CEDAR 2017

Tutorial on Plasma-Neutral Interactions in the MLT-X

[MLT-eXtended from the Upper Mesosphere through the Middle Thermosphere (80-200 km)]

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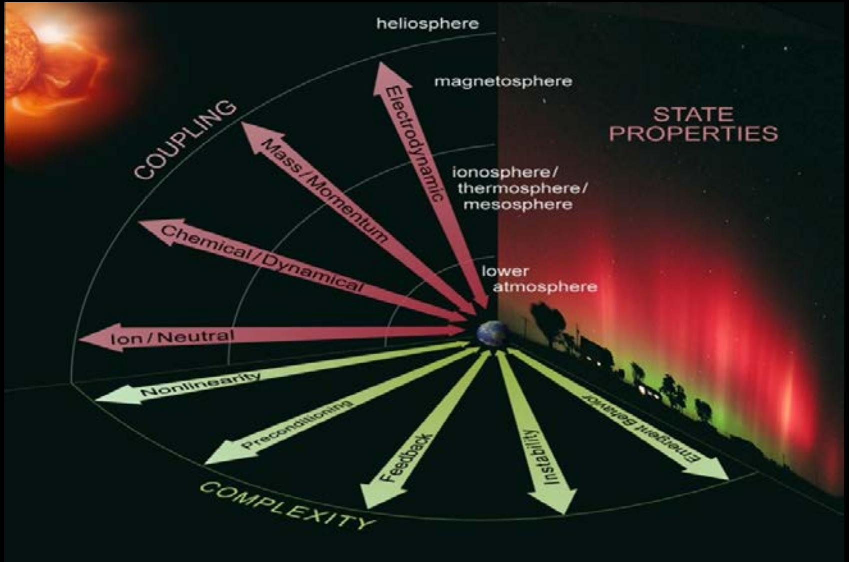


The Universality of Plasma-Neutral Interactions

- Planetary Space-Atmosphere Interaction Regions
- Stellar Chromospheres
- Dusty Plasmas
- Interplanetary Space Weather (Planetary Habitability)
- Interstellar Space Weather (Exoplanets)

Tutorial Outline

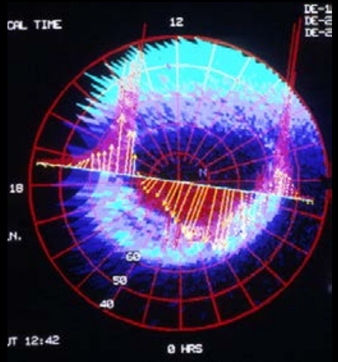
- Earth's Space-Atmosphere Interaction Regions (SAIR)
  - Weakly ionized gas description
  - Transport Equations
  - Ionosphere plasma motion
  - Conductivity and Currents
  - Frictional and Joule Heating Rates

- Our Sun's Chromosphere
  - Weakly ionized gas description
  - Plasma mobilities
  - Joule Heating Rates

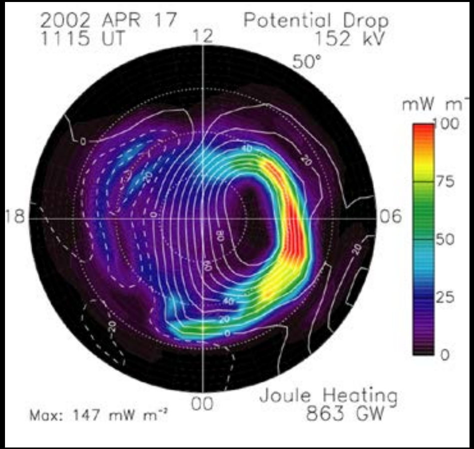
SAIR Plasma-Neutral Interactions

Plasma-Neutral Chemistry

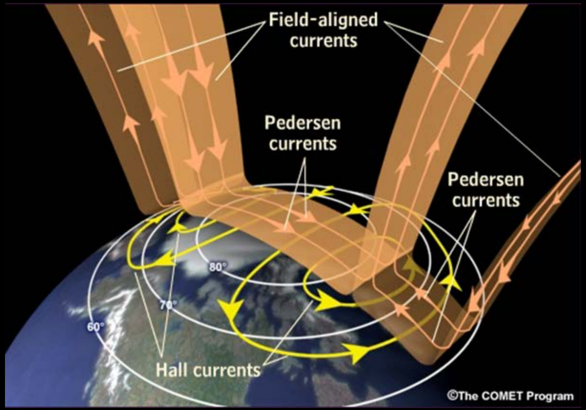
Plasma-Neutral Drag Forces



Plasma-Neutral Frictional Heating

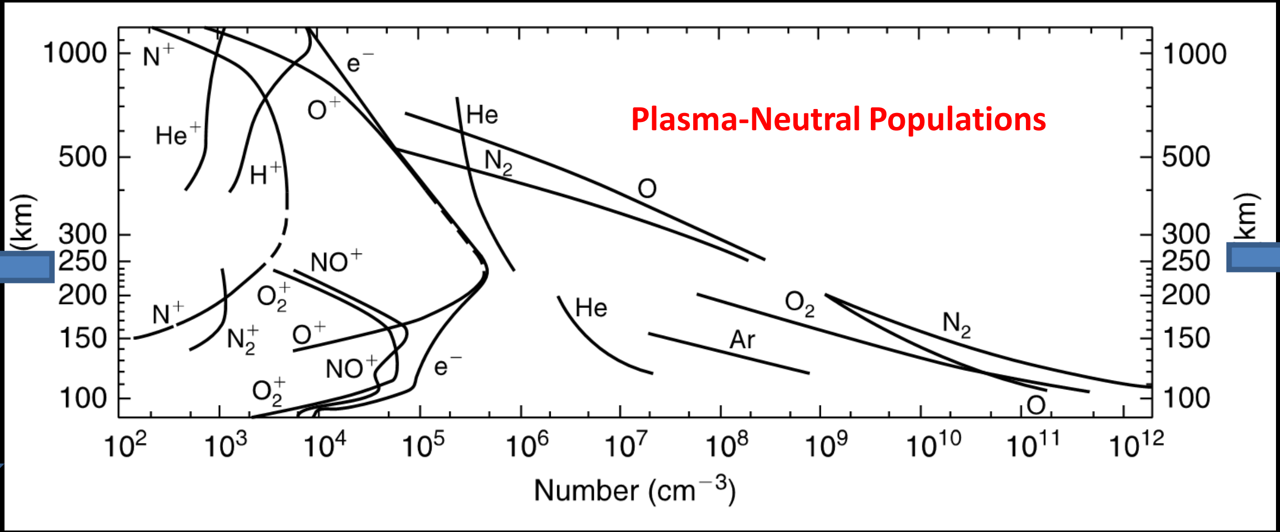


Plasma-Neutral Electrodynamics



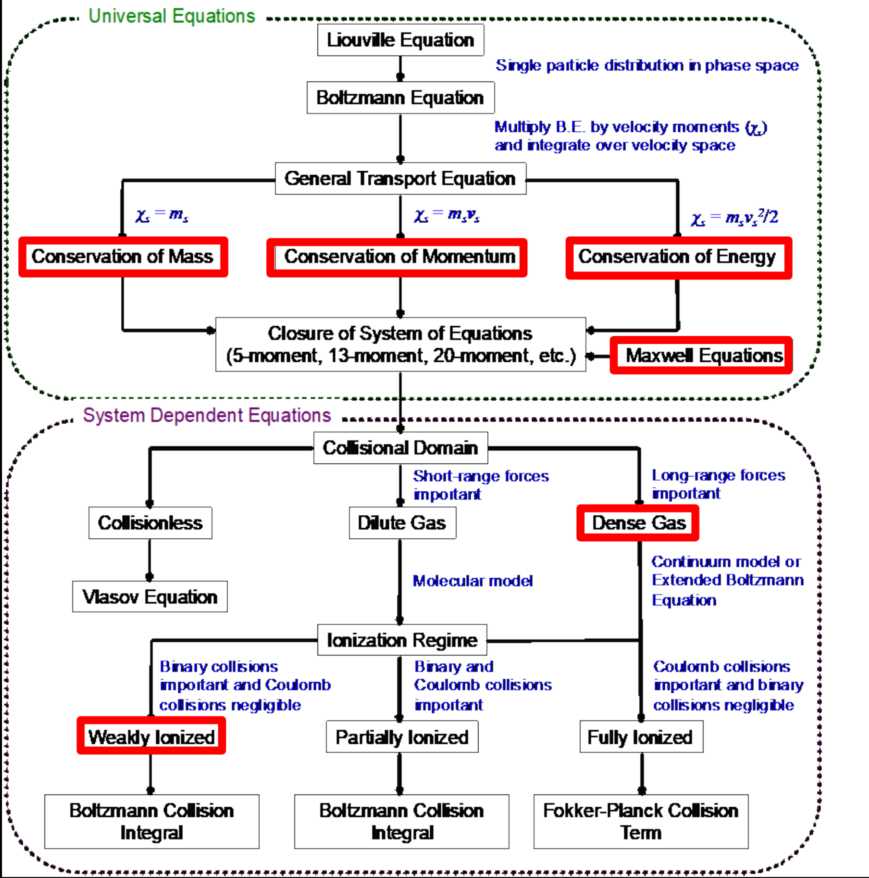
Earth's Ionosphere/Thermosphere

Partially Ionized Gas Above 250 km – plasma-neutral and Coulomb interactions are equally important

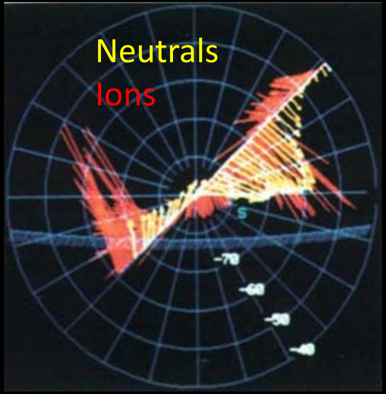


Weakly Ionized Gas (or a strongly neutral gas) below 250 km – plasma-neutral interactions dominate over Coulomb interactions

Upper Atmosphere System of Equations



Upper planetary atmospheres must include coupled equations for the neutral gas and plasma (electron and ion) typically defined in a rotating coordinate system.



The equations become system dependent when considering the collisional aspects of the environment and the definition of an average velocity by which all higher moments are defined.

Upper Atmosphere Transport System of Equations

(Schunk and Nagy: Ionospheres Physics, Plasma Physics, and Chemistry)

Taking velocity moments of the Boltzmann Equation leads to various forms of the transport equations:

- 5th moment (n=1, **u**=3, T=1): assumed drifting Maxwellian distribution with isotropic pressure and all higher order moments neglected
- 13th moment (n=1, **u**=3, T=1, **q**=3, τ=5) assumed small departure from Maxwellian with higher order moments expressed in terms of the five variables
- 20th moment (n=1, **u**=3, T=1, τ=5, $\boldsymbol{Q}$=10) assumed large departure from Maxwellian with the full heat flux tensor required to adequately represent the gas or plasma behavior

Maxwell's Equations

Maxwell Equations in vacuum

$$\vec{\nabla} \bullet \vec{E} = \frac{\rho_c}{\varepsilon_0} \quad (Gauss's\, Law)$$

$$\vec{\nabla} \bullet \vec{B} = 0$$

$$\frac{\partial \vec{B}}{\partial t} = -\vec{\nabla} \times \vec{E} \quad (Faraday's\, Law)$$

$$\mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} = \vec{\nabla} \times \vec{B} - \mu_0 \vec{J} \quad (Ampere's\, Law)$$

Maxwell Equations applied to Ionosphere

$$\vec{\nabla} \bullet \vec{E} = \frac{\rho_c}{\varepsilon_0}$$

$$\vec{\nabla} \bullet \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = 0 \quad (\vec{E} = -\nabla \Phi)$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}$$

Conservation of Charge

$$\vec{\nabla} \bullet \vec{J} = -\frac{\partial \rho_c}{\partial t} \approx 0$$

Charge Neutrality

$$n_e \approx \sum_{ions} n_i$$

Ionosphere Ohm's Law (in neutral frame)

$$\vec{j} = \sigma_P \vec{E}'_\perp - \sigma_H \frac{\vec{E}'_\perp \times \vec{B}}{B} + \sigma_\parallel \vec{E}'_\parallel$$

Upper Atmosphere Transport System of Equations

Two main Points to Remember Throughout this Tutorial:

Define your coordinate system and reference frame:

- Often determined for mathematical or numerical convenience
  - Pressure coordinates in the vertical are often used to make equations more tractable mathematically and/or numerically
- Often Earth-fixed frame
  - Rotating reference frame

Understand your coordinate system and reference frame:

- Physical Interpretation
  - Earth-fixed frame is non-inertial frame: requires Coriolis and Centripetal accelerations
  - Average velocity definition of the system (important for defining higher order moments (pressure, temperature, viscosity) and describing behavior in a multiconstituent gas

Multiconstituent Momentum Eqs for a Weakly Ionized Gas

Neutrals:

$$n_n m_n \frac{d\vec{U}_n}{dt} = -\vec{\nabla} P_n - \nabla \bullet \vec{\tau}_n + n_n m_n \left[\vec{g} - 2\vec{\Omega} \times \vec{U}_n - \vec{\Omega} \times \left(\vec{\Omega} \times \vec{r} \right) \right] - n_n m_n \upsilon_{ni} \left(\vec{U}_n - \vec{V}_i \right)$$

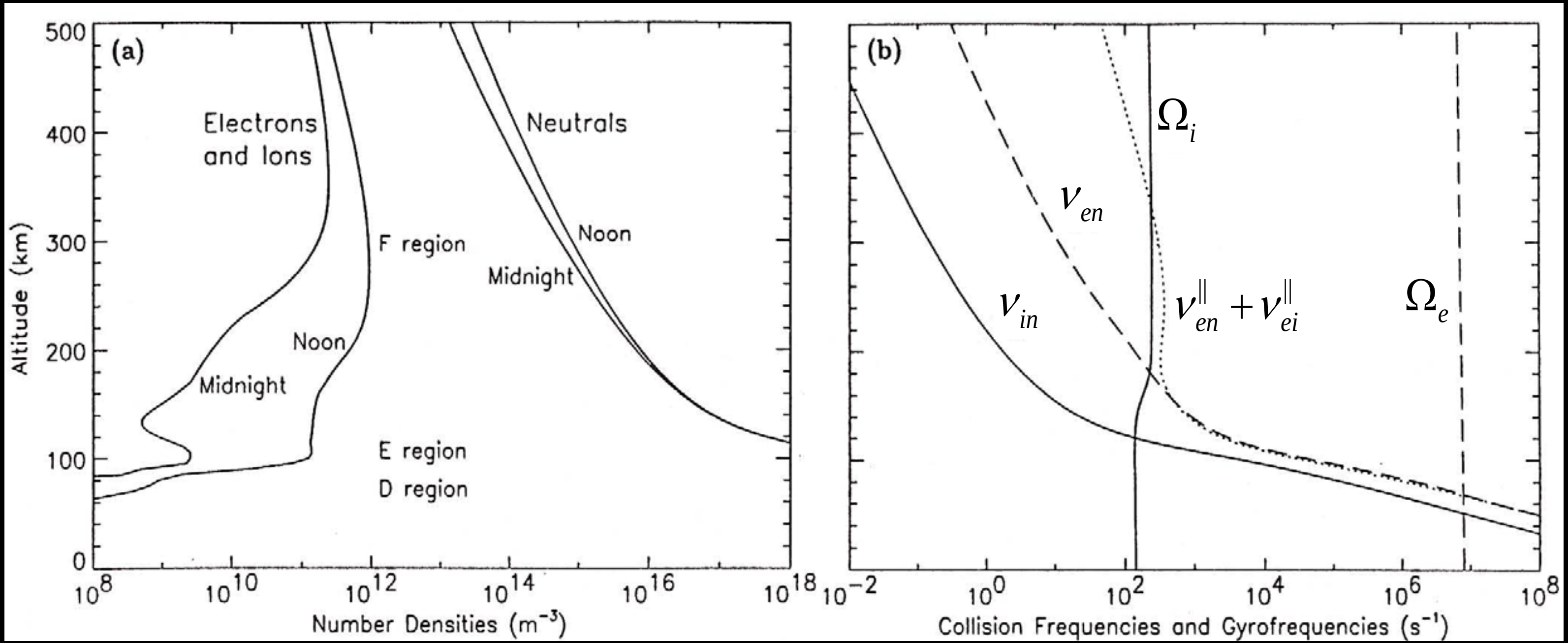
Ions:

$$n_i m_i \frac{d\vec{V}_i}{dt} = -\vec{\nabla} \vec{P}_i + n_i m_i \vec{g} + e n_i \left(\vec{E} + \vec{V}_i \times \vec{B} \right) - n_i m_i \upsilon_{in} \left(\vec{V}_i - \vec{U}_n \right)$$

Electrons:

$$n_e m_e \frac{d\vec{V}_e}{dt} = -\vec{\nabla} \vec{P}_e + n_e m_e \vec{g} + e n_e \left(\vec{E} + \vec{V}_e \times \vec{B} \right) - n_e m_e \upsilon_{en} \left(\vec{V}_e - \vec{U}_n \right)$$

I/T: Plasma-Neutral Collisions



$k = \dfrac{\Omega}{\nu}$, mobility

$\Omega = \dfrac{qB}{m}$, gyrofrequency

ν_{en}, electron-neutral collision frequency

ν_{in}, ion-neutral collision frequency

Richmond, A.D., and J.P. Thayer, Ionospheric electrodynamics: A tutorial, *Magnetospheric Current Systems,* Geophysical Monograph Volume 118, 2000

Ion and Electron Momentum Eqs for a Weakly Ionized Gas

Ion and electron momentum equation accounts for pressure gradient, gravitational, electric, magnetic, and collisional forces

$$n_i m_i \frac{d\vec{V}_i}{dt} = -\vec{\nabla}\vec{P}_i + n_i m_i \vec{g} + e n_i \left(\vec{E} + \vec{V}_i \times \vec{B}\right) - n_i m_i \upsilon_{in}\left(\vec{V}_i - \vec{U}_n\right)$$

$$n_e m_e \frac{d\vec{V}_e}{dt} = -\vec{\nabla}\vec{P}_e + n_e m_e \vec{g} + e n_e \left(\vec{E} + \vec{V}_e \times \vec{B}\right) - n_e m_e \upsilon_{en}\left(\vec{V}_e - \vec{U}_n\right)$$

Assume only static E- and B-fields and neutral collisions with U_n=0,

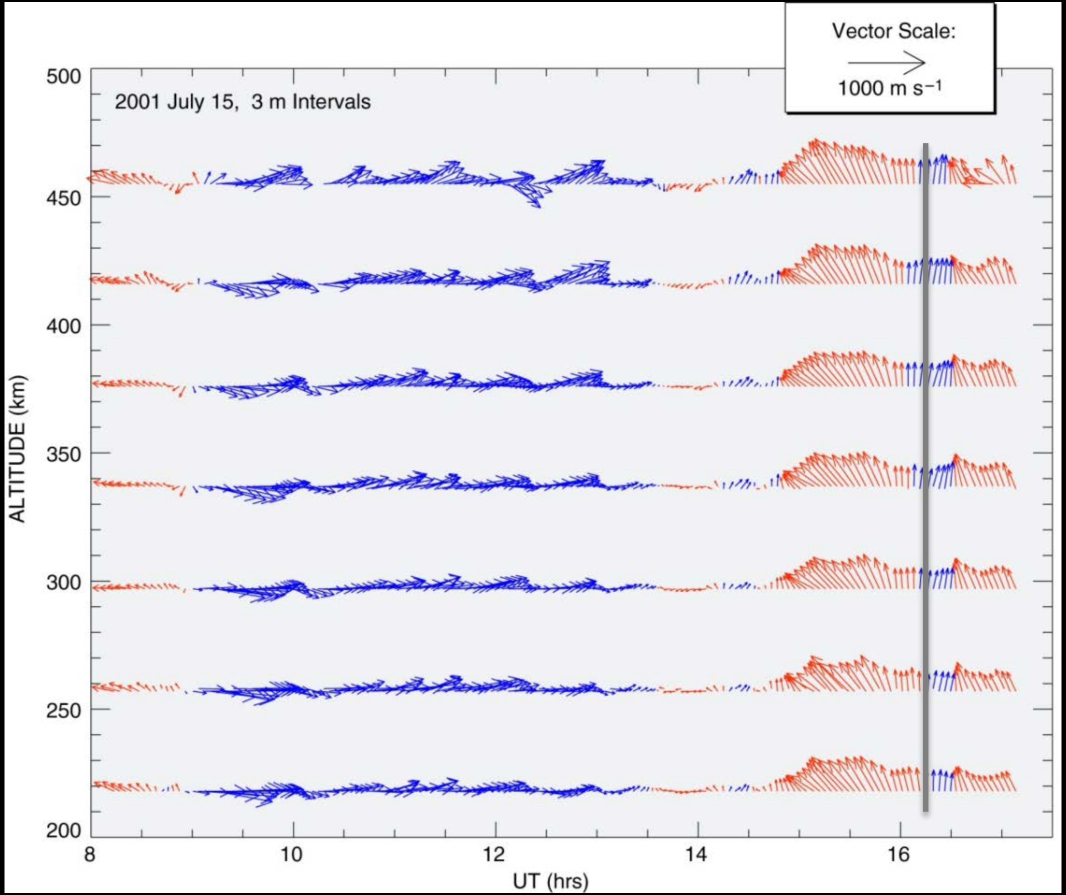
Ions:

$$\vec{V}_i = \frac{1}{1+k_i^2}\left\{\frac{k_i}{B}\vec{E} + \left(\frac{k_i}{B}\right)^2 \vec{E}\times\vec{B} + \left(\frac{k_i}{B}\right)^3 \left(\vec{E}\bullet\vec{B}\right)\vec{B}\right\} \qquad \text{where } \; k_i = \frac{\Omega_i}{\upsilon_{in}}$$

Electrons:

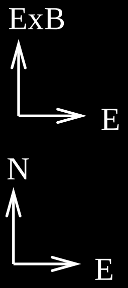
$$\vec{V}_e = \frac{1}{1+k_e^2}\left\{\frac{-k_e}{B}\vec{E} + \left(\frac{k_e}{B}\right)^2 \vec{E}\times\vec{B} - \left(\frac{k_e}{B}\right)^3 \left(\vec{E}\bullet\vec{B}\right)\vec{B}\right\} \qquad \text{where } \; k_e = \frac{\Omega_e}{\upsilon_{en}}$$

Plasma Drift Measurements – “Frozen-In” Flux

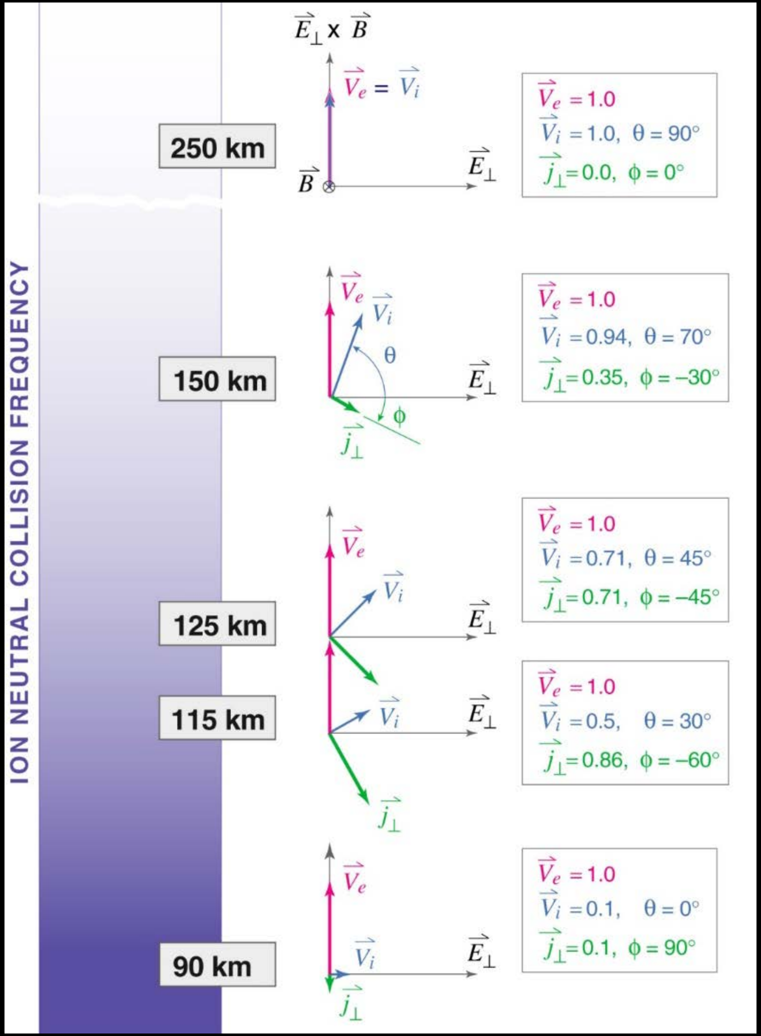


$$when \quad k_i, k_e >> 1$$

$$\vec{V}_{e,i}^{\perp} = \frac{\vec{E} \times \vec{B}}{B^2}$$



Ionosphere Plasma Motion and Currents



$$\vec{V}_i^{\perp} = \frac{1}{1+k_i^2}\left\{\frac{k_i}{B}\vec{E} + \left(\frac{k_i}{B}\right)^2 \vec{E}\times\vec{B}\right\}$$

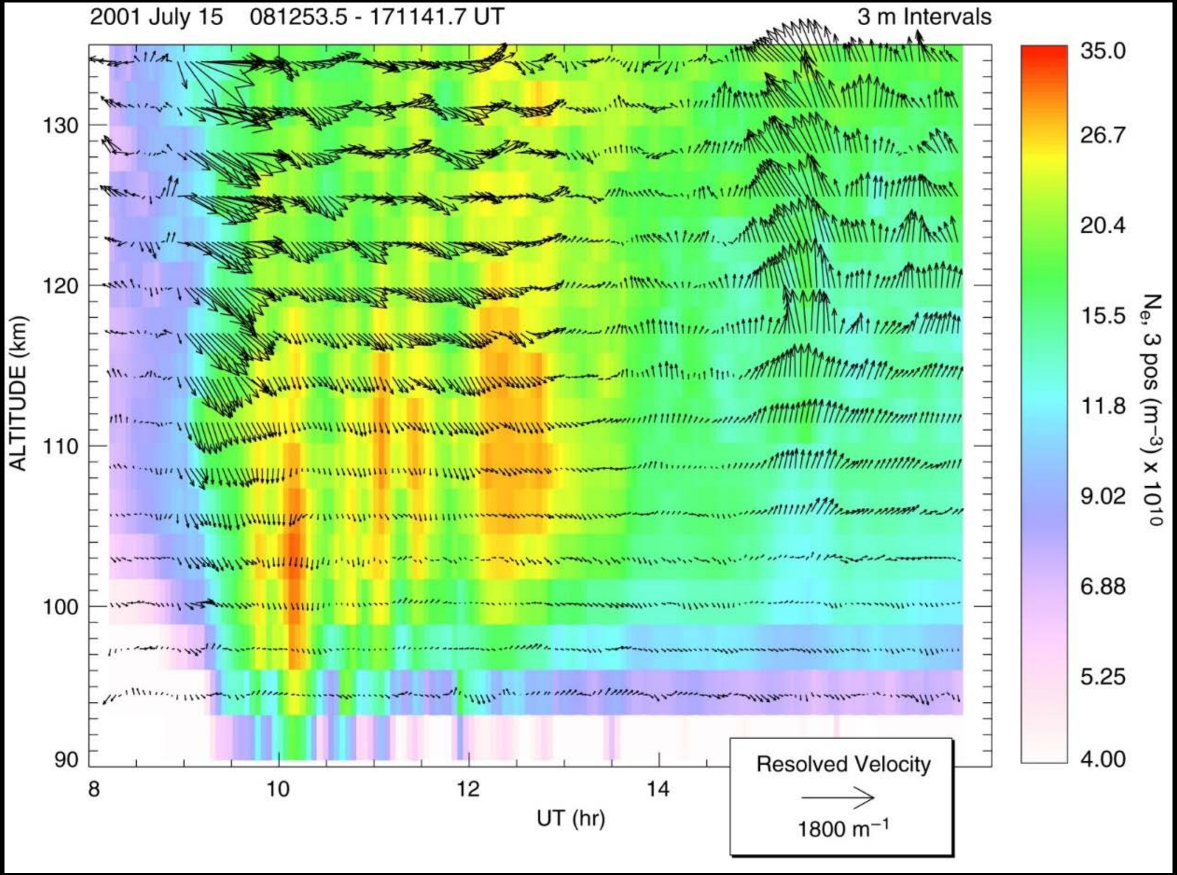
- Ion motion perpendicular to B rotates towards the electric field as collision frequency increases with decreasing altitude
- Ion magnitude perpendicular to B decreases with increasing collision frequency

$$\vec{j}^{\perp} = en_e\left(\vec{V}_i^{\perp} - \vec{V}_e^{\perp}\right)$$

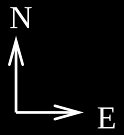
- Currents perpendicular to B rotate towards the –ExB direction
- Current magnitude increases with increasing collision frequency (to a point)

Observed E-region Ion Motion and Electron Density

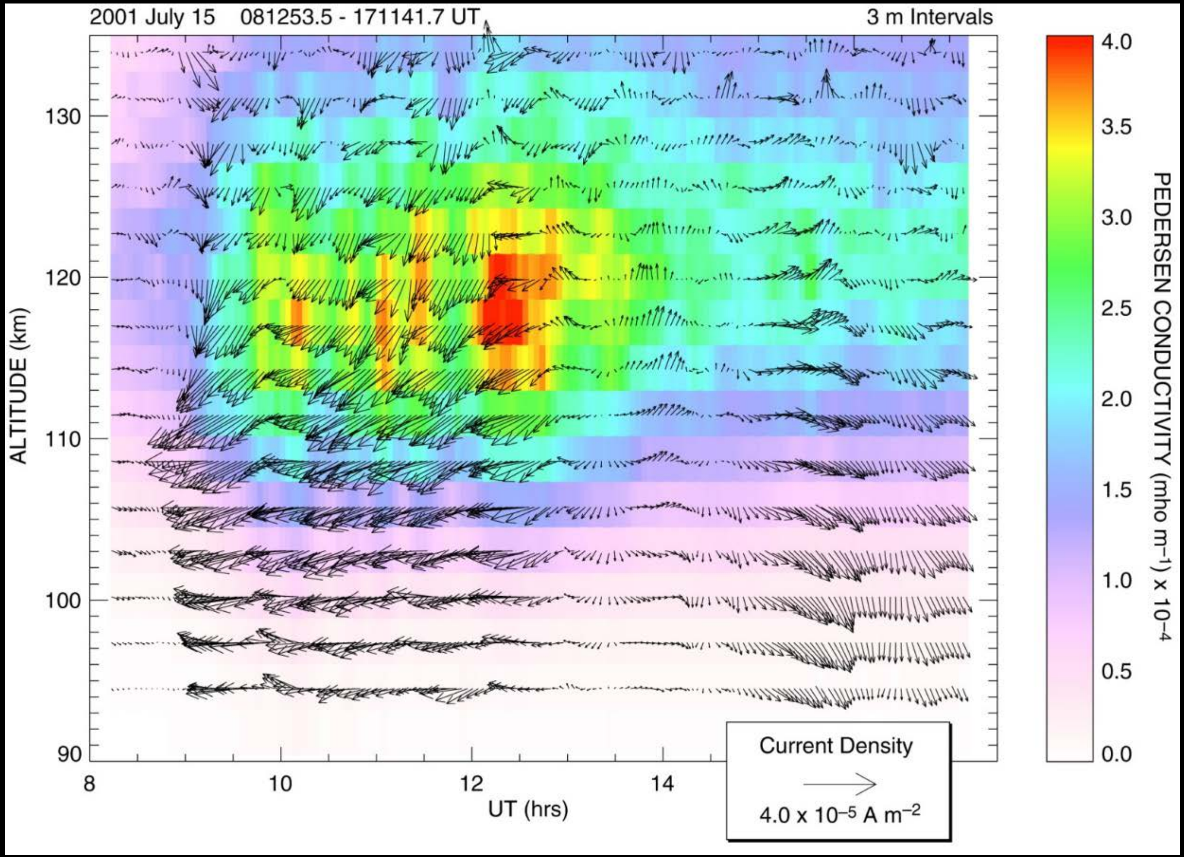
Where the Frozen-In Flux gets Slushy



$$\vec{V}_i^{\perp} = \frac{1}{1+k_i^2}\left\{\frac{k_i}{B}\vec{E} + \left(\frac{k_i}{B}\right)^2 \vec{E}\times\vec{B}\right\}$$



Currents and Pedersen Conductivity Resolved in the E-region Ionosphere

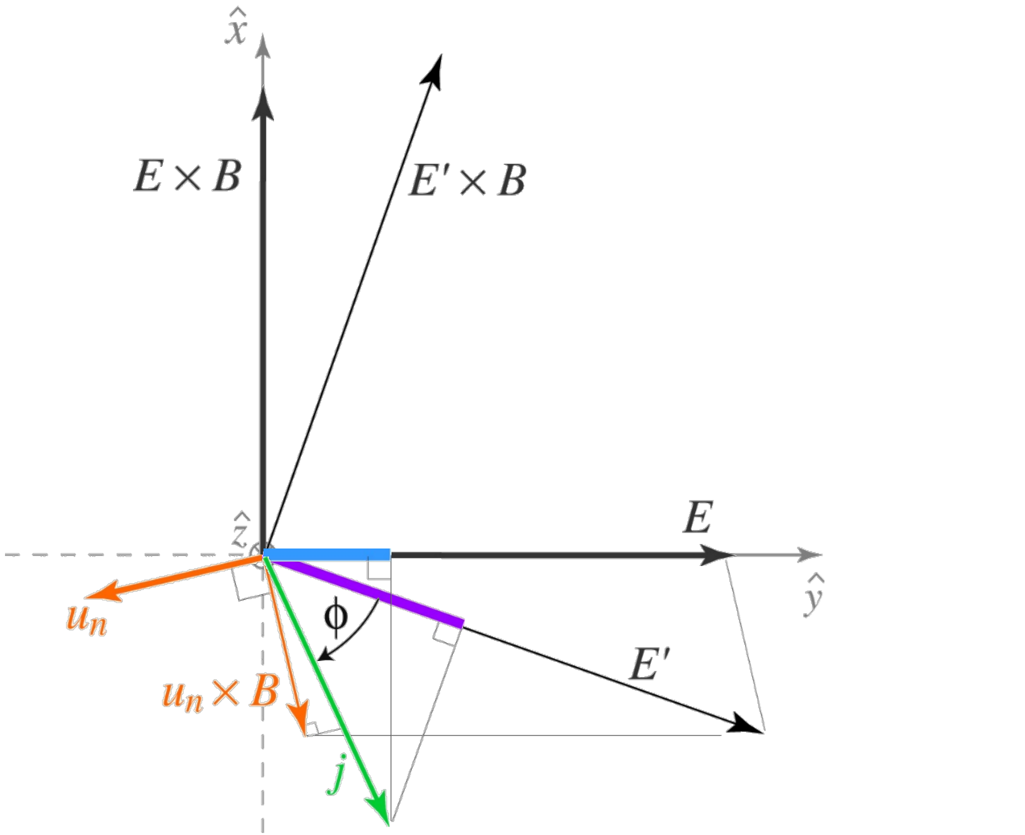


$$\vec{j}_\perp(z) = eN_e(z)\left(\vec{V}_i^\perp(z) - \vec{V}_e^\perp\right)$$

N

E

Currents and Neutral Winds



Thayer, J.P., High latitude currents and their energy exchange with the ionosphere-thermosphere system, JGR 2000

Thayer, J.P., Height-resolved Joule heating rates in the high-latitude E region and the influence of neutral winds, JGR 1998

Electrodynamics with Neutral Winds

Ion momentum equation:

$$\vec{V}_i' = \vec{V}_i - \vec{U}_n = \frac{1}{1+k_i^2}\left\{\frac{k_i}{B}\vec{E}' + \left(\frac{k_i}{B}\right)^2 \vec{E}'\times\vec{B} + \left(\frac{k_i}{B}\right)^3 \left(\vec{E}'\bullet\vec{B}\right)\vec{B}\right\}$$

Electron momentum equation:

$$\vec{V}_e' = \vec{V}_e - \vec{U}_n = \frac{1}{1+k_e^2}\left\{\frac{-k_e}{B}\vec{E}' + \left(\frac{k_e}{B}\right)^2 \vec{E}'\times\vec{B} - \left(\frac{k_e}{B}\right)^3 \left(\vec{E}'\bullet\vec{B}\right)\vec{B}\right\}$$

Current density:

$$\vec{j} = en_e\left(\vec{V}_i - \vec{V}_e\right) = en_e\left(\vec{V}_i - \vec{U}_n - \left(\vec{V}_e - \vec{U}_n\right)\right) = en_e\left(\vec{V}_i' - \vec{V}_e'\right) = \vec{j}'$$

$$\vec{j} = en_e\left\{\left(\frac{k_e}{1+k_e^2} + \frac{k_i}{1+k_i^2}\right)\frac{\vec{E}'}{B} - \left(\frac{k_e^2}{1+k_e^2} - \frac{k_i^2}{1+k_i^2}\right)\frac{\vec{E}'\times\vec{B}}{B^2} + \left(\frac{k_e^3}{1+k_e^2} + \frac{k_i^3}{1+k_i^2}\right)\frac{\left(\vec{E}'\bullet\vec{B}\right)\vec{B}}{B^3}\right\}$$

Ionospheric Ohm's Law (in neutral frame):

$$\vec{j} = \sigma_P \vec{E}_\perp' - \sigma_H \frac{\vec{E}_\perp' \times \vec{B}}{B} + \sigma_\parallel \vec{E}_\parallel' \qquad \textit{where}\ \ \vec{E}' = \vec{E} + \vec{U}_n \times \vec{B}$$

Interpretation of Ohm's Law is Reference Frame Dependent

Generalized Ohm's Law:

$$\frac{\partial \vec{j}}{\partial t} = pressure\ term + gravity\ term + electric\ field\ term + current\ density\ term + \ldots$$

Ionospheric Ohm's Law:

$$\vec{j} = \sigma_P \vec{E}'_\perp - \sigma_H \frac{\vec{E}'_\perp \times \vec{B}}{B} + \sigma_\parallel \vec{E}'_\parallel$$

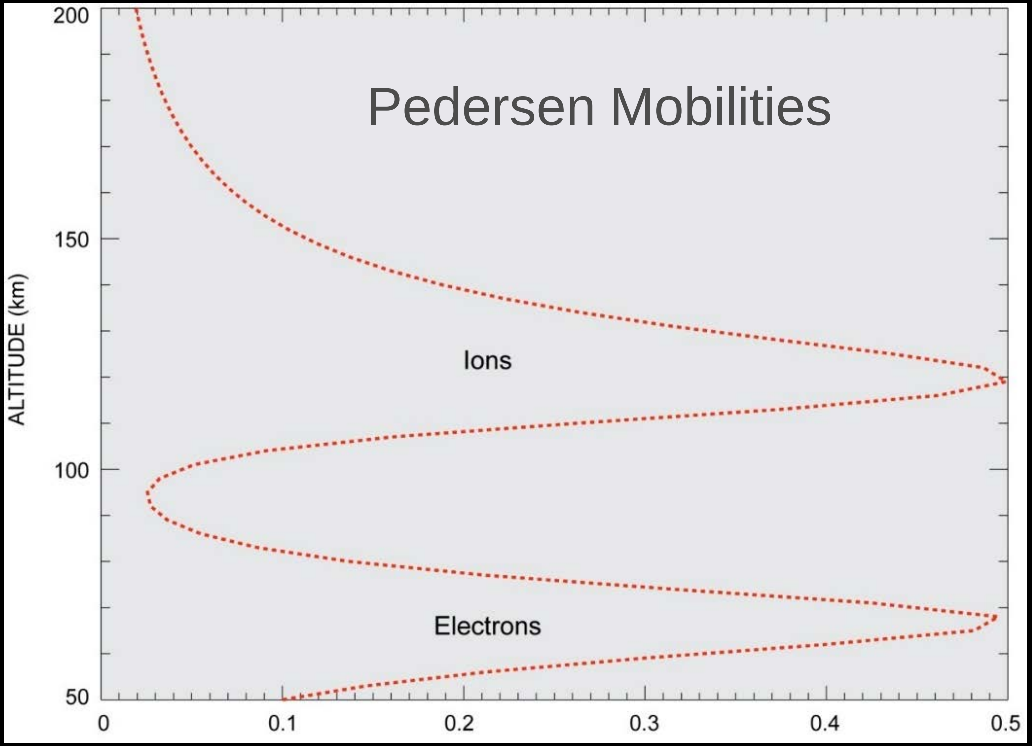
Ohm's Law (in neutral frame): $\vec{E}' = \vec{E} + \vec{U}_n \times \vec{B}$

$$\overset{\leftrightarrow}{\sigma}^{neutral} \neq \overset{\leftrightarrow}{\sigma}^{plasma}$$

Ohm's Law (in plasma frame): $\vec{E}' = \vec{E} + \vec{V}_p \times \vec{B}$

(Song et al., JGR 2001)

Pedersen Mobility (in Neutral Frame)

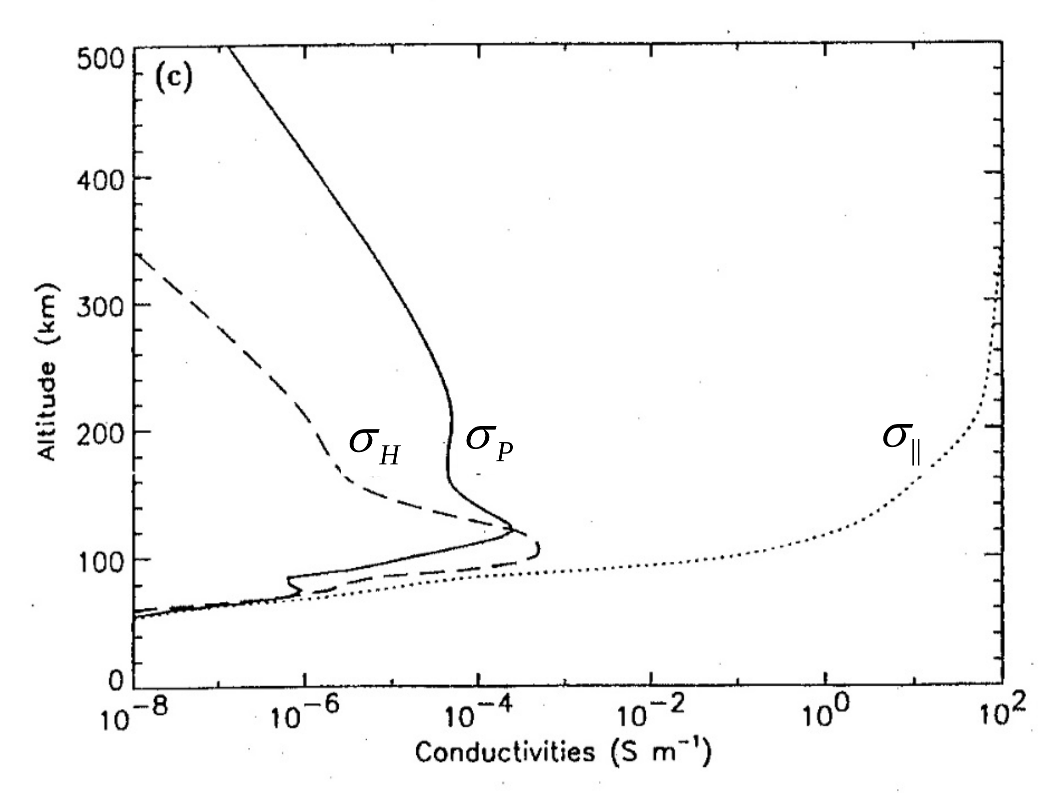


$$\mu_p = \sigma_p \frac{B}{eN_e} = \left(\frac{k_i}{1+k_i^2} + \frac{k_e}{1+k_e^2} \right)$$

$$k_i = \frac{\Omega_i}{\nu_{in}} \qquad k_e = \frac{\Omega_e}{\nu_{en}}$$

$$\mu_P = \left(\frac{k_i}{1+k_i^2} + \frac{k_e}{1+k_e^2} \right)$$

Ionosphere Conductivity (in Neutral Frame)



- Hall conductivity peaks in lower ionosphere below 120 km
  - Essentially removed at night (unless aurora)
- Pedersen conductivity distributed in two regions
  - E-region greater than F-region during the daytime
  - F region greater than E region at night.
- Parallel conductivity greater than transverse conductivities everywhere above 90 km.

Neutral Frictional Heating

Neutral Energy Eq

$$\frac{\delta E_n}{\delta t} = \sum_i \frac{n_n m_n \nu_{ni}}{m_n + m_i} \left\{ \begin{aligned} & 3k_B (T_i - T_n) + \\ & + m_i (\vec{U}_n - \vec{V}_i)^2 \end{aligned} \right\} + ..$$

$$\frac{\delta E_n}{\delta t} = \sum_i \frac{n_n m_n \nu_{ni}}{m_n + m_i} \left\{ \begin{aligned} & m_n (\vec{V}_i - \vec{U}_n)^2 + \\ & + m_i (\vec{V}_i - \vec{U}_n)^2 \end{aligned} \right\} + ...$$

Ion Energy Eq

$$\frac{\delta E_i}{\delta t} = 0$$

$$\therefore \; 3k_B (T_i - T_n) \cong m_n (\vec{V}_i - \vec{U}_n)^2$$

$n_n m_n \nu_{ni} = n_i m_i \nu_{in}$ and $m_n \approx m_i$

Approximate Neutral Frictional Heating

$$\frac{\delta E_n}{\delta t} = \sum_i n_i m_i \nu_{in} (\vec{V}_i - \vec{U}_n)^2 \quad , \quad \left[\frac{W}{m^3}\right]$$

(Thayer and Semeter, JASTP 2004)

Joule Heating Rate (Neutral Frame)

$$\vec{j}\bullet\vec{E}' = \sum_i e n_i \left(\vec{V}_i' - \vec{V}_e'\right)\bullet E' \quad \Rightarrow \quad \vec{j}\bullet\vec{E}' = \sum_i e n_i \left(\frac{k_e}{1+k_e^2} + \frac{k_i}{1+k_i^2}\right)\frac{\vec{E}'}{\vec{B}}\bullet\vec{E}' = \sigma_p \vec{E}'^2$$

Assume k_e is large, valid above 80 km: $$\vec{j}\bullet\vec{E}' = \sum_i m_i n_i \Omega_i \left(\frac{k_i}{1+k_i^2}\right)\bullet\frac{E'^2}{B^2}$$

Recall, the magnitude of the ion velocity from the momentum equation is

$$V_i'^2 = \left(\vec{V}_i - \vec{U}_n\right)^2 = \frac{k_i^2}{1+k_i^2}\frac{E'^2}{B^2}$$

Solve for $\frac{E'^2}{B^2}$, $\quad \vec{j}\bullet\vec{E}' = \sum_i n_i m_i \nu_{in}\left(\vec{V}_i - \vec{U}_n\right)^2$

Joule Heating Rate is "Equal" to the Neutral Frictional Heating rate

$$\vec{j}\bullet\vec{E}' = \sum_i n_i m_i \nu_{in}\left(\vec{V}_i - \vec{U}_n\right)^2 \quad \Rightarrow \quad \frac{\delta E_n}{\delta t} = \sum_i n_i m_i \nu_{in}\left(\vec{V}_i - \vec{U}_n\right)^2$$

Interpretation of Joule Heating is Reference Frame Dependent

Vasyliūnas, V. M., and P. Song (2005), Meaning of ionospheric Joule heating, J. Geophys. Res., 110, A02301, doi:10.1029/2004JA010615

Uses plasma velocity as their rest frame

Classical Joule heating

$$\dot{q}_j = \vec{j}\bullet\left(\vec{E}+\vec{V}_e\times\vec{B}\right)+\sum_i m_i n_i \nu_{in}\left(\vec{V}_i-\vec{U}_n\right)^2 = \eta J^2 + \sum_i m_i n_i \nu_{in}\left(\vec{V}_i-\vec{U}_n\right)^2$$

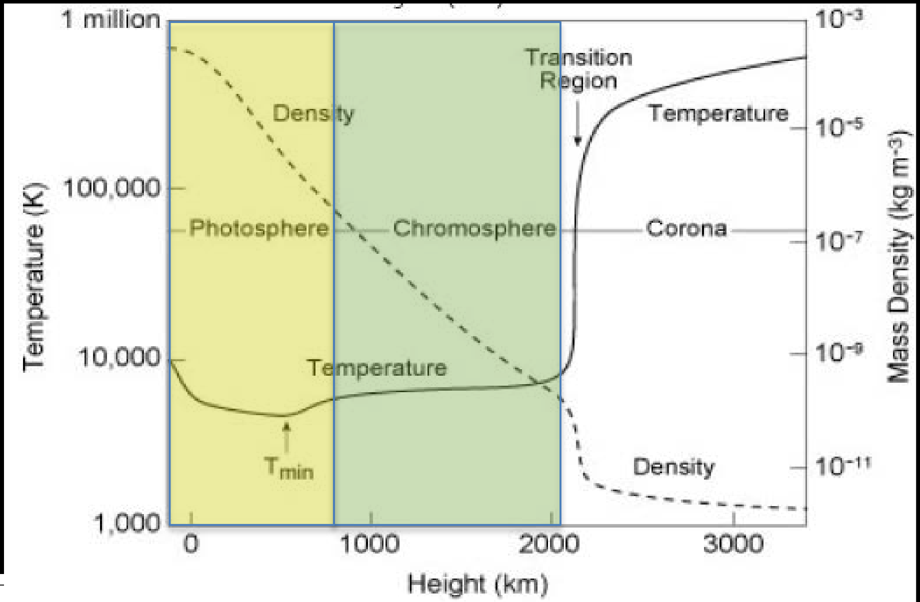
Note:

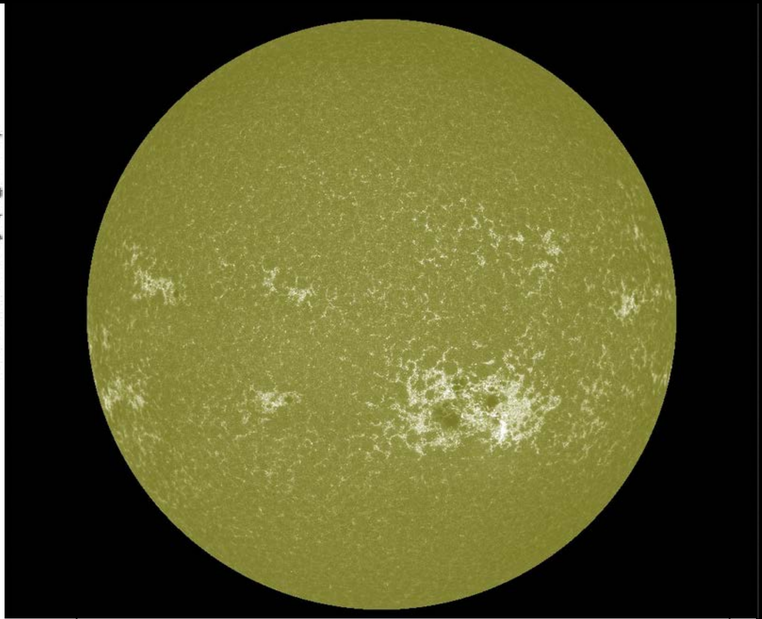
$$Resistivity: \quad \eta = \frac{m_e \upsilon_e}{e^2 n_e} = \frac{B}{e n_e}\frac{\upsilon_e}{\Omega_e} \quad , \quad << 1 \; above \; 90km$$

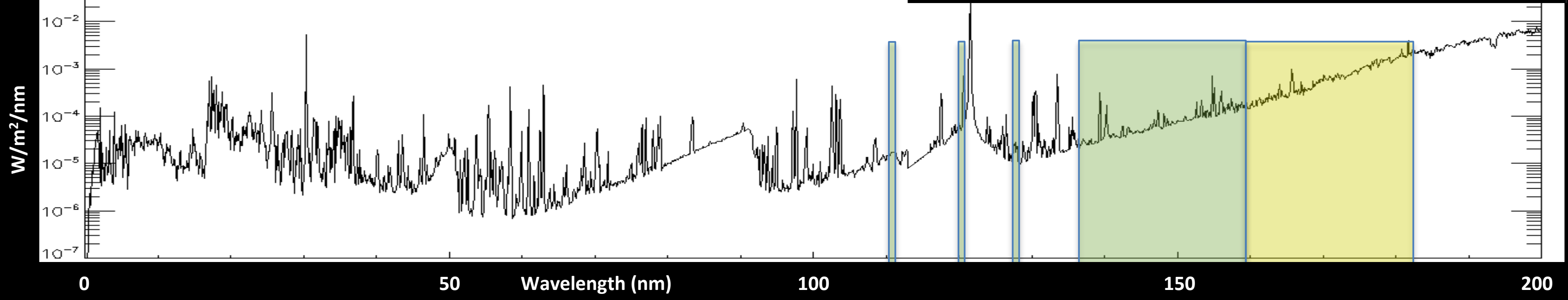
Therefore, their form agrees with the form we just derived but approached differently,

$$\dot{q}_j = \sum_i m_i n_i \nu_{in}\left(\vec{V}_i-\vec{U}_n\right)^2$$

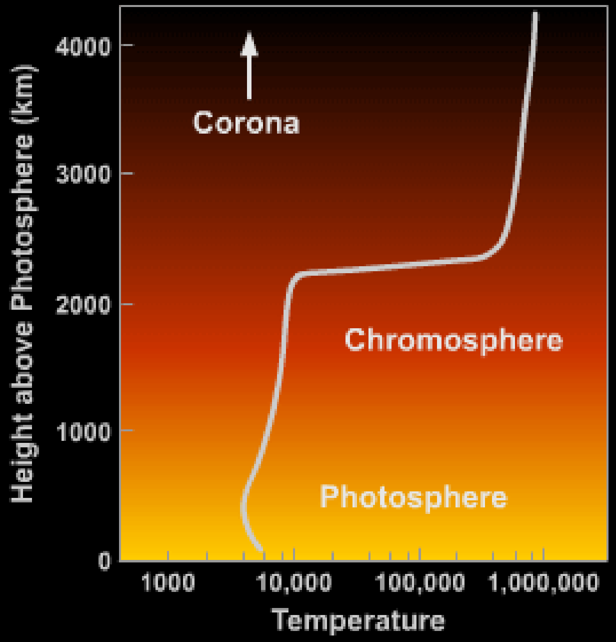
Plasma-Neutral Interactions: Solar Chromosphere



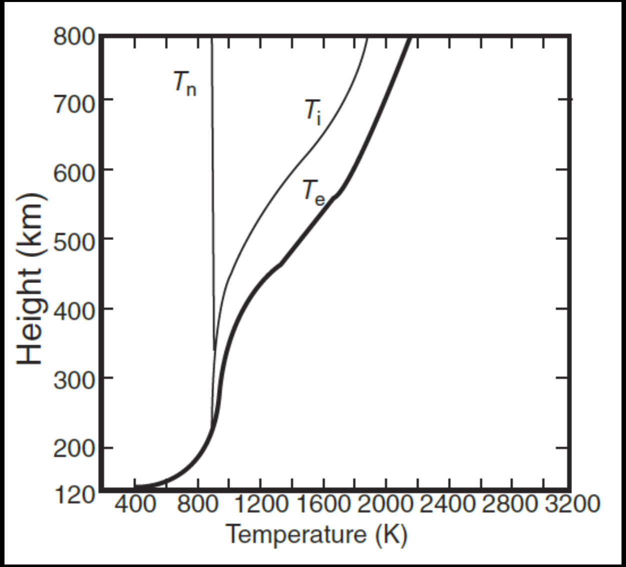




Chromosphere / Ionosphere Comparison



Solar Chromosphere

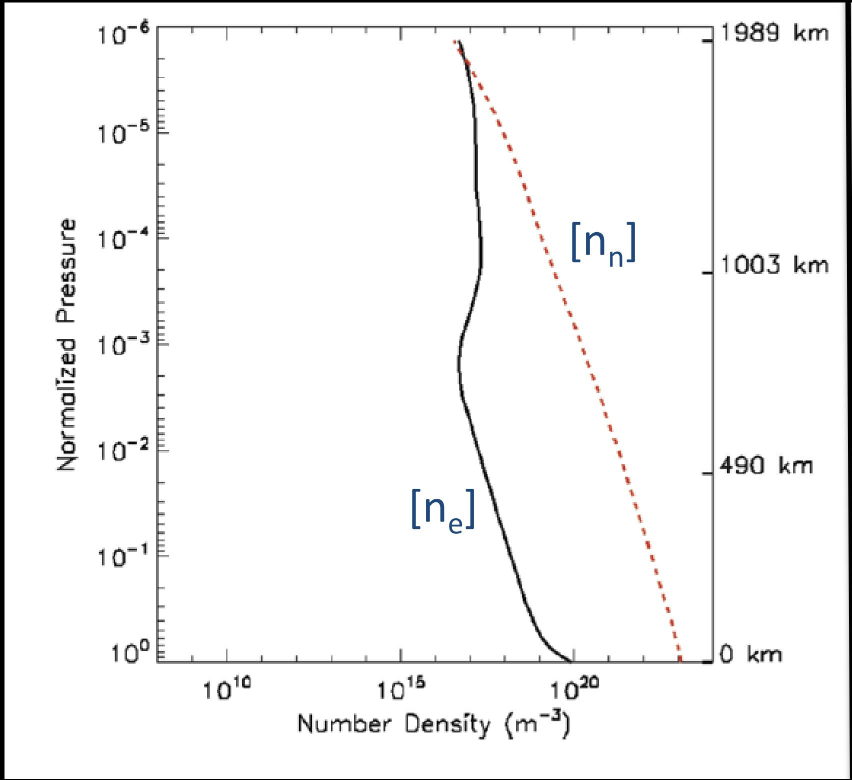


Earth's Ionosphere/Thermosphere

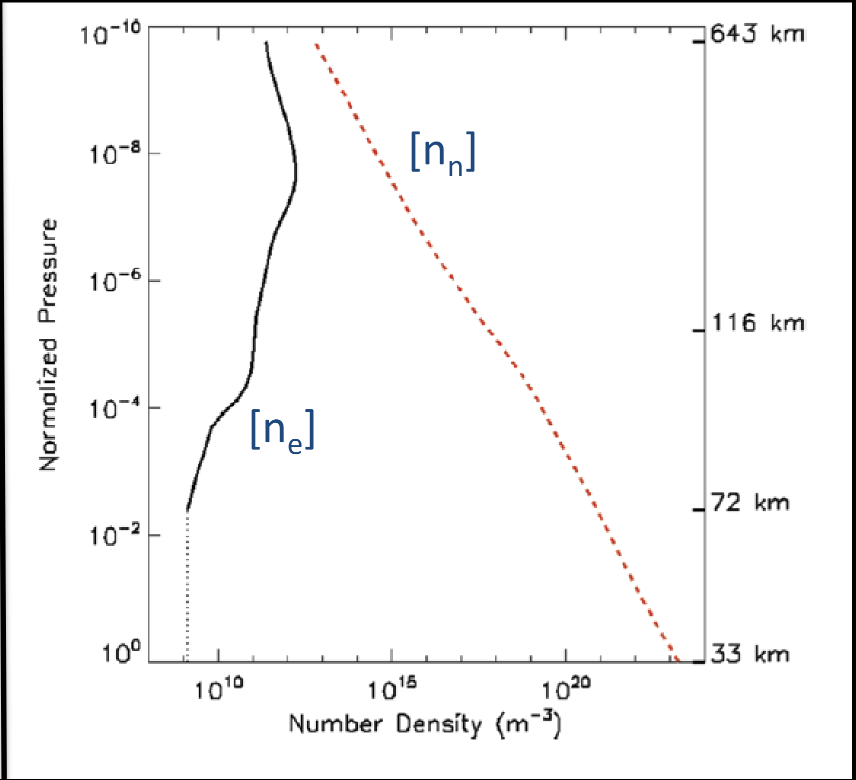
Leake, J. E.; DeVore, C. R.; Thayer, J. P.; Burns, A. G.; Crowley, G.; Gilbert, H. R.; Huba, J. D.; Krall, J.; Linton, M. G.; Lukin, V. S.; Wang, W. (2014), Ionized Plasma and Neutral Gas Coupling in the Sun's Chromosphere and Earth's Ionosphere/Thermosphere, Space Science Reviews, Volume 184, Issue 1-4, pp. 107-172, doi: 10.1007/s11214-014-0103-1

Weakly Ionized Gas

Solar Chromosphere

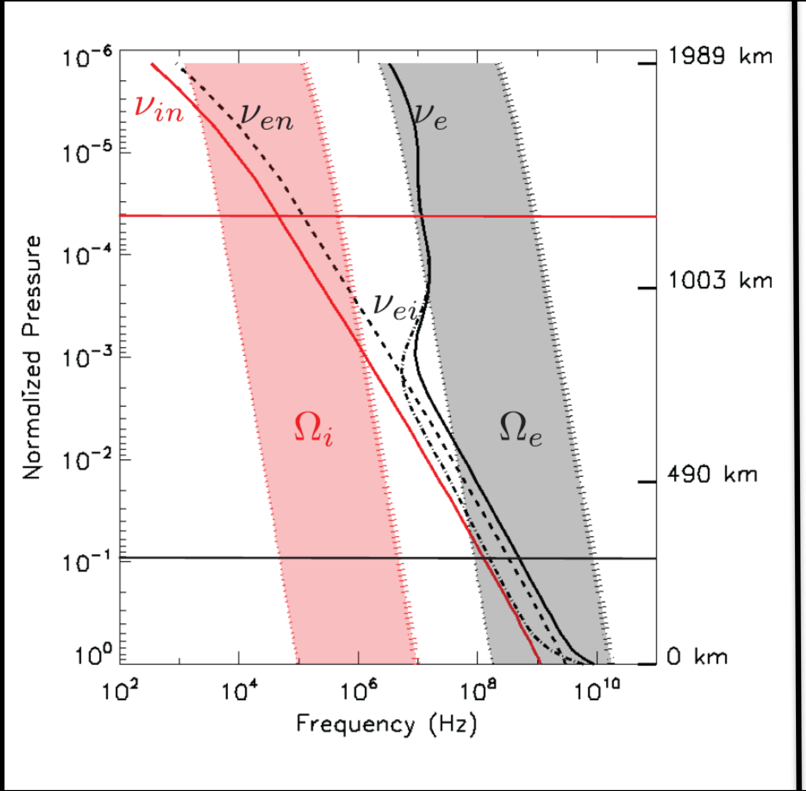


Earth's Ionosphere / Thermosphere

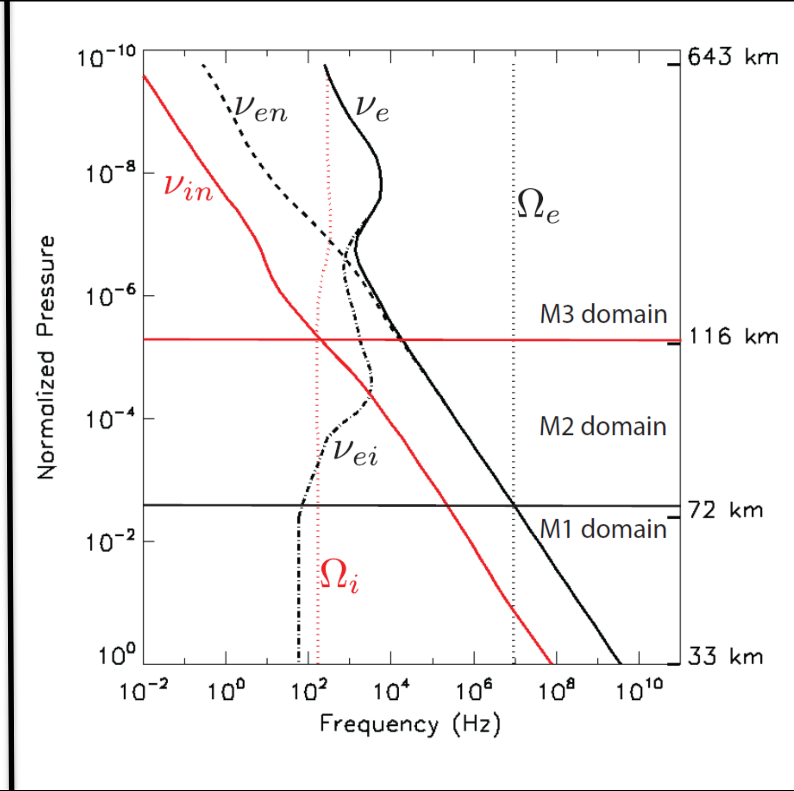


Plasma – Neutral Collisions

Solar Chromosphere

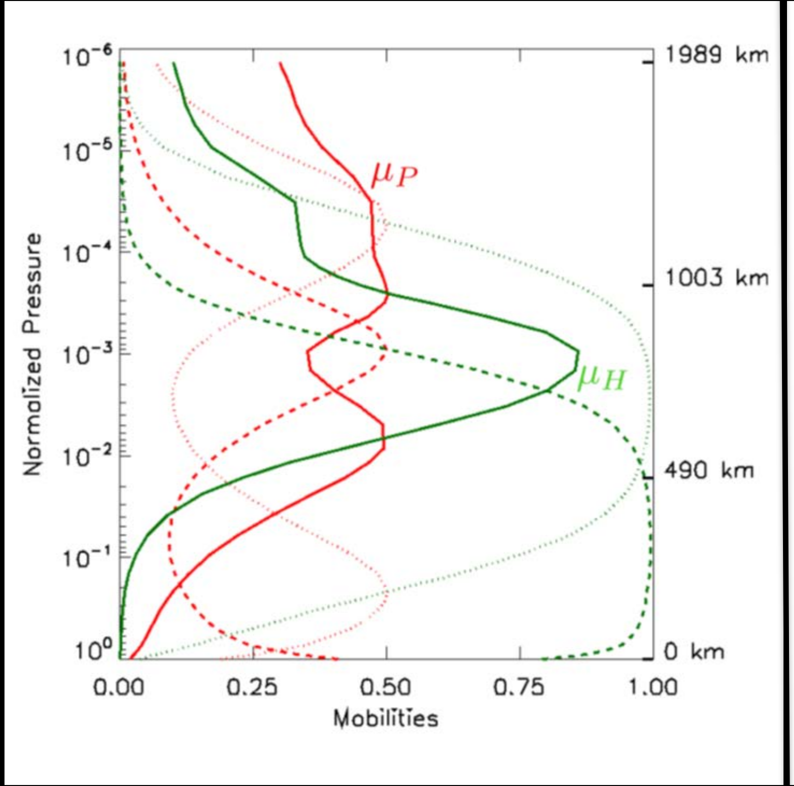


Earth's Ionosphere / Thermosphere

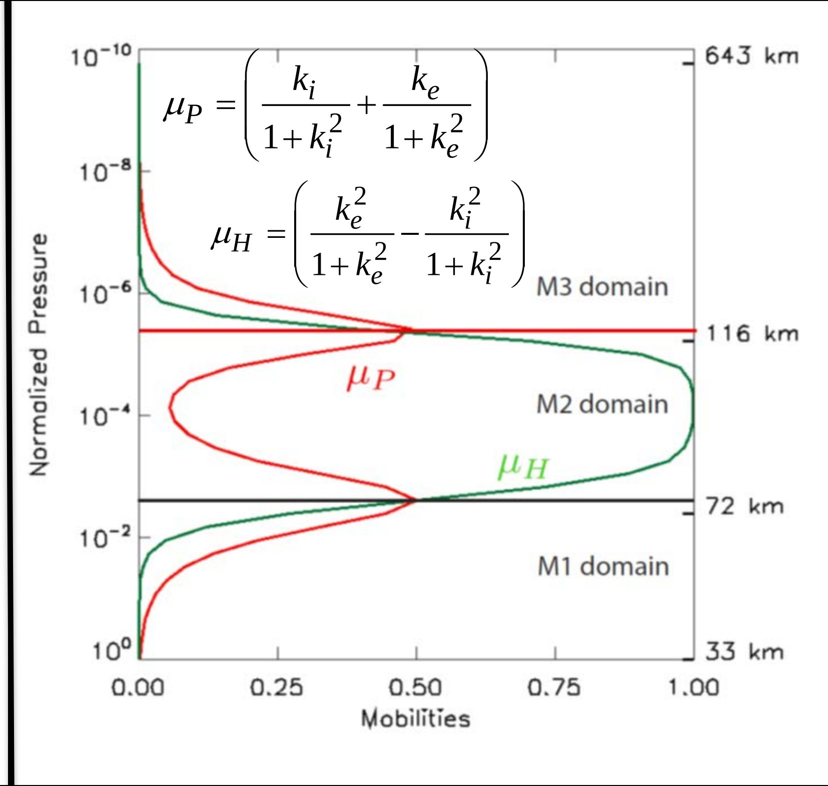


Charge Mobilities

Solar Chromosphere

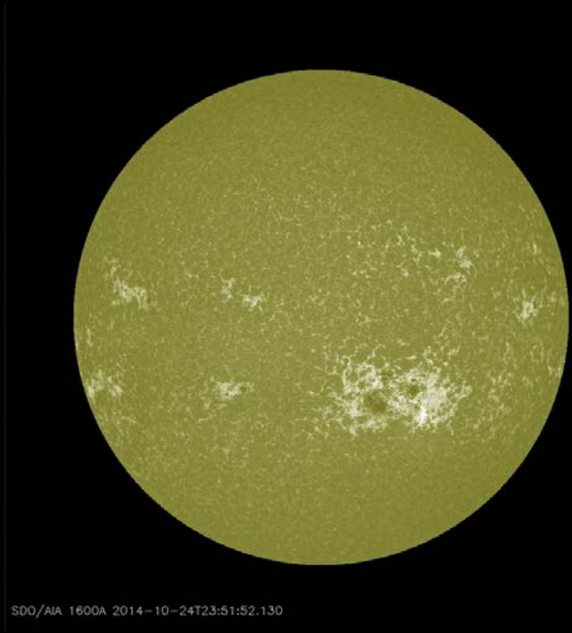


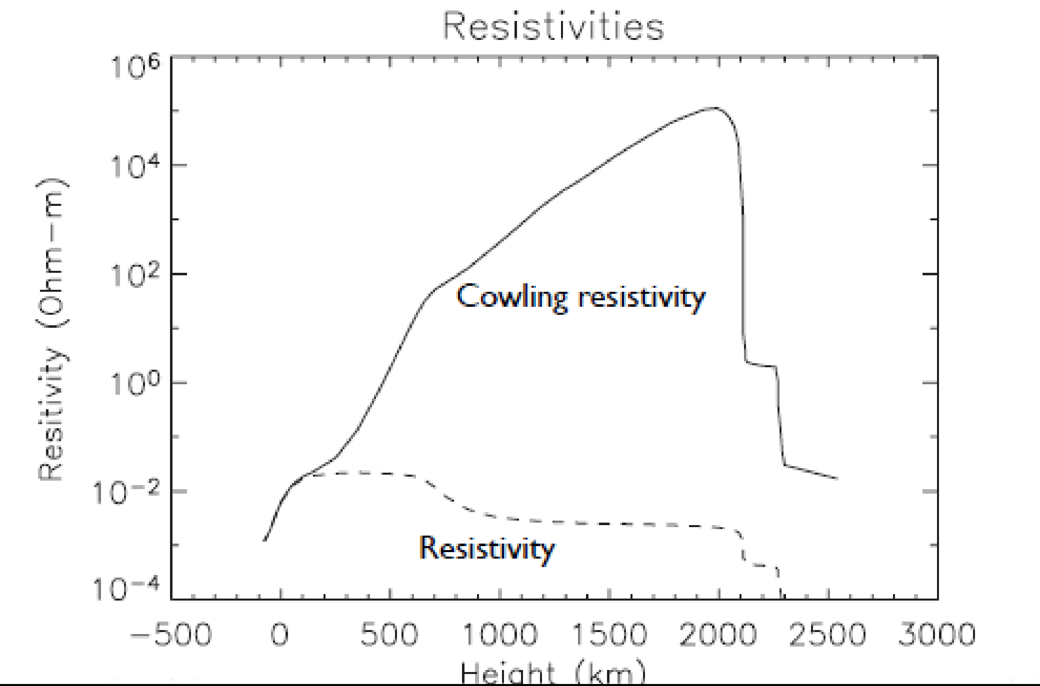
Earth's Ionosphere / Thermosphere



Solar Chromosphere: Joule Heating

$$\frac{\vec{j}^2}{\sigma_c}, where\ \sigma_c = \sigma_p + \frac{\sigma_H^2}{\sigma_p}$$





Summary

- Define and know your coordinate system and reference frame in order to properly interpret plasma-neutral interactions, enabling more universal interpretation of:
  - Planetary Ionospheres / Thermospheres
  - Stellar Chromospheres

Leake et al. (2014), Ionized Plasma and Neutral Gas Coupling in the Sun's Chromosphere and Earth's Ionosphere/Thermosphere, Space Science Reviews.

- Ionospheric Ohm's Law provides no causal relationship but simply states the current and electric field are linearly related by conductivities defined for the given reference frame.

- Frictional heating may be a more appropriate description of heat transfer in the Ionosphere/Thermosphere system than Joule heating.
  - Can have neutral, ion, and electron frictional heating. However, increased plasma temperatures will transfer heat to the neutral gas due to temperature differentials. With some approximations this overall heat transfer to the neutrals can be equated to Joule heating (but not in the classical sense).

Plasma-Neutral Interaction Challenges in the 80 - 200km Domain

- “Missing” energy in M-I coupling (lacking adequate conductivity descriptions with dependencies on electron and neutral density)
- “Transforming” energy in I-T coupling (lacking sufficient neutral wind observations to determine energy dissipation and generation)
- “Modifying” dynamo processes (lacking neutral wind observations coincident with plasma measurements)
- “Profiling” neutral and plasma properties in near-spatial and temporal simultaneity (lacking vertical structure description, i.e. gradients)

The MLT-X Grand Challenge Workshop: Frontier Science and Sensing

Coupling and Transport Processes from the Upper Mesosphere through the Middle Thermosphere (80-200 km)

CEDAR 2017

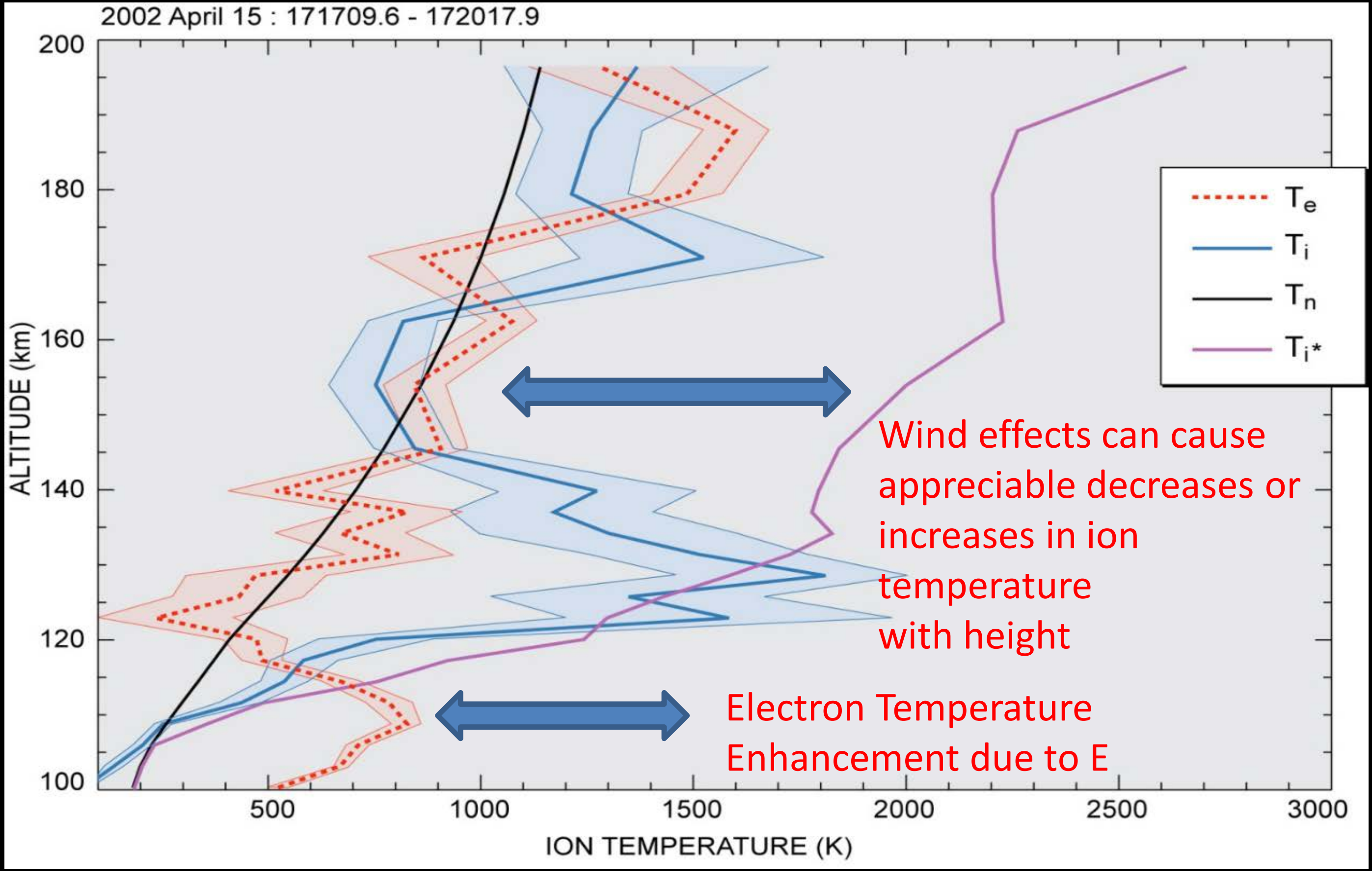
Challenges:

- What is the role of the neutral gas in coupling with the plasma to establish the predominant state of the Earth's upper atmosphere and ionosphere between 80 and 200 km?

- How do wave-induced transport, dissipation and turbulence influence the structure, composition and circulation of Earth's upper atmosphere between 80 and 200 km?

Backup Slides

Ion Frictional Heating



$$T_i = T_n + \frac{m_n k_i^2}{3K_B}\frac{(E'/B)^2}{1+k_i^2}$$

$$T_i = T_n + \frac{m_n}{3K_B}\left(\vec{V}_i - \vec{U}_n\right)^2$$

$$T_i^* = T_n + \frac{m_n}{3K_B}\left(\vec{V}_i\right)^2$$

Plasma-Neutral Interactions: Frictional Heating a Grand Challenge

The inability to adequately quantify the most variable energy source of the upper atmosphere, often exceeding EUV solar radiation in the polar regions and dramatically impacting upper atmosphere properties globally, hinders progress in many aspects of M-I and I-T coupling

- Grand Challenge in M-I coupling
  - "Missing" Energy
- Grand Challenge in I-T Coupling
  - "Transforming" Energy