SM33A-15

A Self-Consistent Approach to Modeling Ion Outflows Associated with Electromagnetic Ion Cyclotron Waves

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PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Outline

- Review Observations of EMIC Waves in Auroral Region
  - satellite (FAST) and rocket data (wave and particle data)
  - preferential heating of helium associated with waves [Lund, 1998]
- Outstanding Questions:
  - How do EMIC waves reach lower altitude through stop bands?
  - How much energy is dissipated (ion cyclotron heating and Joule dissipation).
  - Why is He^+ preferentially heated?
  - What is the "steady state" ion profile in the presence of the waves?
- Full wave solution technique necessary (ray tracing inadequate)
  - collisional ionospheric model
  - dissipation at heavy ion resonances
- Ion heating and approach to steady state
  - Monte Carlo model determines ion profiles given an altitude dependent heating rate
  - Steady state achieved by iterative solution technique

EMIC Waves (10-100 Hz)

- Fast Observations (4000km)
  - Waves⇔secondary electrons
  - $f<f_p$ ⇒downward Poynting flux ($3x10^{-5}W/m^2$)
  - Associated with heated ion conics

Chaston et al., GRL, 1998
Lund et al., GRL, 1998
Chaston et al., JGR, 2002

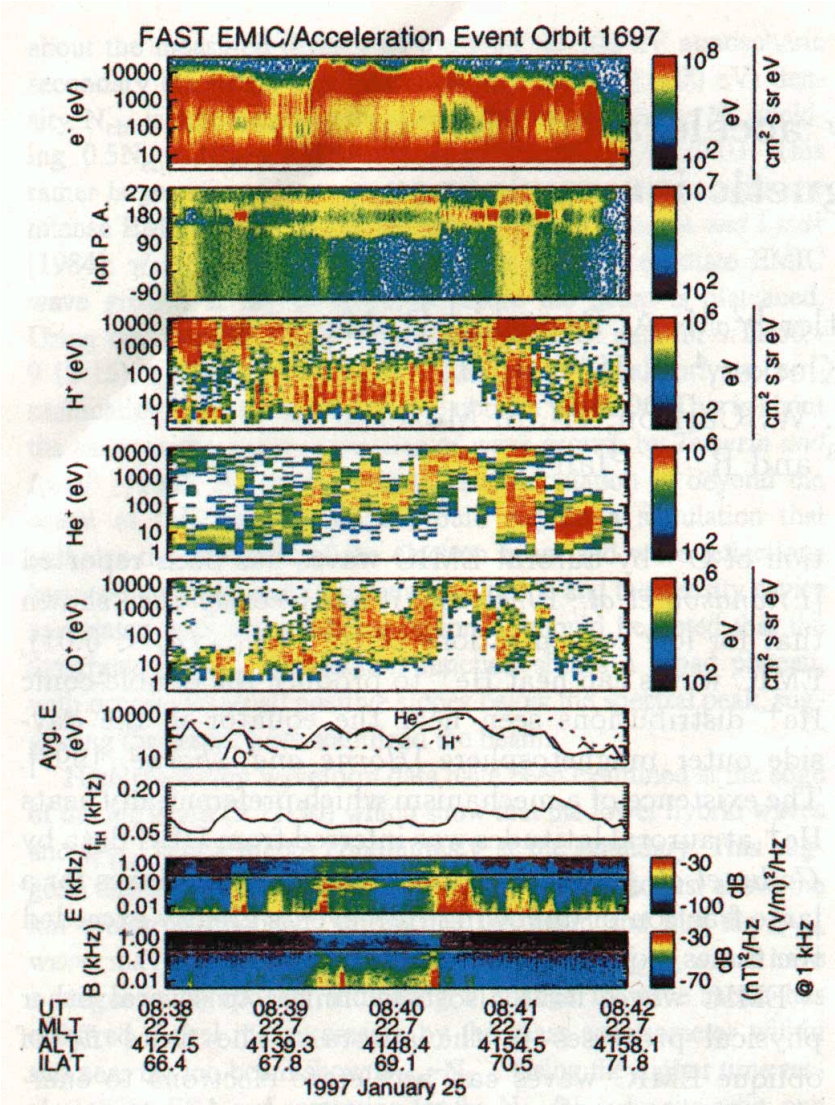
- Rocket flights (400km)
  - Peaks at 10 Hz and 100Hz
  - Downward Poynting flux ($10^{-5}W/m^2$)
  - Waves correlate well with electron modulations

Lund and LaBelle, JGR, 1997

Possible Sources of Waves

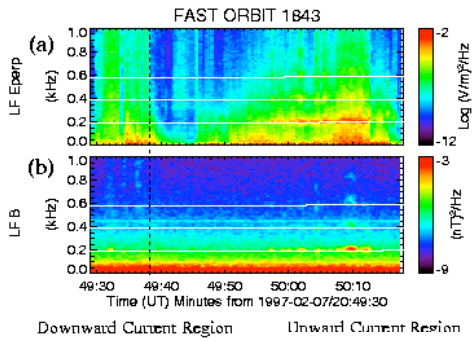
- Field Aligned Currents/ Electron Beams
  - Kindel and Kennel, 1971, Bergmann, 1984, Temerin and Lysak, 1984
- Upflowing Ion Beams
  - Bergmann, 1984, Catell et al., 1998,
- Velocity Shear
  - Ganguli, 1988, Koepke, 1994,1995,1999, Amatucci et al., 1998
  - Lakhina, 1987, Gavrishchaka, PRL, 2000
- Temperature Anisotropy/Loss Cones
  - Oscarsson and Andre, 1986

FAST Observation

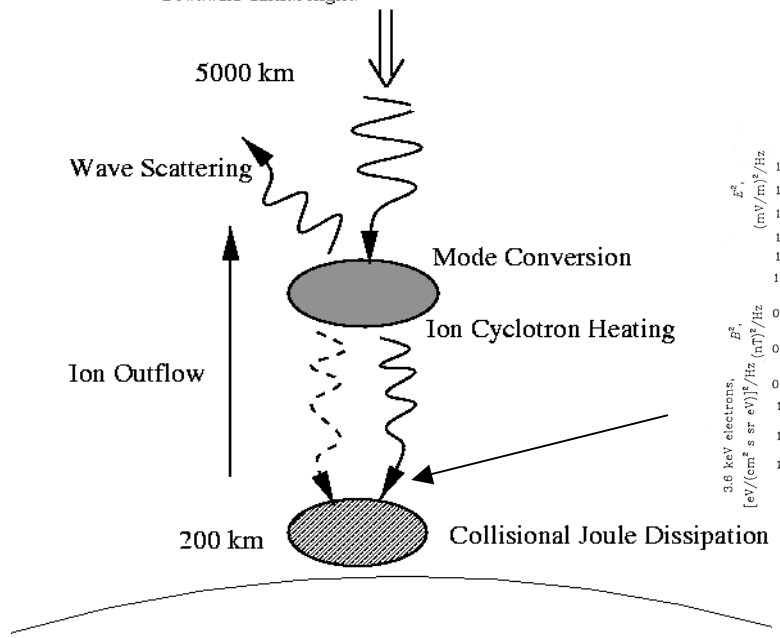


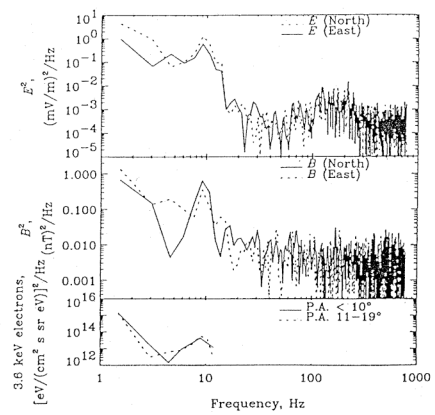
- Lund et al., 1998
- Fast satellite pass through Auroral zone at 4000km
- Heated Ion Conics
- Preferential Heating of He^+
- Electromagnetic Waves f~80-100Hz

Waves Reach Rocket Altitudes



Fast Satellite
[Ergun, 1998]





Rocket Observation
[Lund, 1997]

Can the Waves Reach Ionospheric Altitude?

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

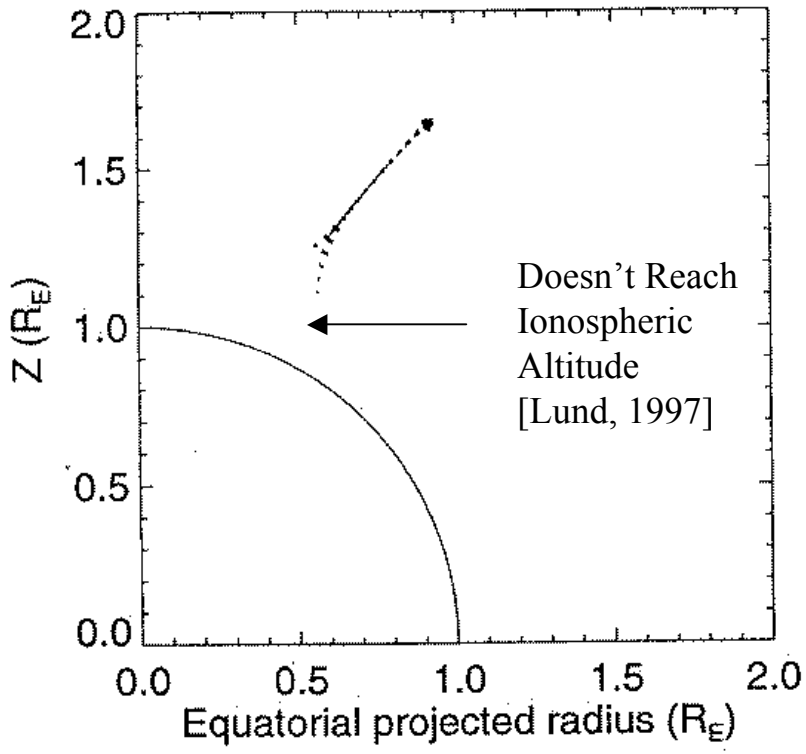
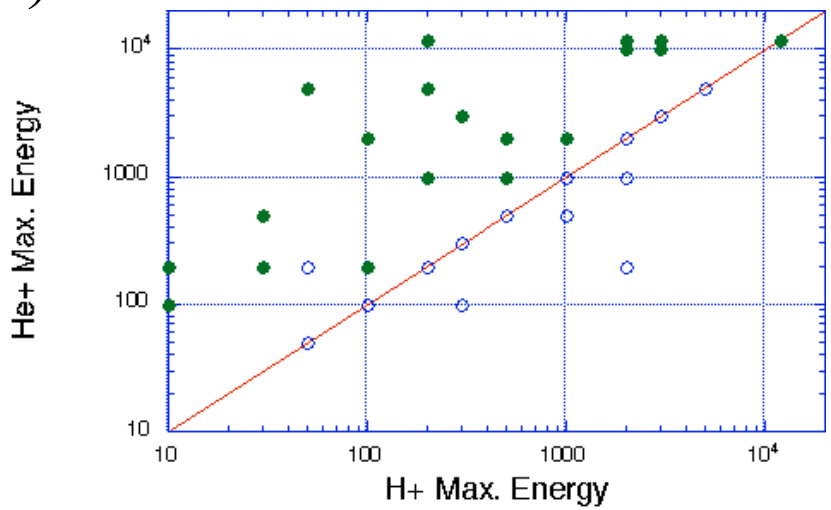


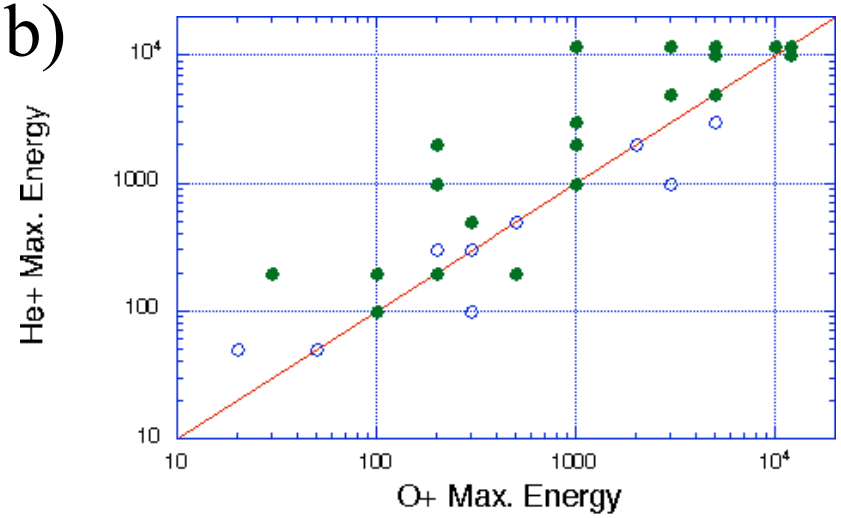
Figure 8. Ray paths of 128-Hz H^+ EMIC waves originating on the $L = 8$ field line at 4460 km ($\sim 0.01 R_E$ below the resonant altitude).

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]

Preferential Heating of Ion Species

- Heuristic heating rate:
  - ¬ $|E_?(\omega = \Omega)|^2$ » $f^{-\alpha}$» $\Omega^{-\alpha}$ » m^{α}
  - ¬ $dW_?/dt=2mD_?=\eta\ (q^2/2m)\ |E_?(\omega = \Omega)|^2$ » $m^{\alpha-1}$
  - ¬ Typically $\alpha > 1$ (α » 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

Wave Equation

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

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

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

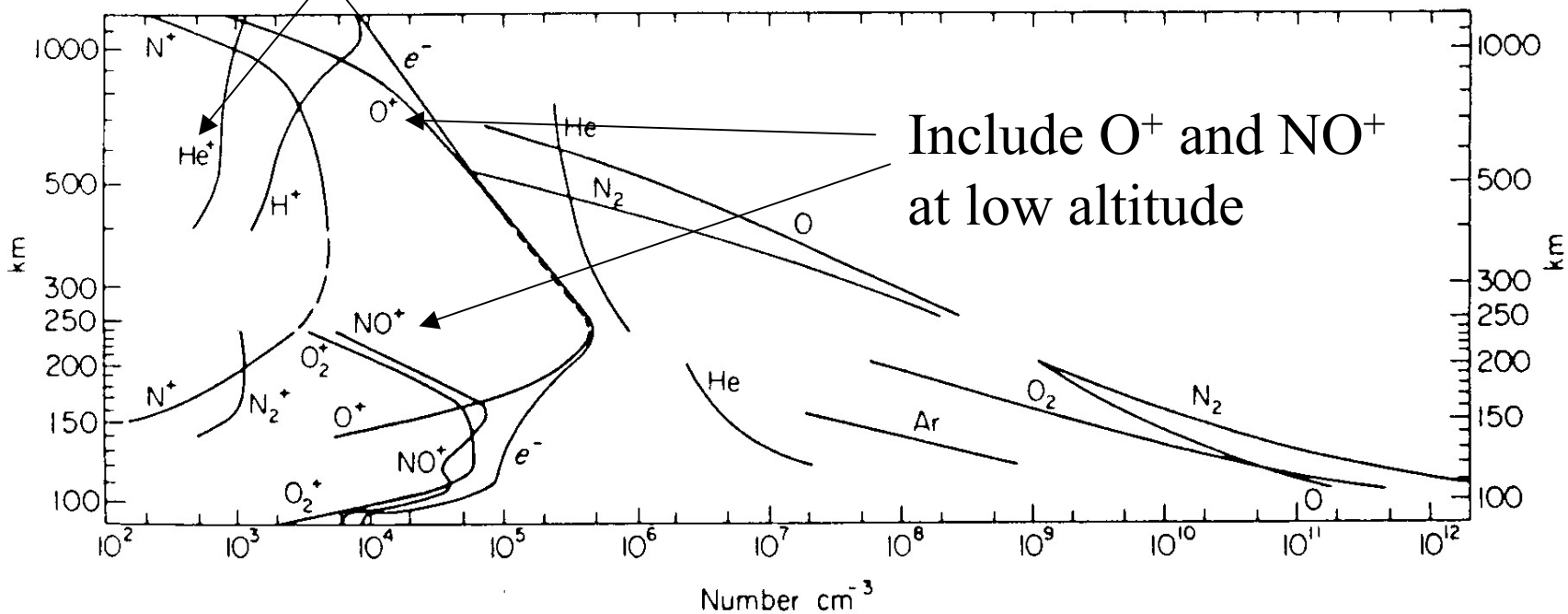
$$S = 1 - \sum_j \frac{\omega_{pj}^2 (\omega + i\nu_j)}{\omega[(\omega + i\nu_j)^2 - \Omega_j^2]}$$

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

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

Model Ionosphere

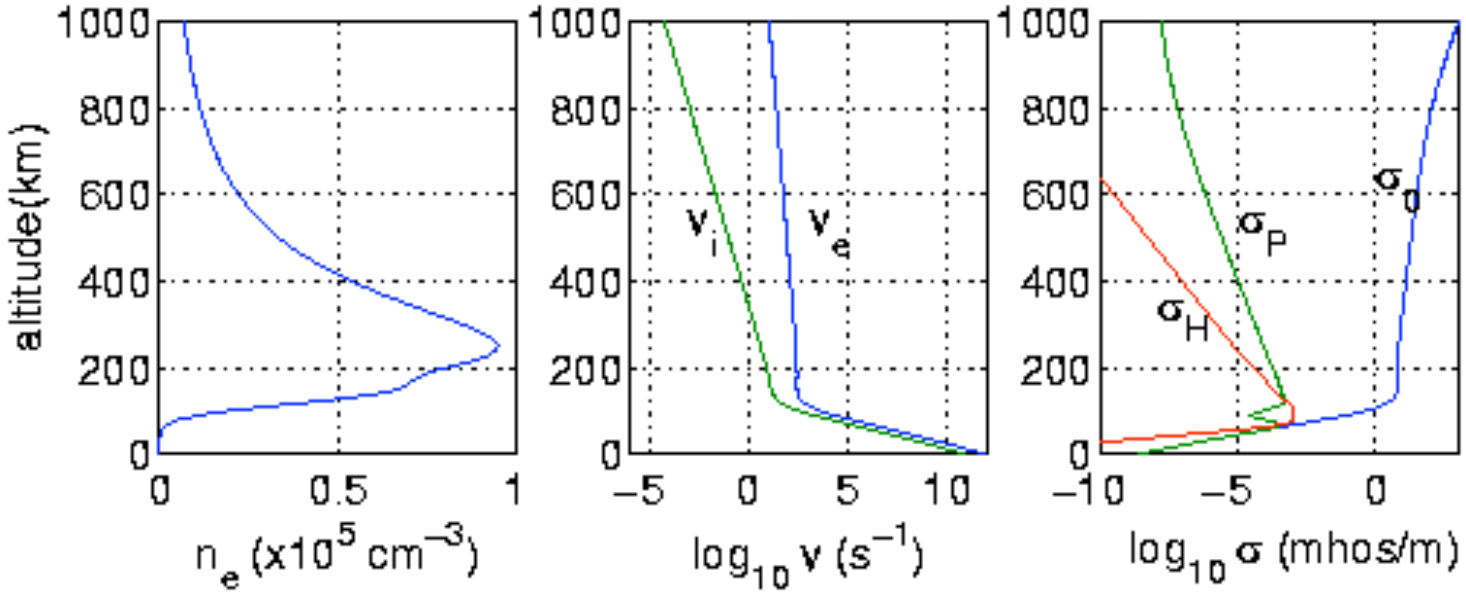
Exponential Falloff to $n=10cm^{-3}$
Fraction of H^+, He^+ and O^+ varies



[Banks and Kockarts, 1973]

Ionospheric Collisions

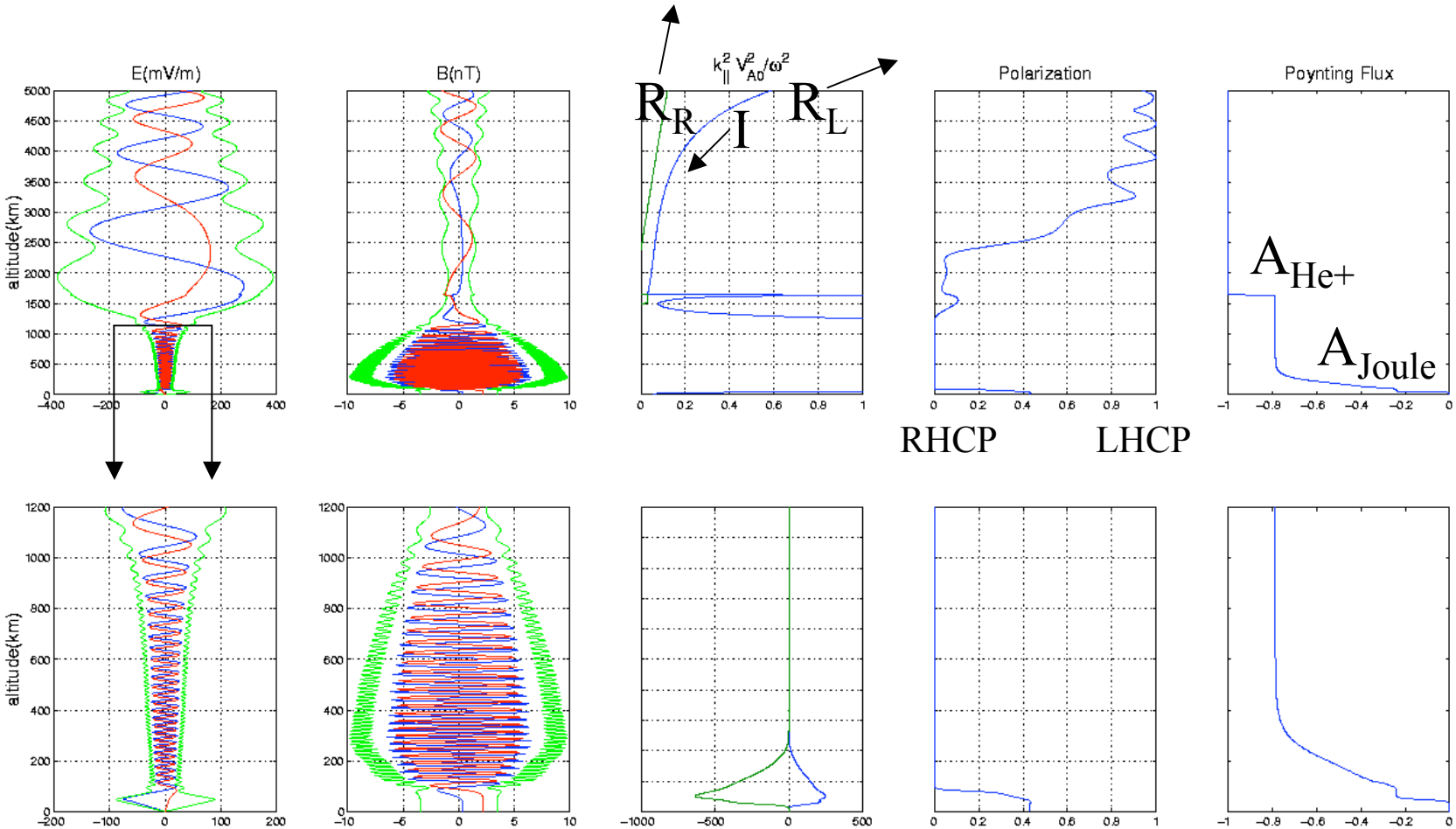
- Electron and Ion Collisions [Banks and Kockarts, 1973]
- Include NO^+ and O^+ [Kelley, 1989]
- Electron/Ion Density includes E and F region peaks



Wave Solutions (f=128Hz, θ=15)

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

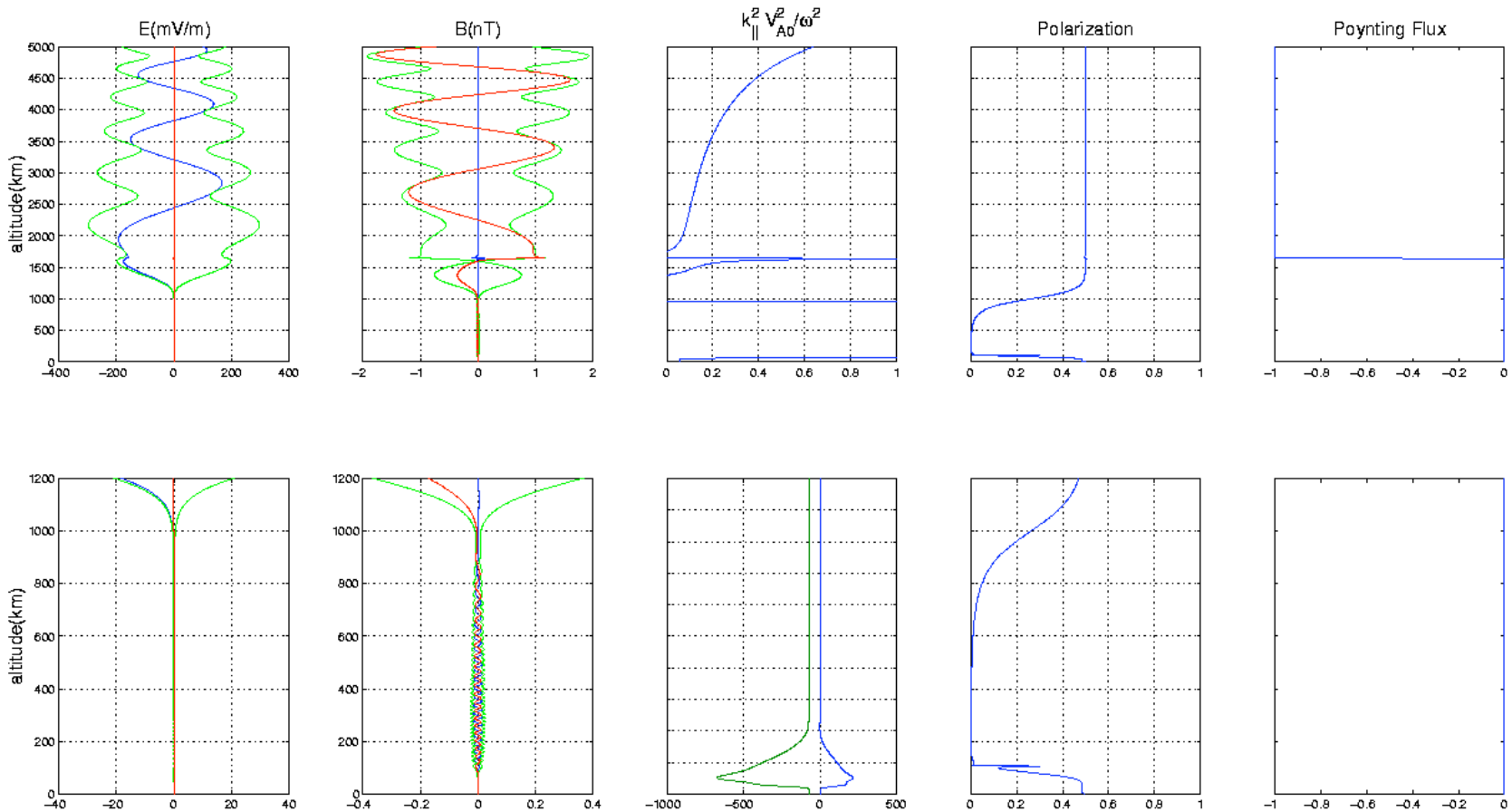
$\eta_{He+} = \eta_{O+} = 5\%$



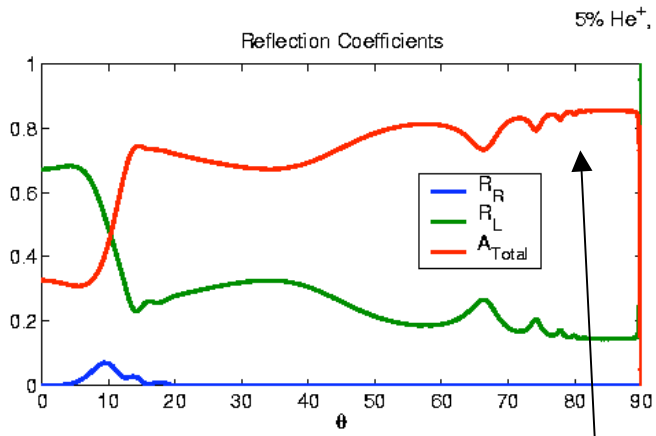
Expanded View in the Ionosphere

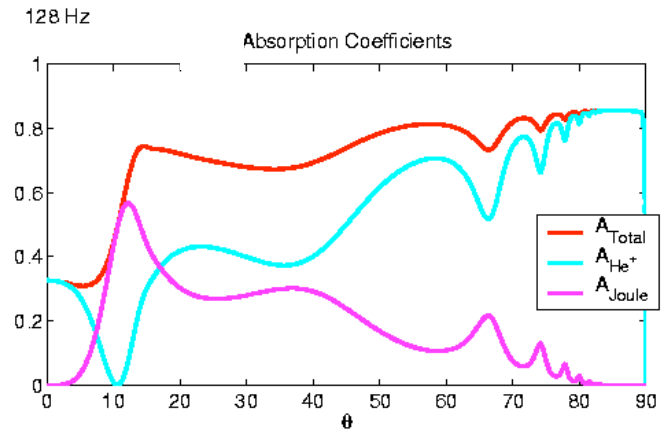
Wave Solutions (f=128Hz, θ=85)

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

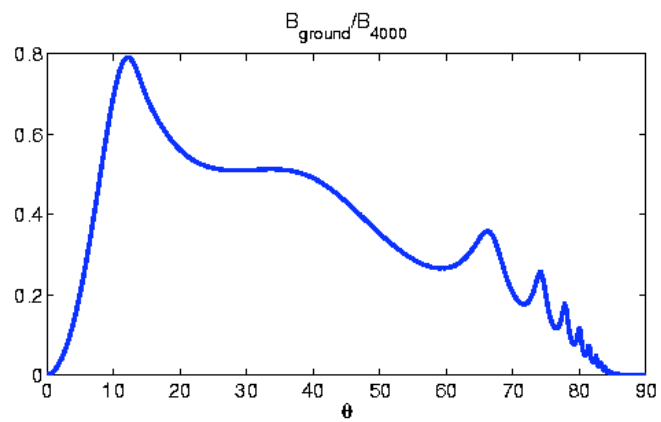


Reflection/Absorption Coefficients



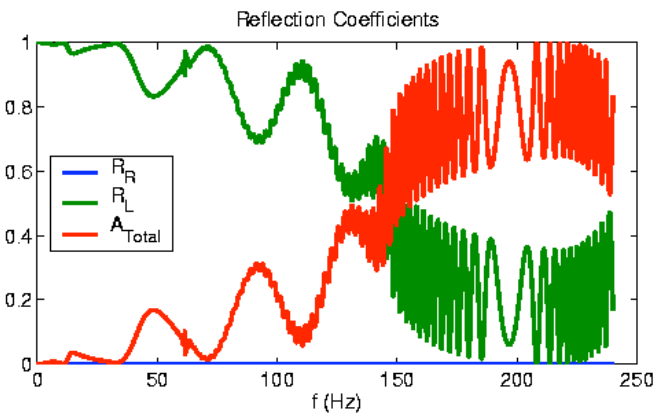


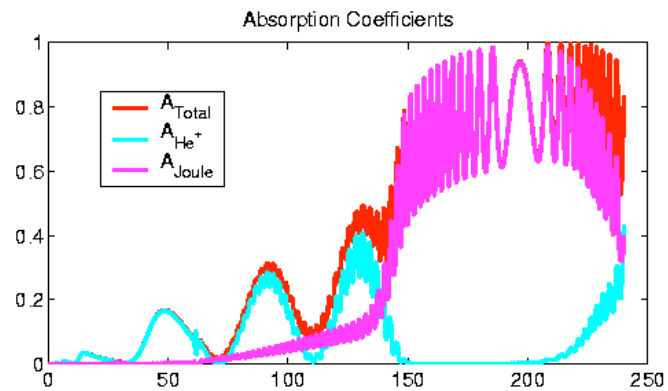
Most Wave Energy is Absorbed by He^+ or by Joule Dissipation in the Ionopshere



The Waves Reach the Ground as Observed!

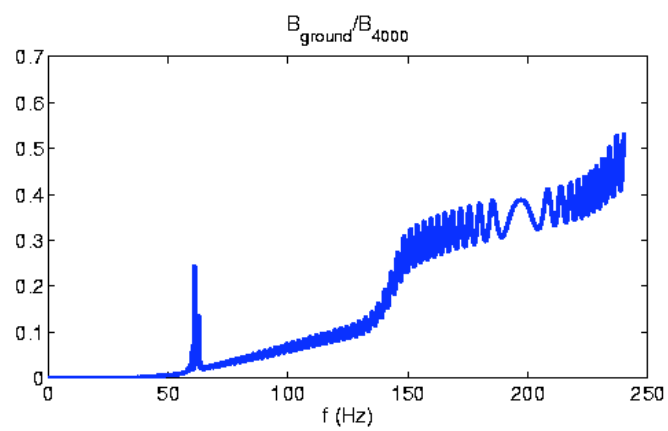
Frequency Dependence of Coefficients (θ=60)





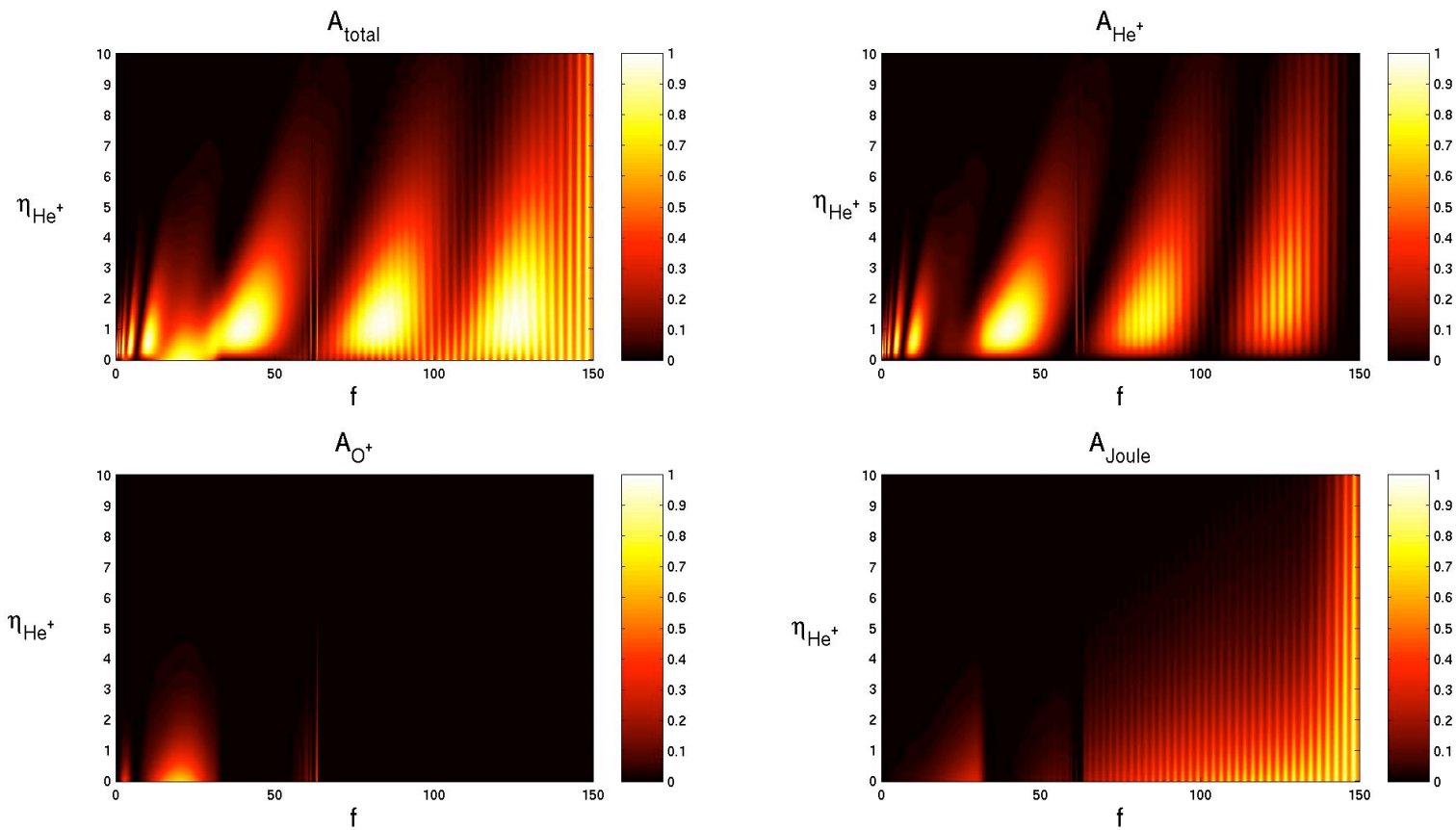
Frequency Modulation ~4Hz

Low frequency waves absorbed at He^+ resonance do not reach ground



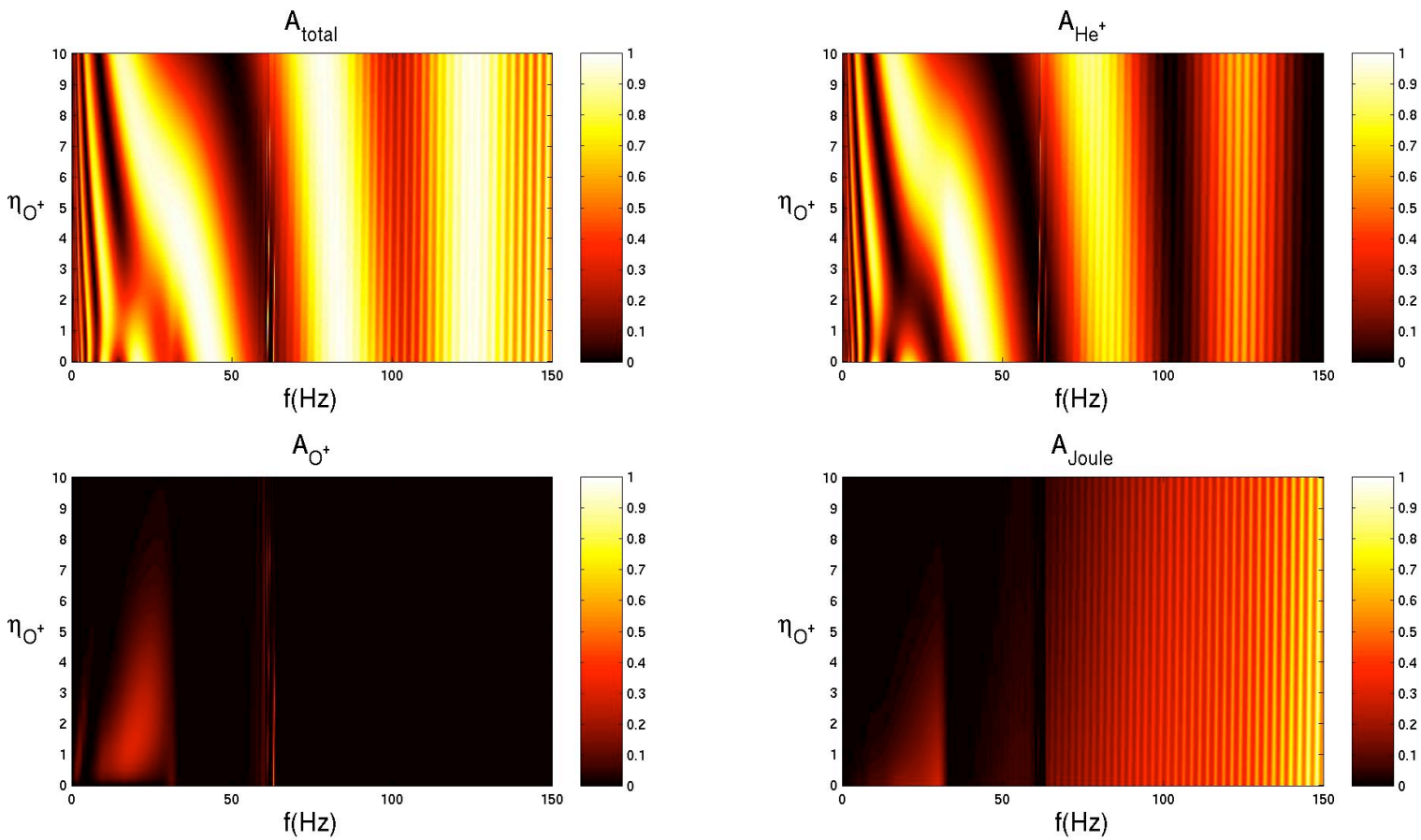
Dependence on He^+ Concentration

η_{O+} =5%; θ=60



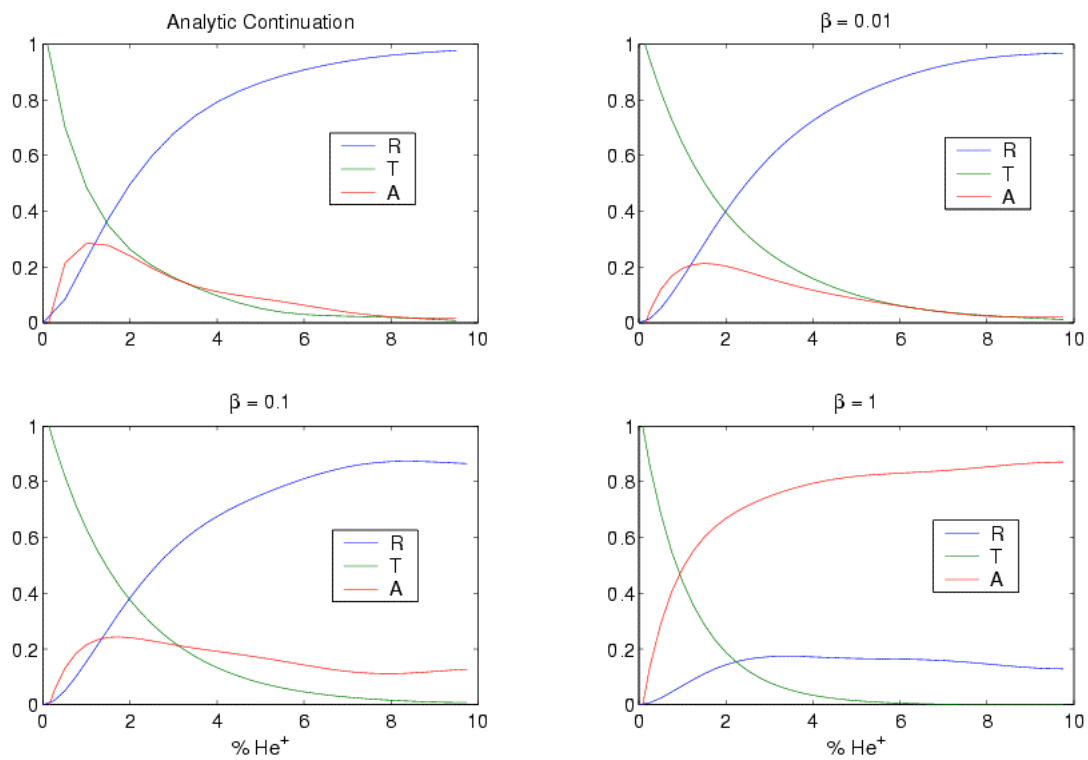
Dependence on O^+ Concentration

η_{He+} =1%; θ=60



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

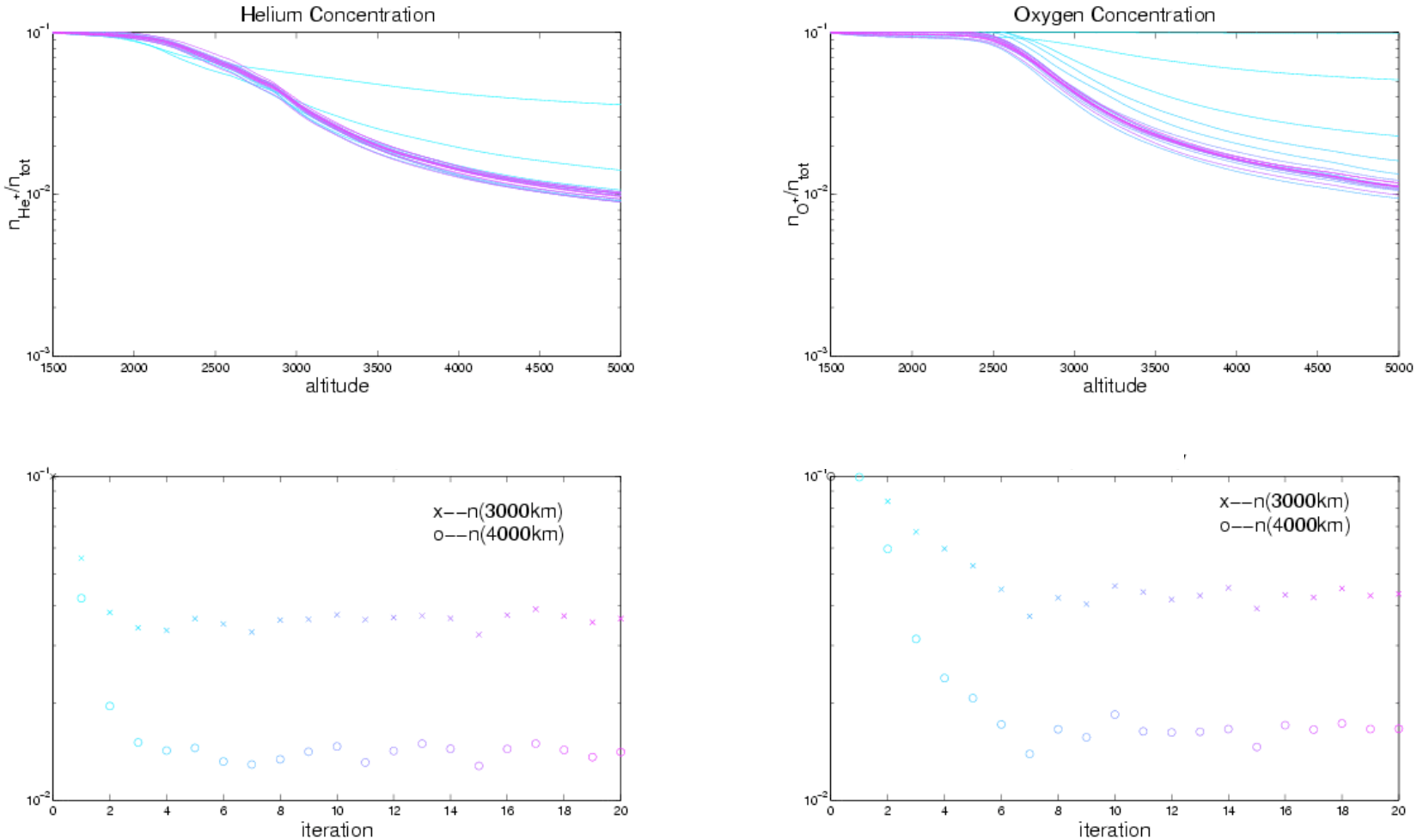
- Background ion profiles determine wave absorption (and generation)
  - Minor ion concentrations and density
  - Local Alfven velocity (which determines wavelength)
  - Spectrum of incident waves (not considered here)
- Wave absorption determines ion heating
  - Heating computed from electromagnetic 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

Iterative Method

- Prescribe wave spectrum at satellite and a plasma profile $d|E|^2/df \gg f^{-\alpha}$; $\alpha = 1.7$
- Initiate with constant density ratio above 1500 km.

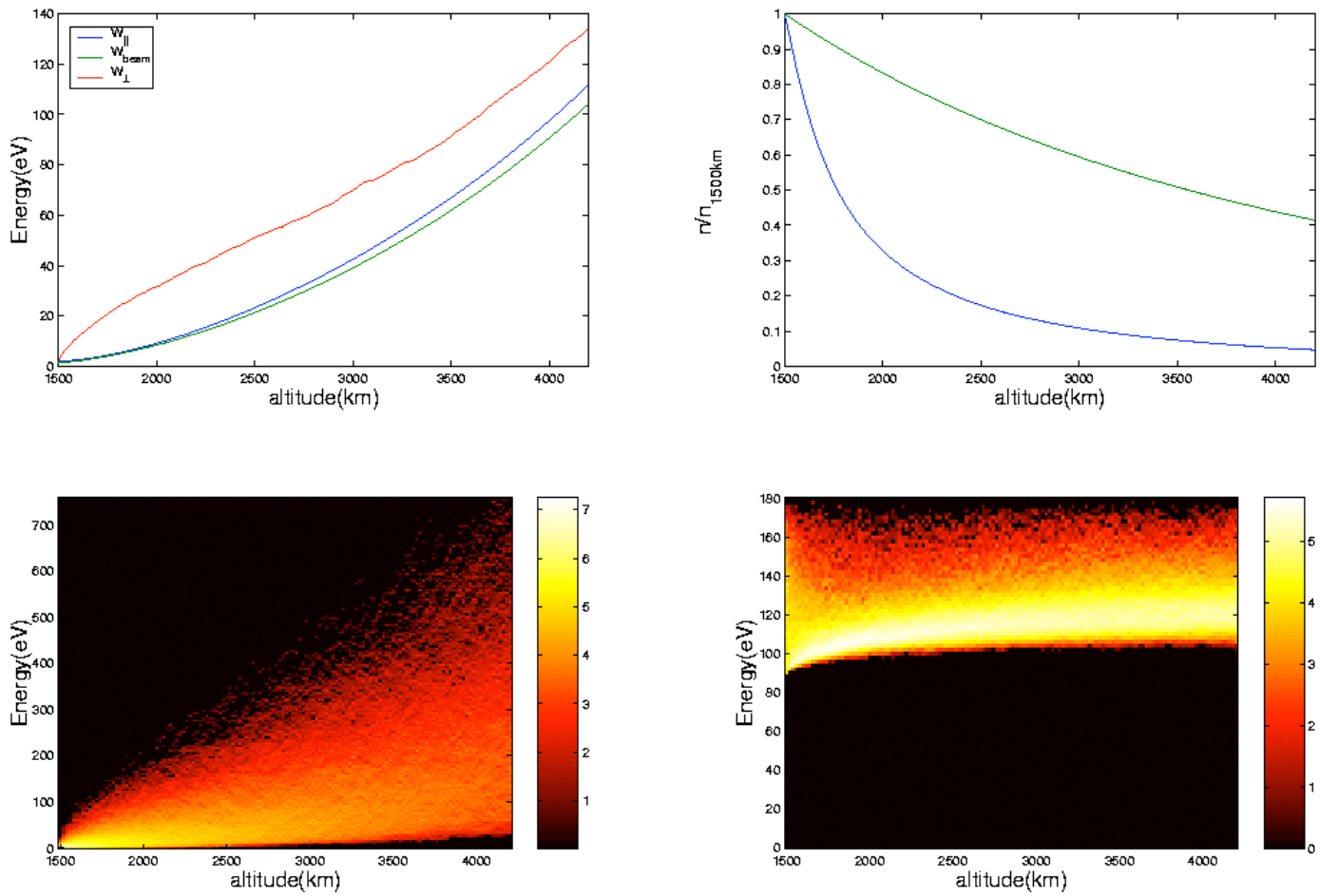
1. Compute linear ion cyclotron wave solutions based on spectrum and model plasma profile
2. Obtain ion heating rate as a function of altitude from the wave absorption
3. Perform Monte Carlo simulation of ions using heating rate
4. Obtain ion density profile and energy moments from the Monte Carlo simulation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

Convergence of Iterative Method



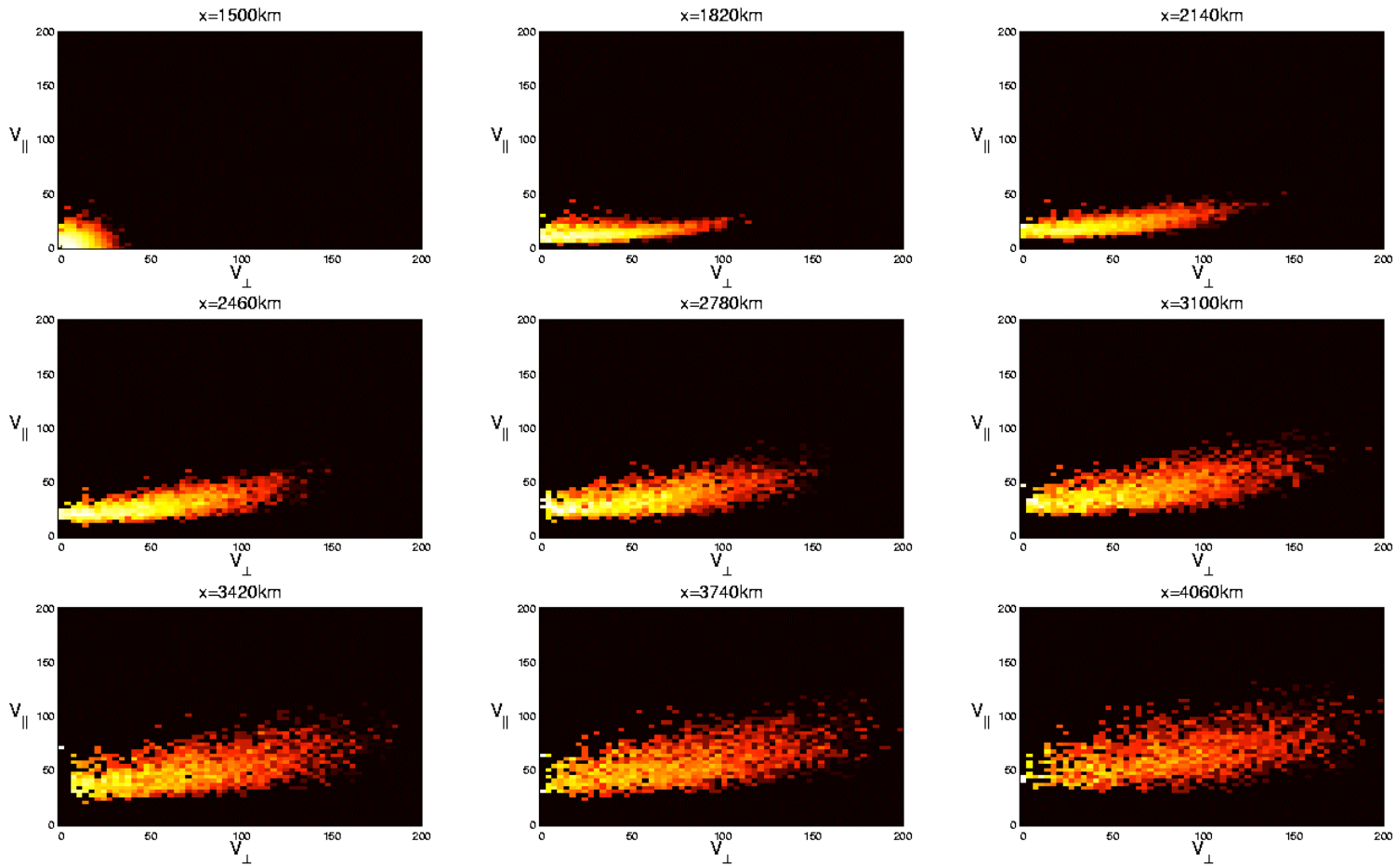
$\theta = 60^o$

Ion Profiles (Heuristic)

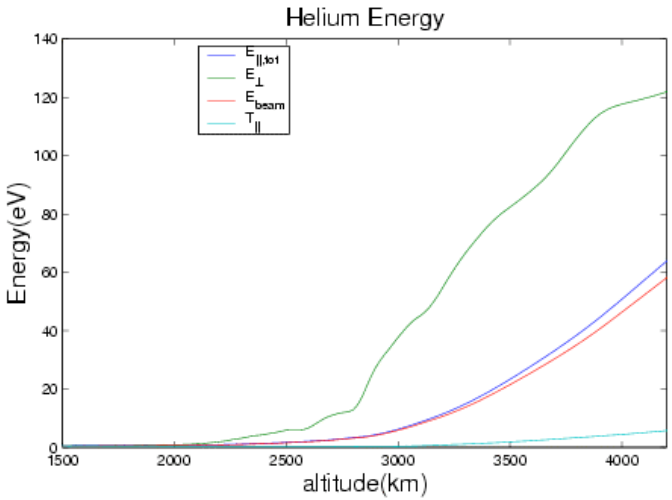


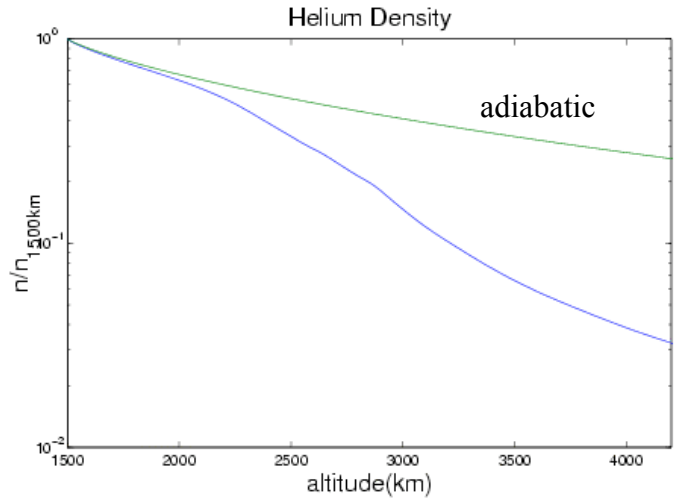
$dW_?/dt = \eta\ (q^2/2m)\ |E_?(\omega = \Omega)|^2$ with $|E_?(\omega = \Omega)|^2$ » $f^{-\alpha}$

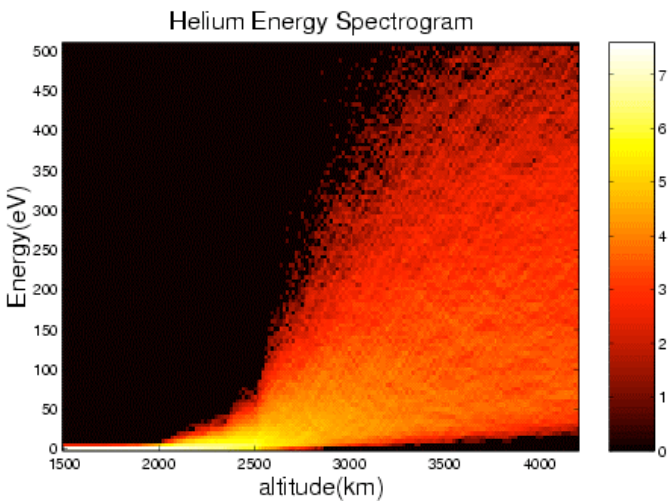
Ion Distribution (Heuristic)

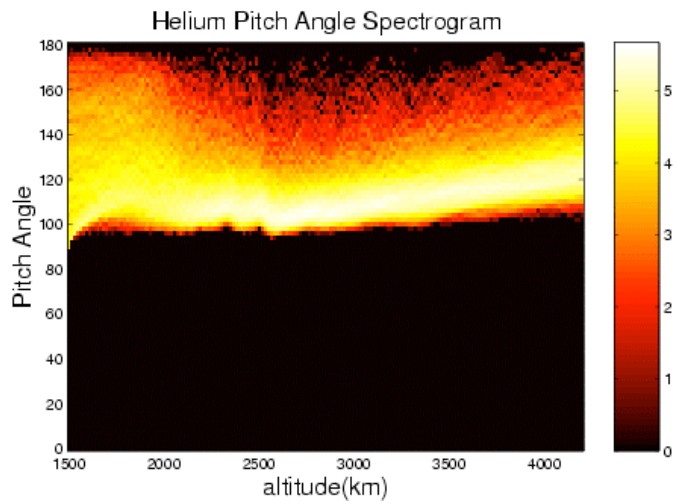


Steady State Helium Profiles θ∴ θ=60, η_{He}=10%,η_O=10%



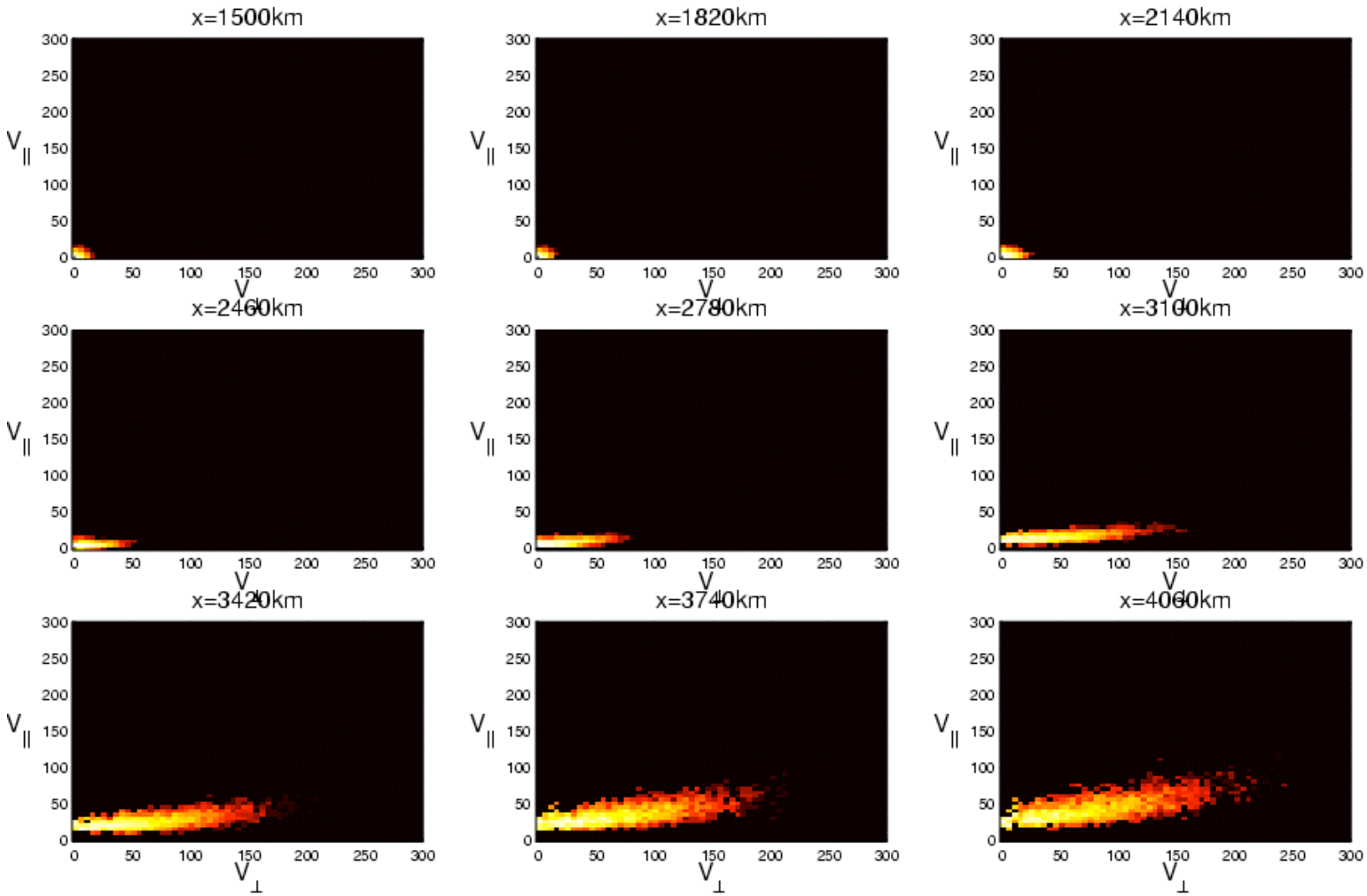




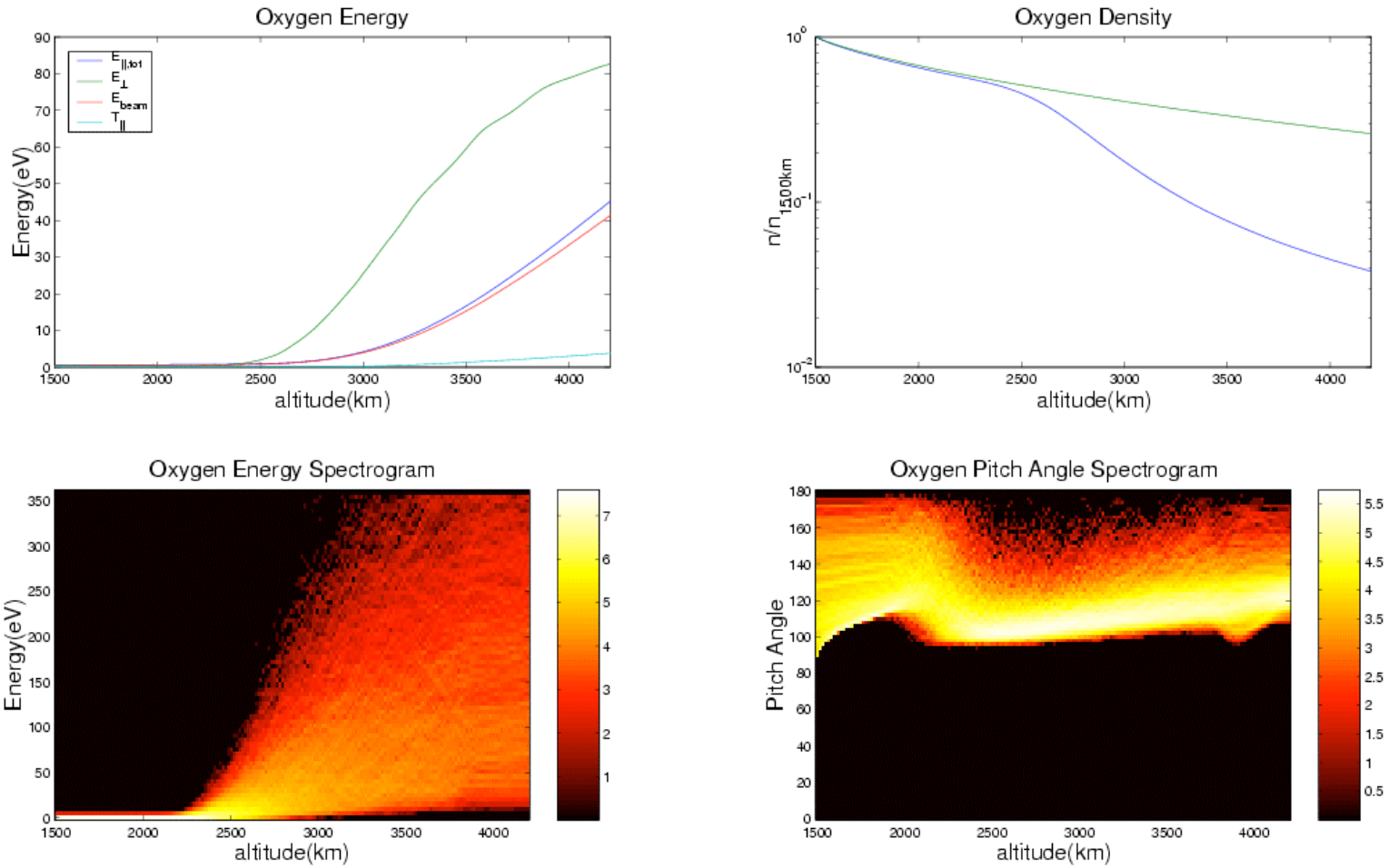


Steady State Helium Distribution

$\theta=60, \eta_{He}=10\%, \eta_{O}=10\%$

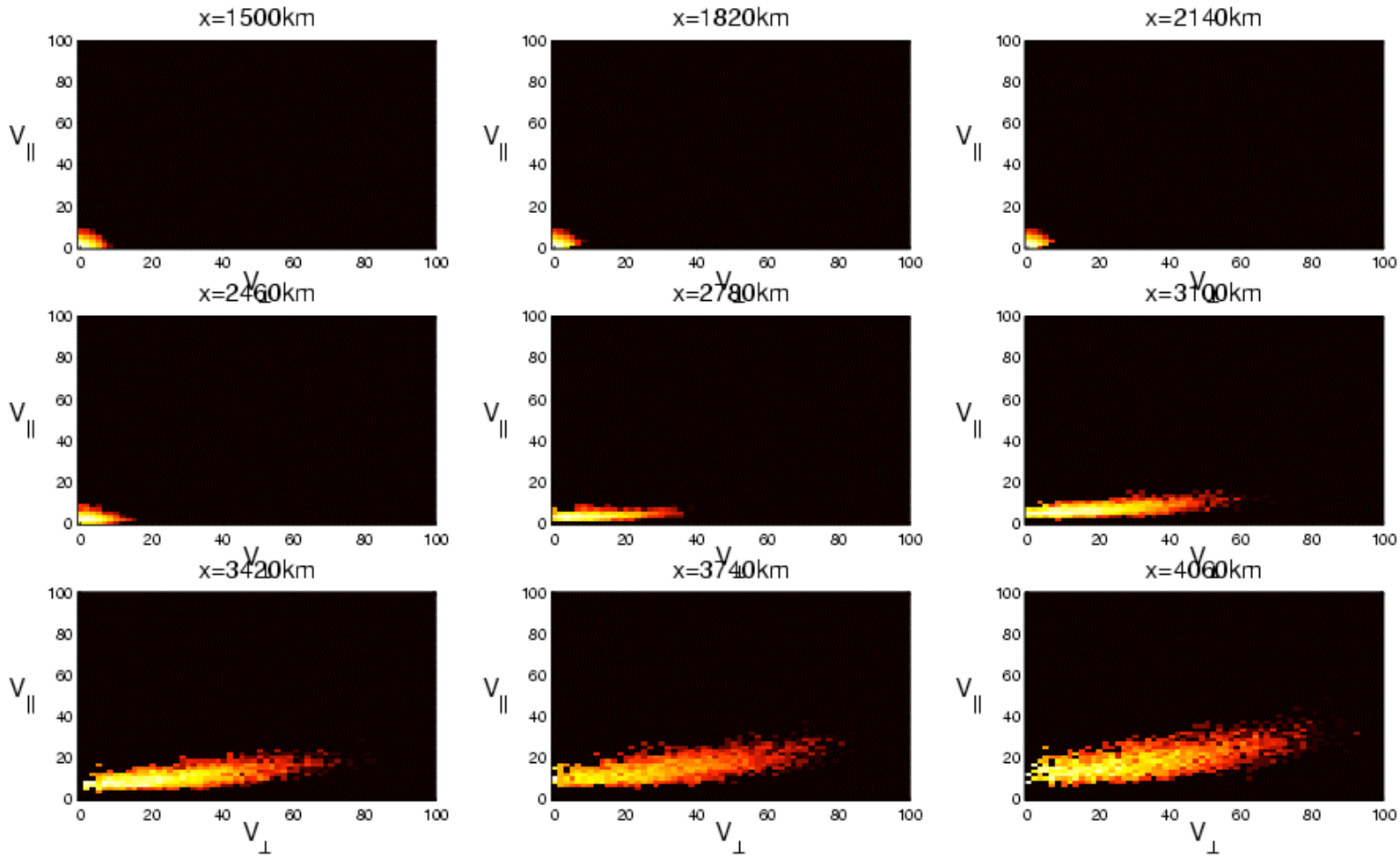


Steady State Oxygen Profiles $\theta=60, \eta_{He}=10\%, \eta_O=10\%$

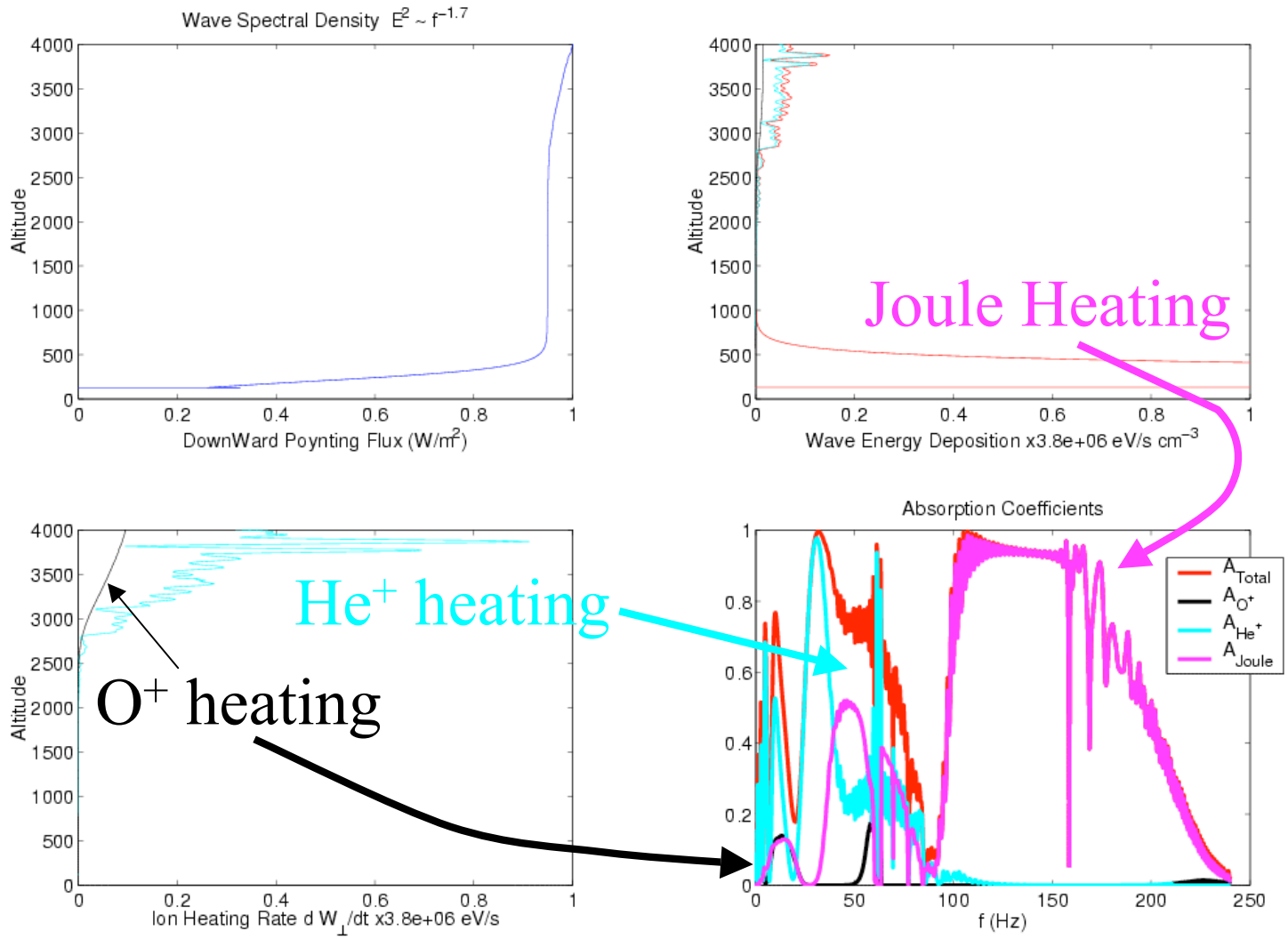


Steady State Oxygen Distribution

$\theta=60, \eta_{He}=10\%, \eta_{O}=10\%$

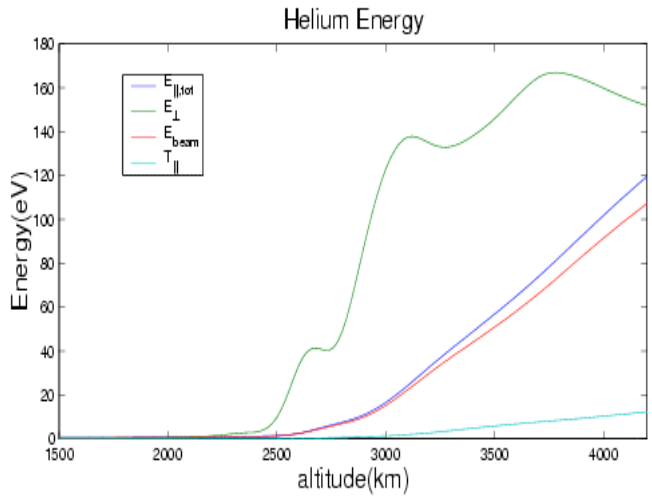


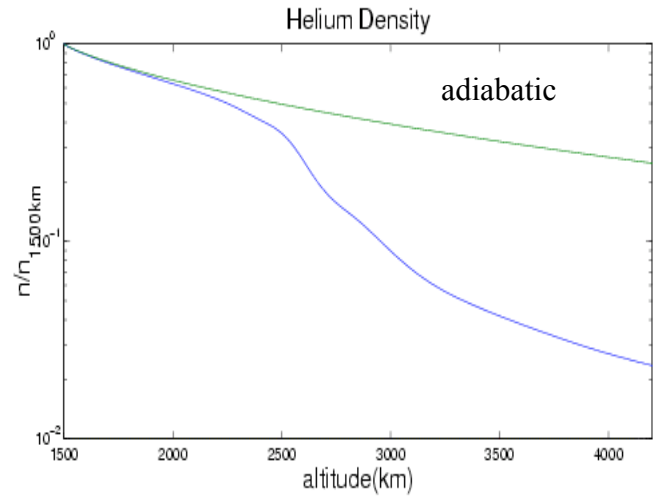
Steady State Heating Rate
$\theta=60, \eta_{He}=10\%, \eta_O=10\%$

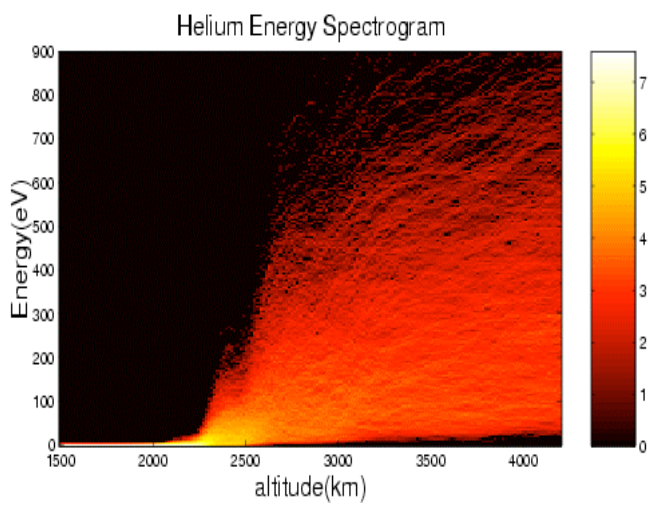


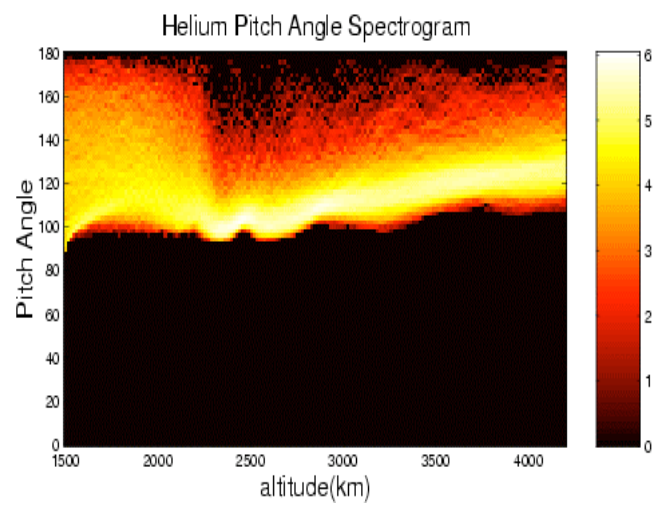
Steady State Helium Profiles

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



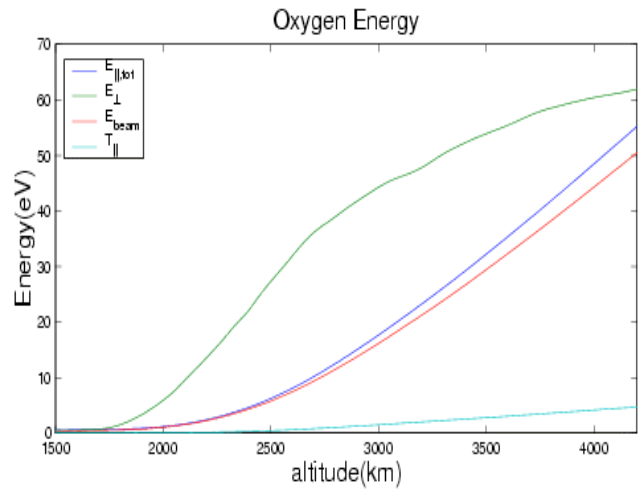


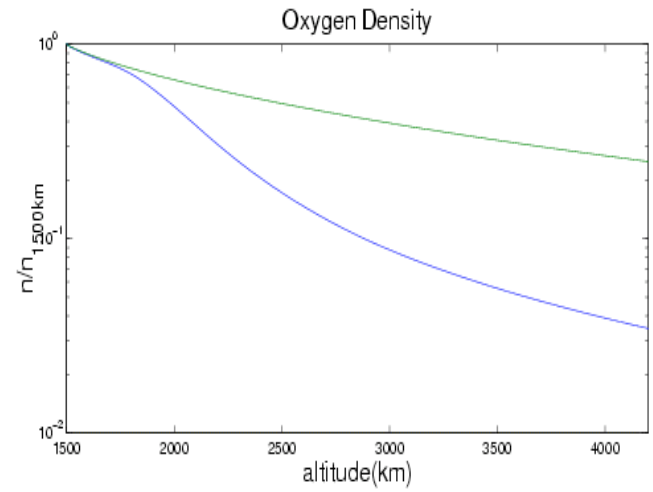


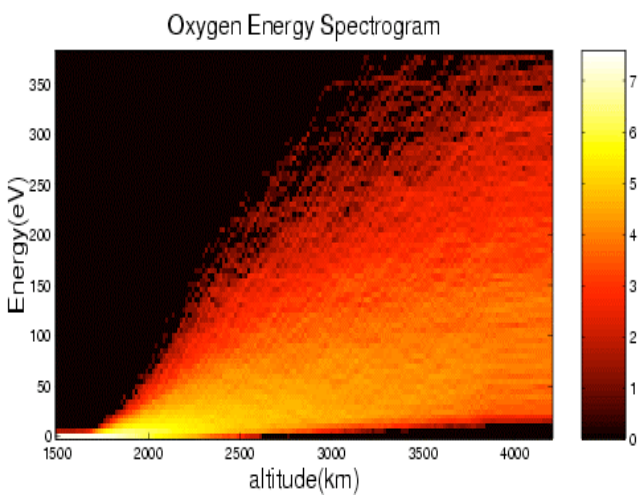


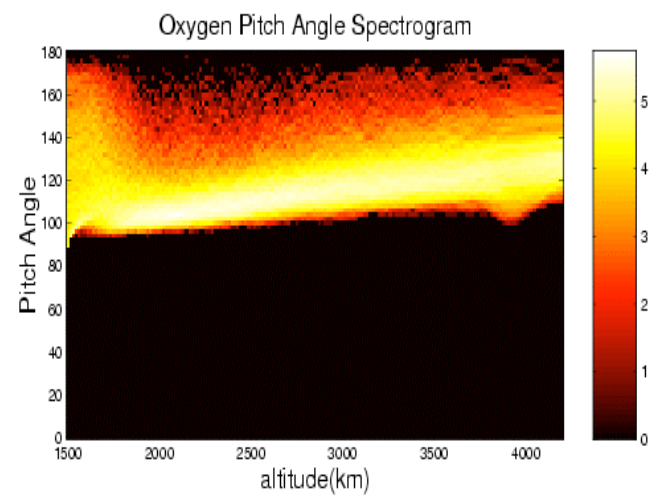
Steady State Oxygen Profiles

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

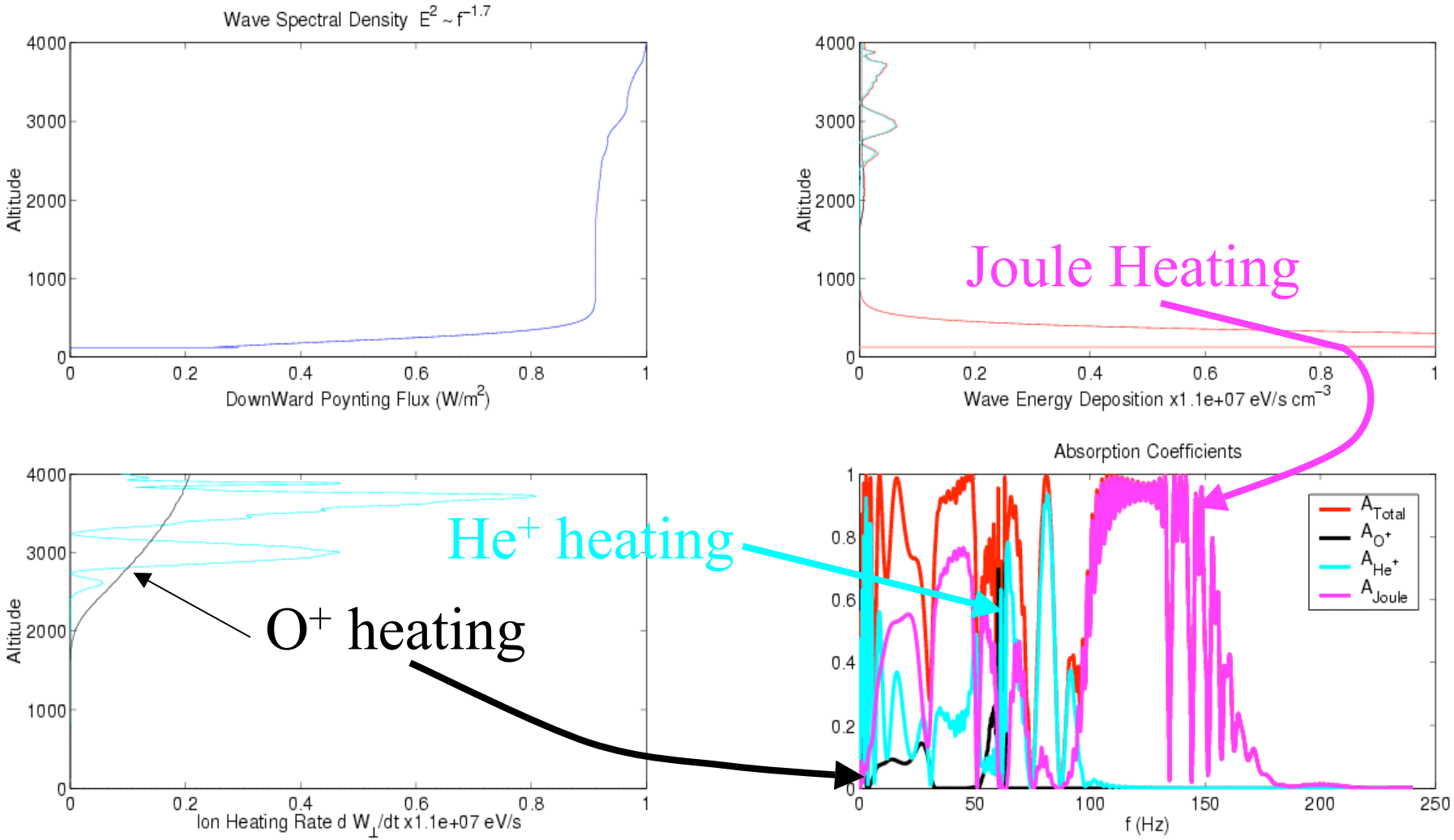




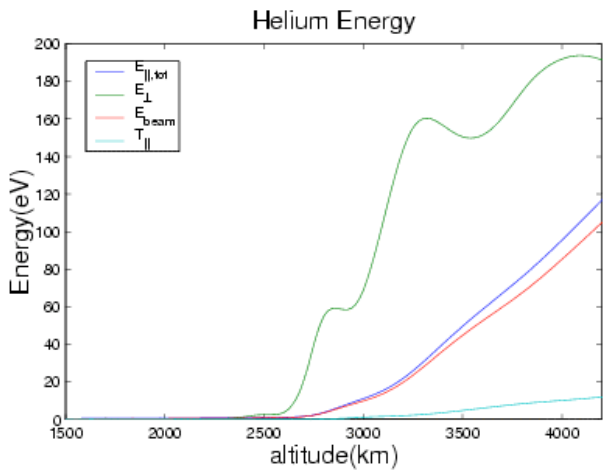


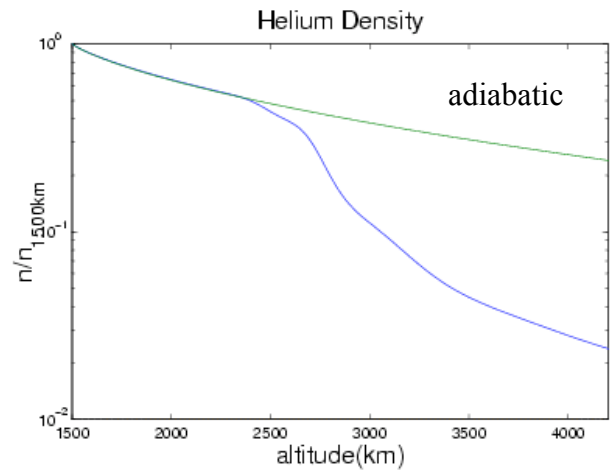


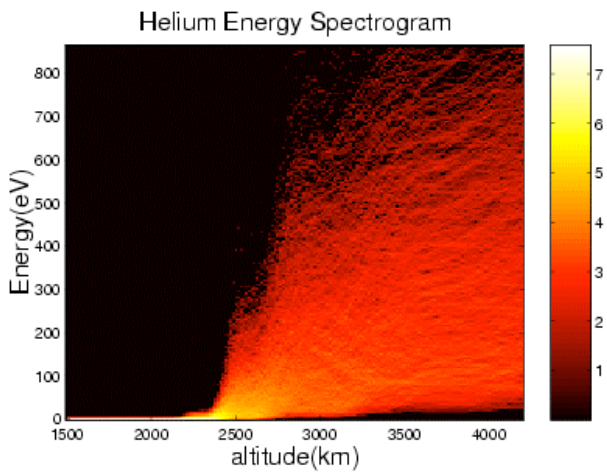
Steady State Heating Rate θ=60, η_{He}=5%,η_O=1%

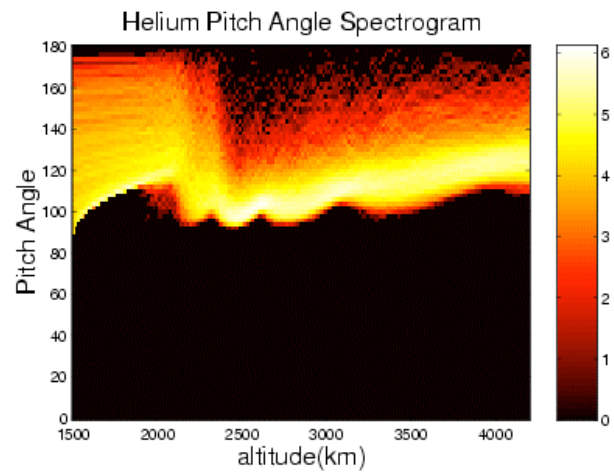


Steady State Helium Profiles
θ=60 η_{He}=5%,η_O=1%



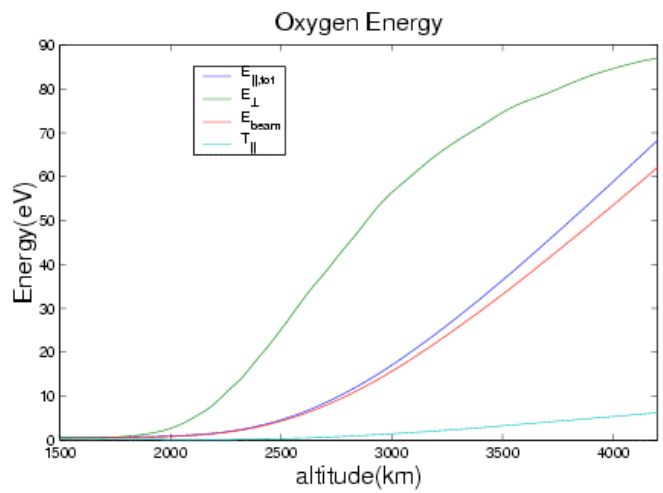


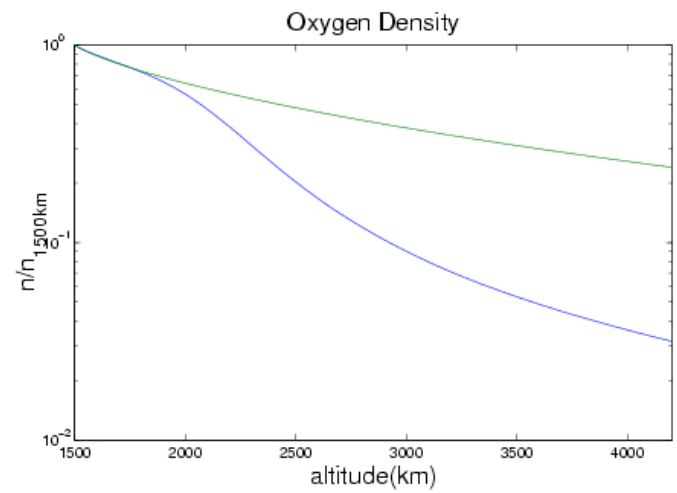


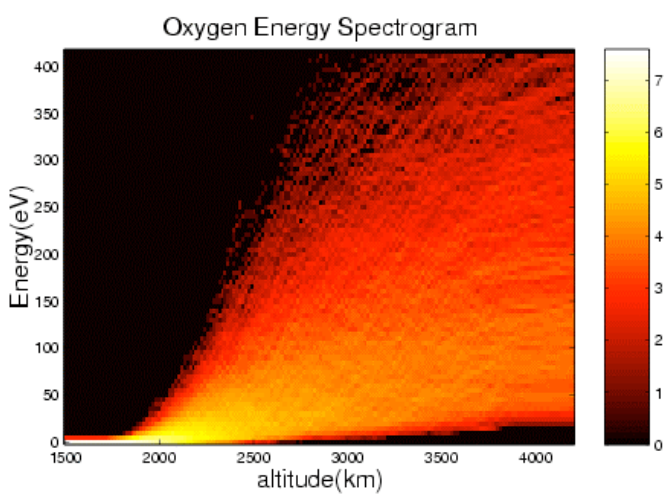


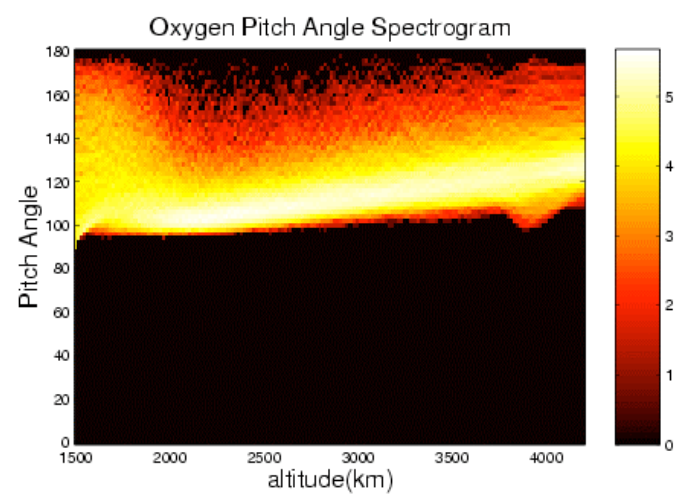
Steady State Oxygen Profiles

$\theta=0, \eta_{He}=5\%, \eta_O=1\%$



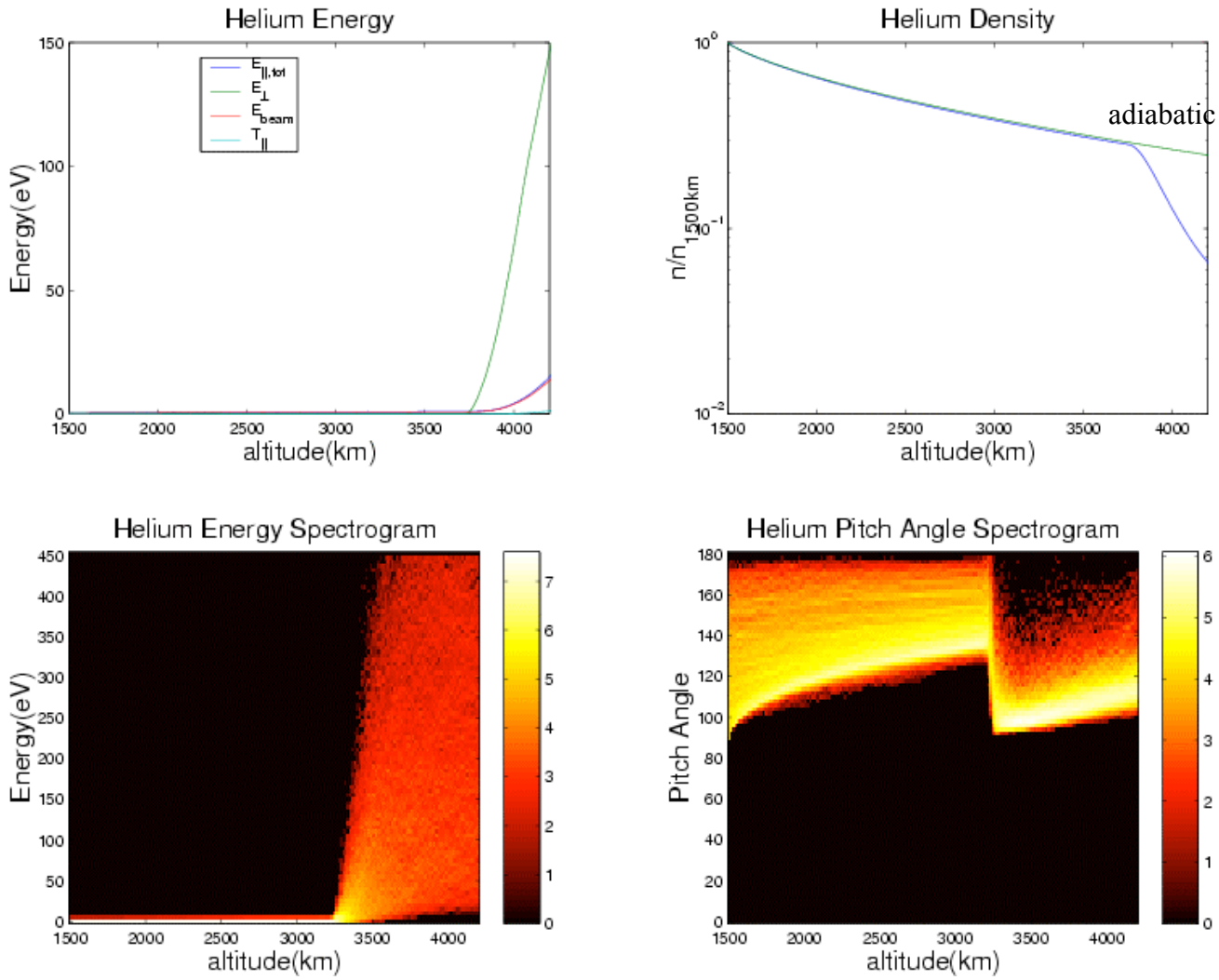






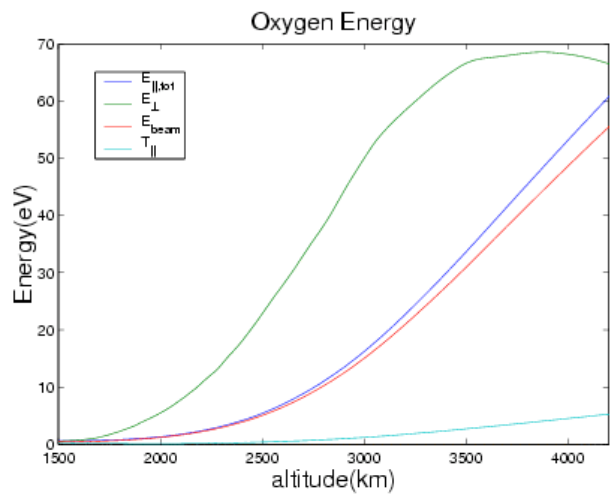
Steady State Helium Profiles

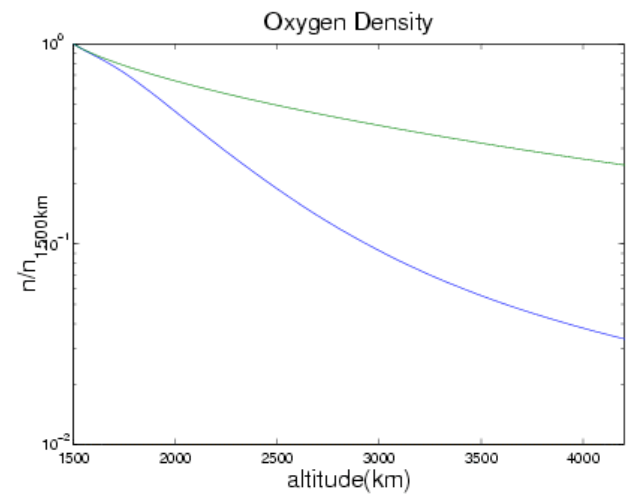
$\theta=89, \eta_{He}=5\%, \eta_O=1\%$

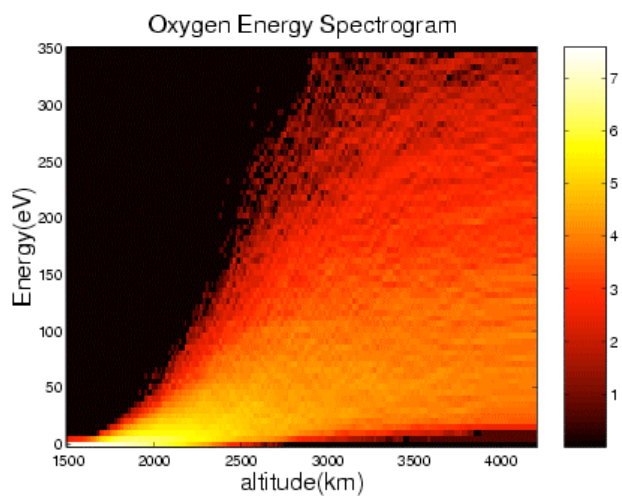


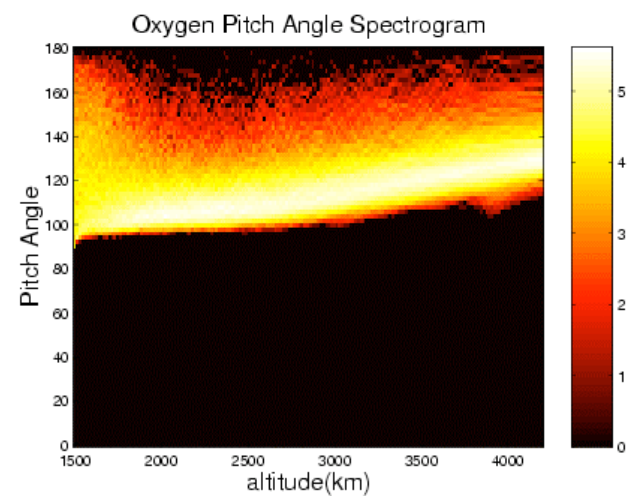
Steady State Oxygen Profiles

$\theta=89, \eta_{He}=5\%, \eta_O=1\%$

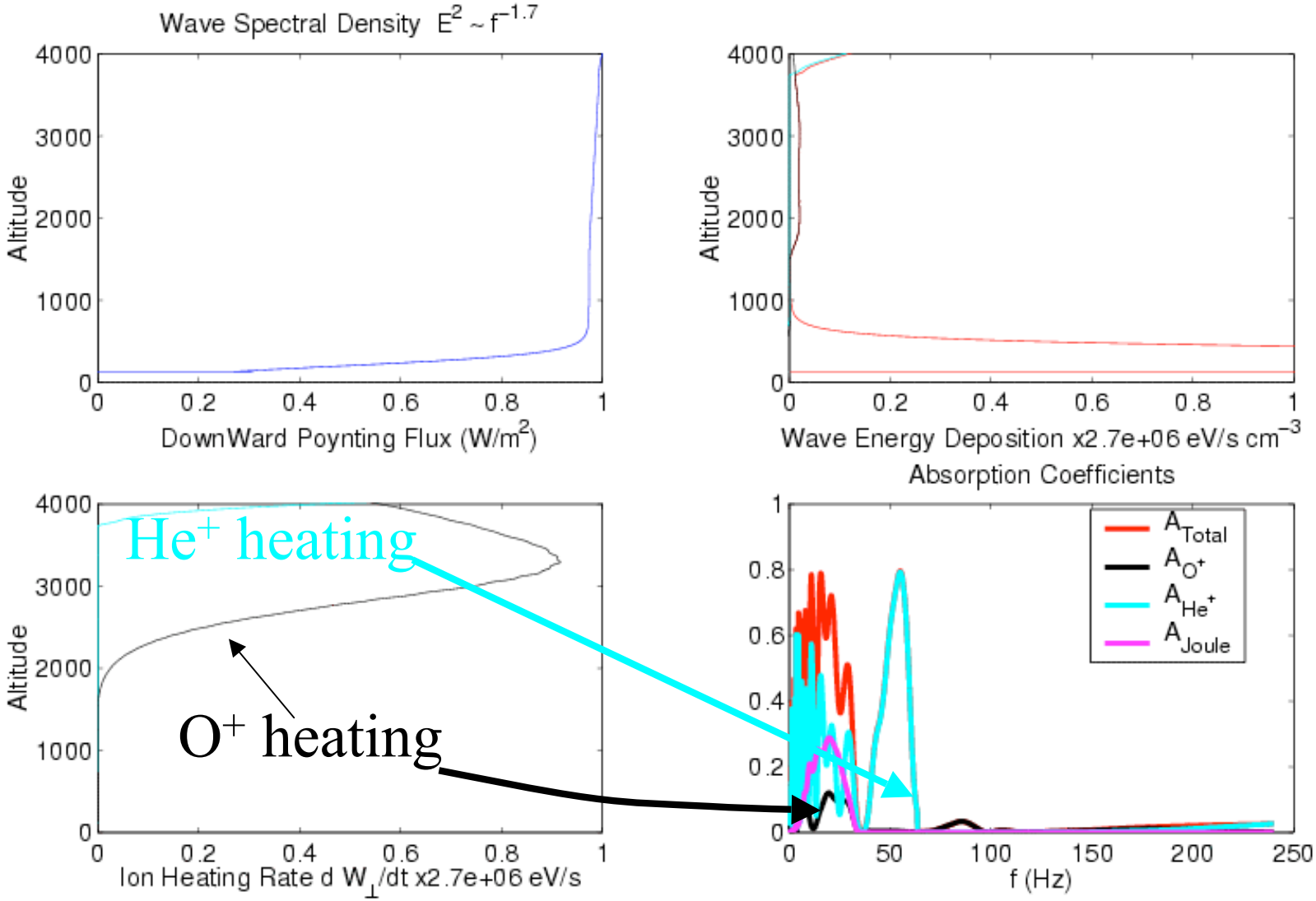








Steady State Heating Rate
$\theta=89, \eta_{He}=5\%, \eta_O=1\%$



Significant Findings

- Significant high frequency wave power (1Hz<f<200Hz) reaches the ground/ionosphere where observed (but not if wavevector oblique)
- Small scale fine frequency dependence of coefficients is due to coupling to compressional modes localized in the F-region
- Oblique modes primarily heat He^+ above 3000km (high frequency waves cannot tunnel)
- Apparently He^+ concentration should decrease prior to O^+ heating
- Preferential heating of He^+

Future Work

- Time development of plasma profile
  - He^+ energization prepares O^+ energization
- Parallel electric field
  - Large-scale field accelerates electrons and provides free energy for EMIC waves
  - Self-consistent ϕ maintains quasineutrality (estimate for our calculation ~10V)
- Feedback of waves on the electron beam generator/potential---integral equation

Reprint Request

Name Address

Unresolved Issues

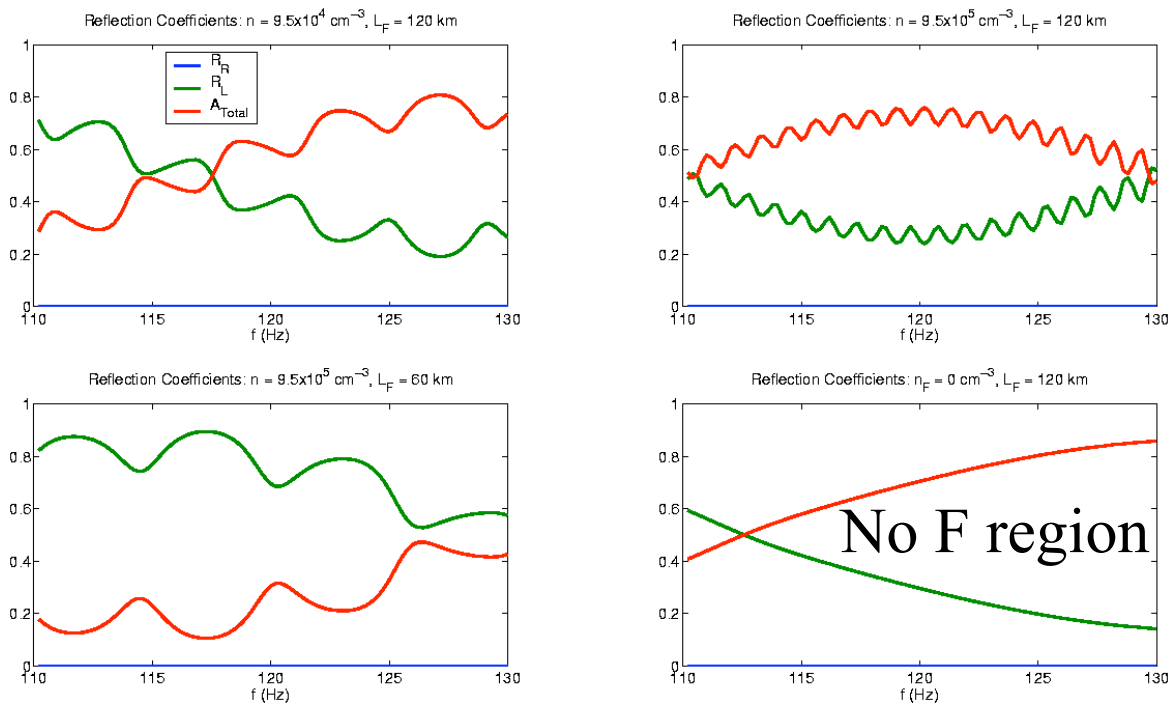
- H^+ EMIC waves f~100Hz observed in the ionosphere and magnetosphere
- Ray tracing cannot explain observations
- Resolution: solve full wave equations
  - Mode conversion
  - Tunneling
- Do the waves produce preferentially heated helium?

Ionospheric Resonator Produces Modulations

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

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

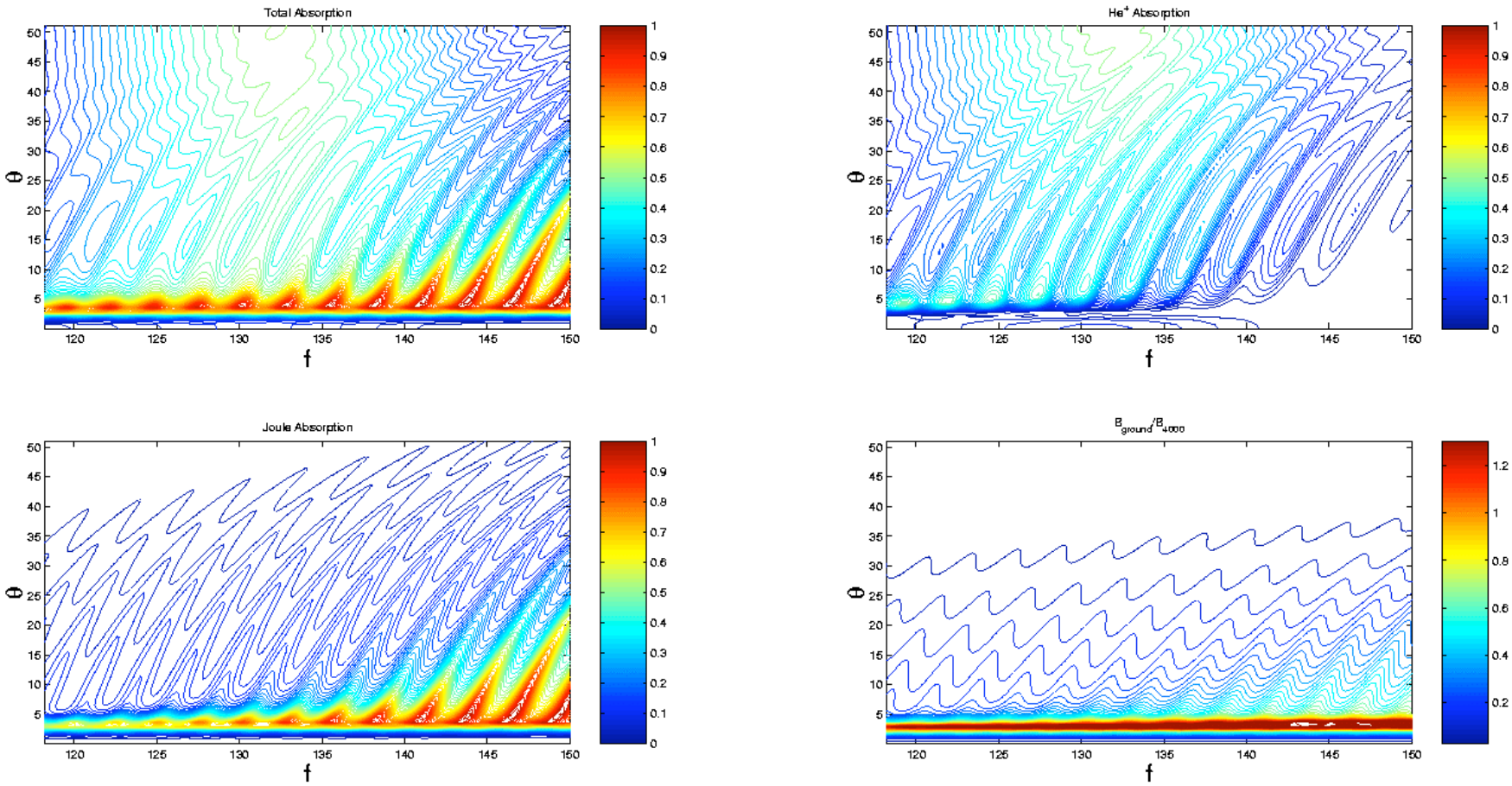
$L_F \downarrow 2 \Rightarrow \Delta f \uparrow 2$



Frequency-Wavevector Relation

Note: Compressional Wave Coupling in Ionosphere

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



Heating Rate

- Assume spectral density: $E(f) \sim E_0 (f/f_0)^{-\alpha}$
- Obtain spectrum of Poynting flux $S(z_0)$
- Remove Poynting flux where absorbed
- Obtain volume heating rate from dS/dz
- $dW/dt = n^{-1} dS/dz$ (energy/particle/sec)

Future Work

- Include parallel electric field
  - Ion heating pulls ions out of the topside ionosphere creating a small charge imbalance
  - A downward electric field would develop to pull the electrons out of the ionosphere with the ions
  - For the case with no outgoing electric beam this electric field is only 10eV and can be neglected
  - In upward current regions, with large beam energy, the parallel electric field must be included
  - Compute parallel electric field by imposing quasineutrality and iterating until the electron and ion density are the same within a given tolerance