International School of Space Science (ISSI)

The Polar Upper Atmosphere: From Science to Operational Issues, L'Aquila, Italy, 16-21 Sep. 2018

"MAKING THE IONOSPHERE — All in a Morning's Work"

by
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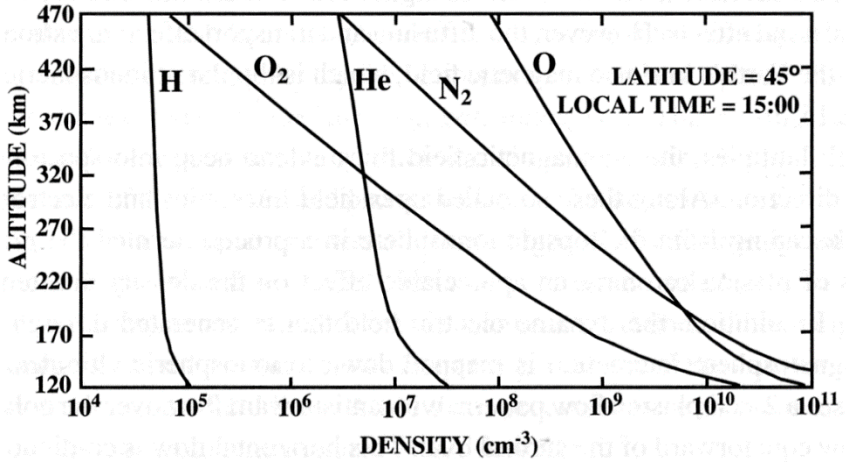
1. The Photo-Ionization Process

- Start with Neutral Atmosphere



- Ionization Potentials of Atoms and Molecules

Species	Energy (ev)	$\lambda_{ionization}$
O	13.62	910 Å
O_2	12.06	1028 Å
N_2	15.58	796 Å

- Photon energy, $E = h\nu = hc/\lambda$

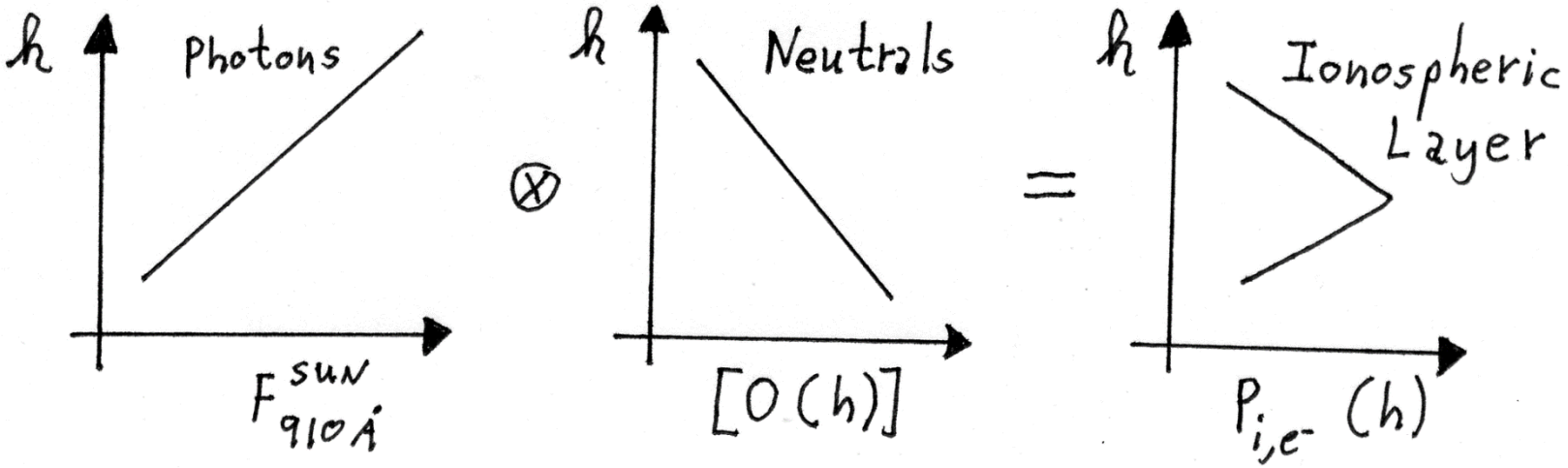
$$\text{or } \lambda(\text{Å}) \approx \frac{12345}{E(\text{ev})}$$

Thus, Photon (910 Å) + O $\rightarrow$ O^+ + e^-

Knowing $\underbrace{F_{910}^{SUN}(h)\ \&\ [O(h)] \rightarrow [O^+(h)] + [e^-(h)]}$

Production Function (P)
for monochromatic ionizing radiation
(called "Chapman Theory")

How should P(h) look?



Algebraically $P_{i,e^-}(h) = F^{sun}_{\lambda_{ion}}(h) \cdot \underbrace{\sigma_{ion}}_{\substack{ionization \\ cross-section}} \cdot [O(h)]$

What happens if photon

- $\lambda > \lambda_{ion}? \rightarrow$ *No ionization*
- $\lambda < \lambda_{ion}? \rightarrow$ *Extra Energy*

i.e., Photon ($\lambda < \lambda_{ion}$) + O $\rightarrow O^+ + e^{-*}$ (energetic photo-electron)

If e^{-*} Kinetic Energy > Ionization Potential
collisions can cause additional ionizations

$e^{-*} + O \rightarrow O^+ + e^-$ ("secondary ionization")

Thus, a very energetic photon can lead to several ion-electron pairs.

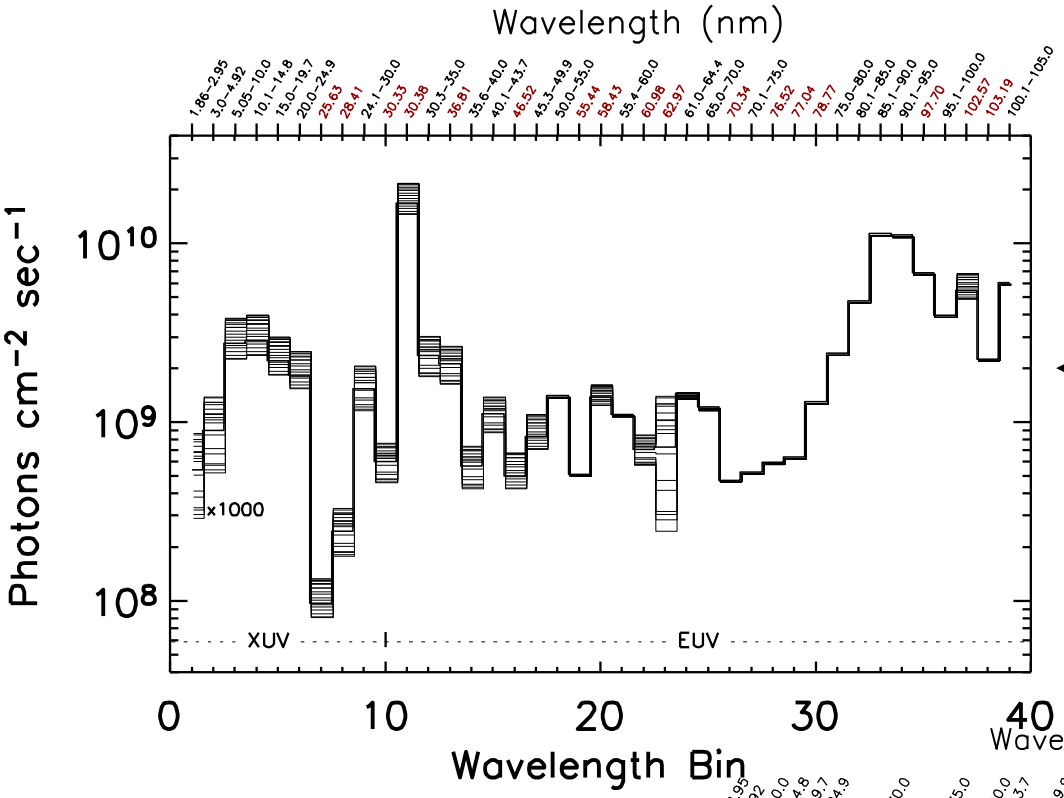
For a complete model of Photo-Ionization, the flux of solar photons at all relevant λs is needed:

$$P_{\text{Total}}(h) = \sum_{\lambda=0}^{\lambda_{\text{ion}}} F_{\lambda}^{\text{sun}}(h) \cdot \sigma_{ion}(\lambda) \cdot [N(h)]$$

Table 2.1. *Solar spectral regions.*

Radio	$\lambda > 1$ mm
Far Infrared	$10\ \mu\text{m} < \lambda < 1$ mm
Infrared	$0.75\ \mu\text{m} < \lambda < 10\ \mu\text{m}$
Visible	$0.3\ \mu\text{m} < \lambda < 0.75\ \mu\text{m}$
Ultraviolet (UV)	1200 Å $< \lambda <$ 3000 Å
Extreme ultraviolet (EUV)	100 Å $< \lambda <$ 1200 Å
Soft x-rays	1 Å $< \lambda <$ 100 Å
Hard x-rays	$\lambda <$ 1 Å

Note: Å $= 10^{-10}$ m. (1 Å = 0.1 nm)



SOLAR2000 IRRADIANCES

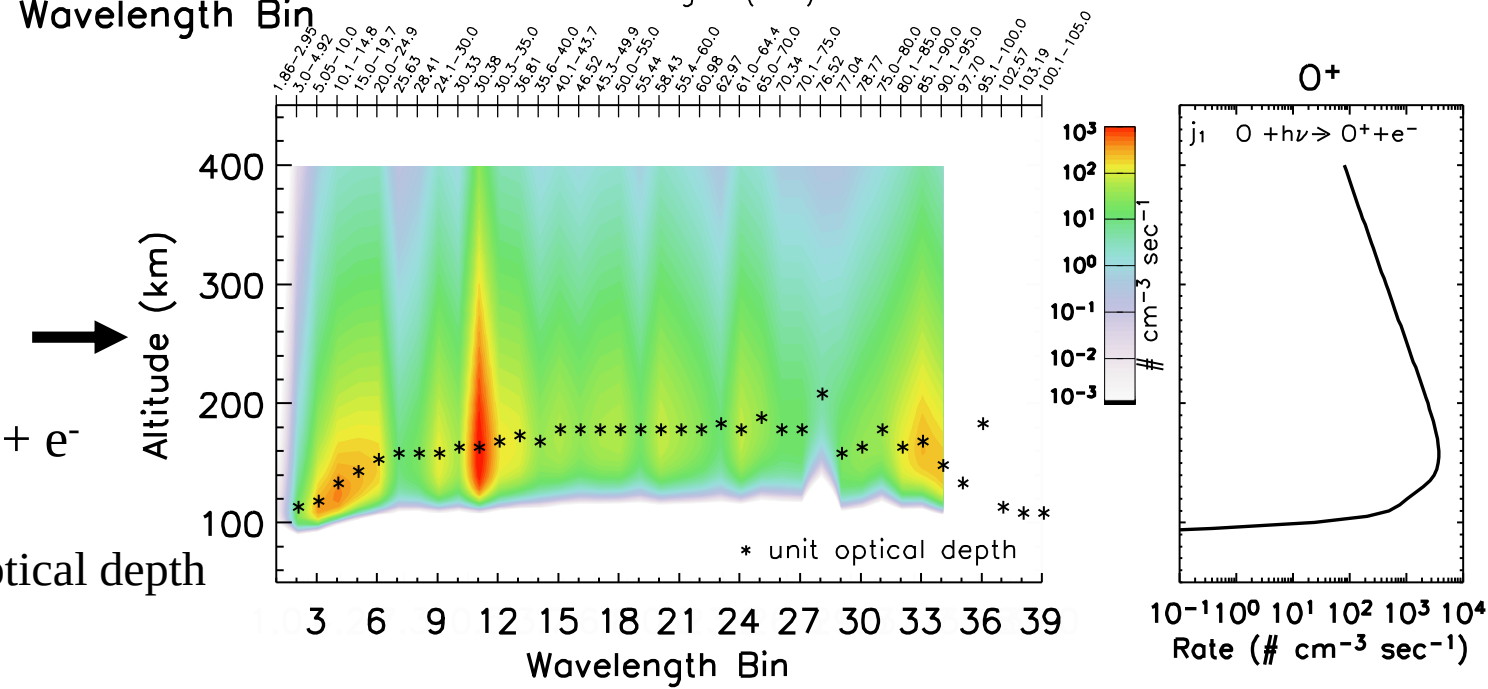
* Flux in 39 wavelength bins (bands + lines)

* Shown here are for 15 consecutive days to portray variability

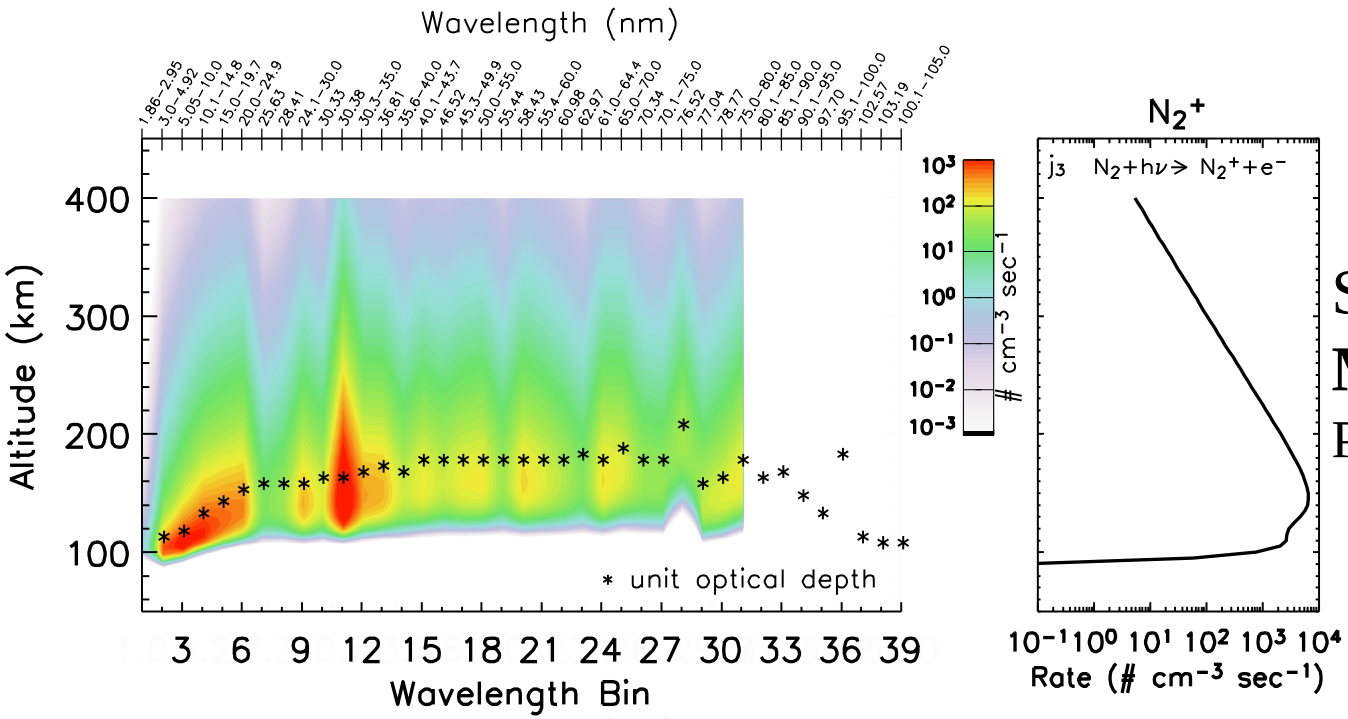
Sample results:

Oxygen

Photons + O $\rightarrow O^+ + e^-$



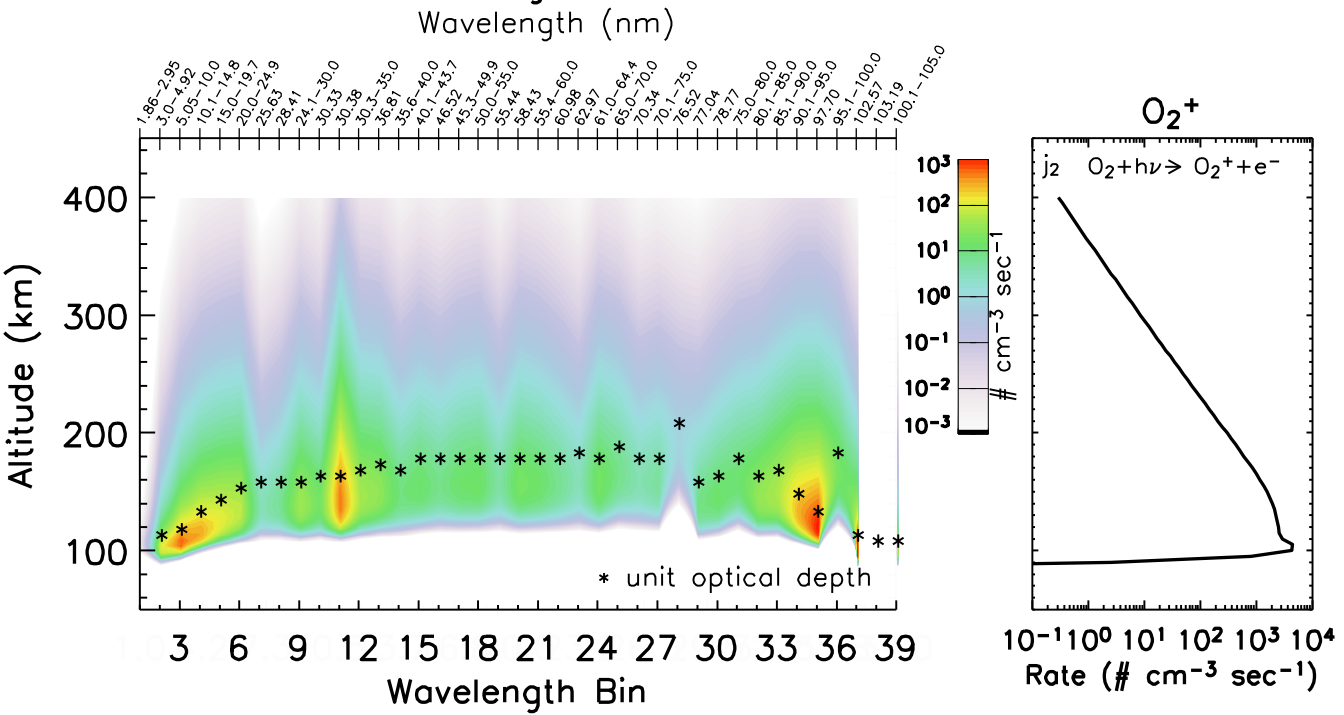
* = unit optical depth



Sample results:

Molecular Nitrogen

Photons + $N_2 \rightarrow N_2^+ + e^-$



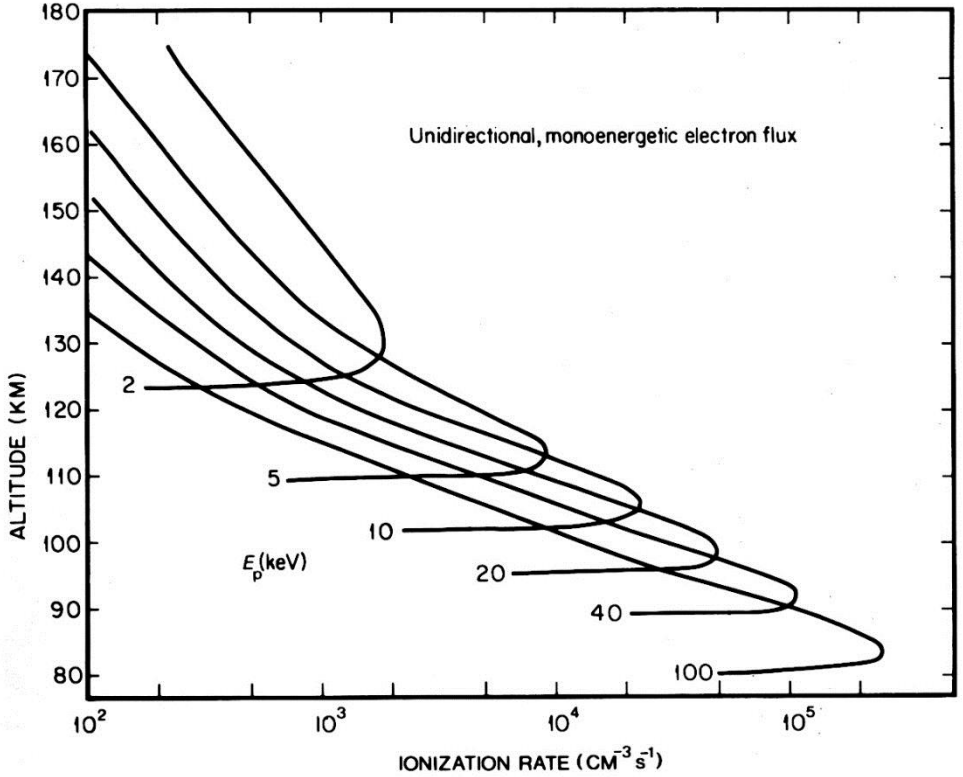
Sample results:

Molecular Oxygen

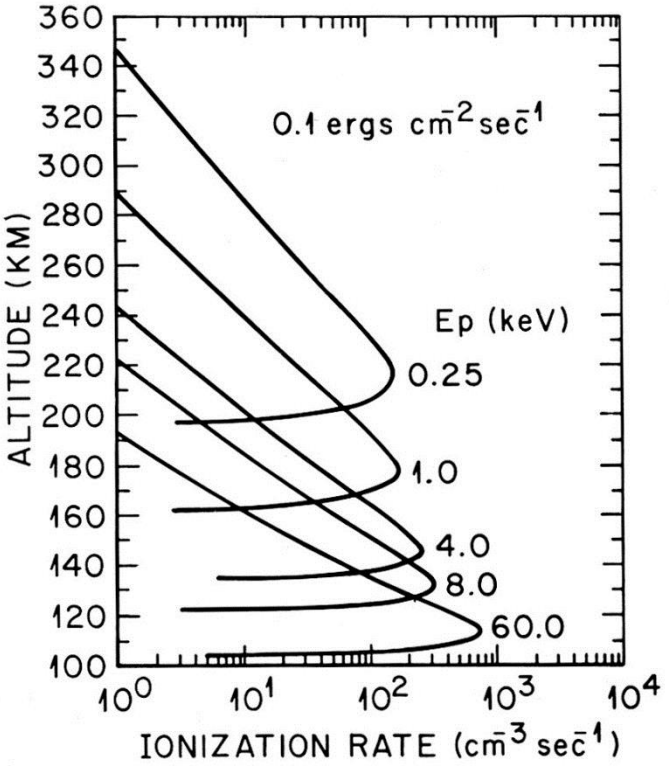
Photons + N2 $\rightarrow O_2^+ + e^-$

Production of Ionospheric Plasma by Energetic Particles

Precipitating Electrons



Precipitating Protons



--- taken from Rees (1989)

2. Ionospheric Transformations

- What does "production only" imply?
  e.g., use $P(O^+)$ value from graphs (photons or particles)

P_{max} = 4000 e $^-$/cm^3/sec x 3 hours ($\approx 10^4$ sec)

gives $N_{max} \approx 4 \times 10^7$ e $^-$/ cm^3 ***Never Measured!!!***

Message: Something happens to these ions and electrons

Answer: Chemistry → Plasma recombination

Answer: Chemistry → Neutral-Plasma Processes

CASE # 1: Atomic ions + electrons

$$O^+ + e^- \xrightarrow{\alpha} O$$ [very rare due to precise energetics needed for electron capture]

CASE # 2: Molecular ions + electrons

$$O_2^+ + e^- \xrightarrow{\alpha} O + O$$ [fast due to excess energetics used for dissociation]

CASE #3: Transform Atomic ions to Molecular ions

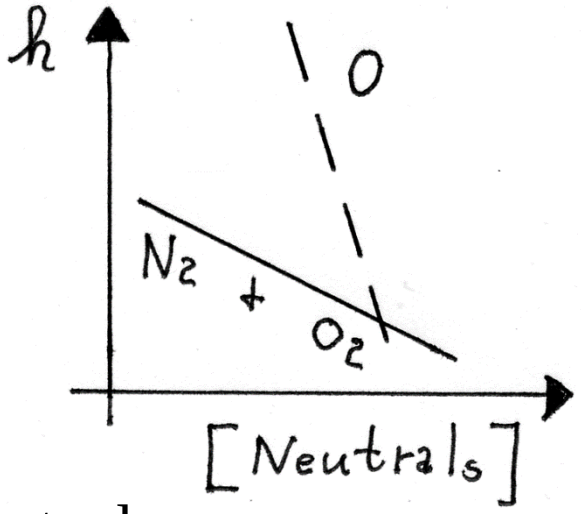
$$O^+ + \begin{bmatrix} N_2 \\ O_2 \end{bmatrix} \xrightarrow{k} \underbrace{\begin{bmatrix} NO^+ \\ O_2^+ \end{bmatrix}}_{\text{followed by CASE \#2 (quick)}} + \begin{bmatrix} N \\ O \end{bmatrix} \quad \text{(slow)}$$

The 2-stage recombination process governed by slower step, e.g.,

$$\boxed{\frac{dN_e}{dt} = -k[N_2]N_e = -\beta N_e}$$

Messages from Simple Photochemical Theory

•Plasmas should be ionized form of dominant neutral



→ CASE #1 : $O^+ + e^-$

→ CASE #2 : $O_2^+ + e^-$

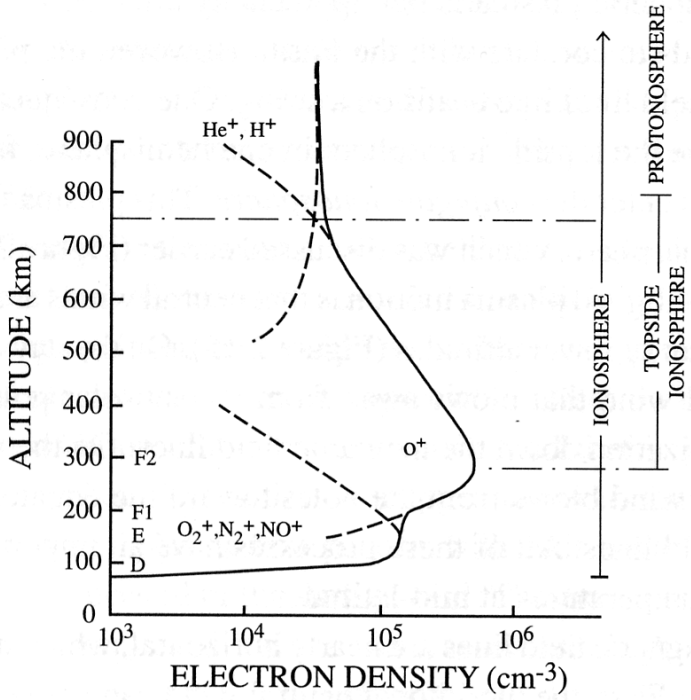
$N_2^+ + e^-$

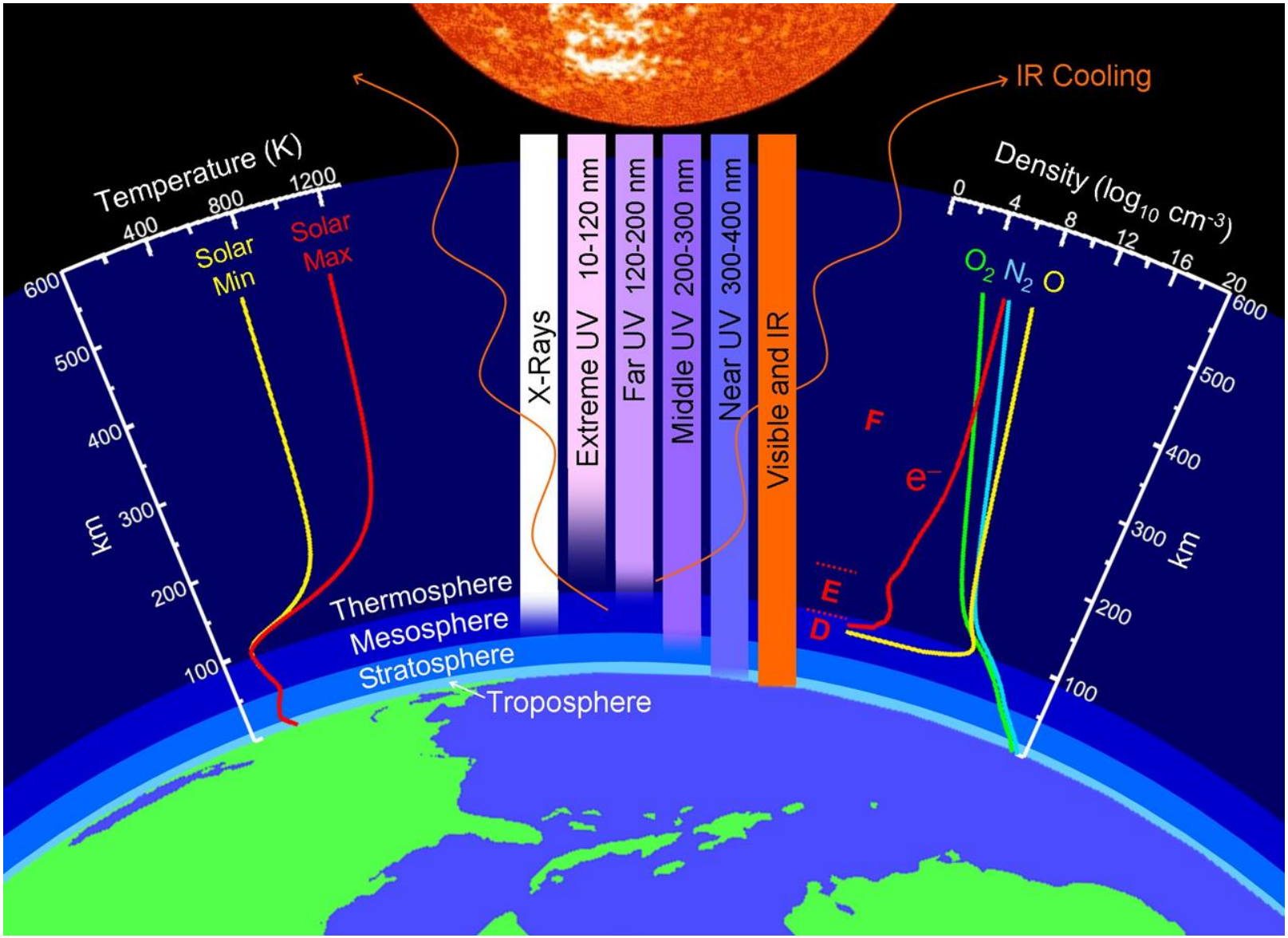
• The actual case:

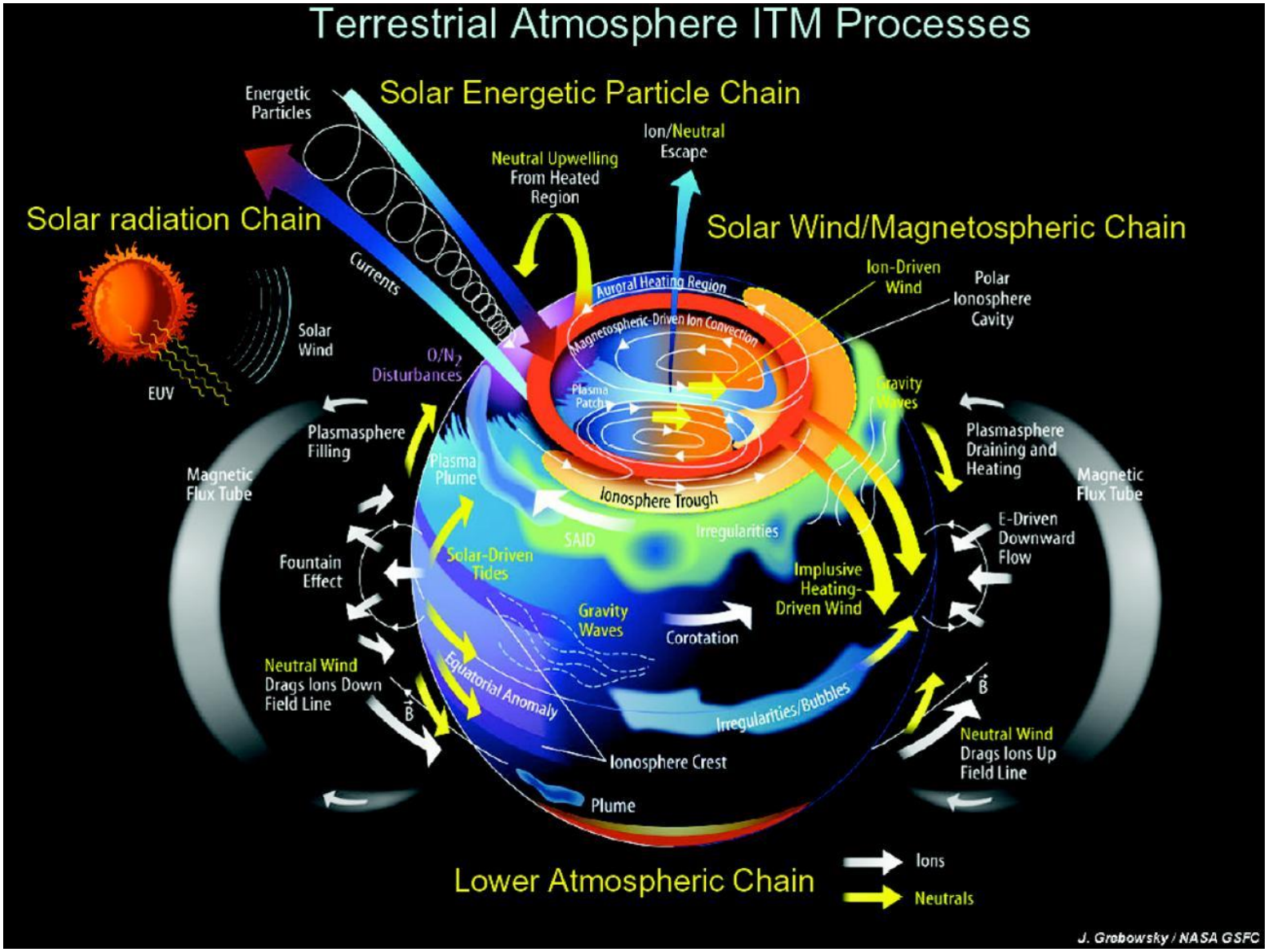
— some chemical transformations to form NO^+ and H^+

• Two main layers: F-layer and E-layer

(EUV) (X-rays)



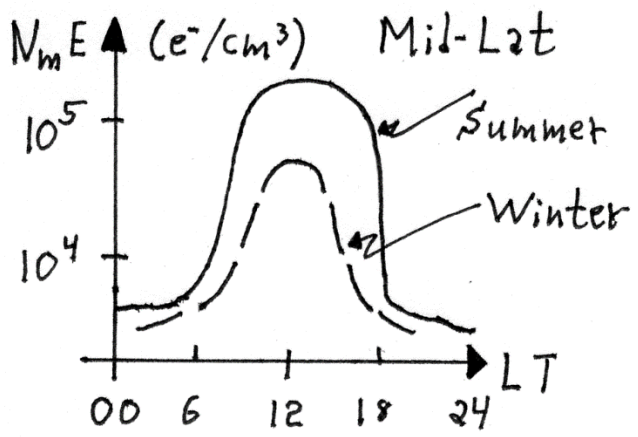

IR Cooling
Temperature (K)
400
800
1200
Solar Min
Solar Max
600
500
400
km 300
200
100
X-Rays
Extreme UV 10-120 nm
Far UV 120-200 nm
Middle UV 200-300 nm
Near UV 300-400 nm
Visible and IR
Thermosphere
Mesosphere
Stratosphere
Troposphere
Density (log_{10} cm^{-3})
0
4
8
12
16
20
O_2 N_2 O
F
e^-
E
D
600
500
400
300 km
200
100

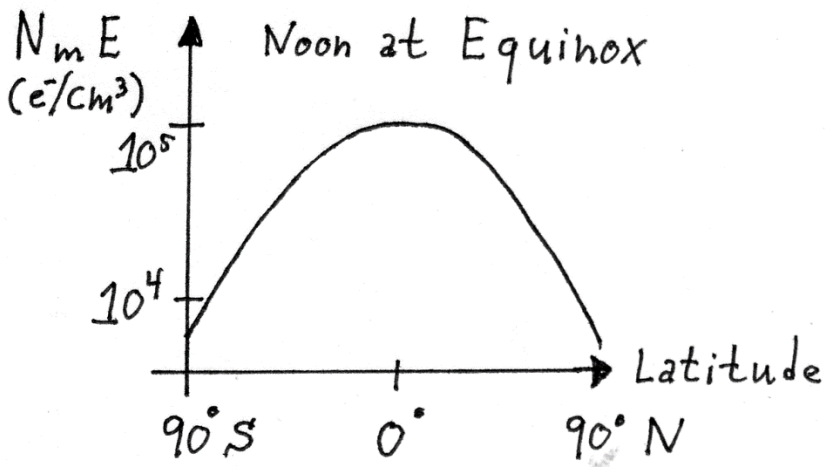

Terrestrial Atmosphere ITM Processes
Solar Energetic Particle Chain
Energetic Particles
Ion/Neutral Escape
Neutral Upwelling From Heated Region
Solar radiation Chain
Solar Wind/Magnetospheric Chain
Currents
Auroral Heating Region
Magnetospheric-Driven Ion Convection
Ion-Driven Wind
Polar Ionosphere Cavity
Solar Wind
EUV
O/N2 Disturbances
Plasma Patch
Gravity Waves
Plasmasphere Filling
Plasmasphere Draining and Heating
Magnetic Flux Tube
Plasma Plume
Ionosphere Trough
Magnetic Flux Tube
SAID
Irregularities
E-Driven Downward Flow
Fountain Effect
Solar-Driven Tides
Implusive Heating-Driven Wind
Gravity Waves
Corotation
Neutral Wind Drags Ions Down Field Line
Equatorial Anomaly
Irregularities/Bubbles
Neutral Wind Drags Ions Up Field Line
Ionosphere Crest
Plume
Lower Atmospheric Chain
Ions
Neutrals
J. Grobowsky / NASA GSFC

Some E-layer Characteristics

- In regions of a dense neutral atmosphere (h ≤ 150 km) all ions are molecular (rapid chemistry) and the ions + electrons stay where produced (too many collisions to move away).

- Example of diurnal behavior

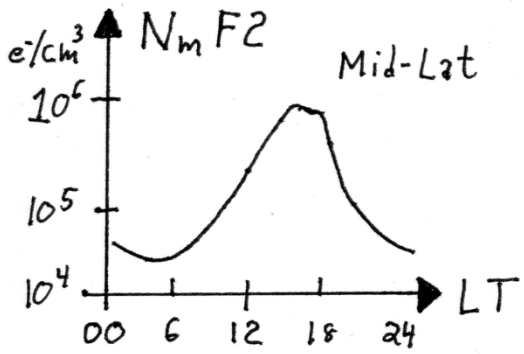


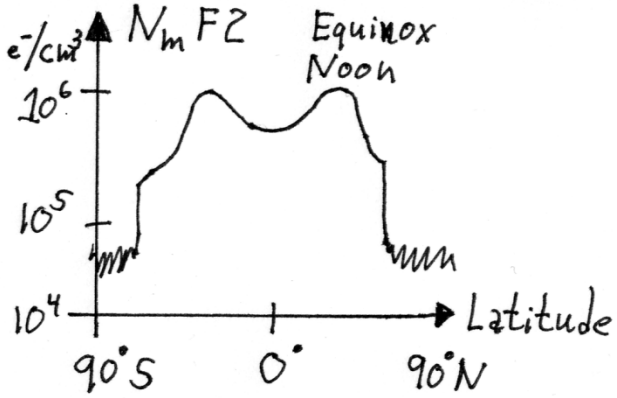


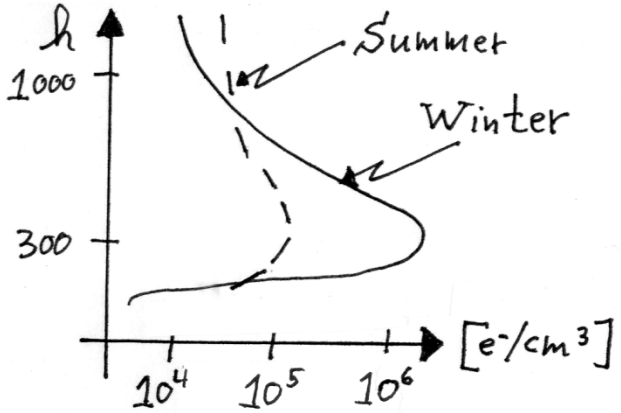
The E-layer is controlled by the Sun's flux and its position (dec + $\chi_\odot$)

3. Photochemistry-Plus-Dynamics

- Some F-layer Characteristics







The F-layer is produced by sunlight BUT its behavior does not follow $\chi_\odot \Rightarrow$ "Anomalies"

What are the causes of vertical motions?

- GRAVITY

- For neutral gas, $\frac{dP}{dh} = -\rho g \Rightarrow \frac{d(NkT)}{dh} = -Nmg$

Solution: Hydrostatic Law

$$N(h) = N_o(h_o)\exp[-(h-h_o)/H_n)$$

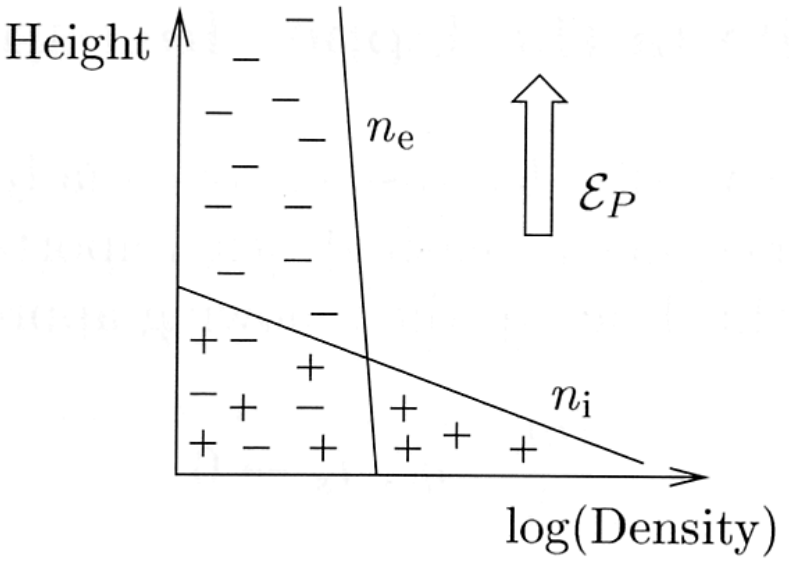
neutral scale height $H_n = \frac{kT}{mg}$

- For plasma → ions + electrons

$$m_i \gg m_e$$

Gravity tends towards "charge separation"

$\Rightarrow$ Polarization $\vec{E}$-field (ε_p)



$$\frac{dP_i}{dh} = -\rho_i g + N_i e \varepsilon_p \qquad \frac{dP_e}{dh} = -\rho_e g - N_e e \varepsilon_p$$

Adding, with $N_i = N_e = N$ and $m_e \leftrightarrow 0$

$$\frac{d(P_i + P_e)}{dh} \approx -N m_i g$$

- Solution $N(h) = N_o(h_o)\exp[-(h-h_o)/H_p)$

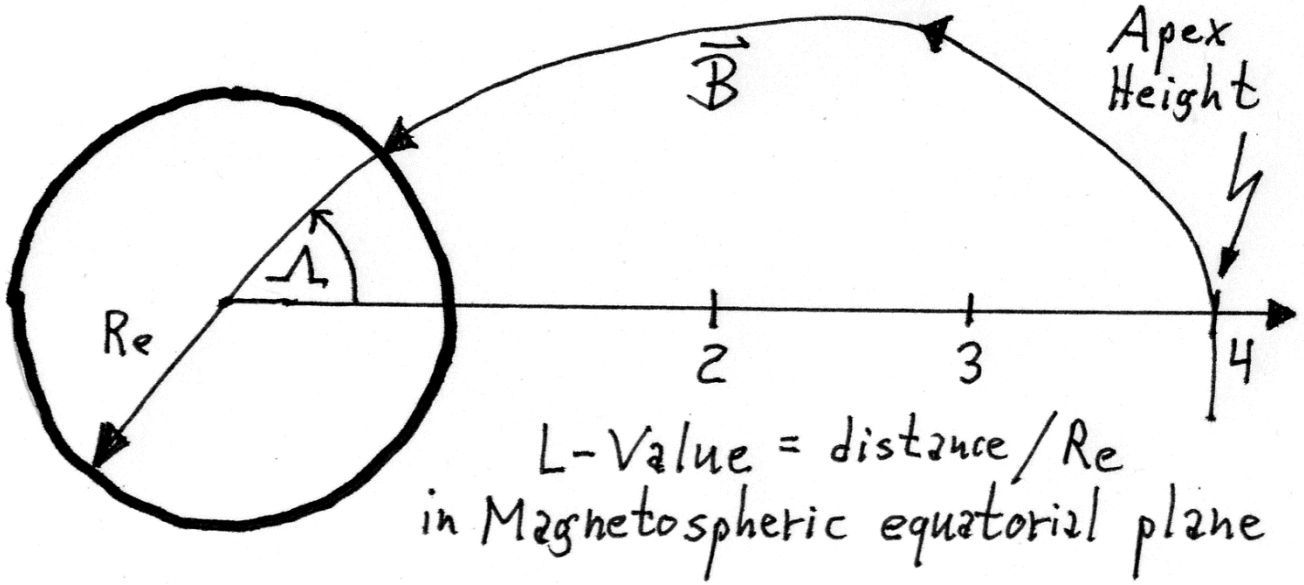
Plasma scale height $H_p = \dfrac{k(T_e + T_i)}{mg}$

$$H_p \geq 2H_n$$

Called "Ambipolar diffusion"

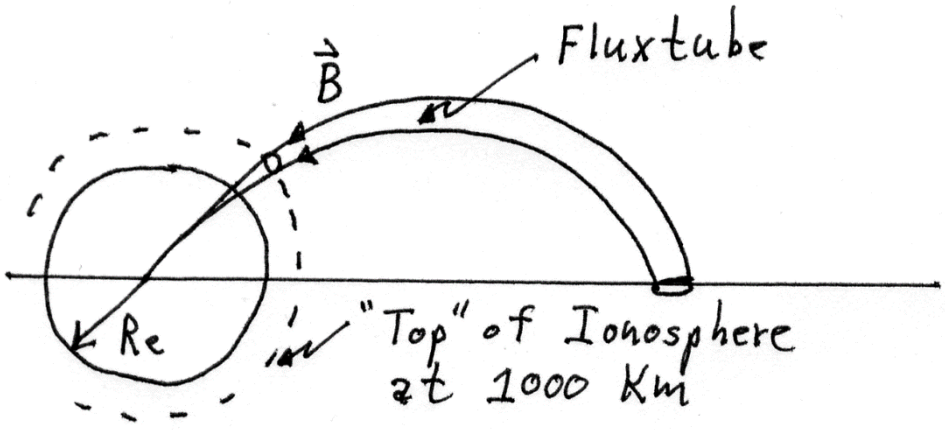
- electrons "pull" ions upward
- ions "pull" electrons downward

- Midlatitudes (extended)



Magnetic Latitude (Λ), $\cos^2\Lambda = 1/L$ (e.g., $L=4 \Rightarrow \Lambda = 60^o$)

What happens to ionospheric plasma diffusing upwards?



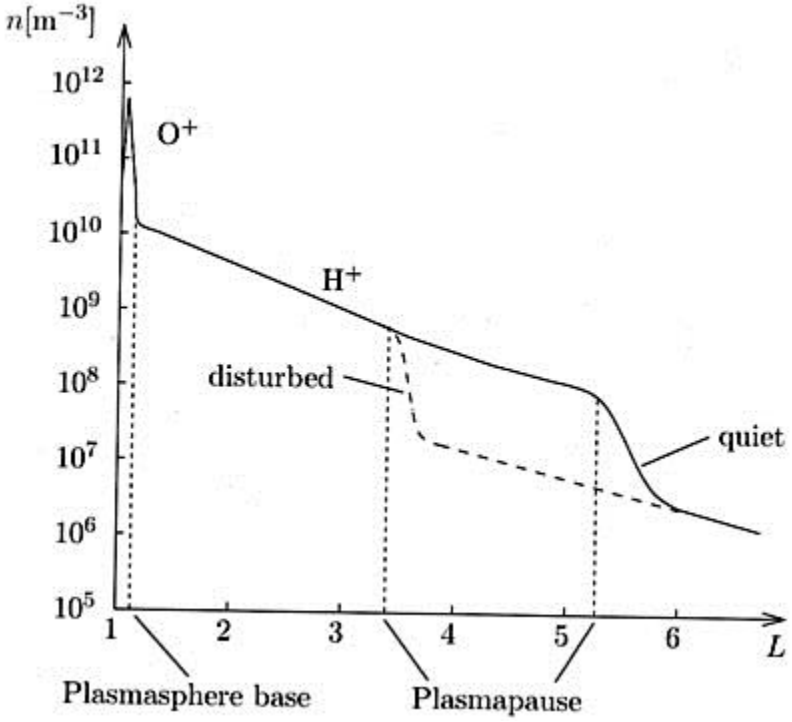
"Charge Exchange"

$$\underbrace{O^+}_{\text{heavy ion}} + H \Leftrightarrow \underbrace{H^+}_{\text{light ion}} + O$$

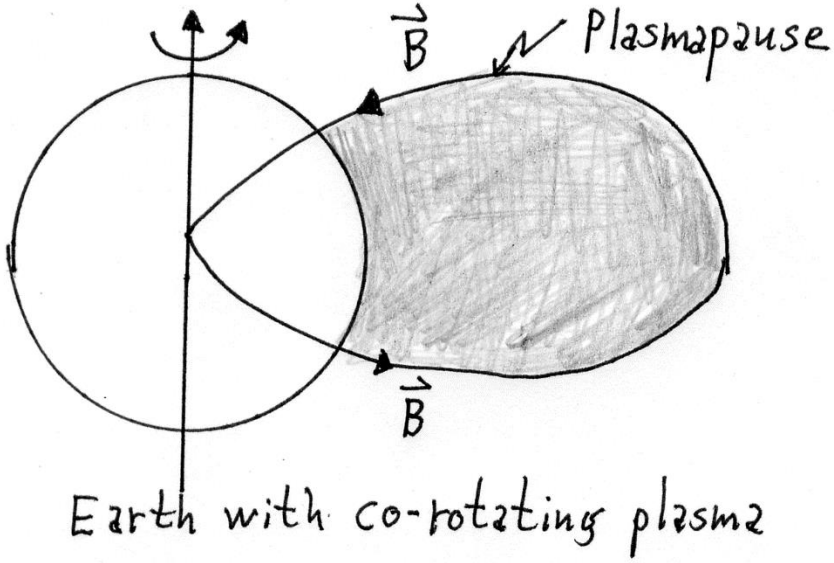
Diffusion affected by reduced gravity, $F_{centripetal}$, light ions

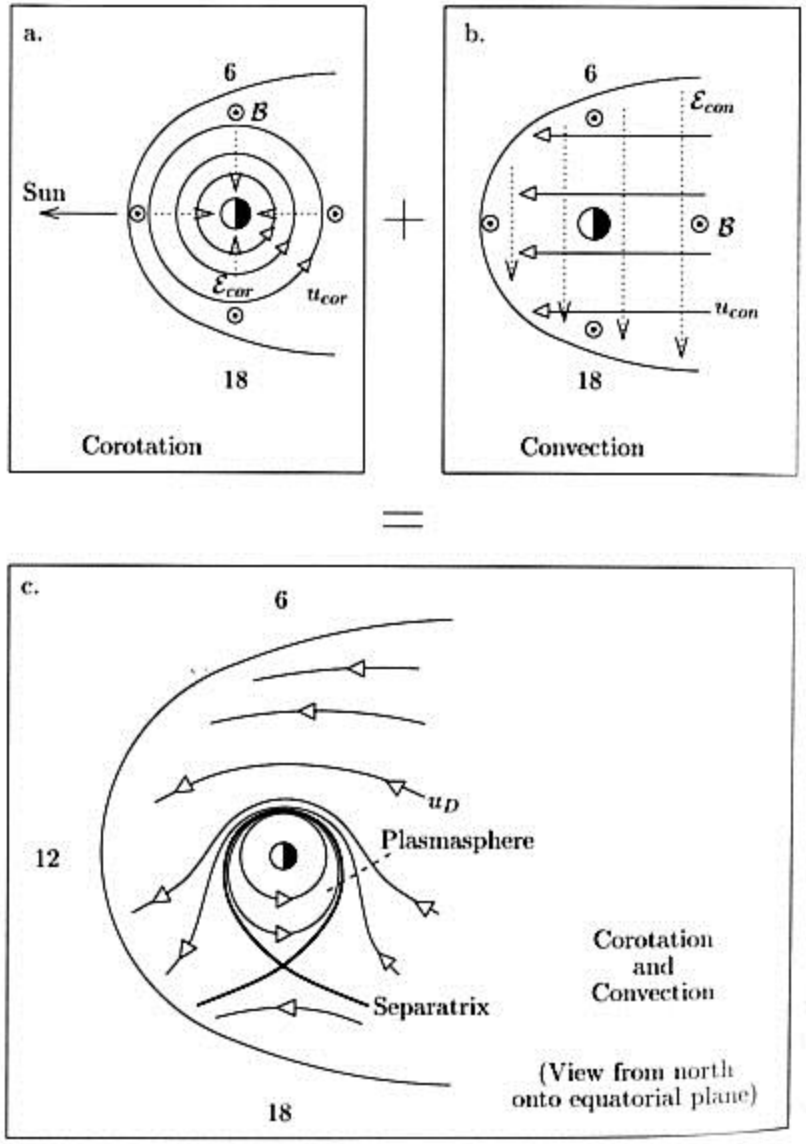
$$\frac{dP}{ds} \rightarrow \text{large } H_p$$

$\longrightarrow$ fluxtubes of plasma of ionospheric origin



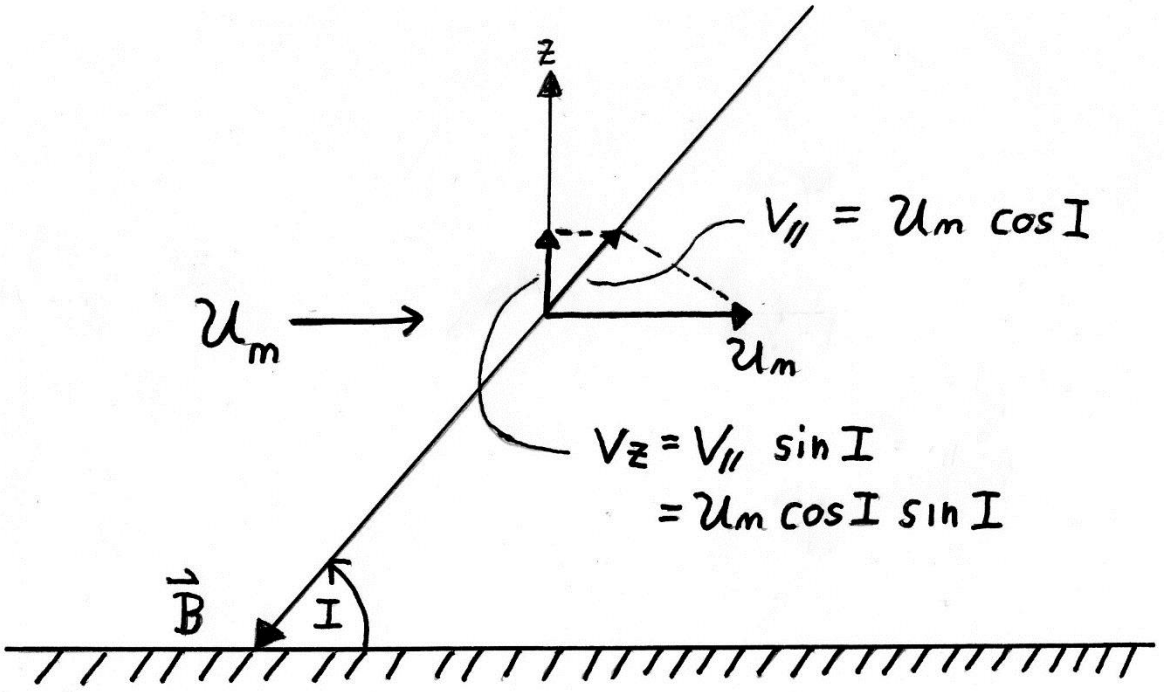
The Plasmasphere in 3-dimensions:





What else causes Vertical Motions? Roles of Magnetic Field

- Neutral Winds (U_m) are horizontal
- Plasma constrained to move $\| \vec{B}$



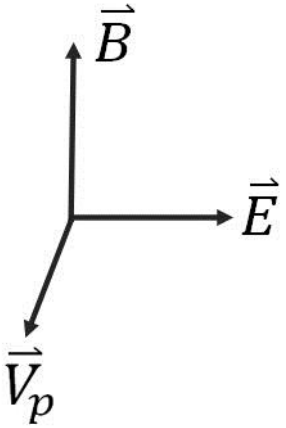
- Middle Latitudes – maximum effect
- Equatorial Latitudes (I = 0º) – small effect
- High Latitudes (I = 90º) – small effect

} Unless U_m generates polarization $\vec{E}$-field

Electrodynamics: Motions caused by induced or penetrating $\vec{E}$ -fields

$$\vec{V}_p = \frac{\vec{E} \times \vec{B}}{|B|^2}$$

At high latitudes

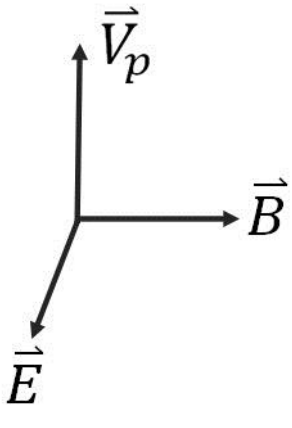


$\vec{B}$ close to vertical

$\vec{E}$ horizontal causes horizontal $\vec{V}_p$

Convection Patterns

At low latitudes

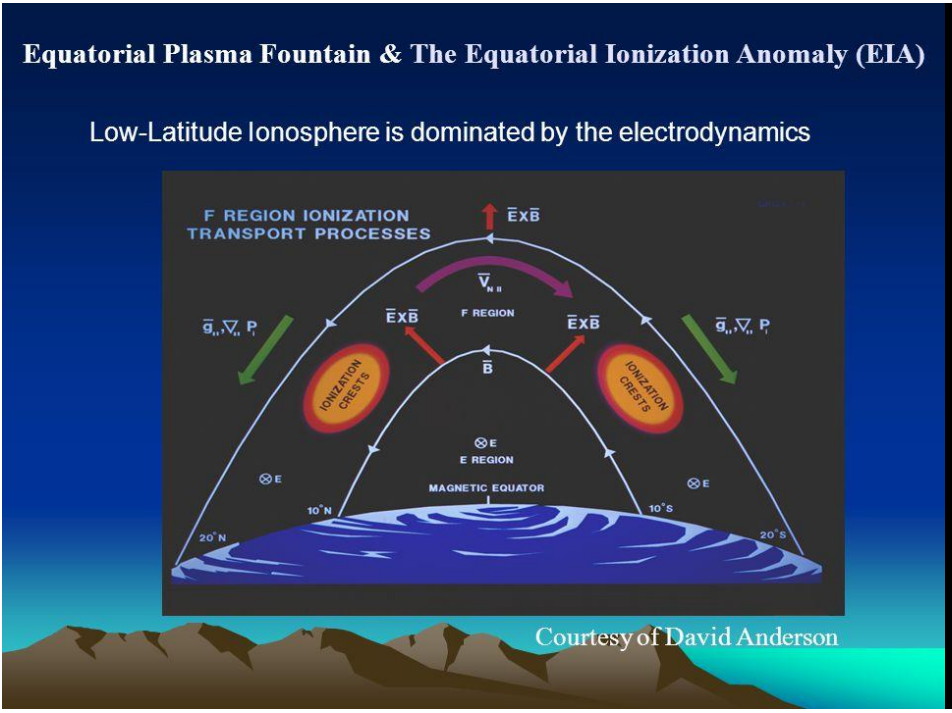


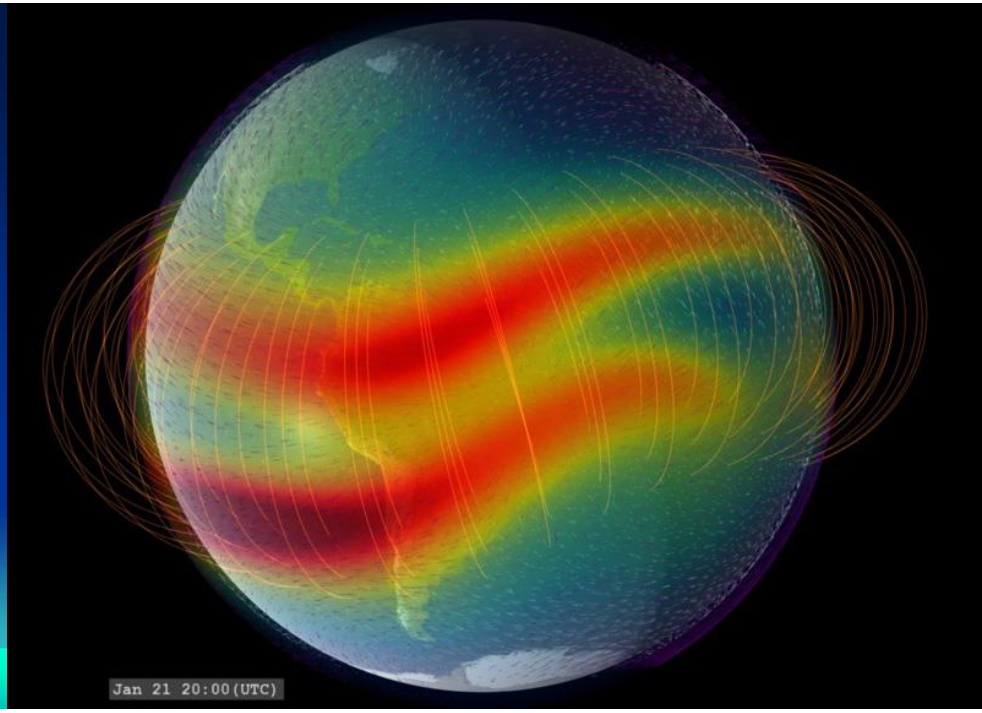
$\vec{B}$ close to horizontal

$\vec{E}$ horizontal causes vertical $\vec{V}_p$

Fountain Effect

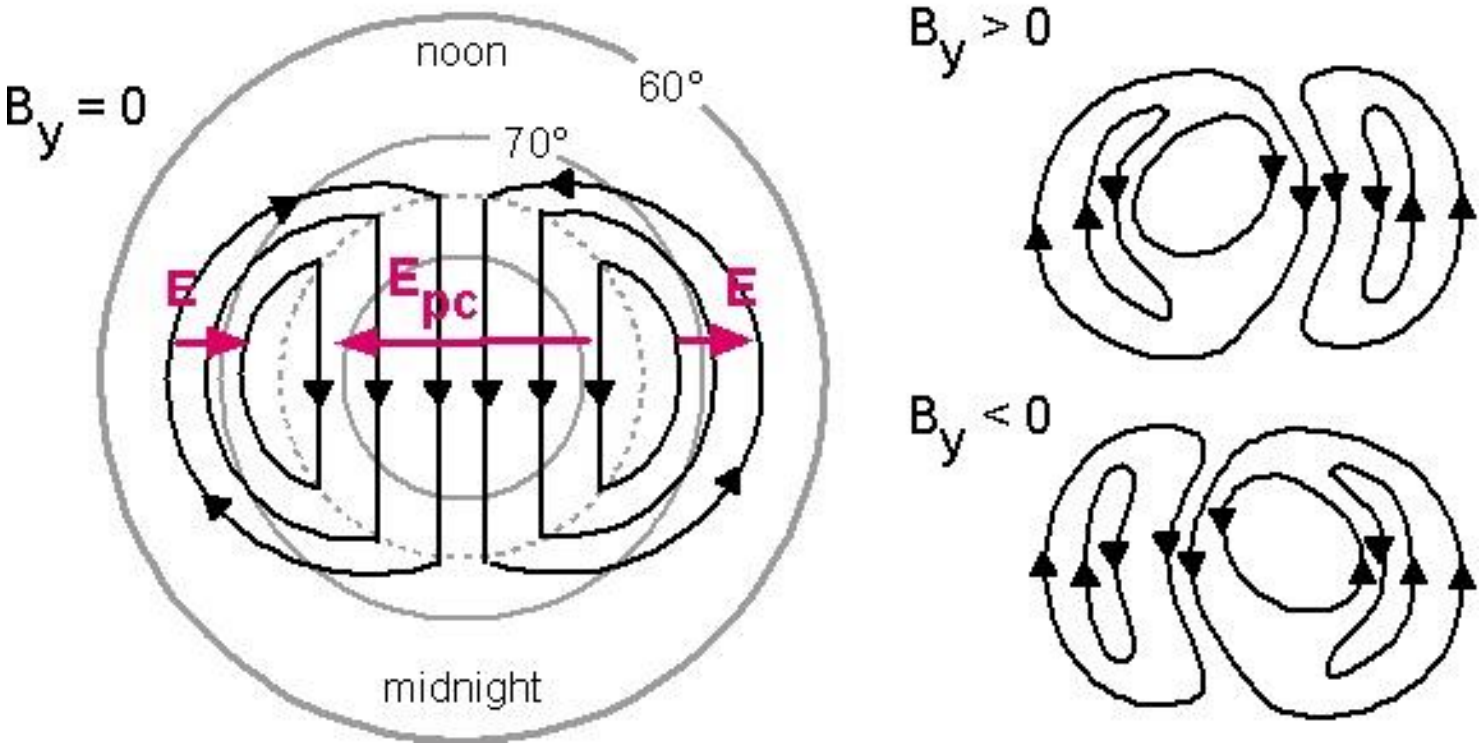
Effects of Electro-Dynamics at Low Latitudes





Effects of Electro-Dynamics at High Latitudes

B_Z southward

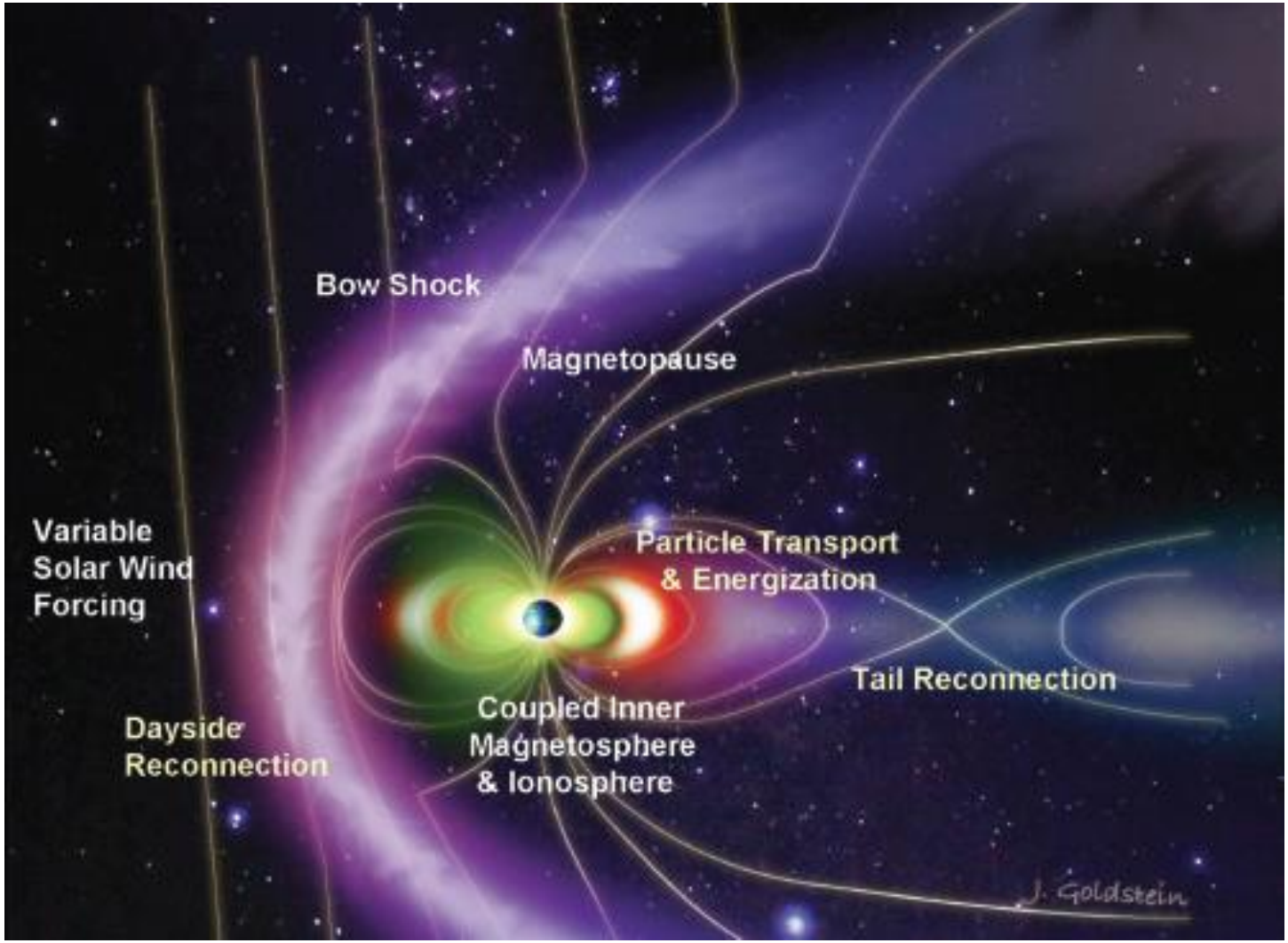


The Polar and High Latitude Ionosphere

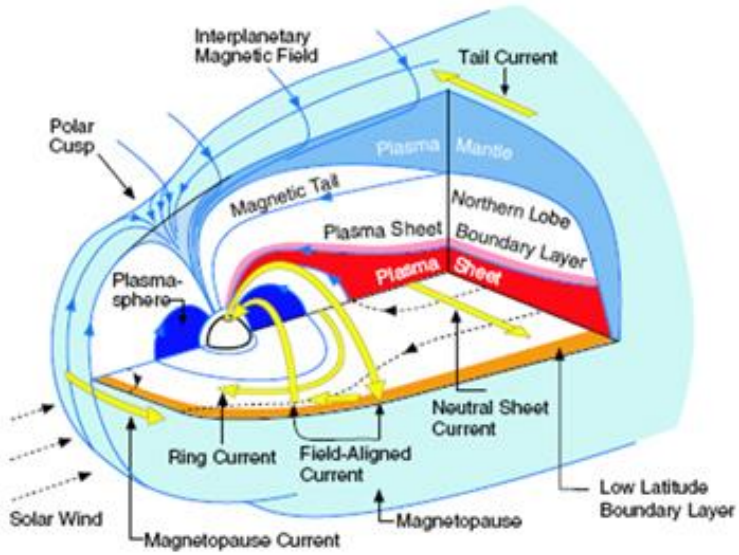
- Minimal production of plasma by solar photons
- Strong production of plasma by precipitation of energetic particles from Magnetosphere (nightside) and solar wind (dayside)
- Strong $\vec{E}$-fields:

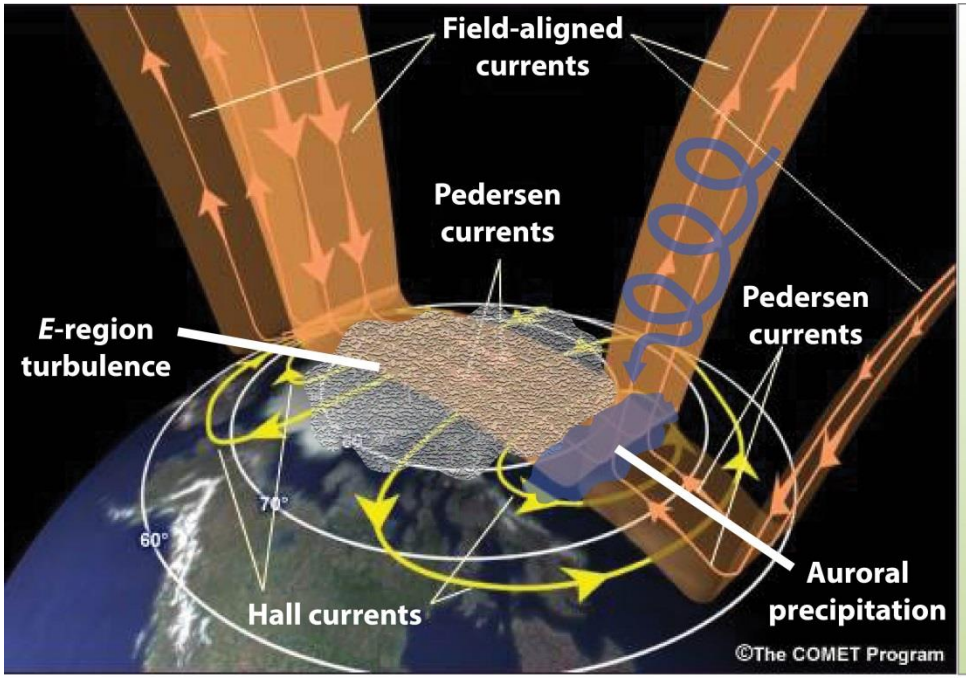
  Solar wind → Magnetosphere → Ionosphere
- Electrodynamics: Horizontal convection/circulation patterns
- Upward diffusion & escape: Polar Wind
- Many ionospheric irregularities due to Plasma Instabilities

Summary #1: External Drivers



Summary #2: A Highly Coupled/Complex System





Current closure (height-integrated Ohm's law) is key to M-I-T coupling

$$\nabla_{\perp} \cdot \left(\vec{\vec{\Sigma}} \cdot \nabla_{\perp} \Phi \right) = J_{\parallel}$$

$$\vec{\vec{\Sigma}} = \int \vec{\vec{\sigma}}\, dh$$

Conductivity regulates interaction between the field-aligned current $J_{\parallel}$, electric potential Φ and Hall and Pedersen currents.

Conductivity $\vec{\vec{\sigma}}\,(n, n_e, n_i)$ and its functional dependences are critical.

Need global distributions of neutral (n), electron (n_e), ion (n_i) densities.

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