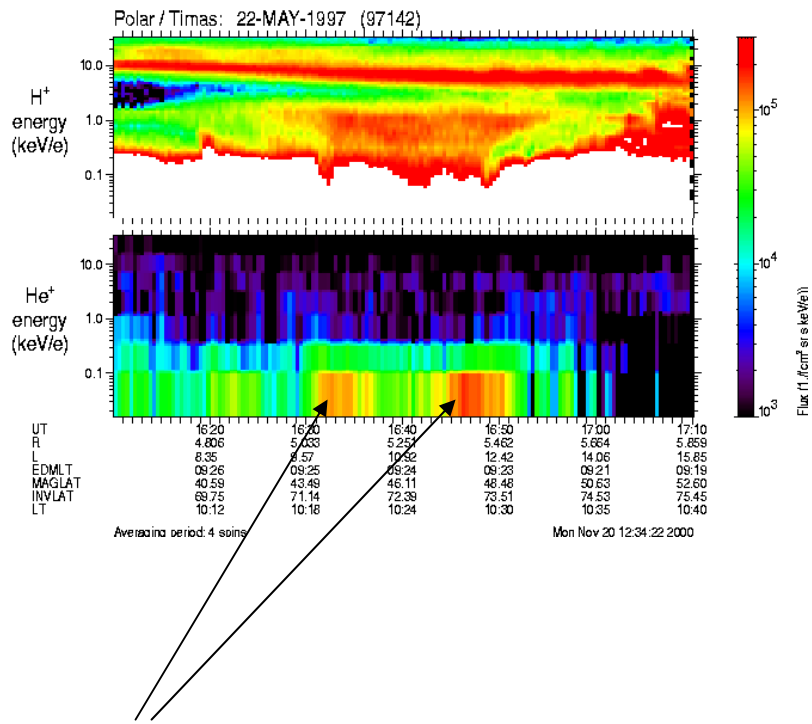
Relationship between Waves and Outflows (POLAR/Ground)

South Pole

P2

Polar



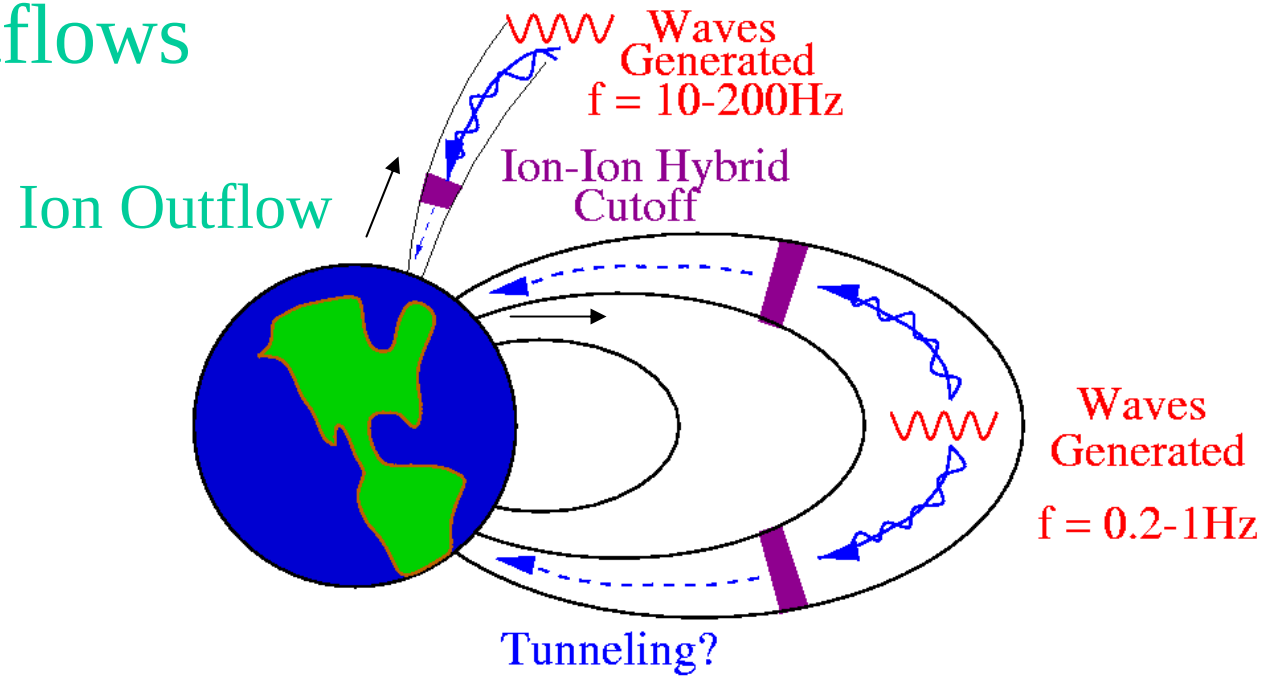


Heated Helium and EMIC Waves

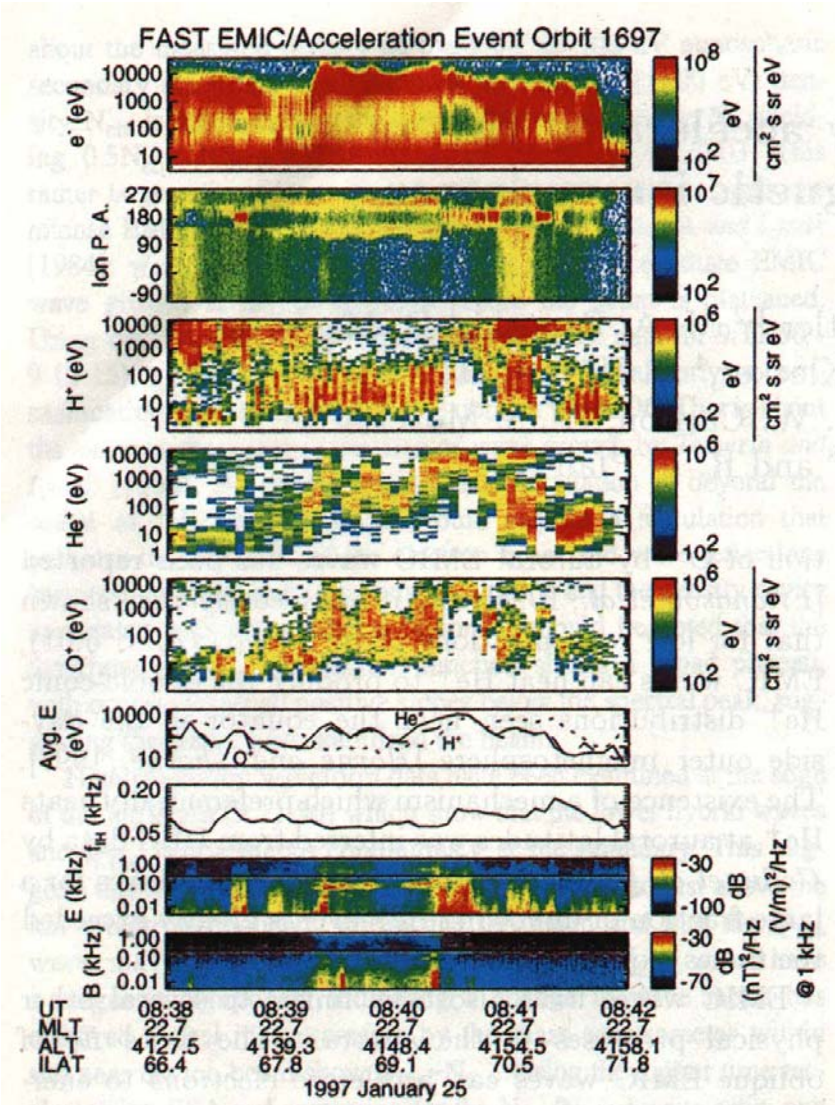
Courtesy Mark Engebretson

Wave-Induced Transport

- Ion Cyclotron Waves and Ion Outflows



FAST Observation



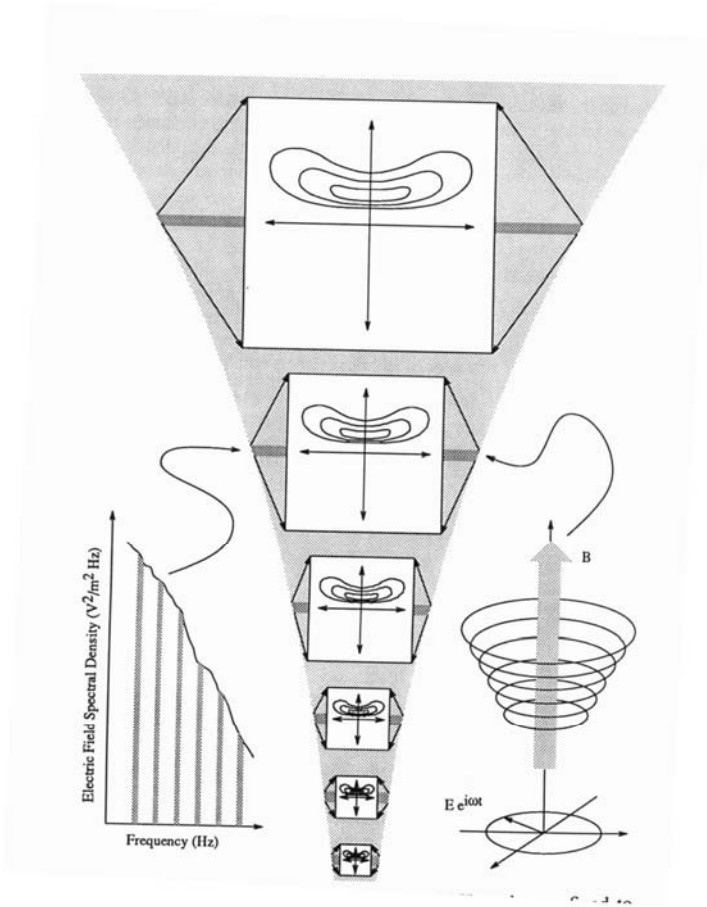
- Lund et al., 1998
- Fast satellite pass through Auroral zone at 4000km
- Heated Ion Conics
- Preferential Heating of He^+
- Electromagnetic Waves f~80-100Hz

Ion Cyclotron Waves Produce Ion Outflows

- Transverse Ion Energization
- Adiabatic Folding

  $(V_\perp)^2/B=\text{const}$

  Waves $\rightarrow V_\perp \rightarrow V_\parallel$

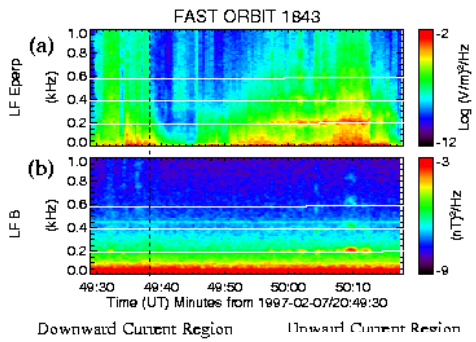


Waves Reach Rocket Altitudes

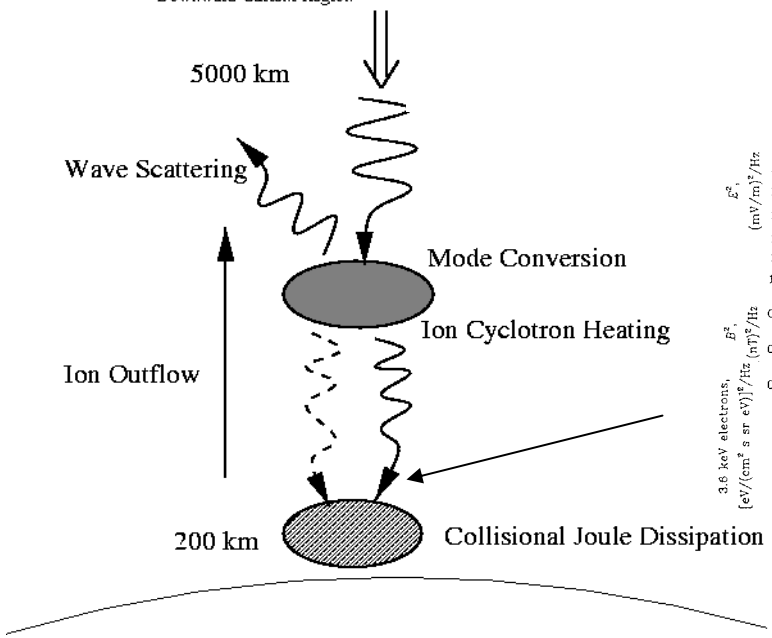
$S \sim 3 \times 10^{-5}$ W/m^2

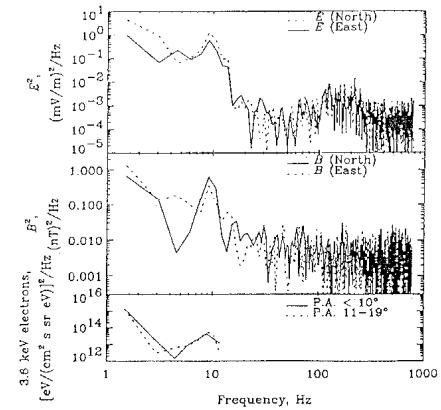
>4000km

f~10-200Hz



Fast Satellite
[Ergun, 1998]





Rocket Observation
[Lund, 1997]

$S \sim 10^{-5}$ W/m^2
400km

Can the Waves Reach Ionospheric Altitude?

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

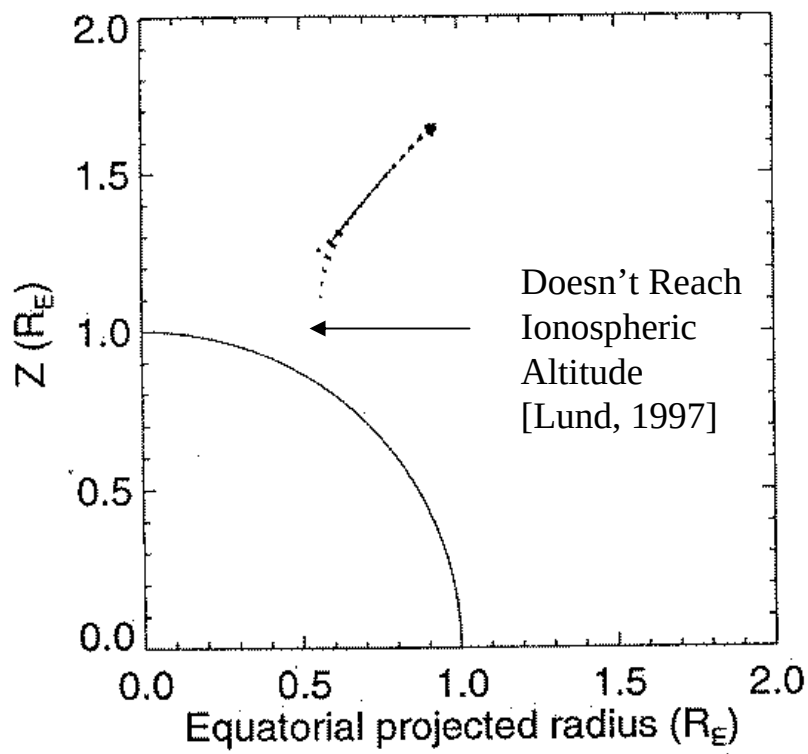


Figure 8. Ray paths of 128-Hz H^+ EMIC waves originating on the $L = 8$ field line at 4460 km ($\sim 0.01 R_E$ below the resonant altitude).

Wave Equation

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

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

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

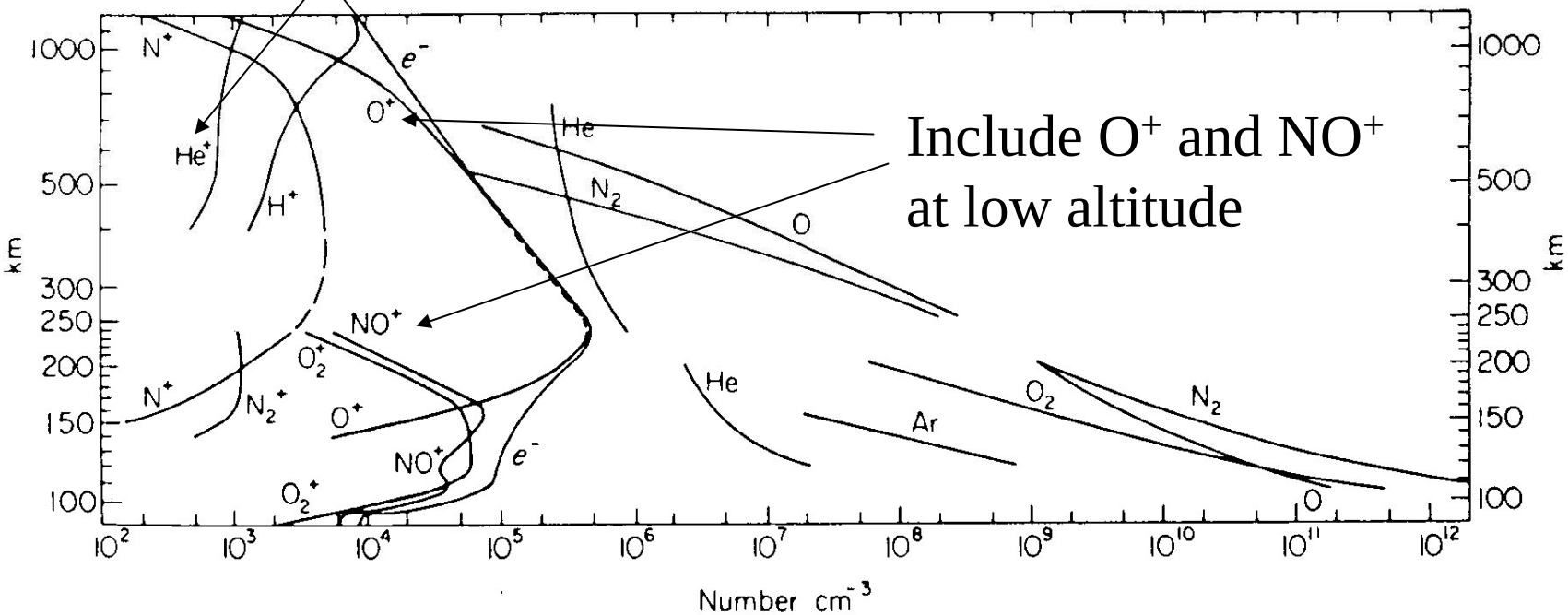
$$S = 1 - \sum_j \frac{\omega_{pj}^2 (\omega + i\nu_j)}{\omega[(\omega + i\nu_j)^2 - \Omega_j^2]}$$

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

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

Model Ionosphere

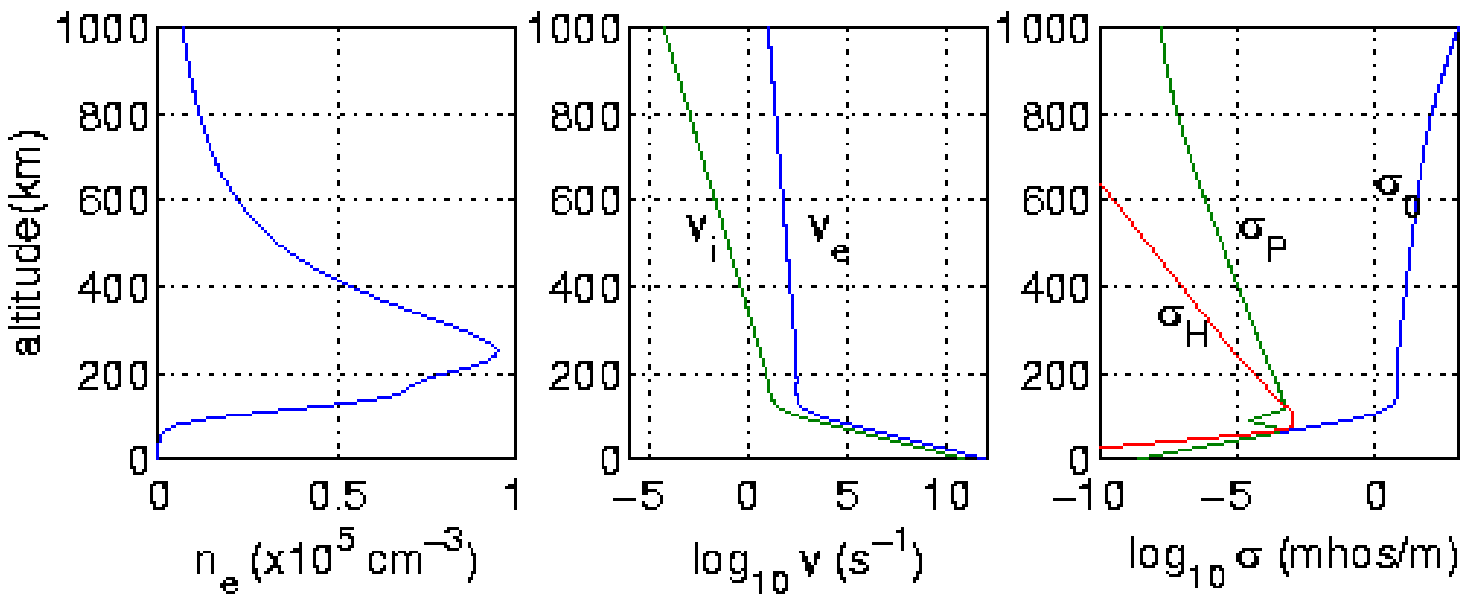
Exponential Falloff to n=10cm^{-3}
Fraction of H^+, He^+ and O^+ varies



[Banks and Kockarts, 1973]

Ionospheric Collisions

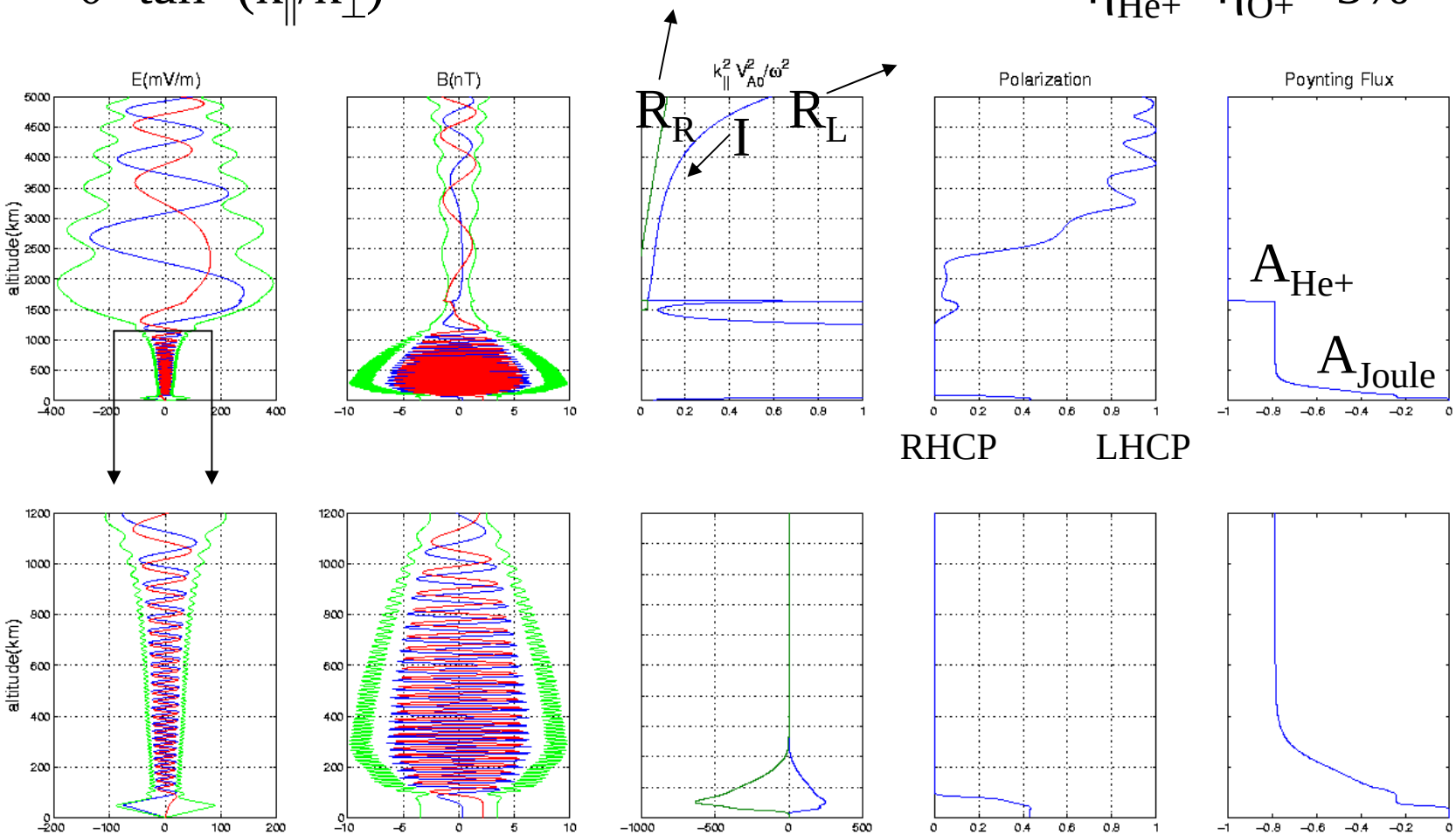
- Electron and Ion Collisions [Banks and Kockarts, 1973]
- Include NO^+ and O^+ [Kelley, 1989]
- Electron/Ion Density includes E and F region peaks



Wave Solutions (f=128Hz, θ=15)

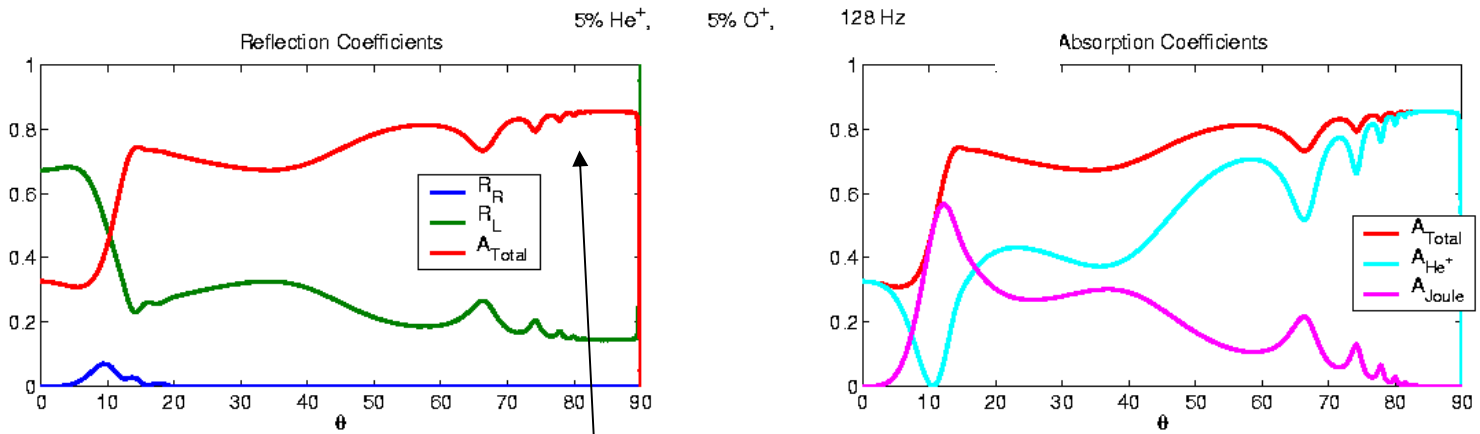
$\theta = \tan^{-1}(k_{\parallel}/k_{\perp})$

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

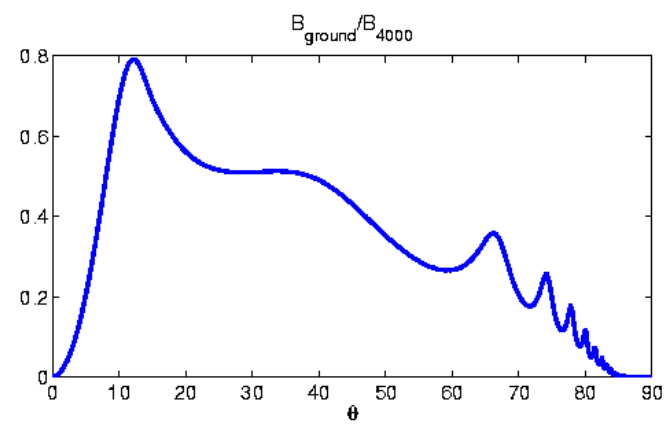


Expanded View in the Ionosphere

Reflection/Absorption Coefficients



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

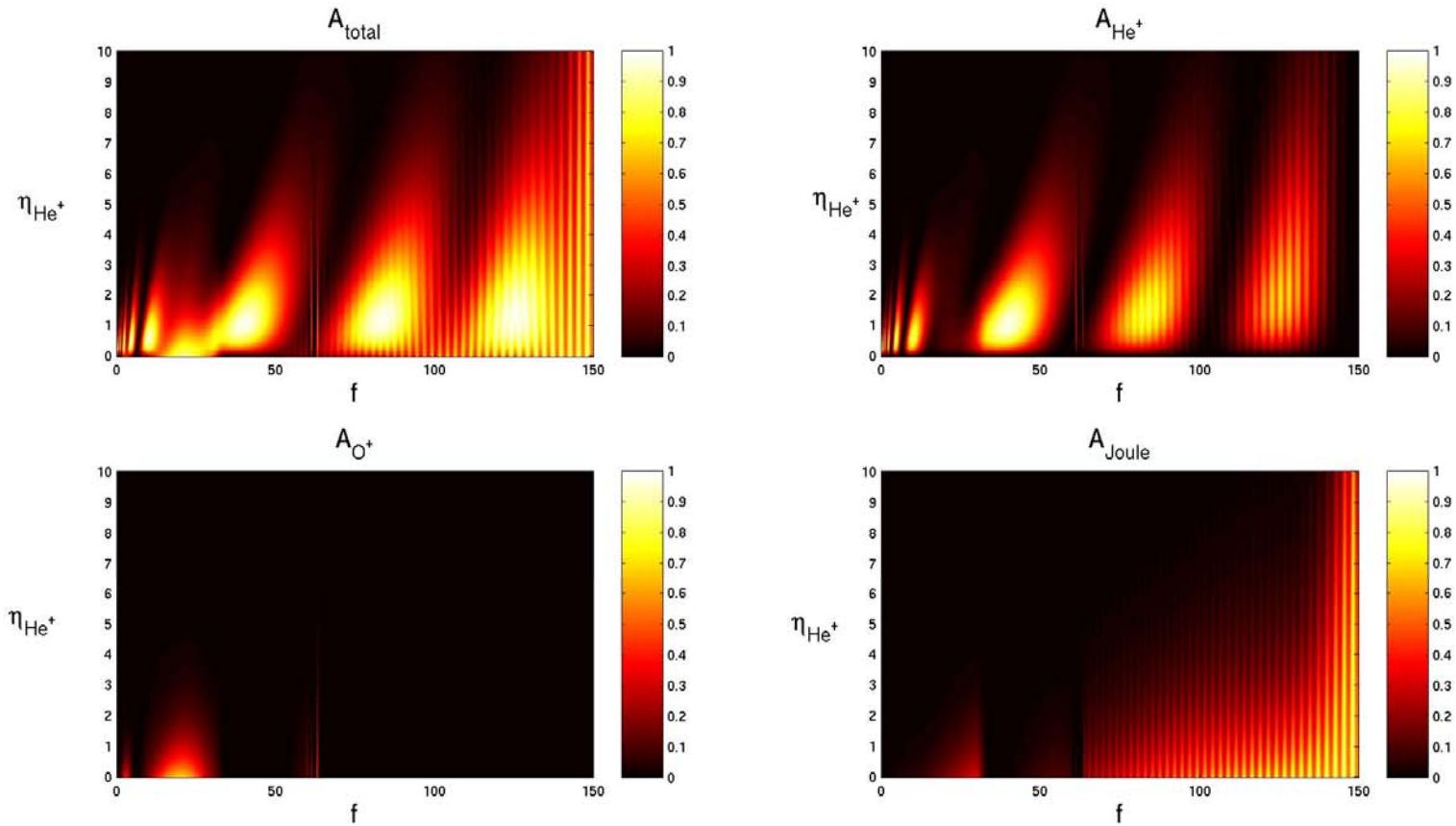


The Waves Reach the Ground as Observed!

Absorption and He^+ Concentration

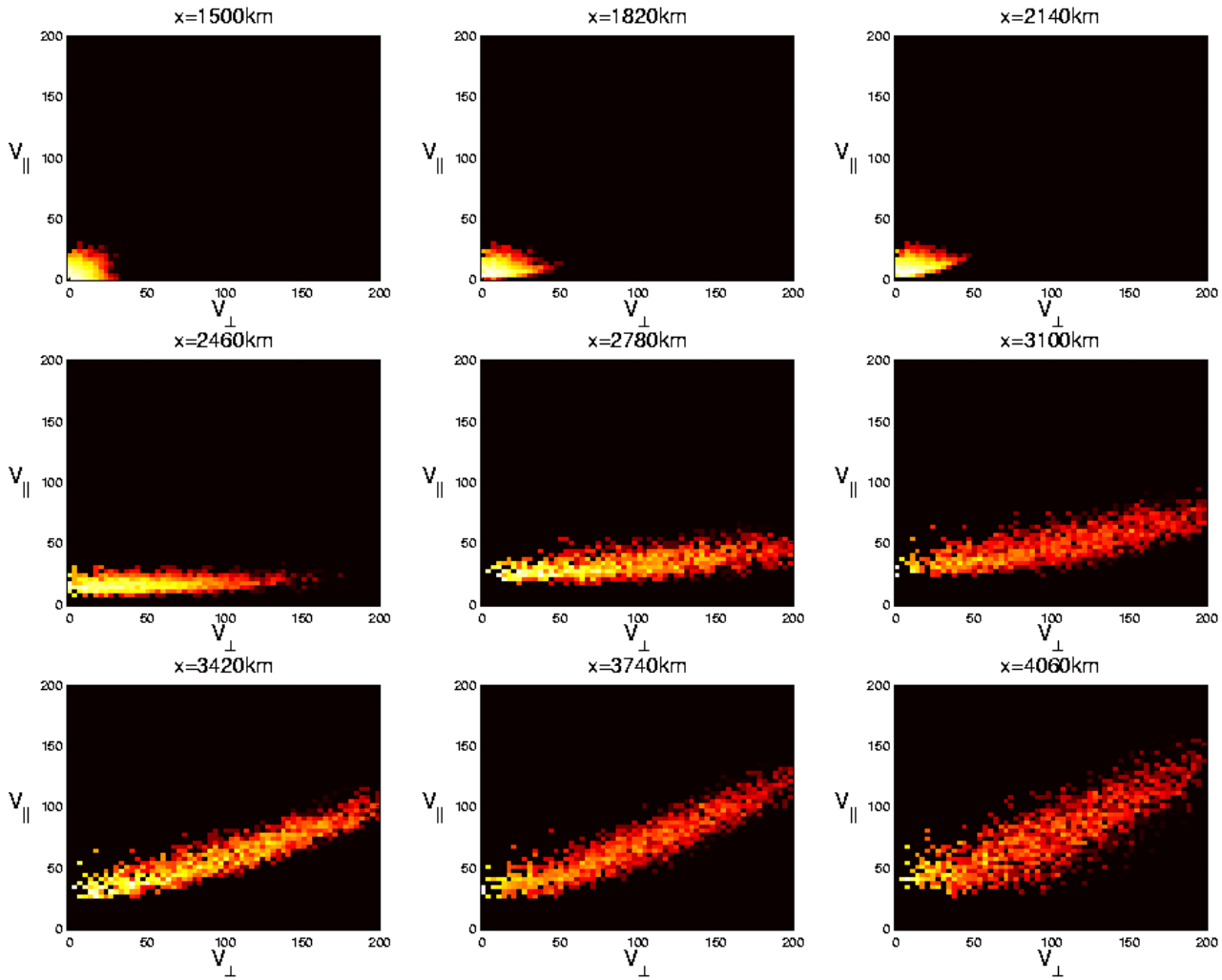
frequency maps to altitude

η_{O+} =5%; θ=60



frequency maps to altitude

Ion Distribution (Wave Model n=1cm^{-3})



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

Iterative Method

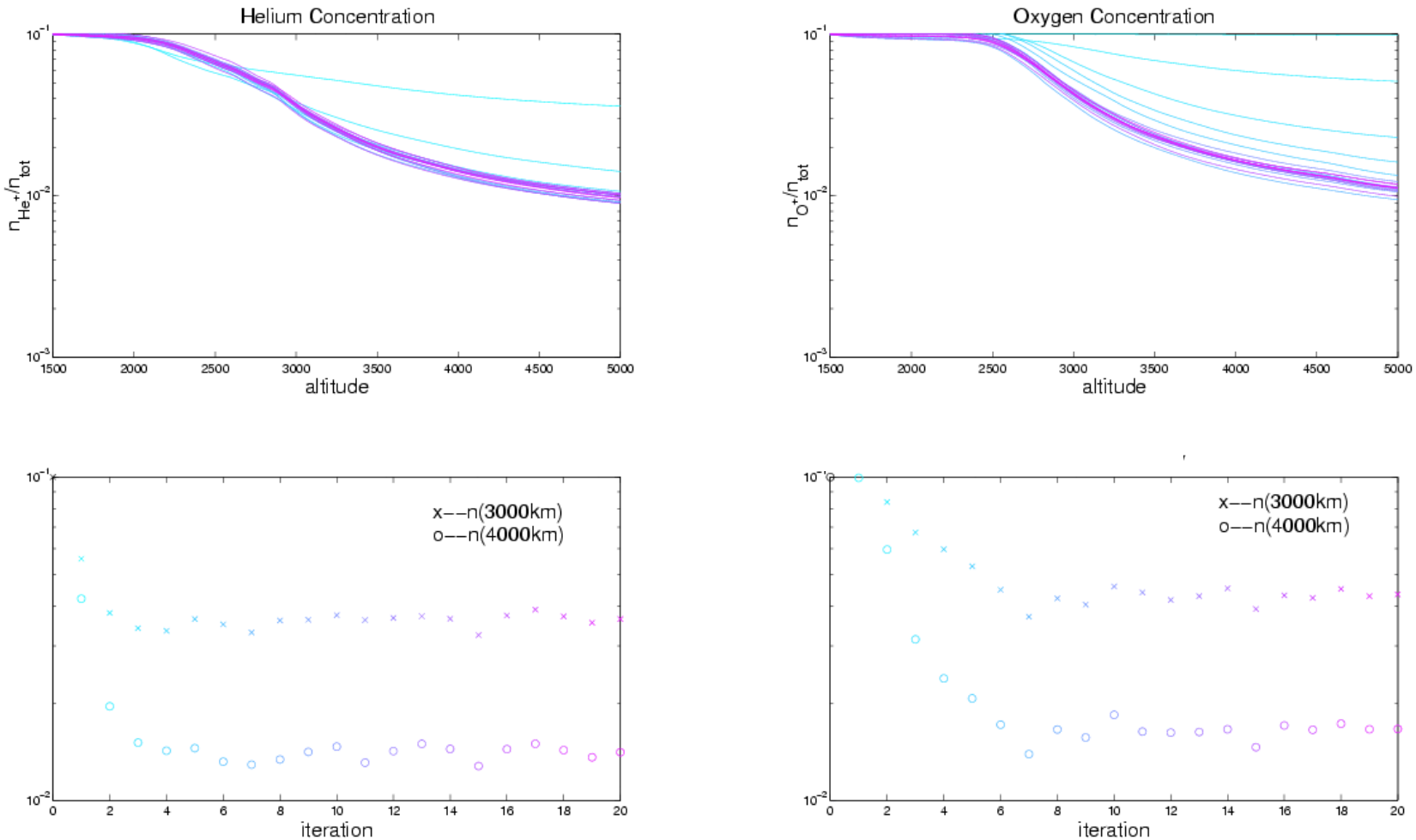
- Prescribe wave spectrum at satellite and a plasma profile

$$d|E|^2/df \sim f^{-\alpha}\ ;\ \alpha = 1.7$$

- Initiate with constant density ratio above 1500 km.

1. Compute linear ion cyclotron wave solutions based on spectrum and model plasma profile
2. Obtain ion heating rate as a function of altitude from the wave absorption
3. Perform Monte Carlo simulation of ions using heating rate
4. Obtain ion density profile and energy moments from the Monte Carlo simulation
5. Modify ionospheric/magnetospheric plasma profile
6. Iterate steps 2-6 until density profile becomes stationary

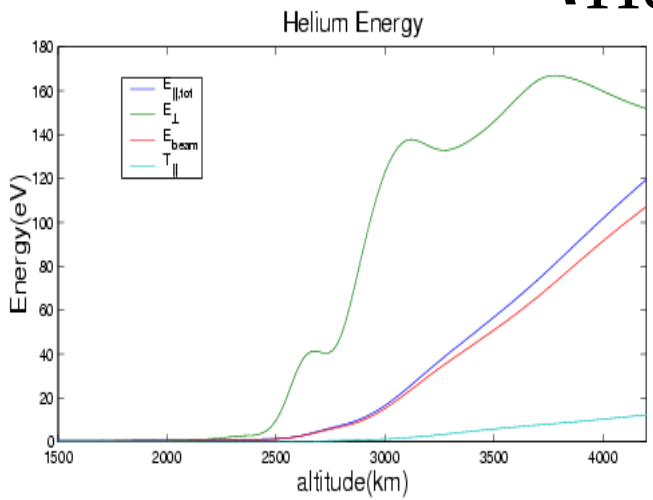
Convergence of Iterative Method

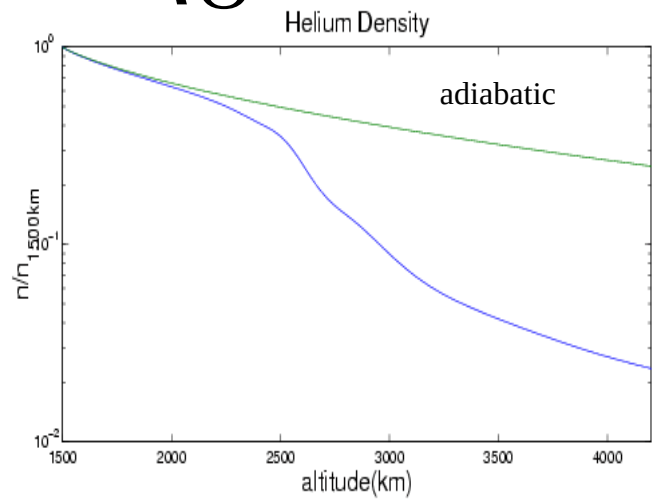


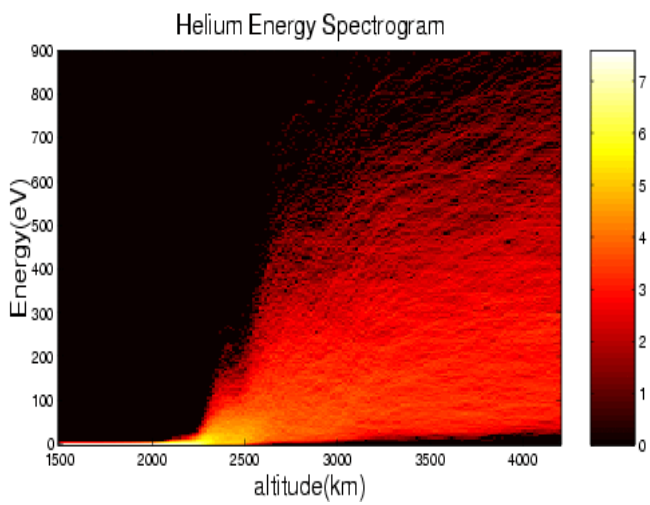
$\theta = 60^o$

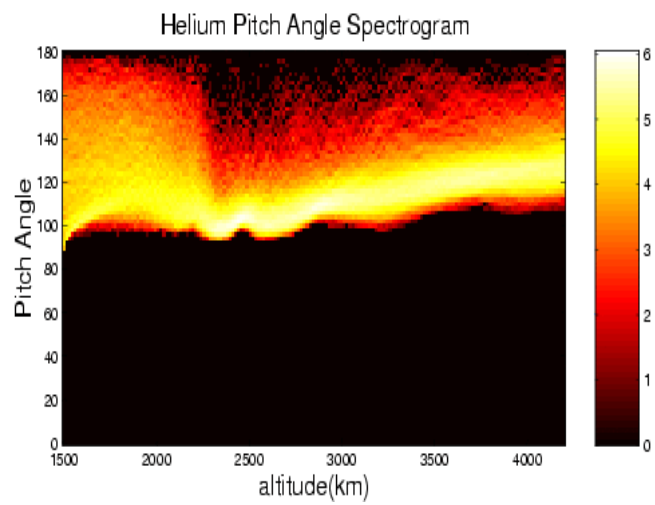
Steady State Helium Profiles

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



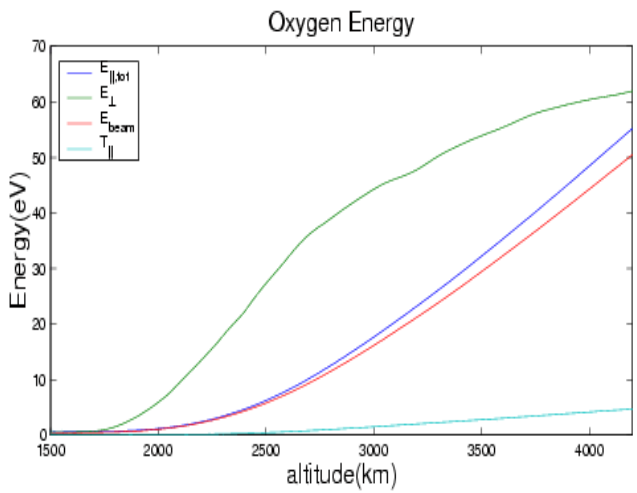


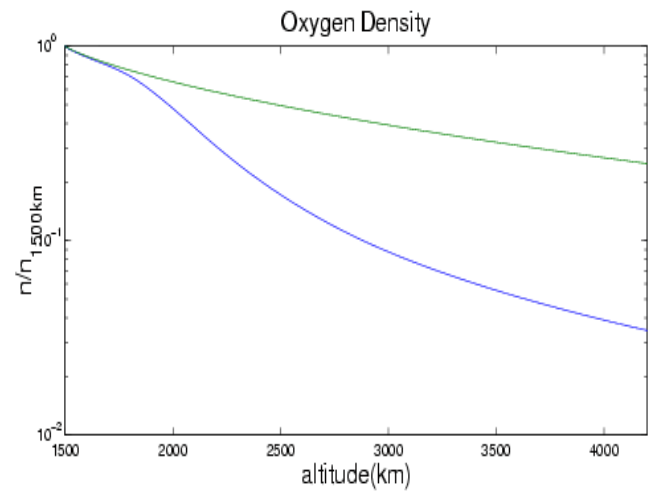


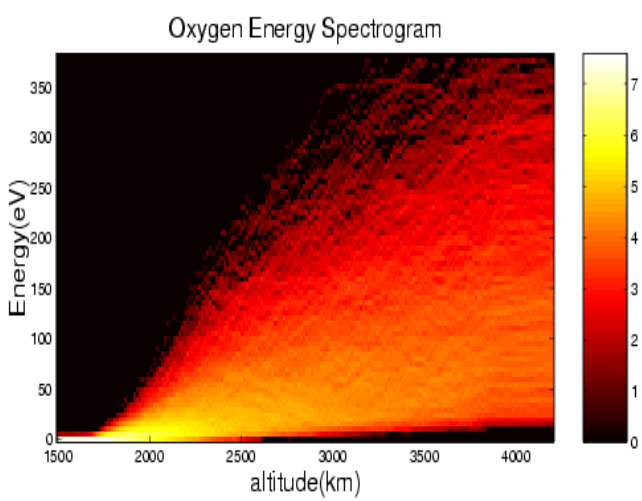


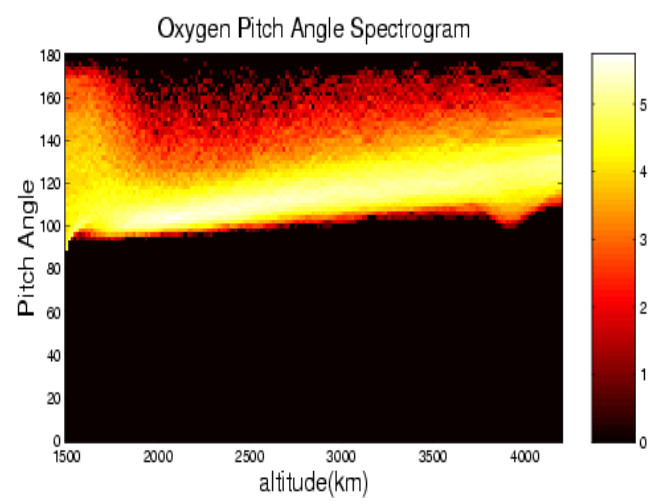
Steady State Oxygen Profiles

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



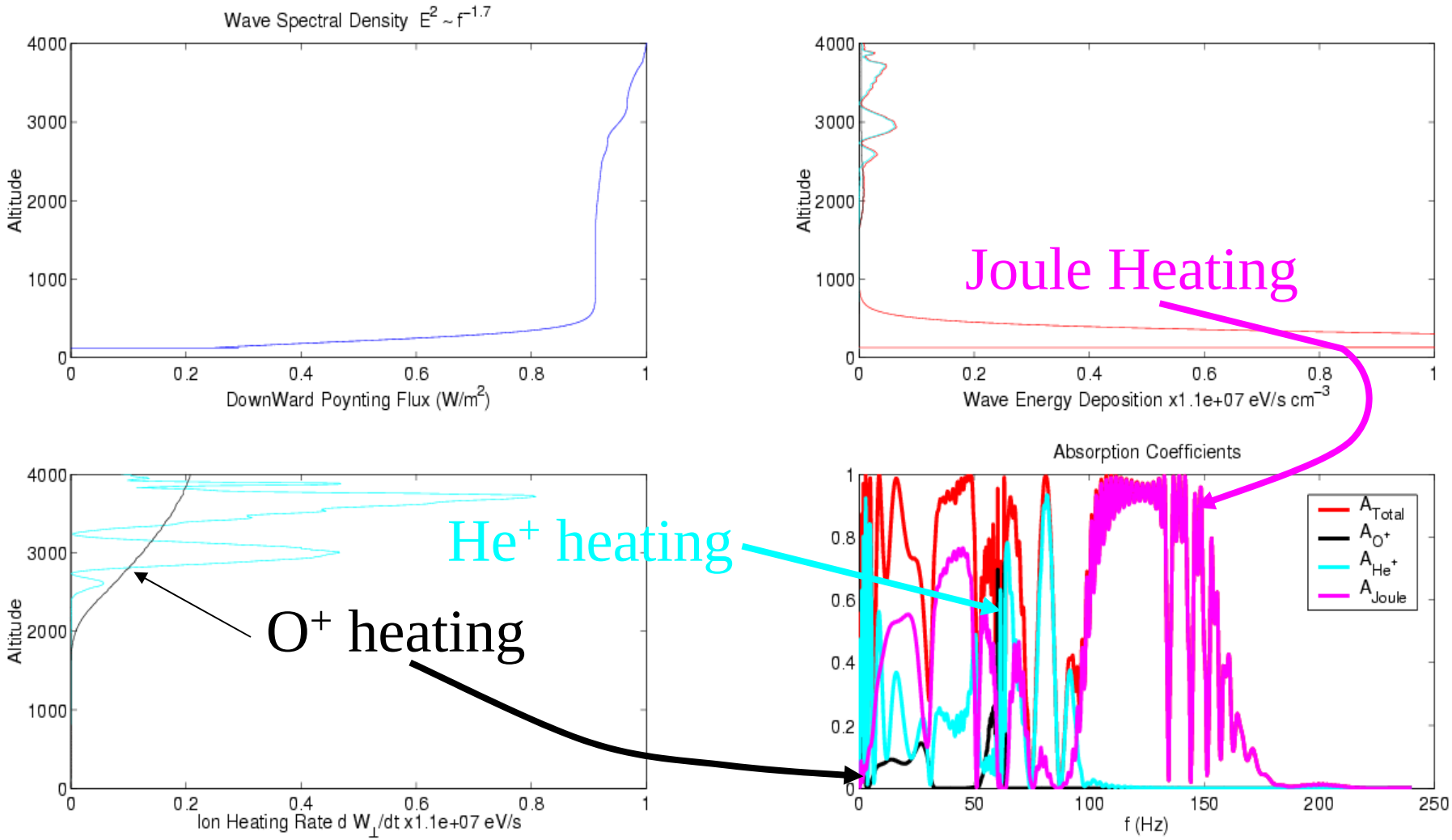






Steady State Heating Rate

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

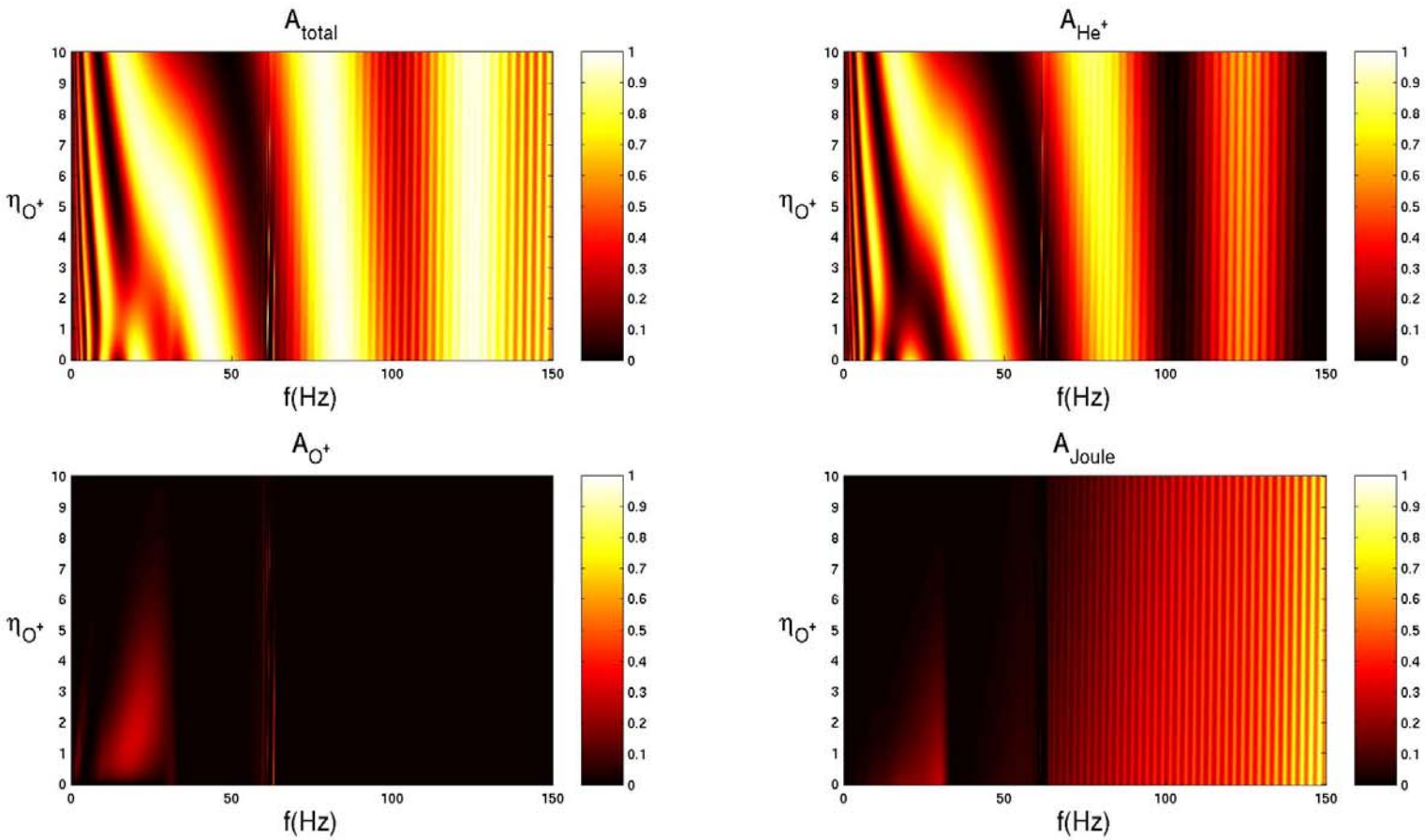


Significant Findings

- Significant EMIC wave power (1Hz<f<200Hz) reaches the ground/ionosphere and heats ions.
- Oblique modes primarily heat He^+ and O^+ above 2500 km.
- He^+ and O^+ concentration strongly affects the heating rate of O^+.
- He^+ should bleed off the topside ionosphere prior to efficient O^+ heating.
- Preferential heating of He^+ may occur due to nonlocal effects and the results are different than heuristic models.

Dependence on O^+ Concentration

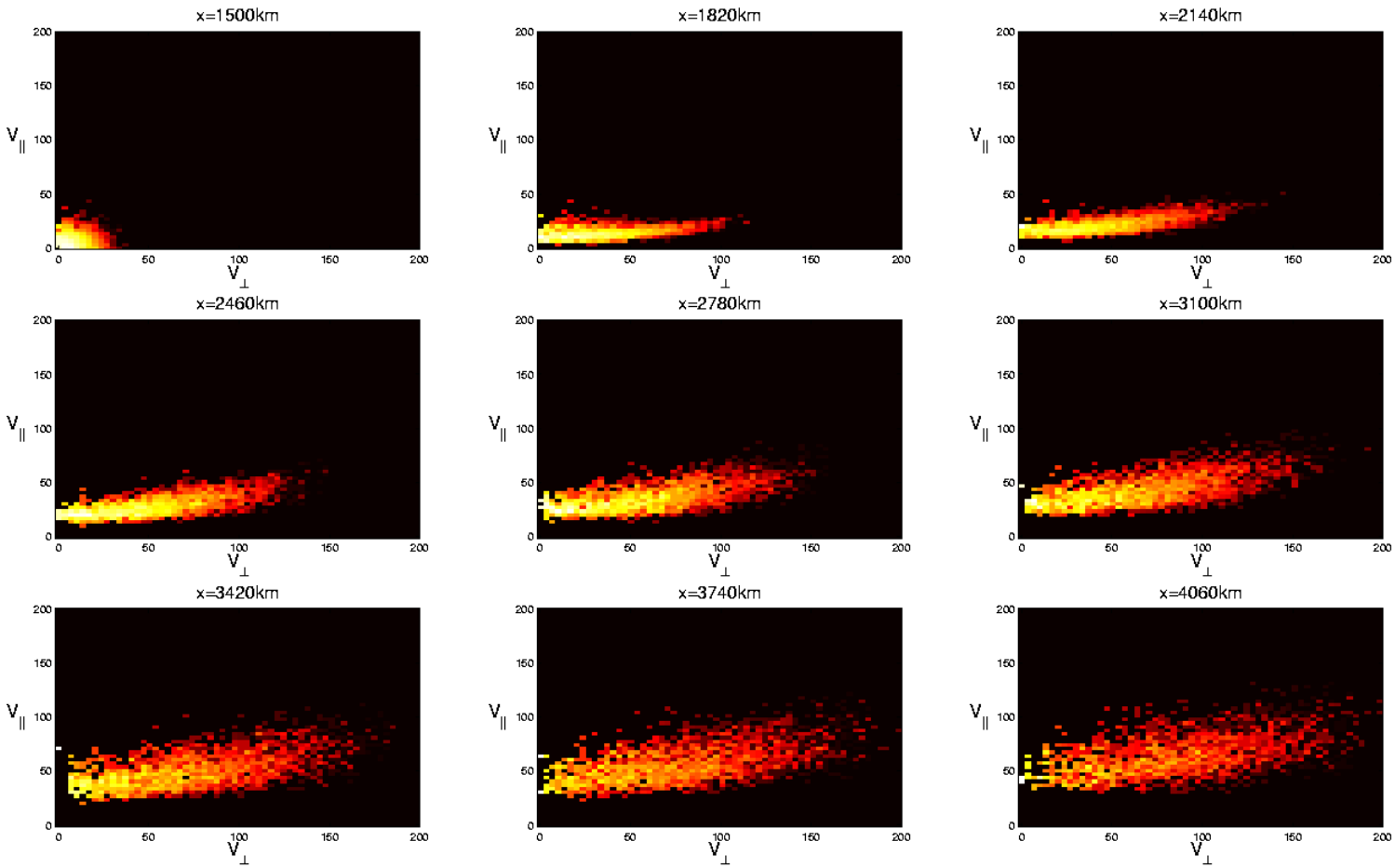
η_{He+} =1%; θ=60



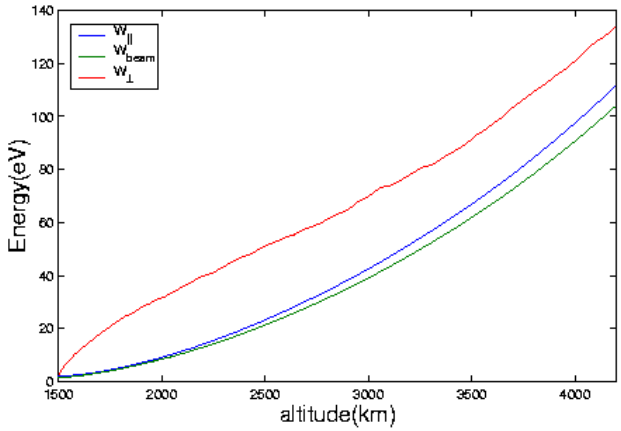
Preferential Heating of Ion Species

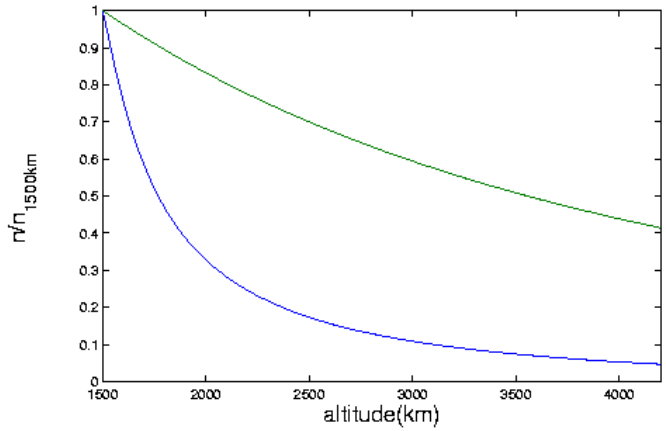
- Heuristic heating rate:
  - $|E_\perp(\omega = \Omega)|^2 \sim f^{-\alpha} \sim \Omega^{-\alpha} \sim m^{\alpha}$
  - $dW_\perp/dt = 2mD_\perp = \eta\,(q^2/2m)\,|E_\perp(\omega = \Omega)|^2 \sim m^{\alpha-1}$
  - Typically $\alpha > 1$ ($\alpha \sim 1.7$ commonly used)
  - Heavy ions should be preferentially heated
- Heating rate derived from spectrum and plasma model:
  - Favors helium over oxygen
  - Consistent with observations that suggest preferential heating of helium

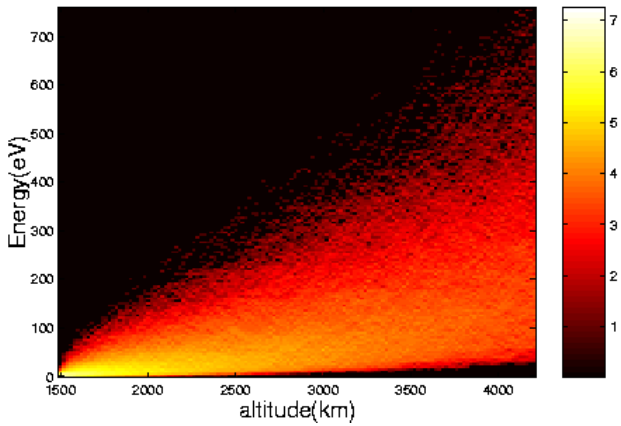
Ion Distribution (Heuristic)

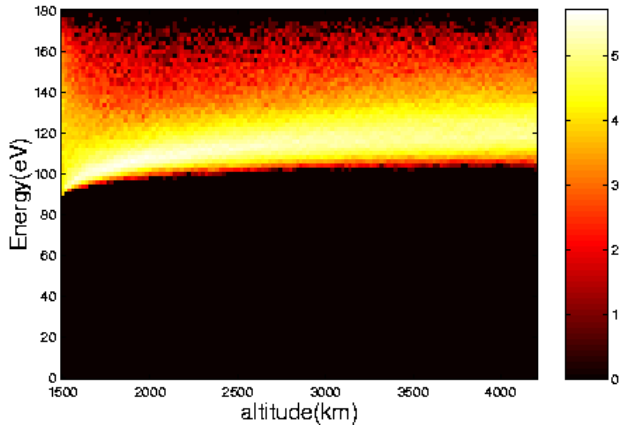


Ion Profiles (Heuristic)



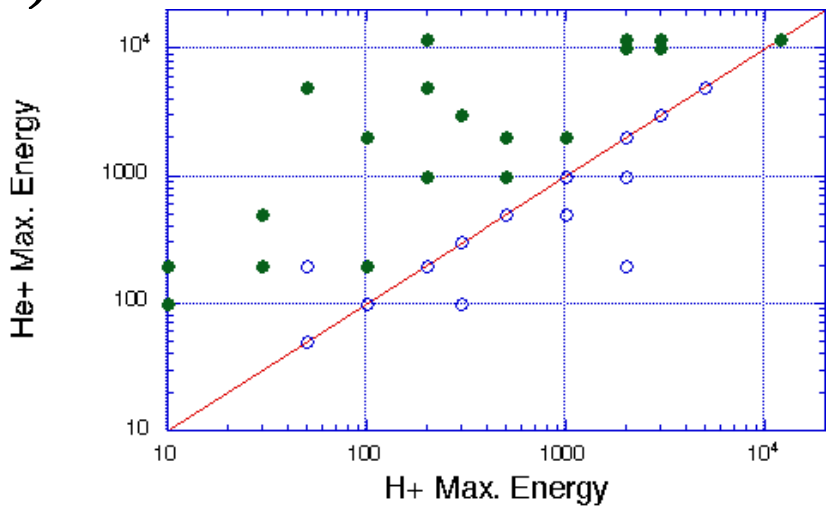




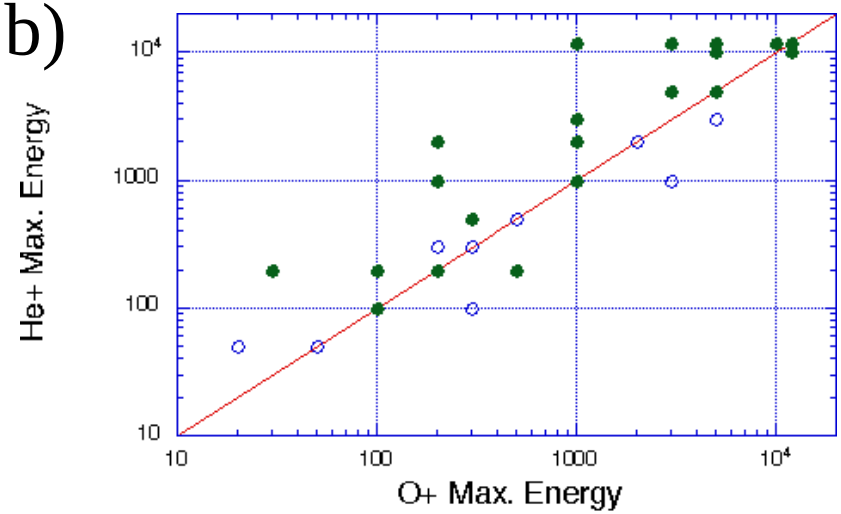


Preferential Heating of Helium

a)



b)



a) Maximum energy of He^+ versus H^+ for 24 ion conics with EMIC waves (solid symbols) and 62 ion conics without EMIC waves (open symbols).

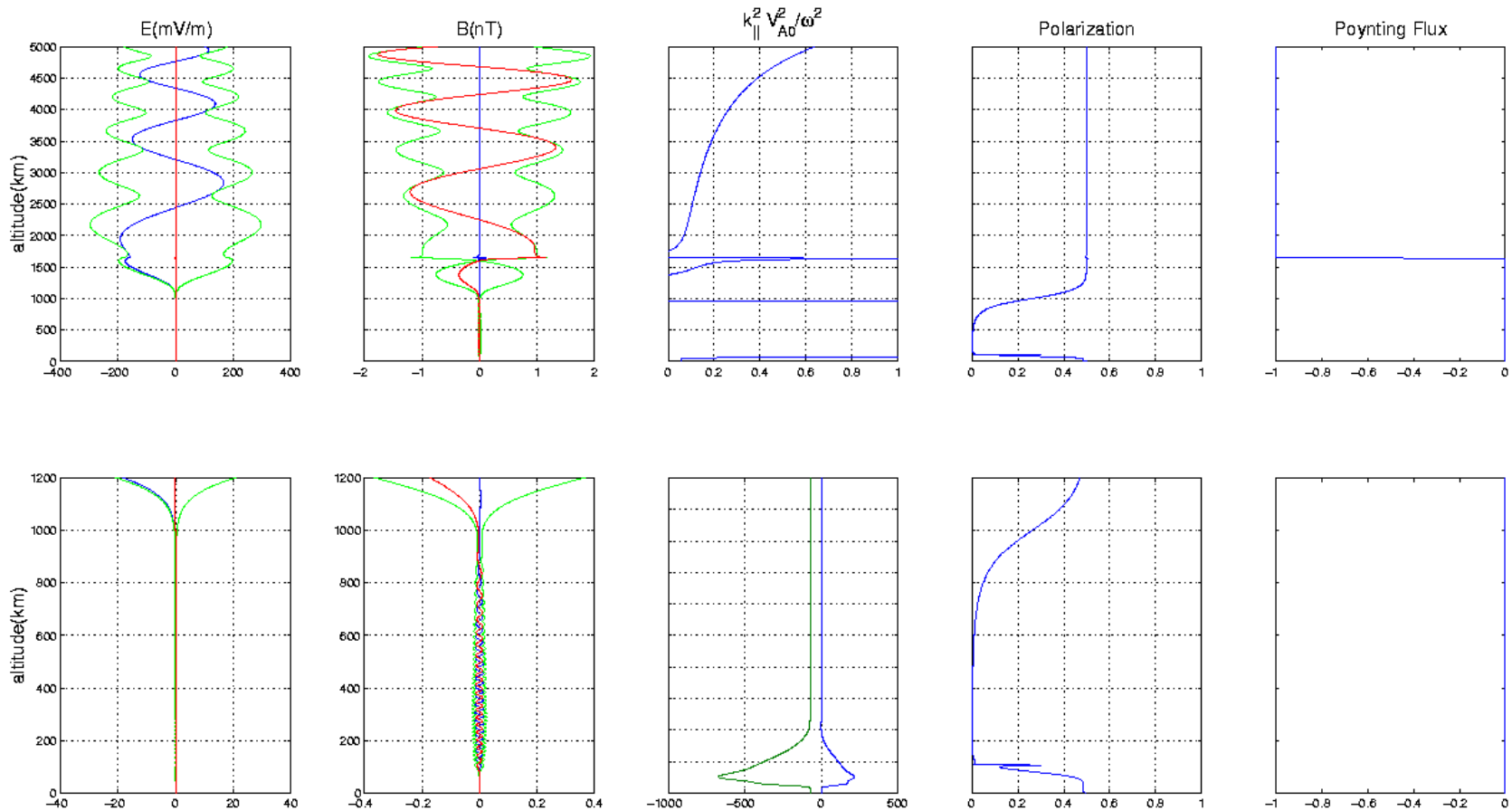
b) Maximum energy of He^+ versus O^+ for these events.

- He^+ preferentially heated relative to O^+

[Lund et al., 1998]

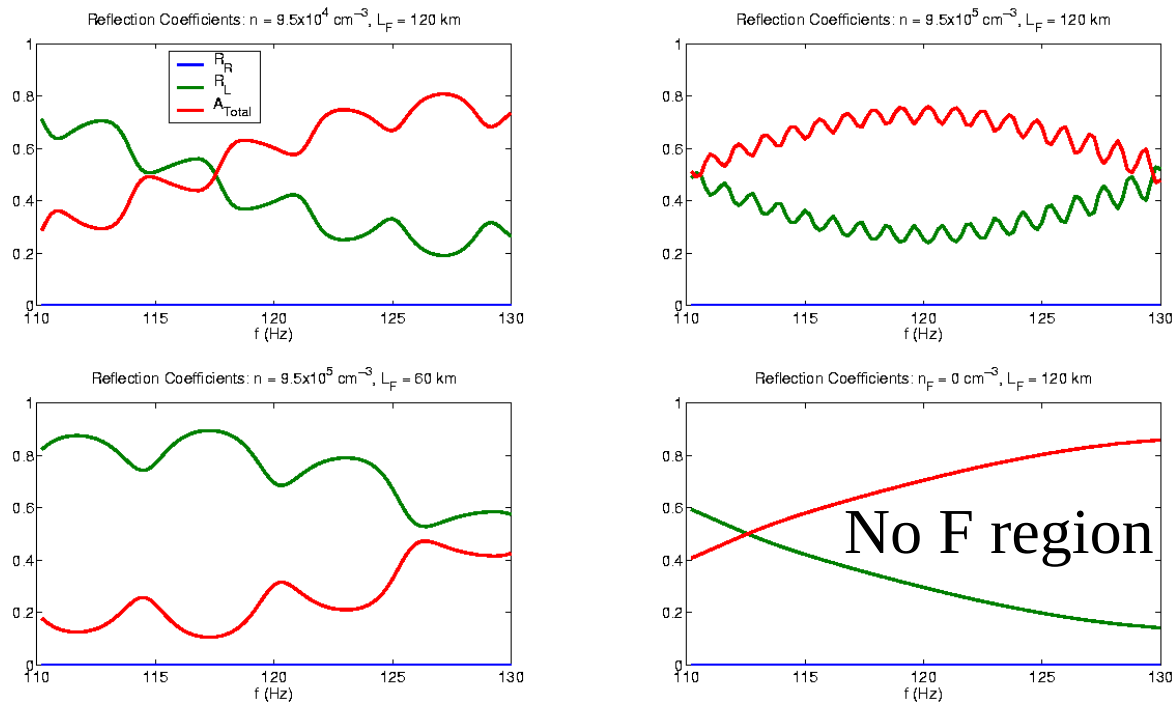
Wave Solutions (f=128Hz, θ=85)

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



Ionospheric Resonator Produces Modulations

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

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

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