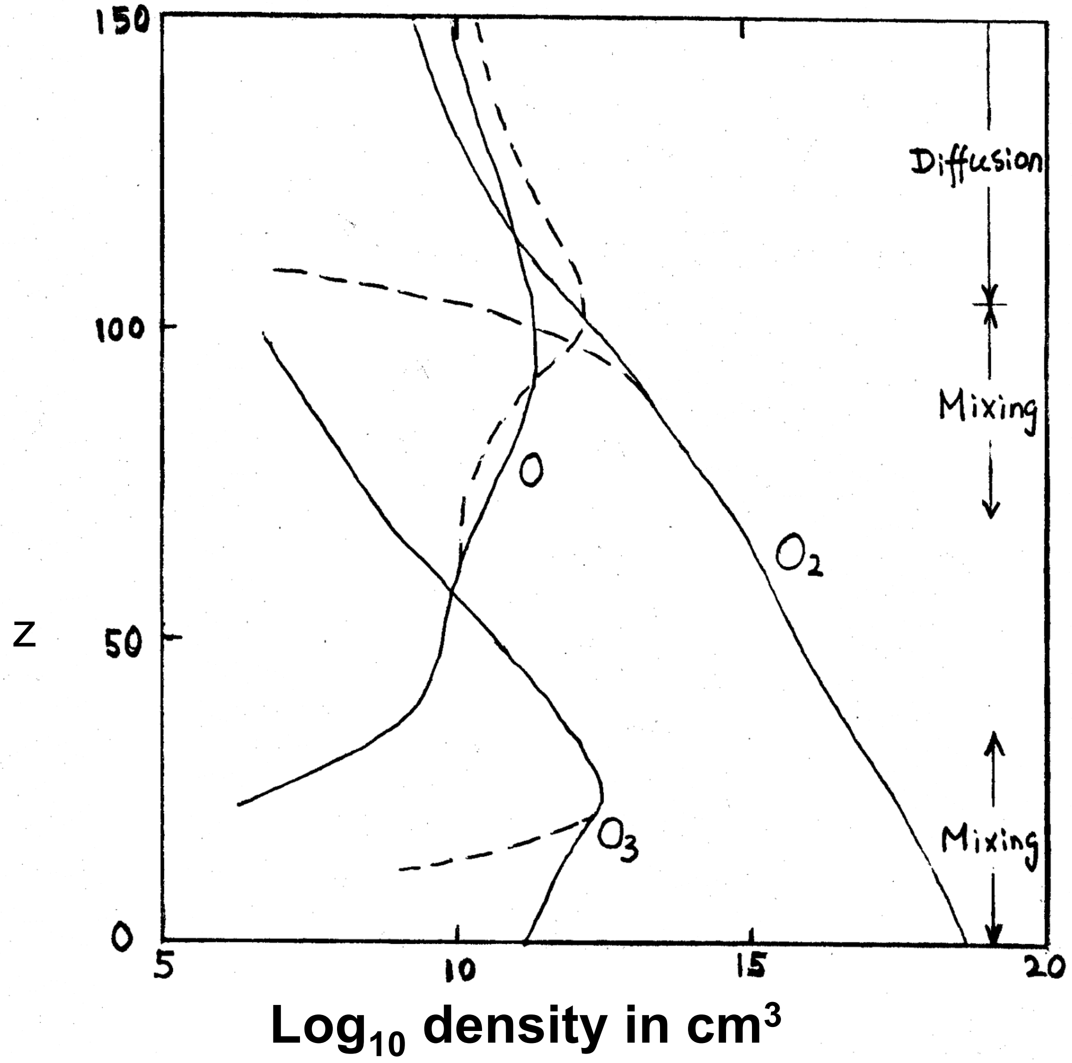
Upper Atmosphere + Ionosphere
Part-4

Diffusion : Molecular + Eddy:
Turbopause
Photo-ionization
Ionosphere : D, E, F1, F2 Regions
Ambipolar Diffusion: F2 Region
Radio Waves + the Ionosphere
Ionosphere of Other Planets

Oxygen Densities

Solid lines: mixing and diffusion:
Dashed lines:photochemical equilibrium (I.e. no mixing and diffusion)



NEED DIFFUSION

Continuity Equation with Diffusion

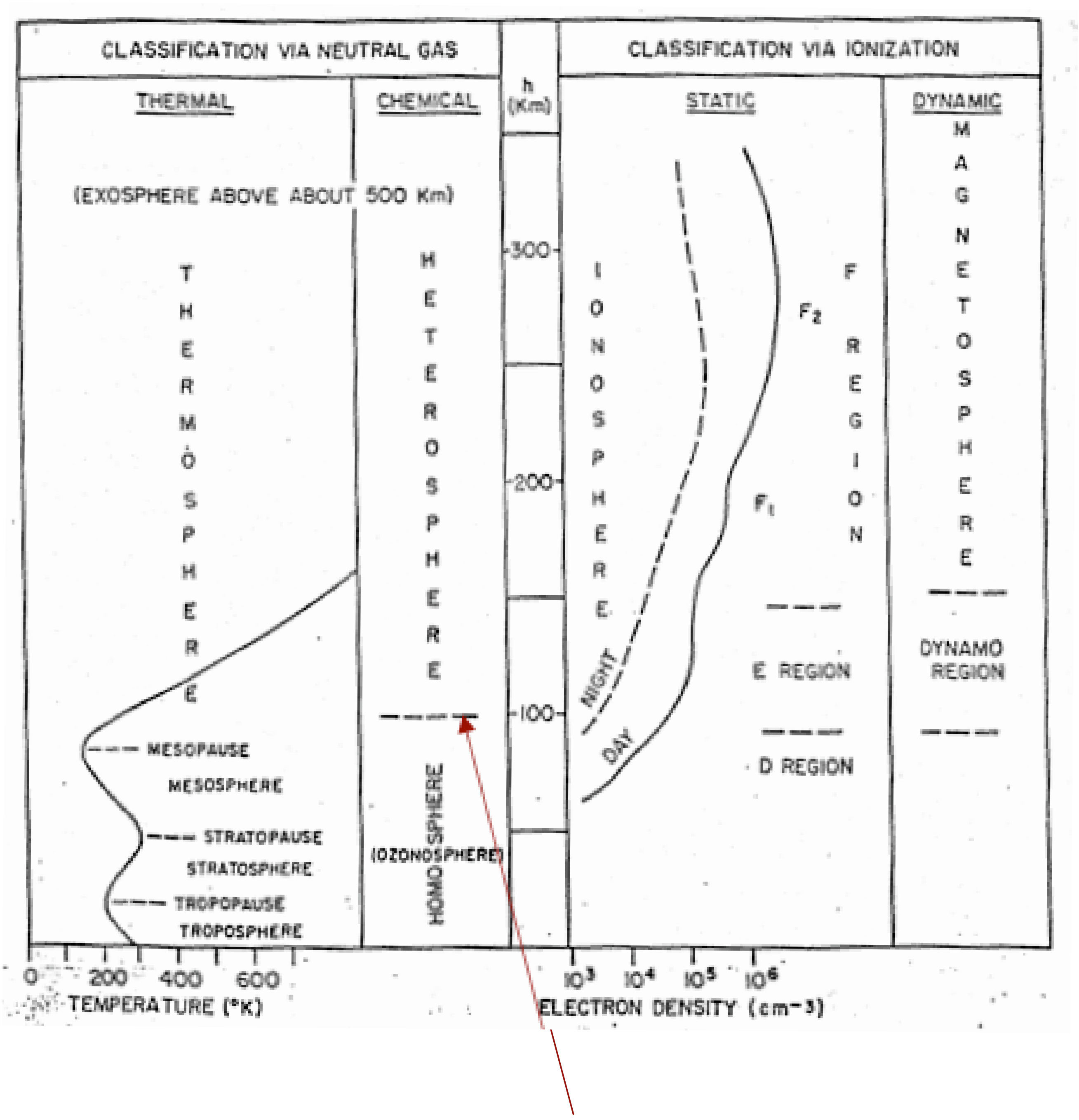
Rate of change of the number of species in dz

= Diffusive Flux + Prod.- Loss

$$\frac{dn_i}{dt} = \frac{d}{dz}[D_i \frac{dn_i}{dz}] + P_i - L_i$$

D is called the diffusion constant

Atmospheric Regions



Turbopause
Mixing ~ Diffusion

Mixing/Diffusion

Turbopause (Homopause)

The altitude where

Turbulent Mixing ≈ Moleular Diffusion

Estimate the height of the turbopause

Eddy Mixing (Turbulence)

ignore the details of the flow at some scale

$L_d \sim$ **the scale of the turbulence** $= L_{eddy}$

$\bar{v}_d = \bar{v}_{eddy}$

can create a diffusion coefficient, like a thermal conductivity

$$D_{eddy} \sim L_{eddy}\,\bar{v}_{eddy} \quad ; \quad L_{eddy} \sim \mathrm{km};\ \bar{v}_{eddy} \sim \mathrm{m/s}$$

Molecular Diffusion (Turbulence)

Length scale is the distance between collisions, λ_{col}

$D_d \sim \lambda_{col}\,\bar{v}_T$, **where** $\bar{v}_T$ is the thermal speed

$$\lambda_{col} \sim \bar{v}_T/[n\sigma_{col}];\ \ \bar{v}_T \sim 600\mathrm{m/s};\ \sigma_{col} \sim 10^{-15}\mathrm{cm}^2;\ n(0) = 2.5\,\mathrm{x}10^{19}/\mathrm{cc}$$

Set them equal; $D_d \sim D_{eddy}$

and find turbopause; $n(z) \sim 10^{13}$ molecules/cc; or $z \sim 60$km

actually ~ 100km

Photochemistry and the Ionosphere

Simple Model

$AB + h\nu$	$\rightarrow AB^+ + e$	J_i
$AB^+ + e$	$\rightarrow A + B$	α
$A + B + M$	$\rightarrow AB + M$	k

$$dn_{AB}{}^+/dt = J_i\, n_{AB} - \alpha\, n_e\, n_{AB}{}^+$$

$$dn_{AB}{}^+/dt = 0 \text{ in steady state}$$

assume $n_e = n_{AB}{}^+$ charge neutrality

get

$$n_{AB+} \approx [n_{AB}\, J_i / \alpha\,]^{1/2}$$

Since $n_{AB} \propto \exp[-z/H_{AB}]$; $J_i \propto \exp[-\tau_i(z)]$

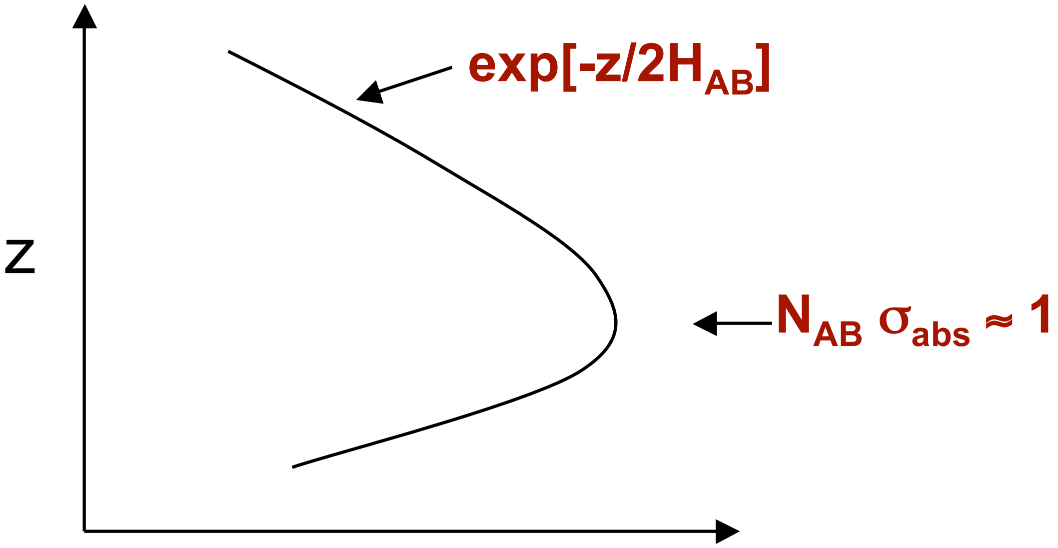
A Chapman Layer for Ion AB^+ is Formed

Ionospheres (continued)

Ionospheric layers are Chapman Layers

$$J_i = J_i^o \, e^{-\tau_i(z)}$$

$$n_{AB} \approx n_{AB}(0)\, e^{-z/H_{AB}}$$

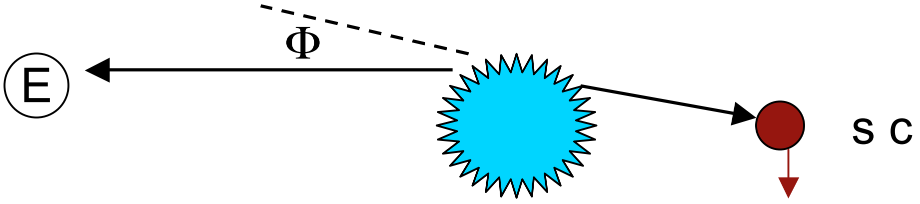


$$n_{AB+} \approx [\, J_i \, n_{AB} / \alpha \,]^{1/2}$$

At top: ion scale height twice neutral H

RADIO WAVES

Spacecraft Observations of Ionosphere



Measure changing index of refraction,
turn it into electron density vs z: $n_e(z)$
Then convert to neutral density using model

(not required)

Compare phase of X band 8400 MHz; ~ 3cm
with the S band 2300 MHz ; ~ 10cm

$$(*) \quad \Phi \approx -\frac{\omega}{c}\int_{\text{path}} (n-1)\, ds \quad , \qquad \omega = 2\pi\nu$$

n = index of refraction

Solve : $m_e \ddot{\vec{x}} = - m_e \nu_c \dot{\vec{x}} - e \vec{E}_0 e^{-i\omega t}$

steady state solution $\Big\}$ $\vec{x} = \dfrac{1}{\omega + i\nu_c} \dfrac{e}{\omega m_e} \vec{E}_0 e^{-i\omega t}$

$$\nu_c << \omega/2\pi$$

$$n = \left[1 - \frac{\omega_p^{\ 2}}{\omega^2}\right]^{1/2} \approx 1 - \frac{\omega_p^{\ 2}}{2\omega^2}$$

$$\omega_p = \left[\frac{4\pi n_e e^2}{m_e}\right]^{1/2}$$

Using (*) $\Phi \propto \int_{\text{path}} n_e\, ds$

Ions are heavy so are much slower to respond:

Measure ionospheric density: $n_e \approx n_i \xrightarrow{\sim} [n_{AB}]^{1/2}$

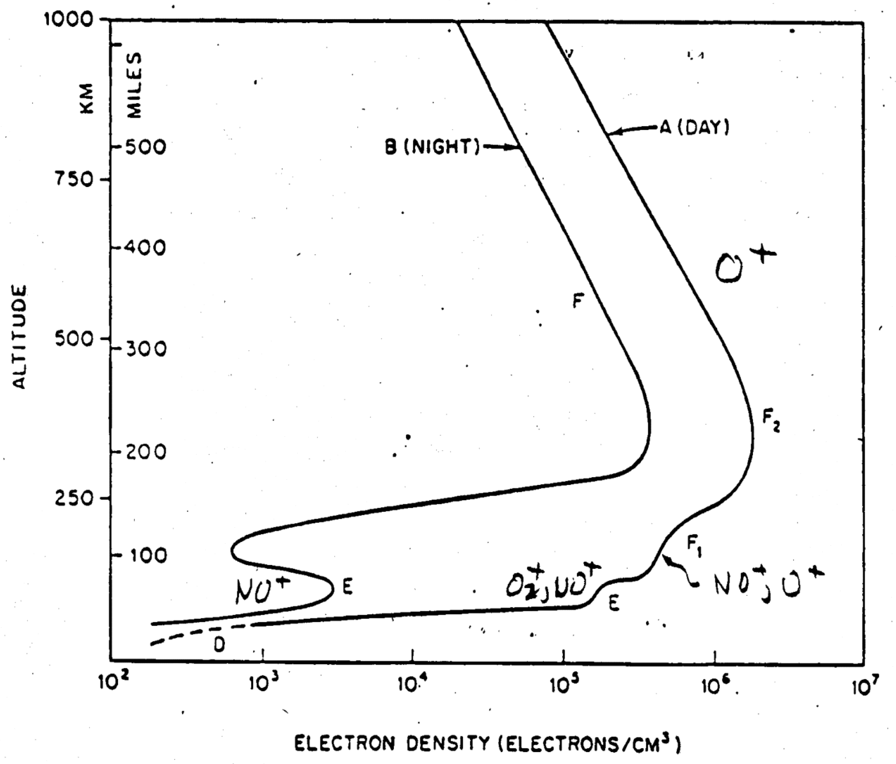
Result applies to most regions

(not F2 region where ambipolar diffusion determines scale height)

Earth’s Ionospheric Layers

Day and Night

Principal Species



Favored ions have lowest ionization energies

$N_2 \rightarrow N_2^+ + e$ (15.5eV)

$O \rightarrow O^+ + e$ (13.6eV)

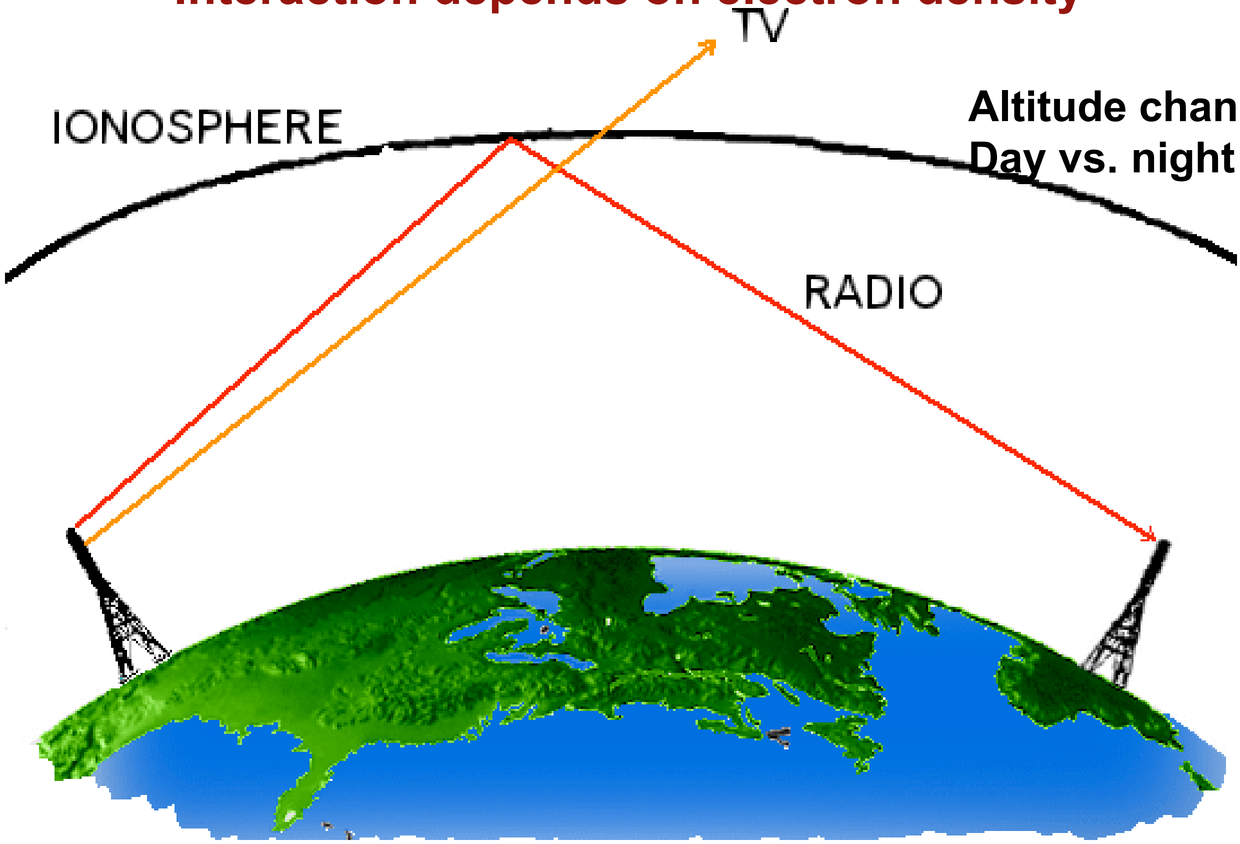
$O_2 \rightarrow O_2^+ + e$ (12.1eV)

$NO \rightarrow NO^+ + e$ (9.3eV)

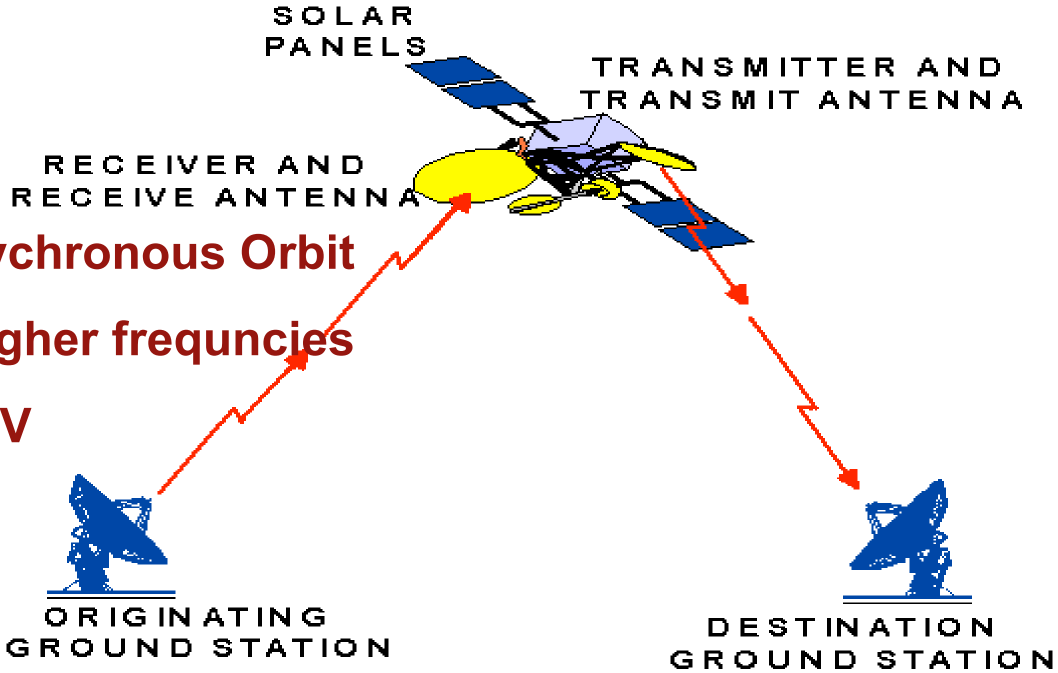
Therefore, if made NO^+ is lives longer

Radio Waves and the Ionosphere

Interaction depends on electron density



Altitude changes
Day vs. night



Geosychronous Orbit

For higher frequncies

Like TV

Ions Produced

Earth : $O + h\nu \rightarrow O^+ + e$

$N_2 + h\nu \rightarrow N_2^+ + e$

$O_2 + h\nu \rightarrow O_2^+ + e$

But ionosphere has a large, sometimes dominant, amount of NO^+

Similarly:Mars : $CO_2 + h\nu$ --> $CO_2^+ + e$
But ionosphere is predominantly O_2^+

Dominant Ions Observed

Ion-molecule reactions are fast and tend toward species with lowest ionization state: $I_A > I_B$,

$A^+ + B$ --> $A + B^+$ exothermic

$B^+ + A$ --> $B + A^+$ endothermic; need energy

Metal ions, if available, dominate: Na, Mg, etc.

Earth's Ionosphere (D-region)
in mesosphere

Initial Ions

O_2^+ , N_2^+ , O^+ , Ar^+ , H_2O^+ , CO_2^+

D region (relatively thick atmosphere, UV, viz. not efficient at ionizing)

~ 50 - 90 km

hard x - rays , lyman alpha photons, cosmic rays)

Weak, variable region, disappears rapidly at night

Density (n_M) large : negative are also formed

$O_2 + M + e \rightarrow O_2^- + M$

$O_2^- + AB^+ \rightarrow O_2 + AB$

$O_2^- + h\nu \rightarrow O_2 + e$ (viz. photons easily remove electrons)

Ions **O_2^- , O_2^+ , H_3O^+ , $H_5O_2^+$**

CO_3^- , HCO_3^- , NO_3^- , CO_3^-

E-region ~ 110 km

above mesopause

100 Å > λ > 30 Å , λ ~ 1000 Å , λ ~ 910 Å

Å = 10^{-8} cm = 10^{-4} μm

Make $\mathbf{N_2^+}$, $\mathbf{O_2^+}$, $\mathbf{O^+}$

Then

$$O^+ + O_2 \rightarrow O_2^+ + O \qquad (1)$$

$$N_2^+ + O \rightarrow NO^+ + O \qquad (2)$$

$$O^+ + N_2 \rightarrow NO^+ + O \qquad (3)$$

Observe

$\mathbf{O_2^+}$, $\mathbf{NO^+}$

Loss : Electron - Ion Recombination

$$O_2^+ + e \rightarrow O + O \qquad (4)$$

$$NO^+ + e \rightarrow N + O \qquad (5)$$

Note : Meteor Showers also add metal ions and the presence of NO neutrals

$$\Rightarrow O_2^+ + NO \rightarrow NO^+ + O_2$$

enhances NO^+ density

E Region (cont)

Time Constant : E – Region

Look only at reactions 3 + 5

$$\frac{dn_{NO^+}}{dt} \approx k_1\, n_{O^+}\, n_{N_2} - \alpha_{NO^+}\, n_{NO^+}\, n_e$$

$$n_e = n_{NO^+} + n_{O_2^+} \approx n_{NO^+} \quad : \text{ most are } NO^+$$

Time constant : $t_{NO^+} \sim n_{NO^+}/[dn_{NO^+}/dt]$:

$$\sim \frac{n_{NO^+}}{k_1\, n_{O^+}\, n_{N_2}} \quad \text{or} \quad \frac{n_{NO^+}}{\alpha_{NO^+}\, n_{NO^+}{}^2}$$

$$t_{NO^+} \sim \frac{1}{\alpha_{NO^+}\, n_{NO^+}} \ ; \ \alpha_{NO^+} \approx 3x10^{-7} cm^3/s$$

Day $n_{NO^+} \approx 3 \times 10^5 / cm^3$

$\mathbf{t_{NO^+} \approx 10\ sec}$

Night $n_{NO^+} \approx 3 \times 10^3$

$\mathbf{t_{NO^+} \approx 10^3\ sec}$ → **15 hours**

Decays but does not go away at night

F1 Region (~180km)

F_1 Region

O and N_2 dominate (O_2 has a smaller scale height)

$O + h\nu \rightarrow O^+ + e$	J_{O^+}
$N_2 + h\nu \rightarrow N_2^+ + e$	$J_{N_2^+}$
$O^+ + N \rightarrow NO^+ + N$	k_1
$N_2^+ + O \rightarrow NO^+ + N$	k_2
$NO^+ + e \rightarrow N + O$	α_{NO^+}

O^+ and NO^+ are the observed ions

F_1 Region (cont.)

O^+ Equations

Form O^+ - Lose O^+

$$0 = \frac{dn_{O^+}}{dt} = J_{O^+} n_o - k_1 n_{O^+} n_{N_2}$$

$$n_{O^+} = \frac{J_{O^+} n_O}{k_1 n_{N_2}}$$

NO^+ Equations

Form NO^+ - Lose NO^+

$$0 = \frac{dn_{NO^+}}{dt} = k_1 n_{O^+} n_{N_2} - \alpha_{NO} n_{NO^+} n_e$$

Combine Eq.

$$0 = J_{O^+} n_O - \alpha_{NO^+} n_e^2$$

$$n_e = \sqrt{\frac{J_{O^+} n_O}{\alpha_{NO^+}}}$$

like the simple first model: $n_e \propto n_O^{1/2}$

TIME CONSTANTS: F1 Region

F_1 region $\quad n_O > n_{N_2} \gg n_{O_2}$

$$O + h\nu \rightarrow O^+ + e \qquad J_{O^+}$$

$$O^+ + N_2 \xrightarrow{k_1} NO^+ + N \qquad k_1 \approx 10^{-11}\ \frac{cm^3}{s}$$

$$NO^+ + e \xrightarrow{\alpha} N + O \qquad \alpha \approx 3\times 10^{-7}\ \frac{cm^3}{s}$$

$$\frac{dn_{O^+}}{dt} = J_{O^+} n_O - k_1\, n_{O^+} n_{N_2} = 0$$

$$\text{Solve :} \quad n_{O^+} = \frac{J_{O^+}\, n_O}{k_1\, n_{N_2}}$$

Time constant : $\quad \mathbf{t_{O^+} = \frac{1}{k_1\, n_{N_2}}}$

200km $\quad n_{N_2} \approx 10^{10}\ / \text{cm}^3$

Time for O^+ = 100 sec

Mostly disappears at night

F_2 – region > 250 km

Source (O is dominat neutral)

$$\mathbf{O + h\nu \rightarrow O^+ + e}$$

But

(1) $O^+ + e \rightarrow O^* + h\nu$ very slow

(2) $O^+ + e + O \rightarrow O^* + O$ slow

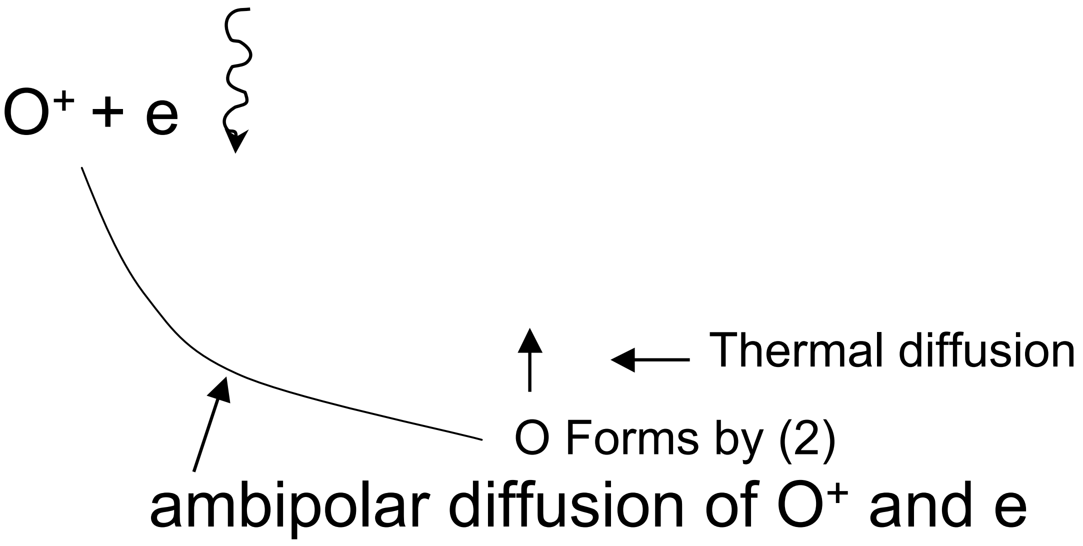
Like thermospheric heat

O^+ diffuses down to where loss [(2)] is fast

BUT

If charges diffuse ⇒ currents!

Ambipolar Diffusion



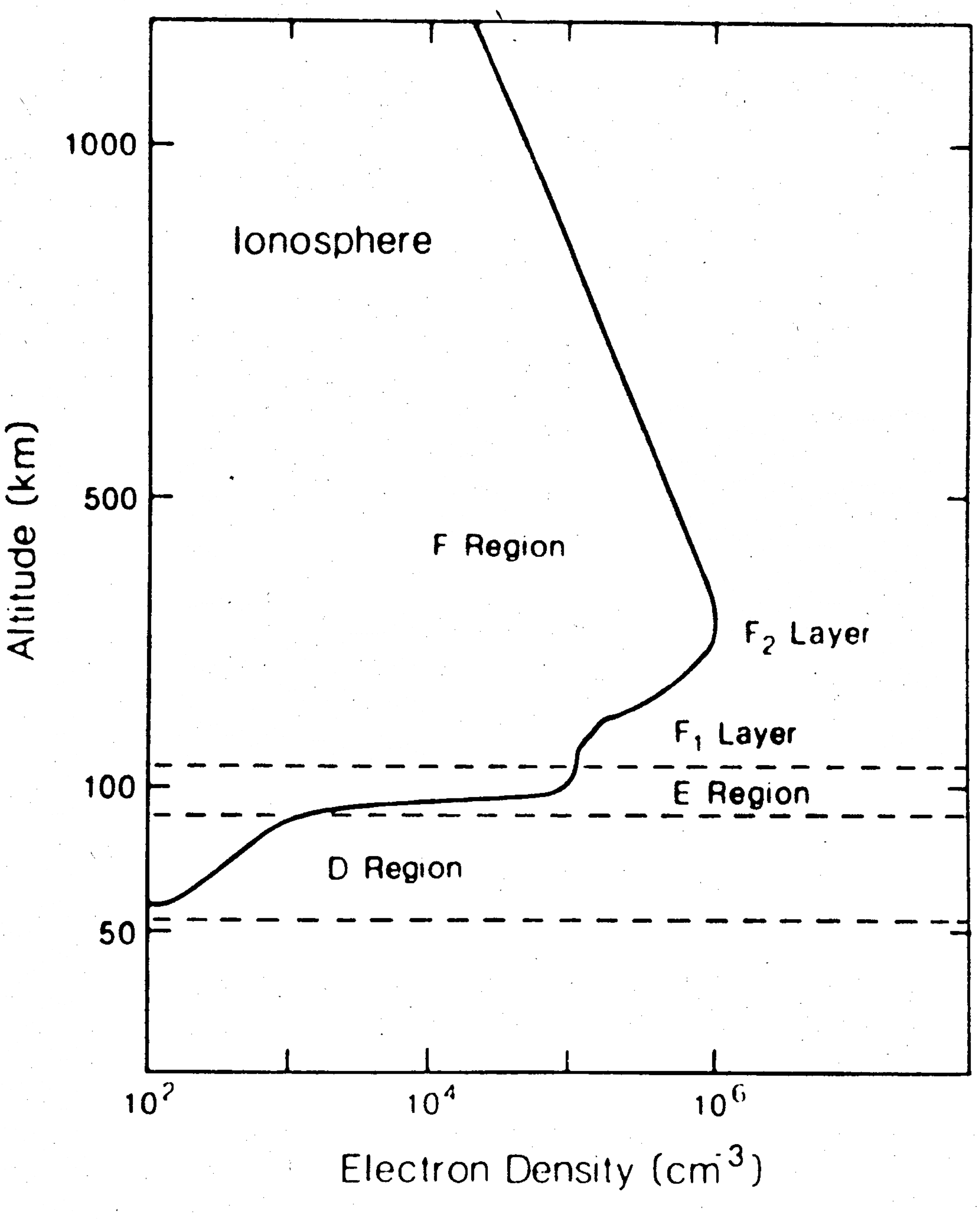
$O^+ + e$

Thermal diffusion

O Forms by (2)

ambipolar diffusion of O^+ and e

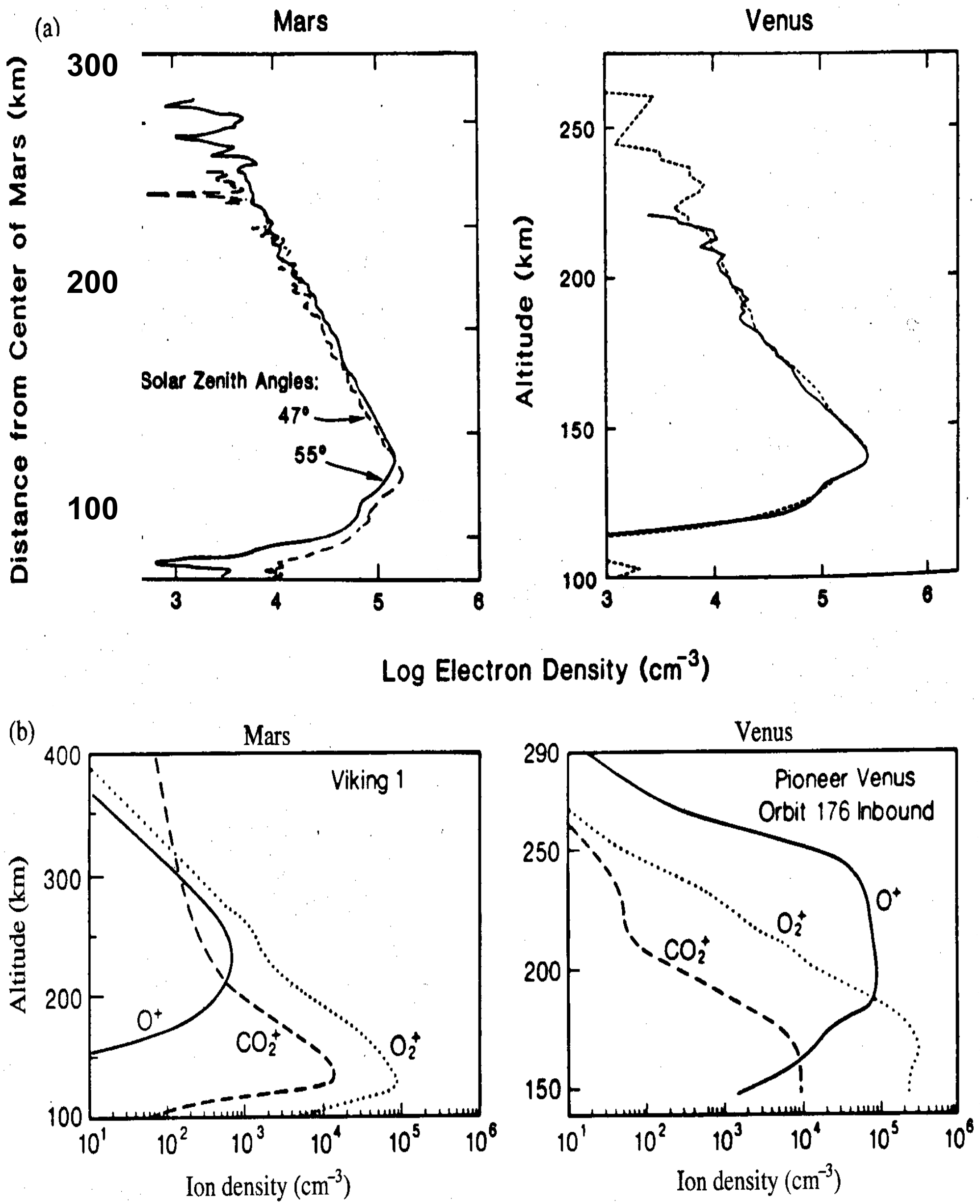
Earth's Ionospheric Layers
Day Time



Mars and Venus Ionospheric Layers

Chapman Layers

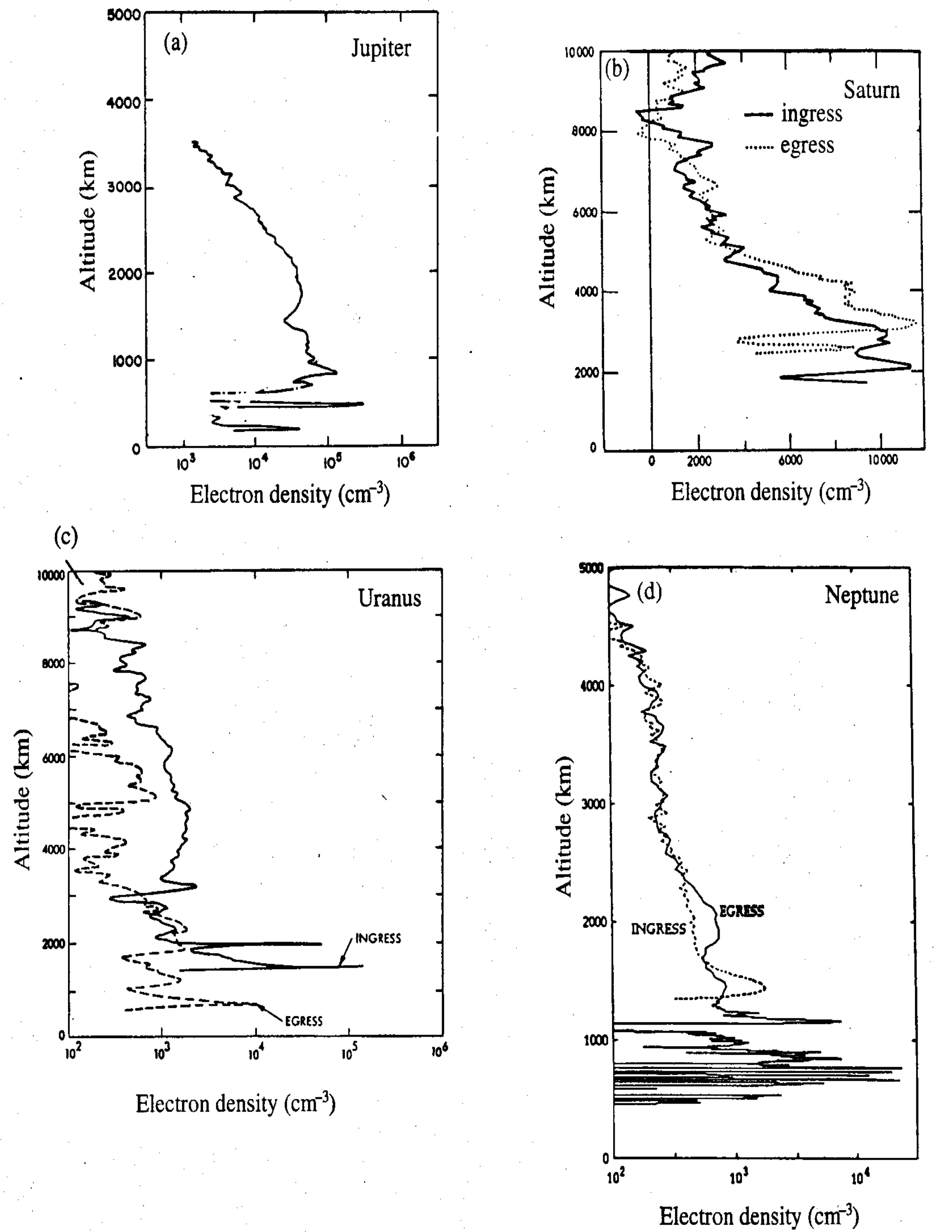
Radio Occultation Measurements



At top interaction with the sun's sields and plasma becomes important

Giant Planet Ionospheres

Chapman structure + waves



$H_2 + h\nu \dashrightarrow H_2^+$ (or $H + H^+$) $+ e$

$H_2^+ + H_2 \rightarrow H_3^+ + H$

Ingress and Egress apply to Voyager radio wave results

Aurora

Interaction of the solar plasma and fields with the earth's upper atmosphere

Communications affected by solar activity

Mostly, but not exclusively, lines of O or O^+

#4 Summary

Things you should know

Turbopause (Homopause)
Diffusive Term
Photo-ionization
Photochemistry of Ionosphere
Layered Ionosphere
Ambi-polar Diffusion
Refraction of SC Radio Signal
Ionospheres of Other Planets