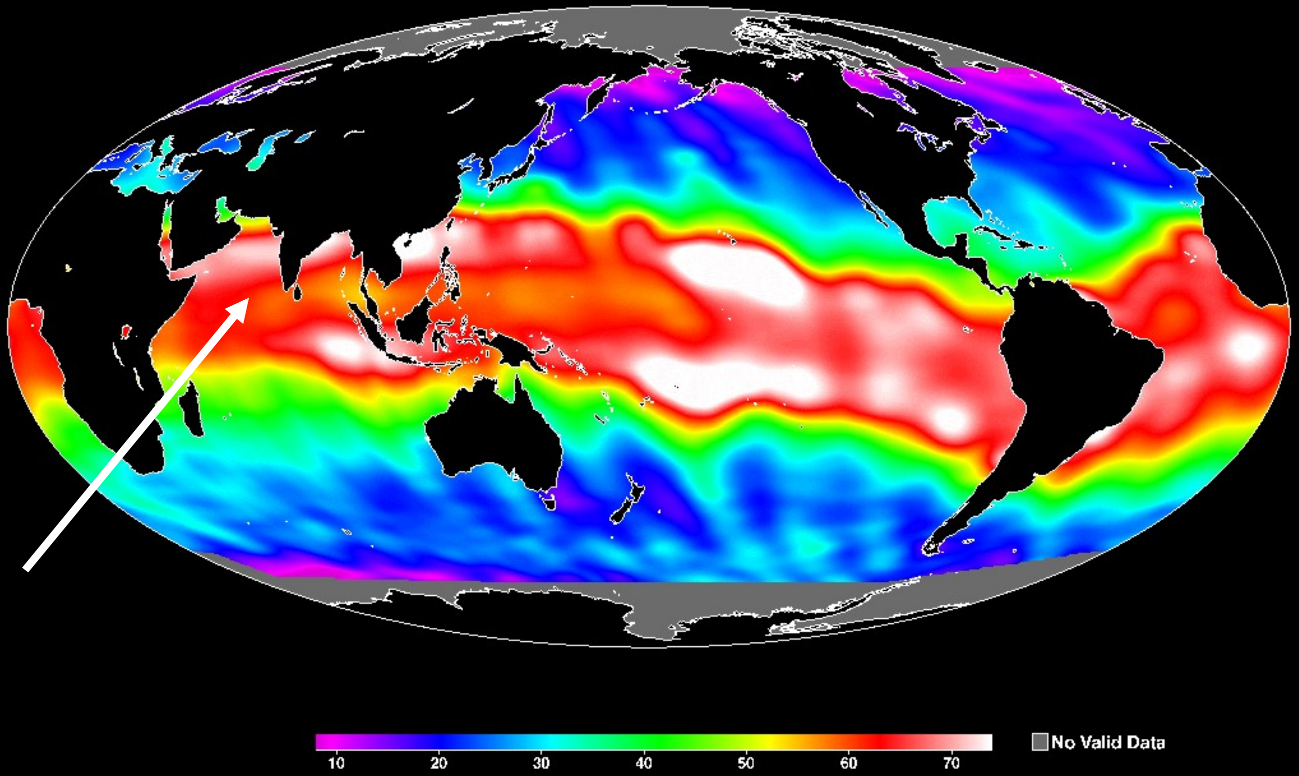
Ideas about the ionosphere

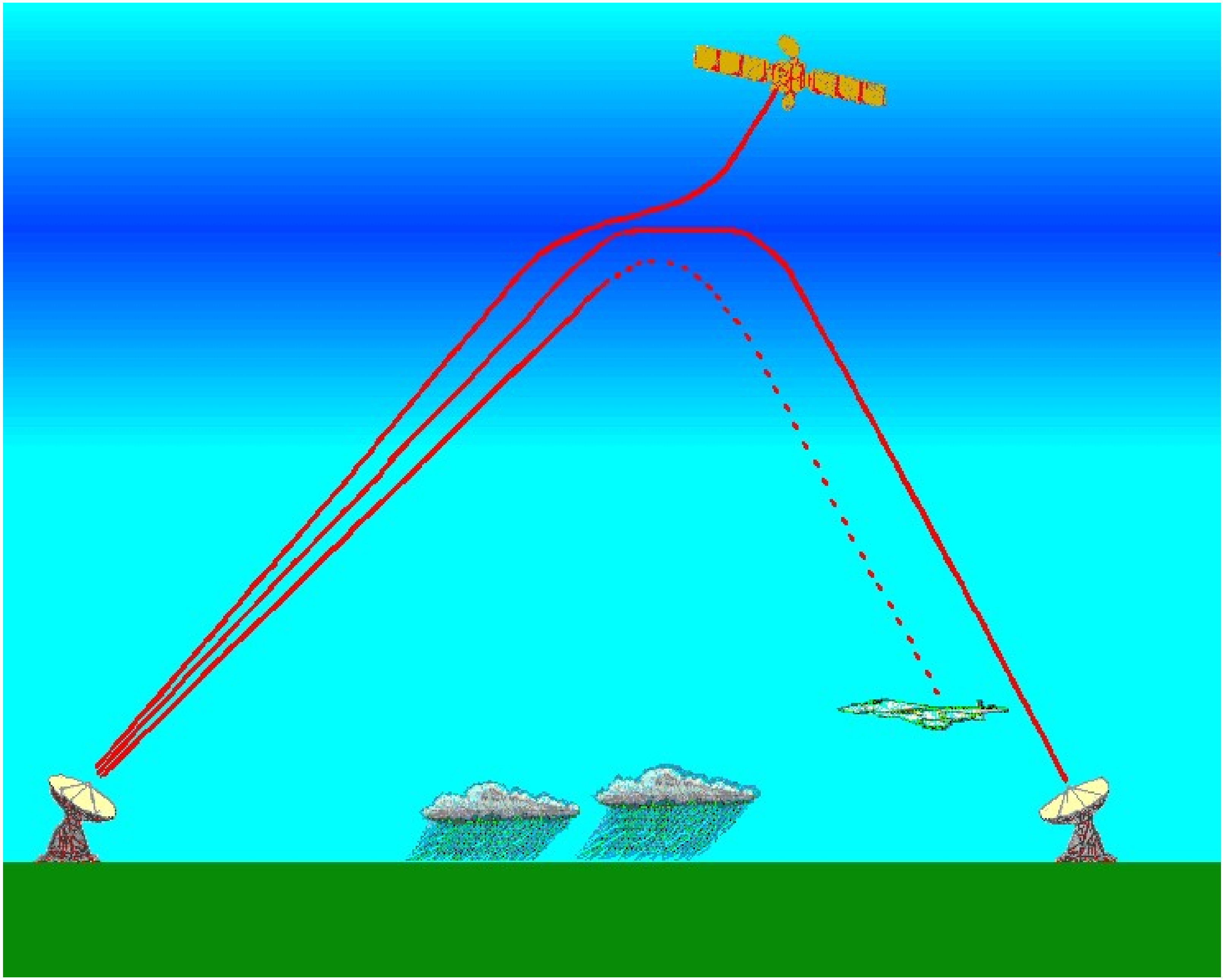
- What generates the ionosphere plasma?
- Ionosphere currents, What is σ?
  - 1. below 85 km altitude σ is isotropic
  - 2. 85 to 150 km (D and E regions) σ is tensor
  - 3. above 150 km σ is just $\sigma_{||}$

The Ionosphere

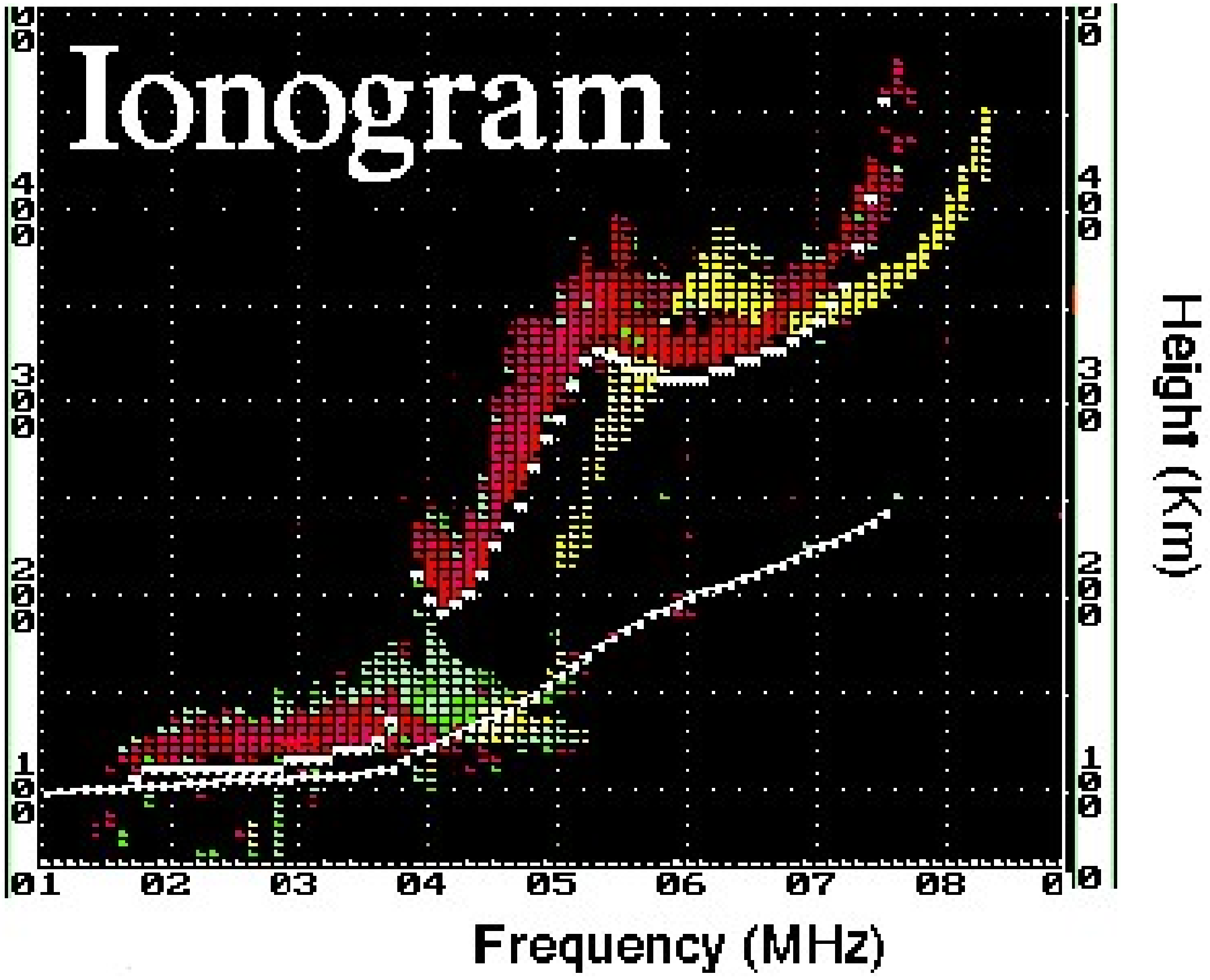


Ionospheric Total Electron Content (10^{16} electrons / m^2)
8am - 7pm Oct 22 - Nov 1, 1992

Equatorial
Anomaly



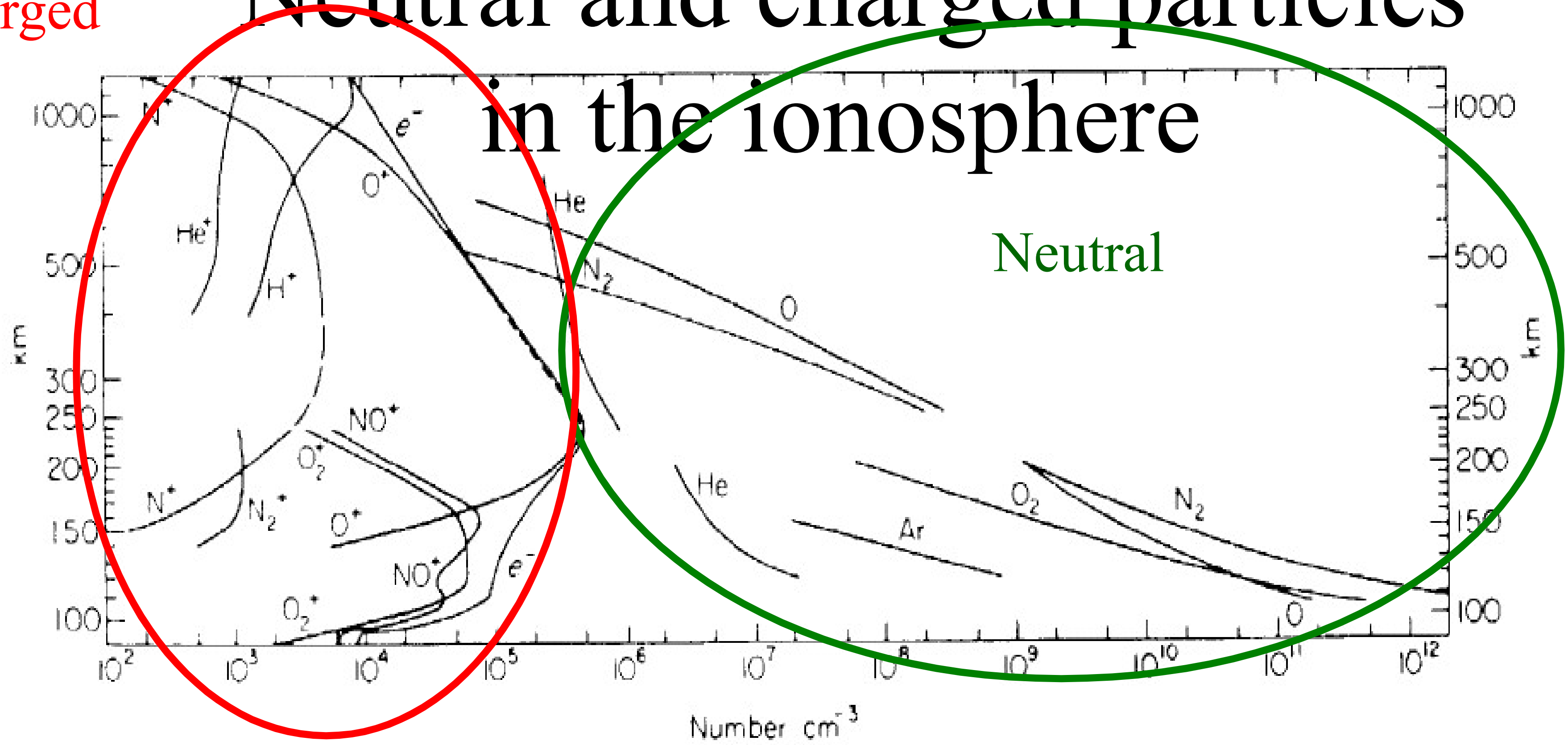
ionogram


Ionogram
400
300
200
100
01
02
03
04
05
06
07
08
0
Frequency (MHz)
Height (Km)

Ionosphere Properties and Structure

- 10^3 to 10^6 electron – ion pairs in every cubic cm
- Sources of ionization: both electromagnetic radiation and energetic particles
- Reflects, or retards radio waves
- layered structure
- Variations on all time scales from ms to solar cycle

Neutral and charged particles in the ionosphere



Charged

Neutral

Fig. 1.2. International Quiet Solar Year (IQSY) daytime atmospheric composition, based on mass spectrometer measurements above White Sands, New Mexico (32°N, 106°W). The helium distribution is from a nighttime measurement. Distributions above 250 km are from the Elektron II satellite results of Istomin (1966) and Explorer XVII results of Reber and Nicolet (1965). [C. Y. Johnson, U.S. Naval Research Laboratory, Washington, D.C. Reprinted from Johnson (1969) by permission of the MIT Press, Cambridge, Massachusetts. Copyright 1969 by MIT.]

What is σ_1 ? (Low Atmosphere)

$$m\frac{d\vec{V}}{dt} + m\nu\vec{V} = e\vec{E} \quad \text{(force eqtn.)}$$

To solve: assume plane wave superposition in steady state:

$$\vec{V} = \frac{e}{m(\nu - i\omega)}\vec{E}_o e^{-i\omega t}$$

From which we can get σ by using

$$\vec{J} = \sum_s n_s e_s \vec{V}_s = \sigma\vec{E} \quad \text{(Ohms Law)}$$

for a single species at dc:

$$\sigma = \frac{ne^2}{m\nu} \quad \text{(Spitzer Conductivity)}$$

What is $\overleftrightarrow{\sigma}$?

σ_1 (atmosphere) - is scalar up to 85 km. For a single atmospheric ion species at dc:

$$\boxed{\sigma = \frac{ne^2}{m\nu} \text{ (Spitzer Conductivity)}}$$

ν is due to ion-neutral collisions and comes from Boltzman Equation:

$$\longrightarrow \quad \frac{\partial f}{\partial t} + \vec{V}\cdot\frac{\partial f}{\partial \vec{r}} + \frac{q}{m}(\vec{E} + \vec{V}\times\vec{B})\frac{\partial f}{\partial \vec{V}} = \left.\frac{\partial f}{\partial t}\right|_c \text{ (= 0 in fluid theory)}$$

$$\left.\frac{\partial f}{\partial t}\right|_c = \frac{f(\vec{r},t) - f_o}{\underset{\text{Velocity Dependent}}{\tau(V)}} \left(\not\simeq\right) \frac{f(\vec{r},t) - f_o}{\tau} \leftarrow \text{mean collision time}$$

set $\nu \equiv \frac{1}{\tau}$ to get: $\sigma = \frac{ne^2}{m\nu}$ for each species

To get n integrate Boltzman eqtn. over $\vec{V}$:

$$\frac{dn}{dt} \rightarrow \frac{\partial n}{\partial t} + \nabla\cdot(n\vec{V}) = 0 = \text{Source} - \text{Sink} \quad \text{(steady state non convecting)}$$

$$= \underset{\text{pair production}}{\Pi} - \underset{\text{recombination}}{\alpha n^2} - \underset{\text{Aerosol Attachment}}{\beta n_A n}$$

Charged and Neutral Structure

1.2 Structure of the Neutral Atmosphere and the Ionosphere 5

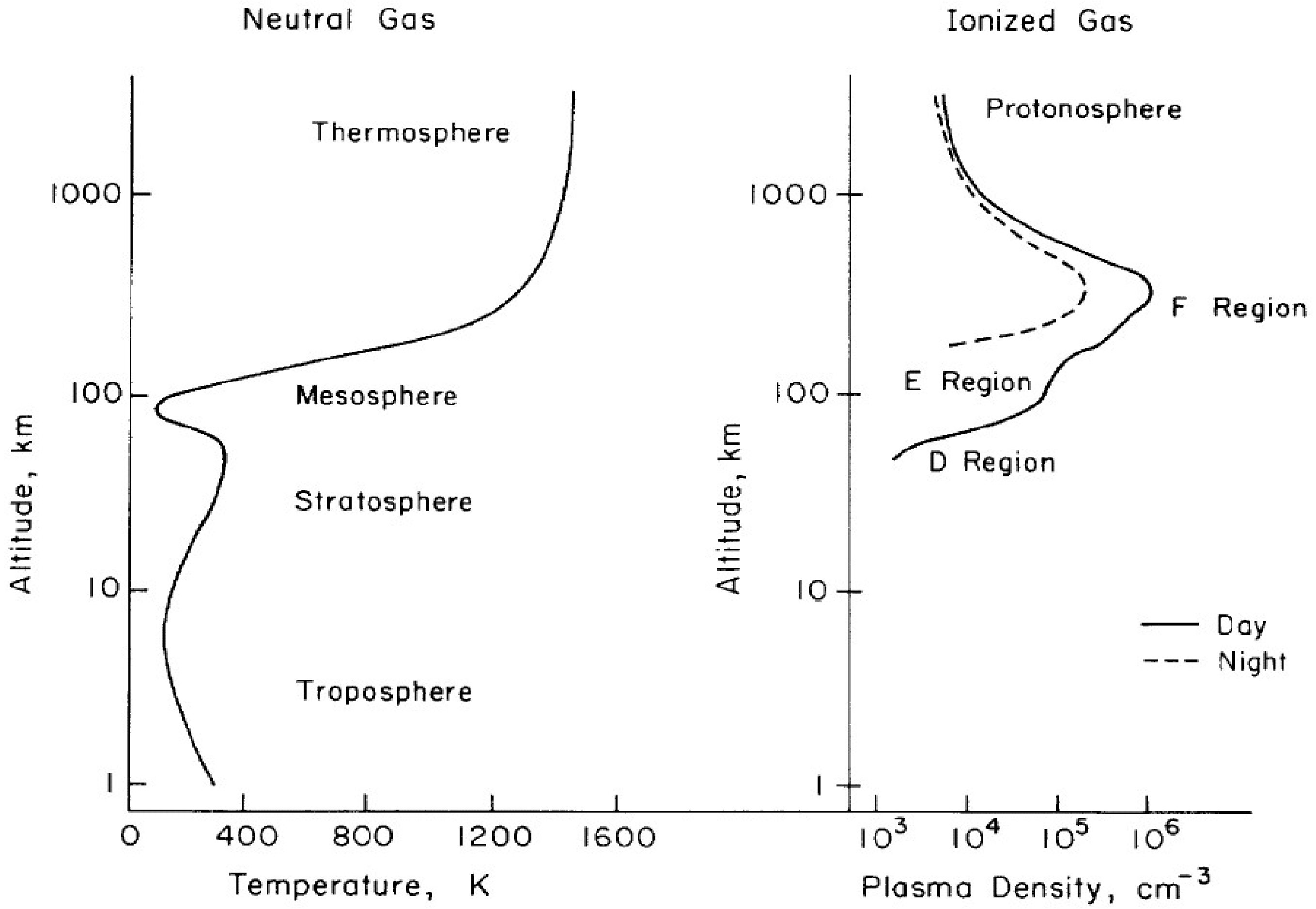
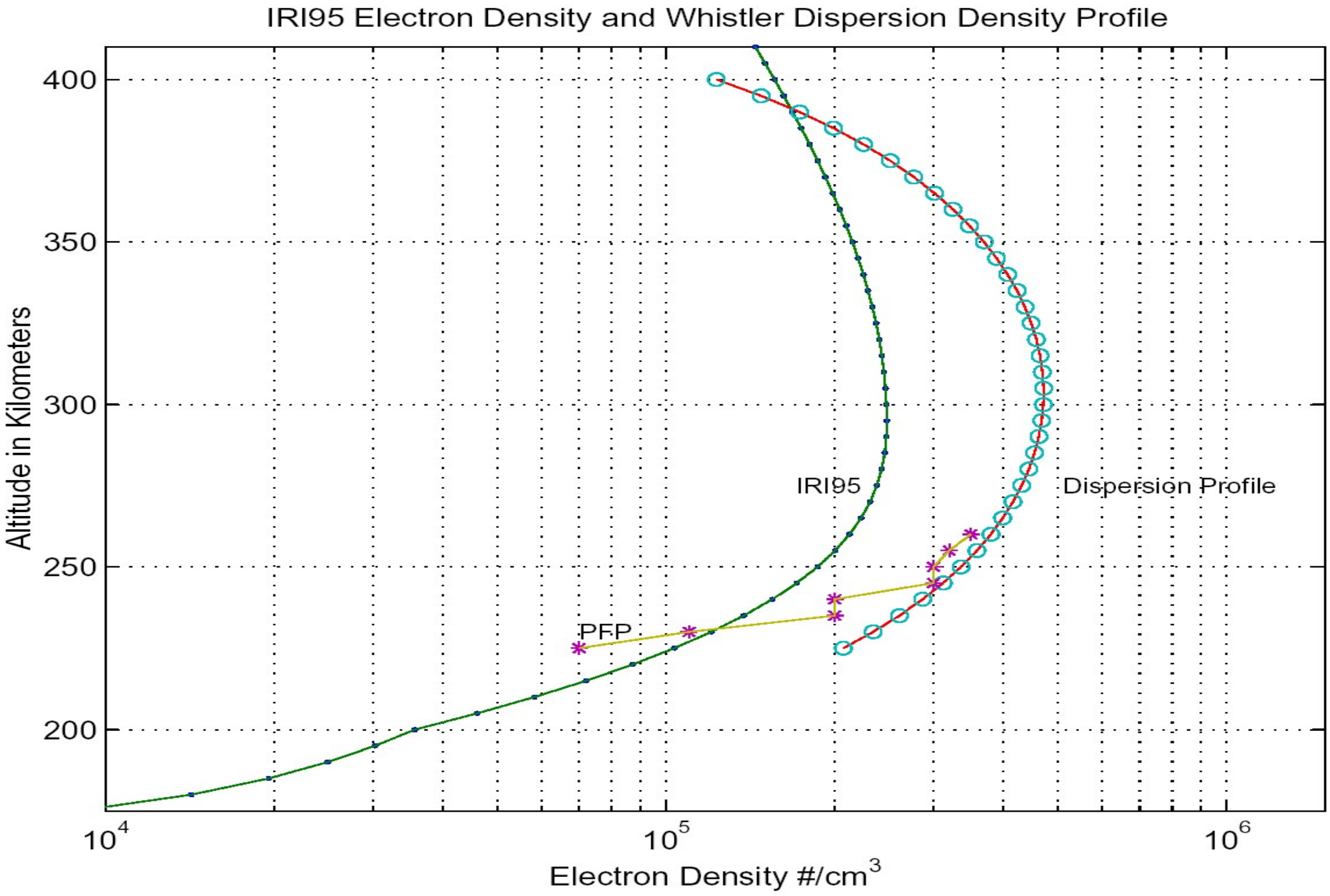


Fig. 1.1. Typical profiles of neutral atmospheric temperature and ionospheric plasma density with the various layers designated.


IRI95 Electron Density and Whistler Dispersion Density Profile
Altitude in Kilometers
400
350
300
250
200
10^4
10^5
10^6
Electron Density #/cm^3
IRI95
Dispersion Profile
PFP

Definition of the Ionospheric Regions

- For convenience, we divide the Ionosphere into four broad regions called D, E, F, and topside. These regions may be further divided into several regularly occurring layers, such as F1 or F2.
- **D-Region:**
- The region between about 75 and 95km above the Earth in which the (relatively weak) ionization is mainly responsible for absorption of high-frequency radio waves.

- **E-Region:**
- The region between about 95 and 150km above the Earth that marks the height of the regular daytime E-layer. Other subdivisions, isolating separate layers of irregular occurrence within this region, are also labeled with an E prefix, such as the thick layer, E2, and a highly variable thin layer, Sporadic E. Ions in this region are mainly O2+.

- **F-Region:**
- The region above about 150km in which the important reflecting layer, F2, is found. Other layers in this region are also described using the prefix F, such as a temperate-latitude regular stratification, F1, and a low-latitude, semi-regular stratification, F1.5. Ions in the lower part of the F-layer are mainly NO+ and are predominantly O+ in the upper part. The F-layer is the region of primary interest to radio communications.

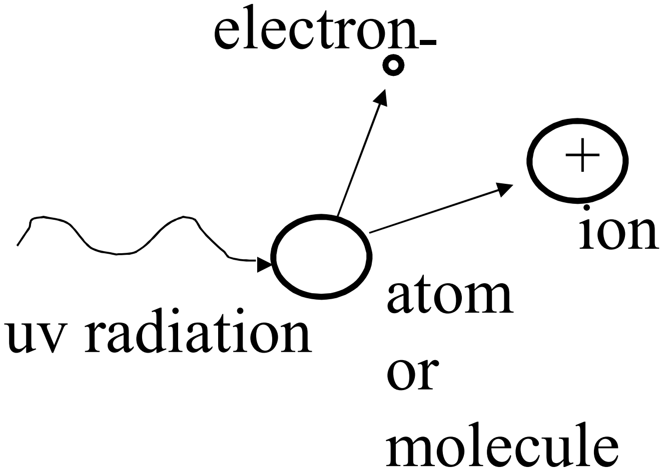
- **Topside:**
- This part of the Ionosphere starts at the height of the maximum density of the F2 layer of the Ionosphere and extends upward with decreasing density to a transition height where O+ ions become less numerous than H+ and He+. The transition height varies but seldom drops below 500km at night or 800km in the daytime, although it may lie as high as 1100km. Above the transition height, the weak ionization has little influence on radio signals.

Why are there free electrons and ions in the ionosphere, and not in the lower atmosphere?

- Ion-electron pair sources:

  uv and xuv solar radiation

  energetic electron bombardment



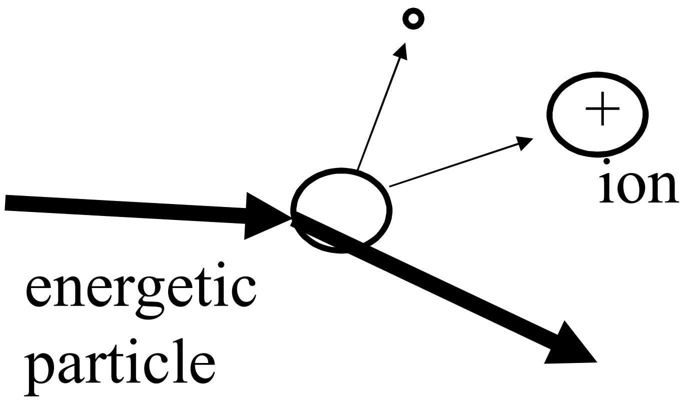
electron -

ion

atom or molecule

uv radiation

Photoelectric Emission



ion

energetic particle

Impact ionization

Ionospheric Variability

- Lightning causes – ms to minutes variations
- Aurora and solar events cause changes in seconds, lasting sometimes hours
- Atmospheric Temperature and waves cause ionospheric variations
- Electric and magnetic fields cause variability
- Earth’s rotation (no uv at night!)

Day to Night Variability

- Solar uv only effective on sunlit side
- After sunset ions recombine with electrons at lower altitudes (D and E regions)
- F-region remains strongly ionized at night because recombination is much slower
- Nighttime E-region goes away except during aurora

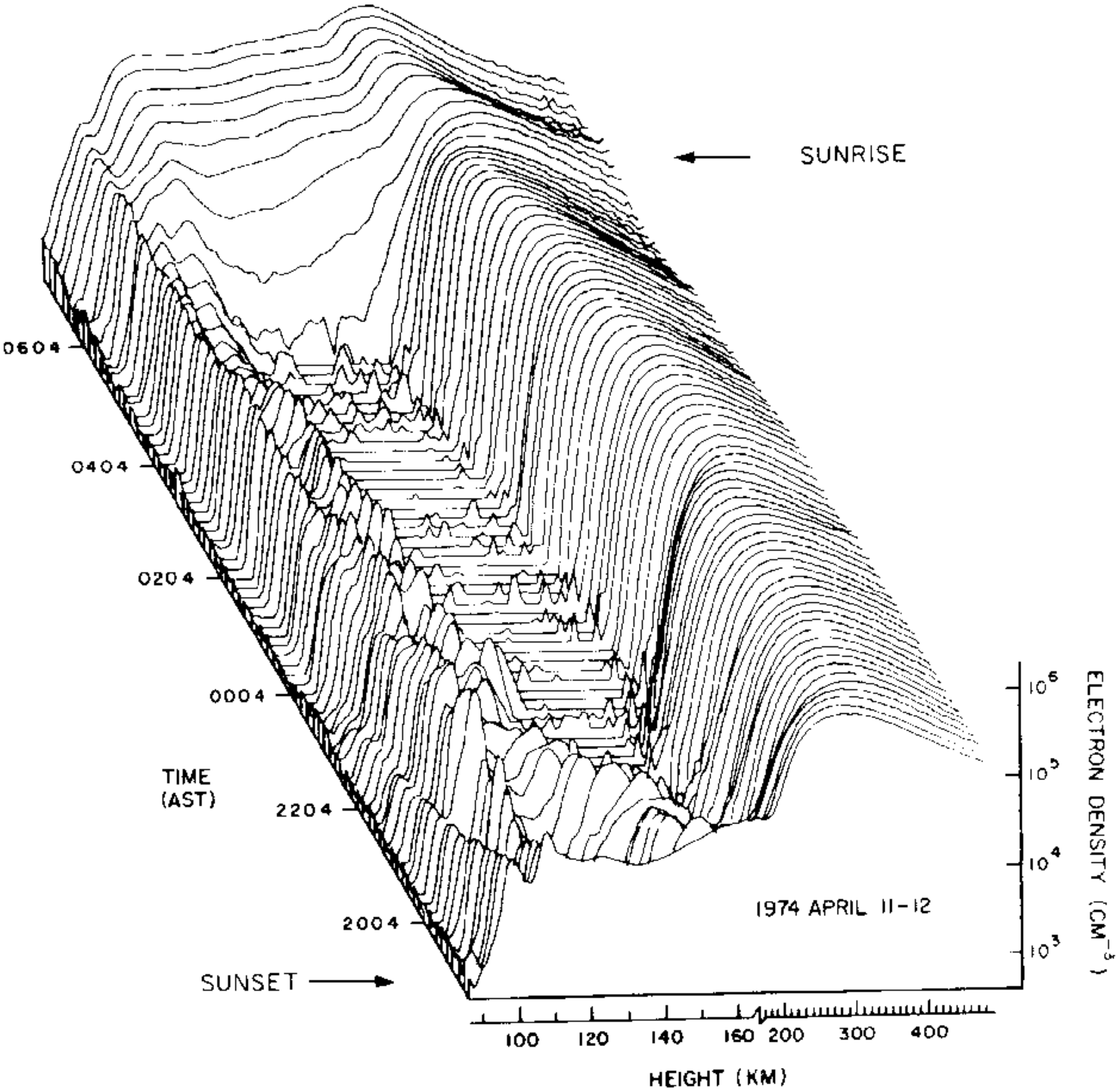
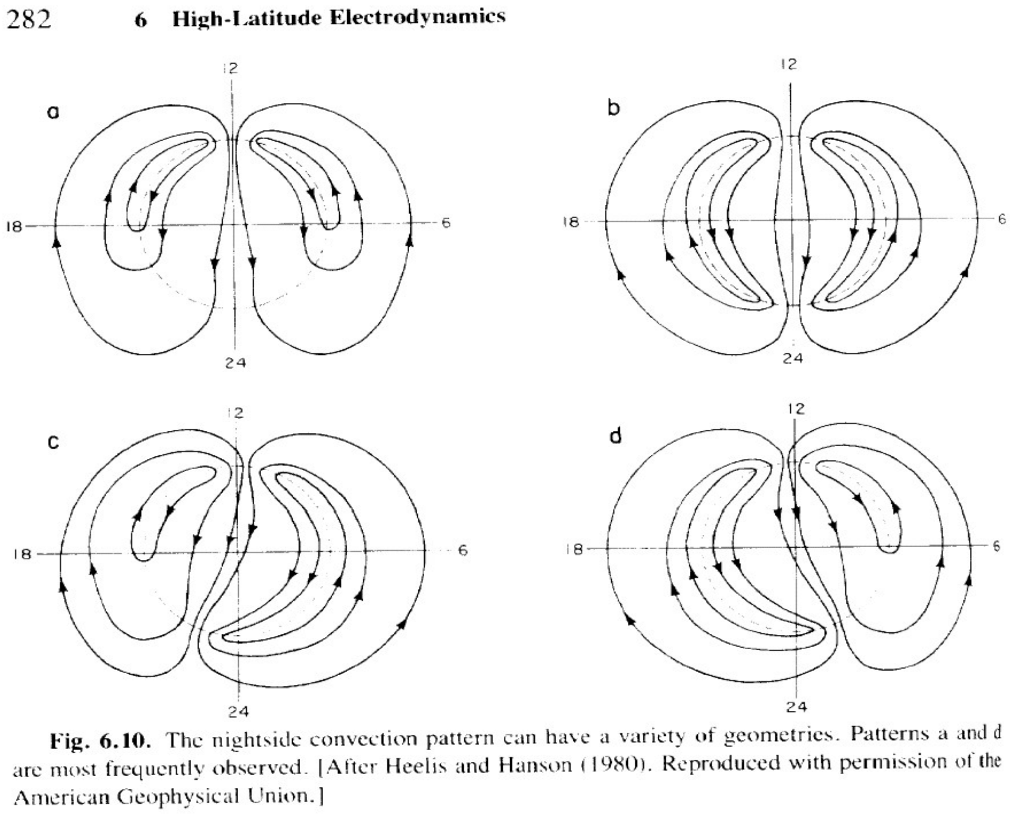


Fig. 1.3. Plasma density contours during a typical night over Arecibo, Puerto Rico. [After Shen *et al.* (1976). Reproduced with permission of the American Geophysical Union.]

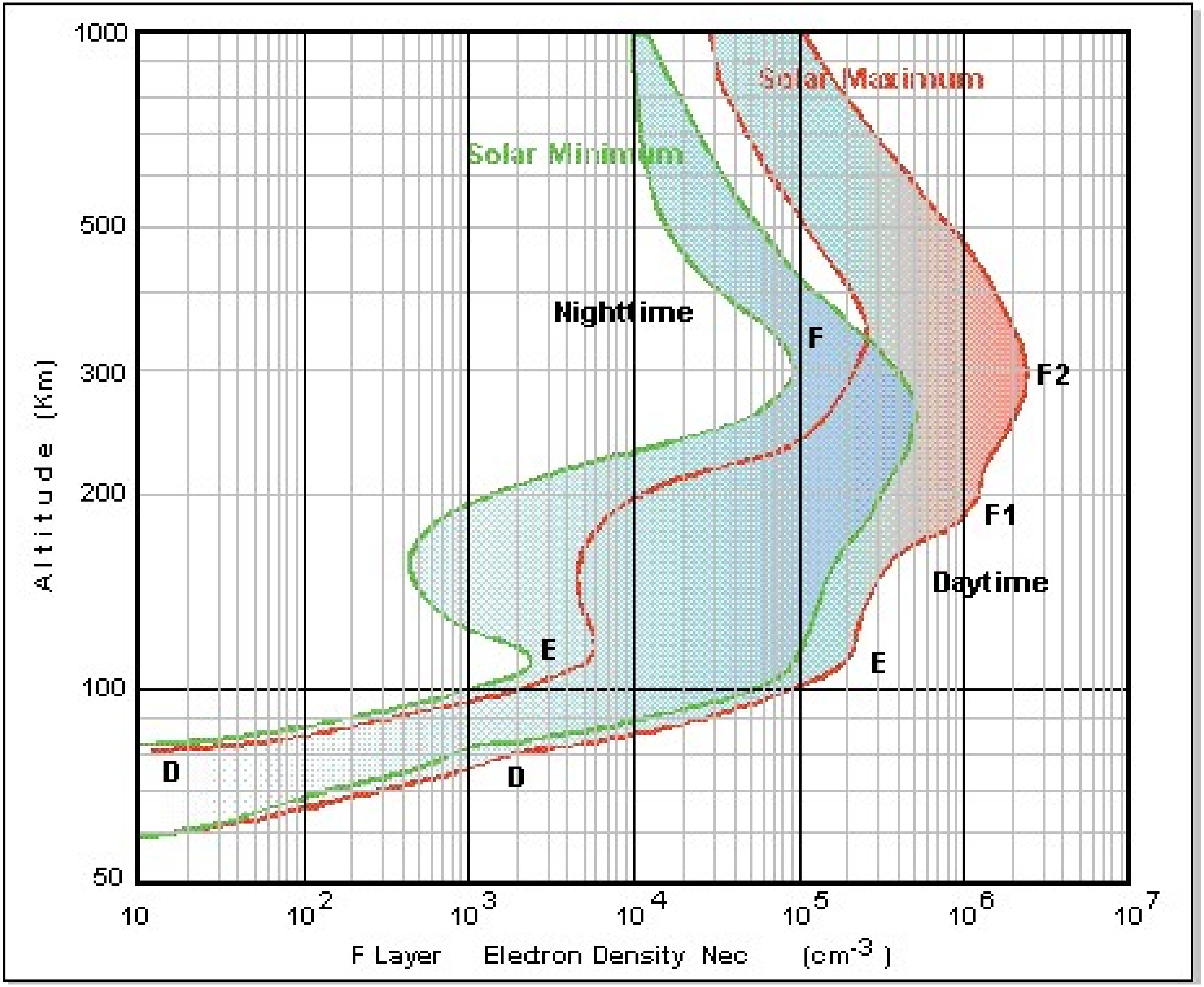
So the whole ionosphere drifts when electric fields are present

View
from
above
N-Pole



282 **6 High-Latitude Electrodynamics**

Fig. 6.10. The nightside convection pattern can have a variety of geometries. Patterns a and d are most frequently observed. [After Heelis and Hanson (1980). Reproduced with permission of the American Geophysical Union.]



Solar Maximum
Solar Minimum
Nighttime
Daytime
F
F2
F1
E
E
D
D
1000
500
300
200
100
50
Altitude (Km)
10
10 2
10 3
10 4
10 5
10 6
10 7
F Layer Electron Density Nec (cm-3)

ionogram

CHAPTER 10

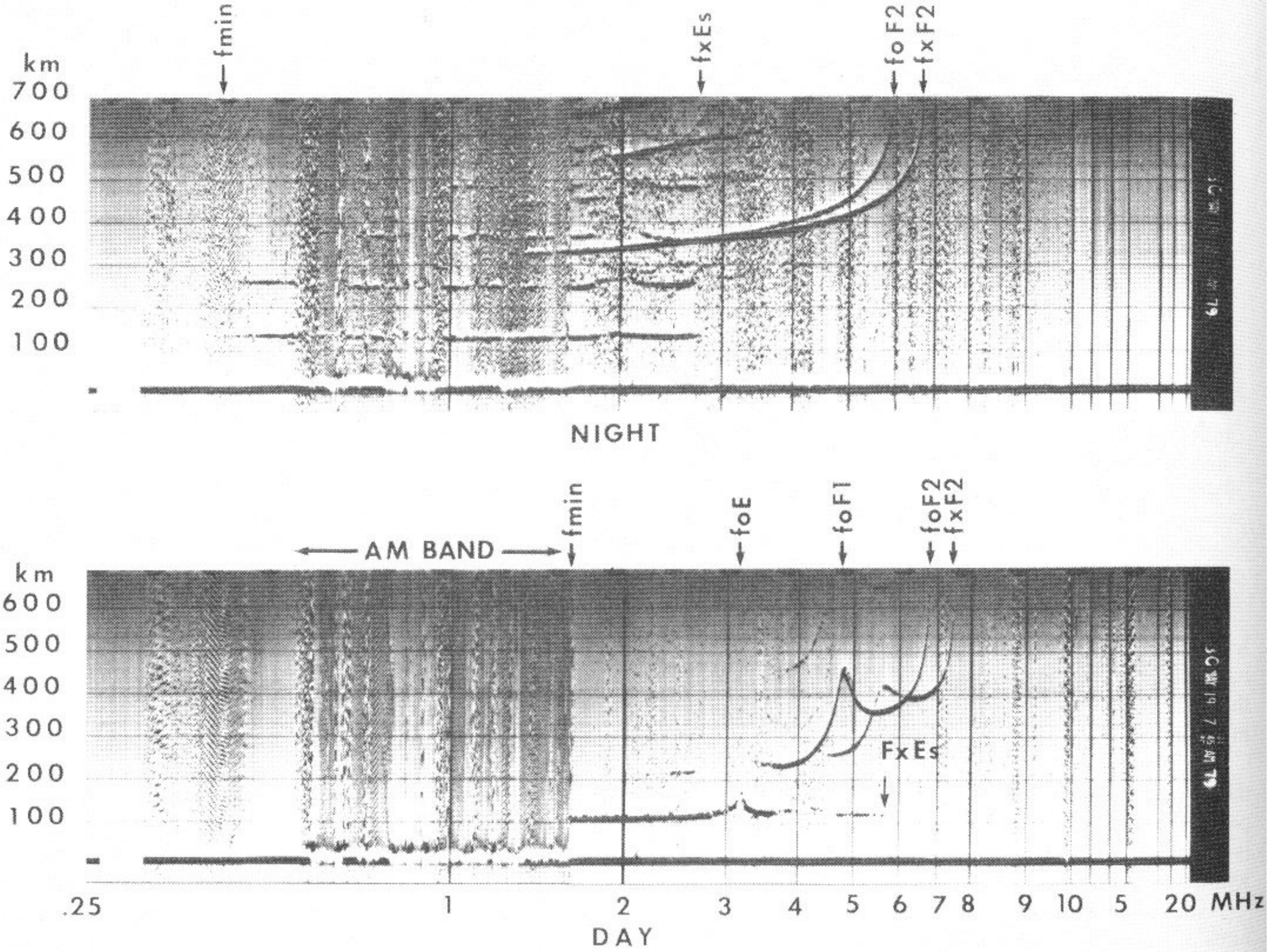
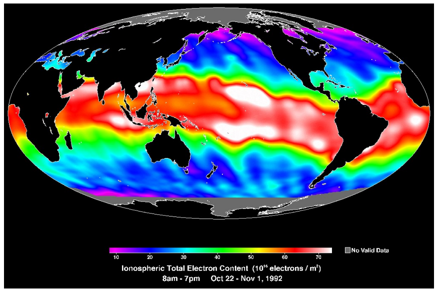


Figure 10-1. Typical midlatitude day and nighttime ionograms, recorded by a C-4 ionosonde at Boulder, Colorado. The daytime ionogram shows reflections from E, Es, F1 and F2 layers; the nighttime ionogram those from Es and F2 layers.

So, what about equatorial anomaly?



- On the day side a strong horizontal electric field exists,
- which causes the plasma to drift up
- This spills down to the off-equatorial latitudes

Aurora

(COURTESY SKY & TELESCOPE

aurora

Three views of ionosphere structure

- Electron density
- Thermal structure
- Ion density and source

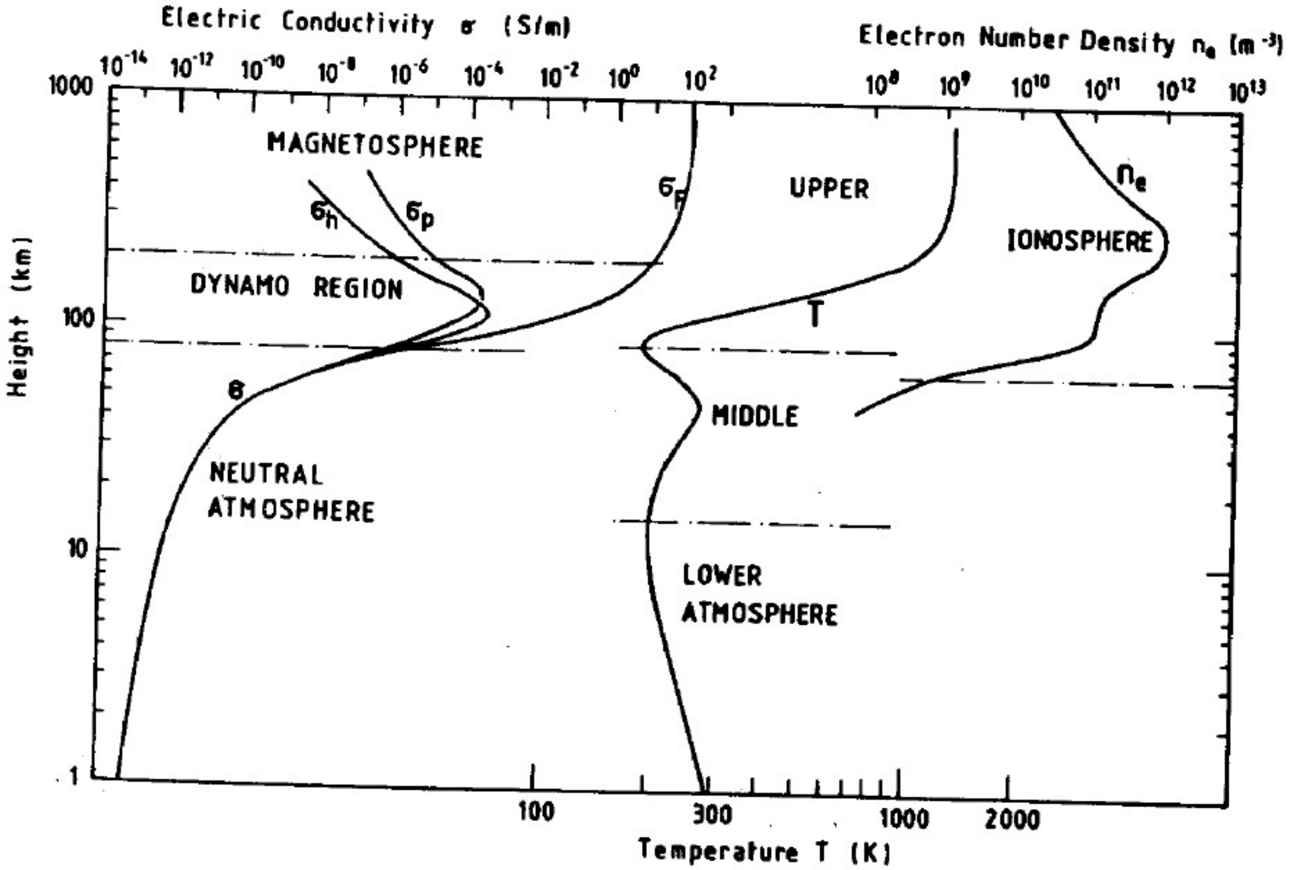


Fig. 1.1. Nomenclature of atmospheric regions based on profiles of electric conductivity, neutral temperature, and electron number density

Back to Ionsopheric currents

- $J = \sigma E$ Ohms Law
- We know there are large scale E fields (why), so what is σ in the ionosphere?

What is Conductivity?

- The scalar conductivity σ is **defined** as the ratio of the current density to the electric field strength σ = J/E. For a resistive medium this is just the Spitzer conductivity:

$$\sigma = \frac{ne^2}{m\nu}$$

- To get the components look at $\overline{\sigma} \cdot \vec{E} = \vec{J}$
- So, σ can have many components:

$$\sigma_{xx}E_x + \sigma_{xy}E_y + \sigma_{xz}E_z = J_x$$

What is σ_1 ? (Low Atmosphere)

(Another way to derive scalar conductivity)

$$m\frac{d\vec{V}}{dt} + m\nu\vec{V} = e\vec{E} \quad \text{(force eqtn.)}$$

To solve: assume plane wave superposition in steady state:

$$\vec{V} = \frac{e}{m(\nu - i\omega)}\vec{E}_o e^{-i\omega t}$$

From which we can get σ by using

$$\vec{J} = \sum_s n_s e_s \vec{V}_s = \sigma\vec{E} \quad \text{(Ohms Law)}$$

for a single species at dc:

$$\sigma = \frac{ne^2}{m\nu} \quad \text{(Spitzer Conductivity)}$$

$$\begin{aligned} e^{\pm i\theta} &= \cos(\theta) \pm i\sin(\theta) \\ \cos(\theta) &= \frac{1}{2}\left(e^{+i\theta} + e^{-i\theta}\right) \\ \sin(\theta) &= \frac{1}{2i}\left(e^{+i\theta} - e^{-i\theta}\right) \end{aligned}$$

e=2.71828182846…

What is $\overleftrightarrow{\sigma}_z$

Conductivity when particles gyrate

Now that we understand better where ν (collision frequency) comes from, we can go back to simple equations again

Look at the force equation on a particle

$$m\frac{d\bar{V}}{dt} + \nu m \bar{V} = e(\bar{E} + \bar{V}\times\bar{B}) \quad \left(\begin{matrix}\text{Lorentz}\\ \text{force}\end{matrix}\right)$$

"ad hoc" resistance term – ultimately from $\left.\frac{\partial f}{\partial t}\right|_{\text{collision}}$ term of Boltzman

take steady state $\left(\frac{\partial}{\partial t} = 0\right)$

and incorporate the $\bar{V}\times\bar{B}$ term into $\overleftrightarrow{\sigma}$

That is $\quad \nu_s m_s \bar{V}_s - e_s \bar{V}_s \times \bar{B} = e_s \bar{E}$ ← same type equation for each species

3 equations and 3 unknowns (V_x, V_y, V_z)

we want $\vec{J} = ne\bar{V} = \overleftrightarrow{\sigma}\cdot\vec{E}$

σ becomes a matrix

so write out component equations

$$\nu m v_x - eV_y B_z + e\cancelto{0}{V_z B_y} = e\vec{E}$$

$\vec{B} \parallel \hat{z}$

$\vdots$

same for x, y z

Sum over species to get

$$\overleftrightarrow{\sigma} = \begin{pmatrix} \sigma_P & \sigma_H & 0 \\ -\sigma_H & \sigma_P & 0 \\ 0 & 0 & \sigma_o \end{pmatrix} \qquad \text{where using } \omega_s = \frac{e_s B}{m_s}$$

$$\sigma_P = \sum_s \frac{n_s e_s^2 \nu_s}{m_s(\omega_s^2 + \nu_s^2)} = ne^2\left(\frac{\nu_-}{(\omega_-^2 + \nu_-^2)m_-} + \frac{\nu_+}{(\omega_+^2 + \nu_+^2)m_+}\right)$$

$$\sigma_H = \sum_s \frac{n_s e_s^2 B}{m_s^2(\omega_s^2 + \nu_s^2)} = ne^2\left(\frac{\omega_-}{(\omega_-^2 + \nu_-^2)m_-} - \frac{\omega_+}{(\omega_+^2 + \nu_+^2)m_+}\right)$$

NOTES:

1. $\sigma_P \rightarrow \sigma_o = \frac{ne^2}{m\nu}$ for $B = 0$

2. For $B \rightarrow 0$, $\sigma_H \rightarrow 0$

3. In E-region ionosphere $\omega_- \gg \nu_-$ (electrons) but $\omega_+ \ll \nu_+$ (ions)

$$\text{so } \sigma_H \approx \frac{ne^2}{m\omega_-}$$

What is σ_3?

σ_3 is similar to σ_2 except that in this region $\sigma_o \to \infty$

So σ_P and $\sigma_H \ll \sigma_o$

Thus we treat the $\vec{B}$ field lines as highly conducting wires for $\lambda > 300$ km and $\tau > 10^2$ sec.

So $\overleftrightarrow{\sigma}_3 = \sigma_o \hat{B}\hat{B}$

Now look at examples.

Note that at some altitude we have that $\Omega = \frac{eB}{m}$ becomes smaller than collision frequency ν

That is below some altitude $\Omega_s << \nu_s$
if this altitude is different for species then can have one species $\bar{E}\times\bar{B}$ drifting because they are still "magnetized" while the other species is colliding too frequently with neutrals to make a gyro orbit.

since $\Omega \propto \frac{1}{m}$ >> for electrons than ions

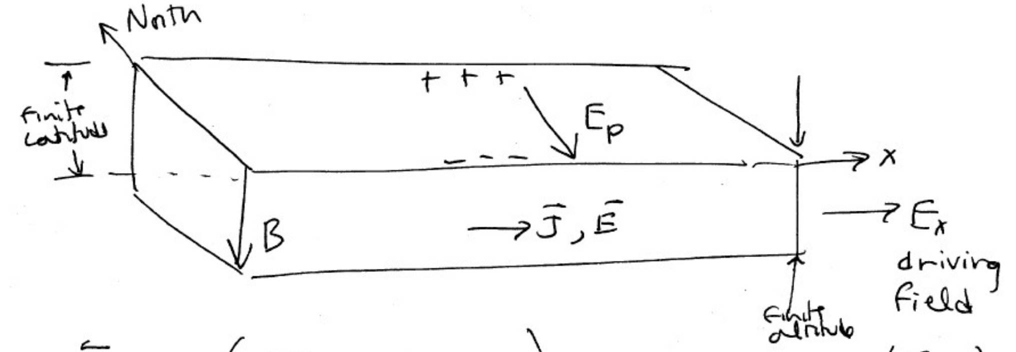
we have a region between ~ 85 and 120km where

$$\Omega_e >> \nu_e \quad \text{but}$$
$$\Omega_i << \nu_i$$

so electrons $\bar{E}\times\bar{B}$ drift but ions do NOT

so the Hall term NOW gives a Current!
(because only one sign of charge is drifting)

Case 1
SLAB of Northern hemisphere Ionosphere



$$\overleftrightarrow{\sigma} = \begin{pmatrix} \sigma_p & \sigma_H & 0 \\ -\sigma_H & \sigma_p & 0 \\ 0 & 0 & \sigma_0 \end{pmatrix} \qquad \vec{E} = \begin{pmatrix} E_x \\ E_p \\ 0 \end{pmatrix}$$

$$\vec{J} = \overleftrightarrow{\sigma} \cdot \vec{E} \Rightarrow \sigma_p E_x + \sigma_H E_p = J_x$$

$$-\sigma_H E_x + \sigma_p E_p = J_y = \underset{\text{bounded in latitude}}{0} \quad \left(\text{assumes } J_\parallel = 0\right)$$

so $E_p = \frac{\sigma_H}{\sigma_p} E_x$

and $J_x = \sigma_p E_x + \frac{\sigma_H^2}{\sigma_p} E_x$

assume $\sigma_H \gg \sigma_p$ (as is the case for E region ionosphere)

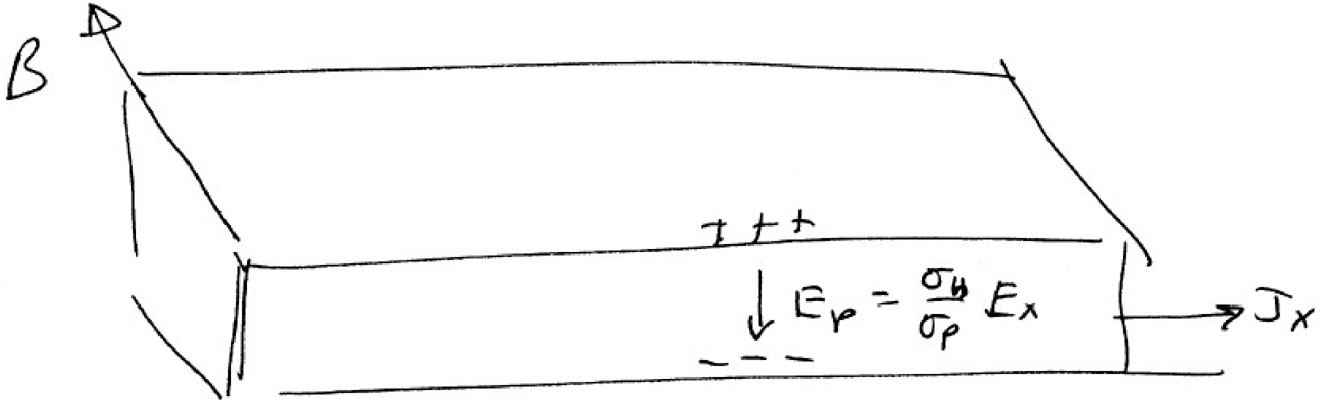
~~$J_x \approx \sigma_p E$~~

$$J_x = \sigma_H E_y \quad \text{and} \quad J_y = -\sigma_H E_x$$

$$\underbrace{\qquad\qquad\qquad\qquad}_{\text{driving fields}}$$

Note, in reality E_p is less than $\left[\frac{\sigma_H}{\sigma_p} E_x\right]$ because field aligned currents bleed off the charge.

Equator Slab of ionosphere



Equatorial Electrojet

$$J_x = \underbrace{\left(\sigma_p + \frac{\sigma_H^{2}}{\sigma_p}\right)}_{\text{cowling conductivity}} E_x$$

eg: if $\sigma_H = 2\sigma_p$ then $J_x = 5\sigma_p E_x$
great enhancement
over simple $\sigma_p E_x$