Q: Why do the Earth & planets have ionospheres? magnetospheres?

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w/ liberal “borrowing” from Fuller-Rowel, Solomon, Sojka, Lean, Vasylinunas, Bagenal, Luhman

Heliophysics chain

Q: Why do the Earth & planets have ionospheres?

A: Because of the **Sun's** corona (its EUV & X-rays)

Q: Why does the Sun have a corona?

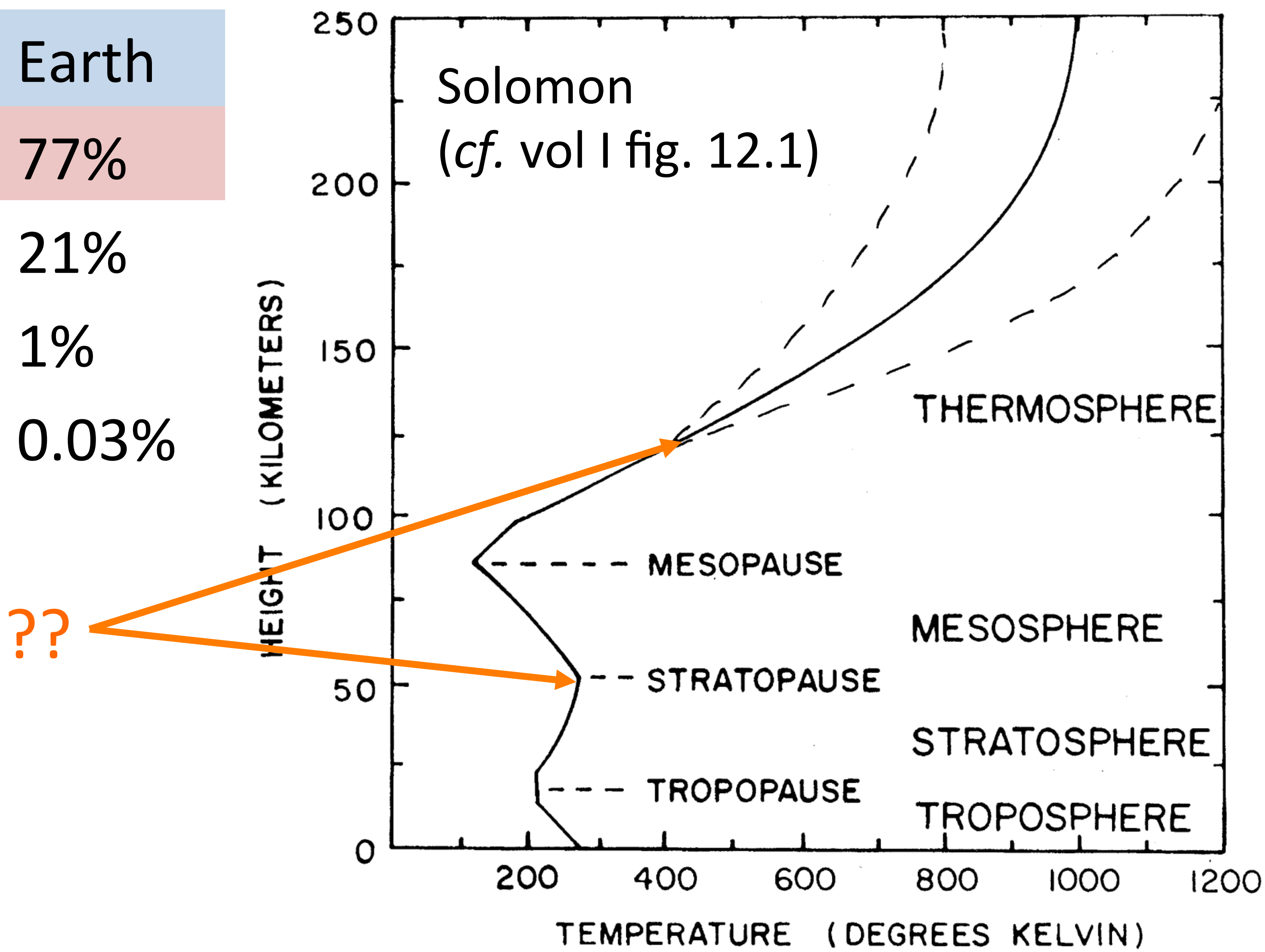
A: Because of its magnetic field (and its heating)

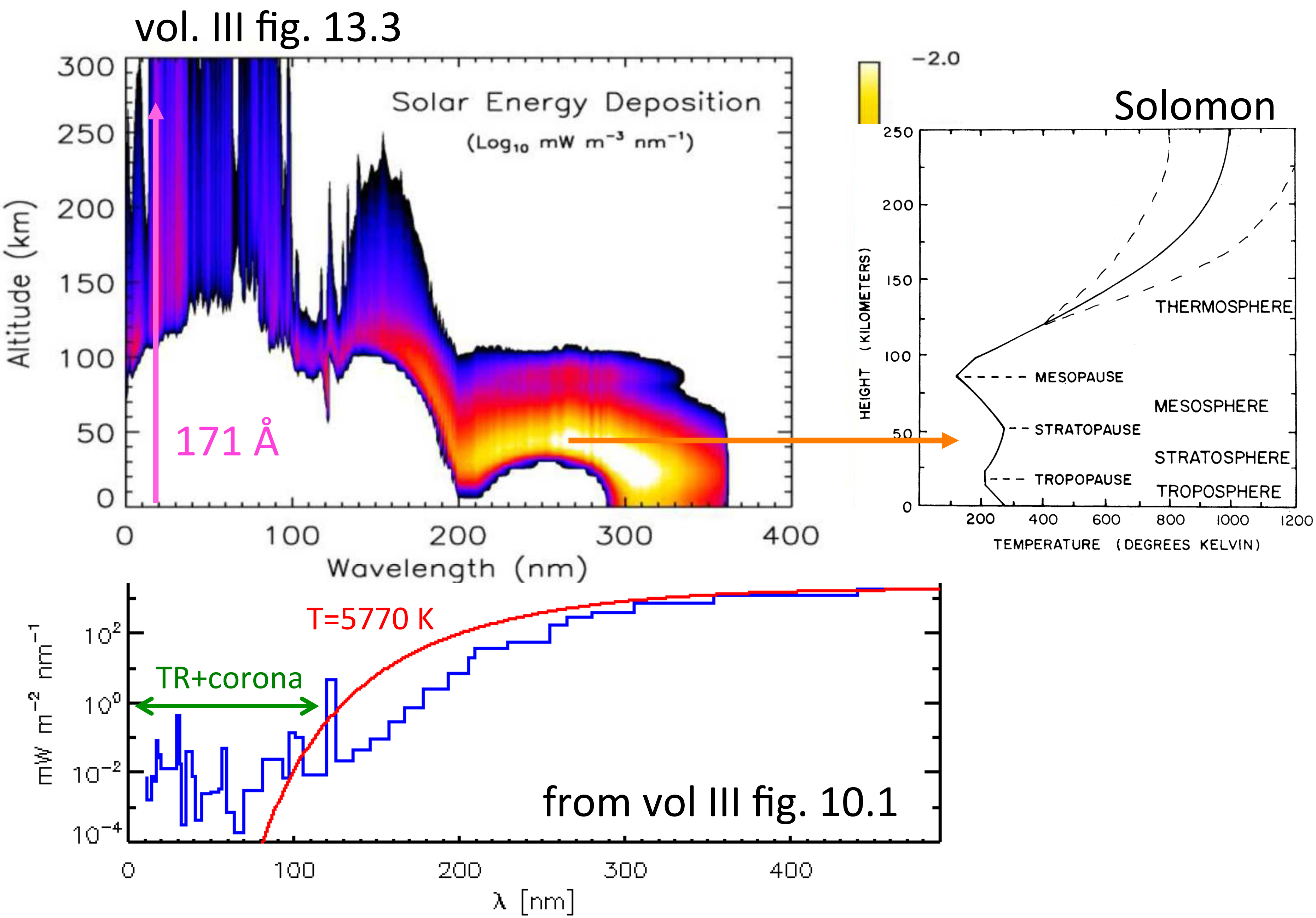
Q: Why does the Sun have a magnetic field?

A: Because of its dynamo

Earth's neutral atmosphere

	Earth
N_2	77%
O_2	21%
H_2O	1%
CO_2	0.03%




vol. III fig. 13.3
Solar Energy Deposition
(Log10 mW m^-3 nm^-1)
Altitude (km)
Wavelength (nm)
171 Å
-2.0
Solomon
HEIGHT (KILOMETERS)
TEMPERATURE (DEGREES KELVIN)
THERMOSPHERE
MESOPAUSE
MESOSPHERE
STRATOPAUSE
STRATOSPHERE
TROPOPAUSE
TROPOSPHERE
T=5770 K
TR+corona
mW m^-2 nm^-1
λ [nm]
from vol III fig. 10.1

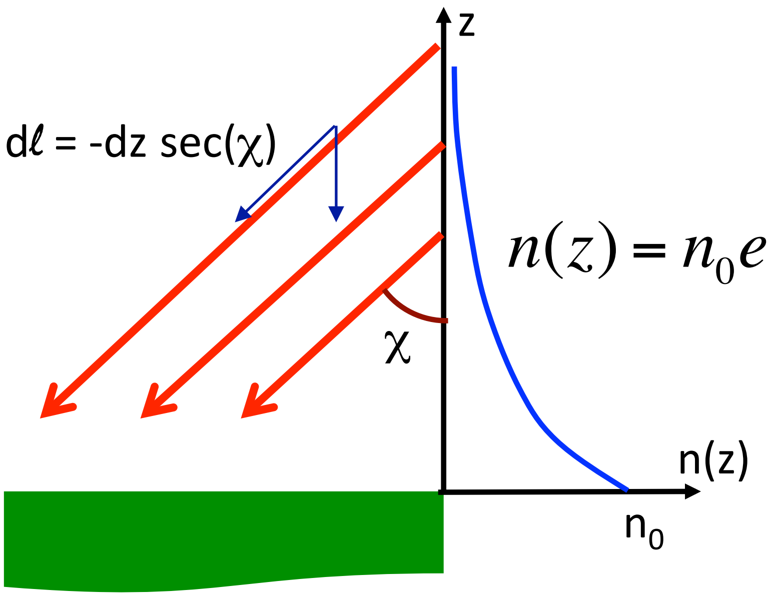
Fate of a photon

w/ absorption x-section σ

optical path $\tau(x)$ = avg. # absorbers in cylinder w/ x-section σ

Prob. of survival: $P(x) = \exp\left[-\int^{x} \sigma n(\ell)\, d\ell \right]$

$\tau=1 \rightarrow$ 1 absorber: mean-free path



$$n(z) = n_0 e^{-z/H}$$

$$\tau(z) = \int_z^{\infty} \sigma n(z')\sec(\chi)\, dz'$$

$$= \sigma n_0 \sec(\chi) \int_z^{\infty} e^{-z'/H}\, dz'$$

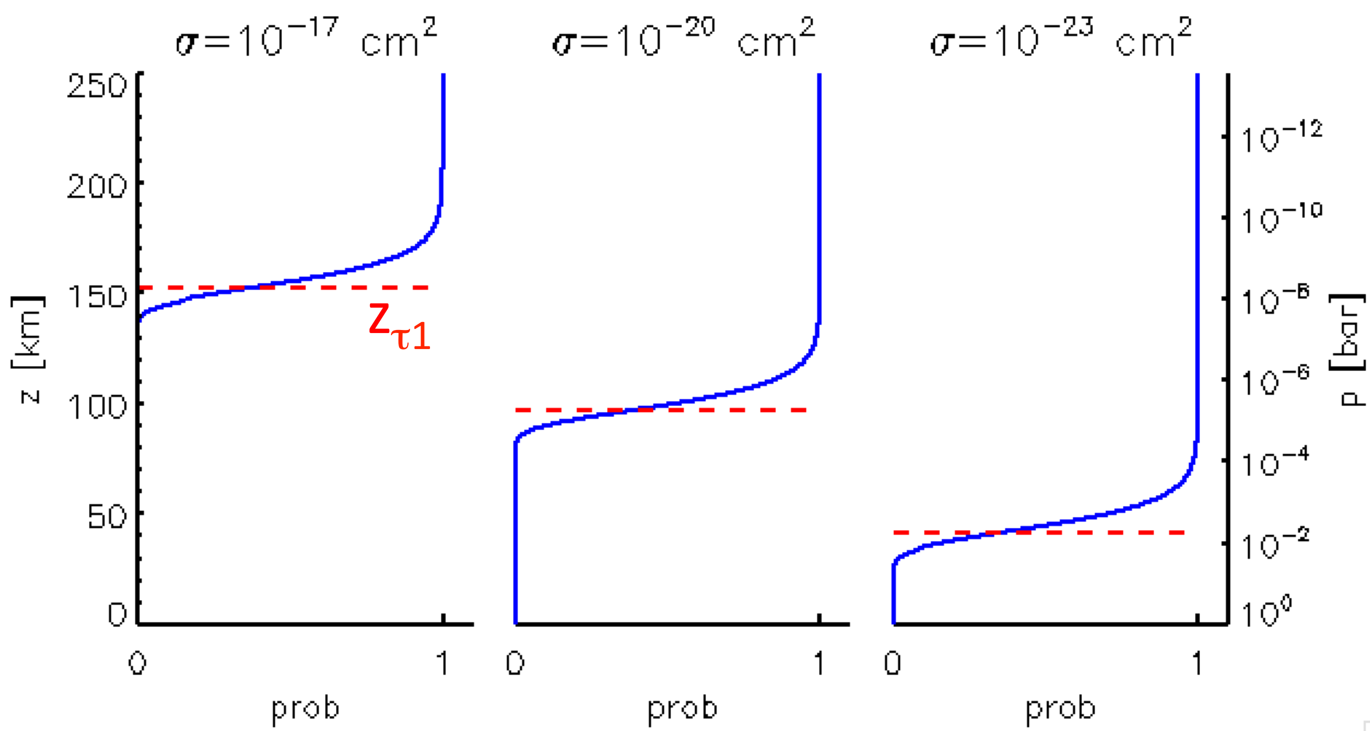
$$\tau(z) = \sigma n_0 H \sec(\chi)\, e^{-z/H} = e^{-(z-z_{\tau 1})/H}$$

height of $\tau=1$: $z_{\tau 1} = H \ln\left[\sigma n_0 H \sec(\chi)\right]$

Prob. of survival: $P(z) = e^{-\tau(z)} = \exp\left[-e^{-(z-z_{\tau 1})/H} \right]$

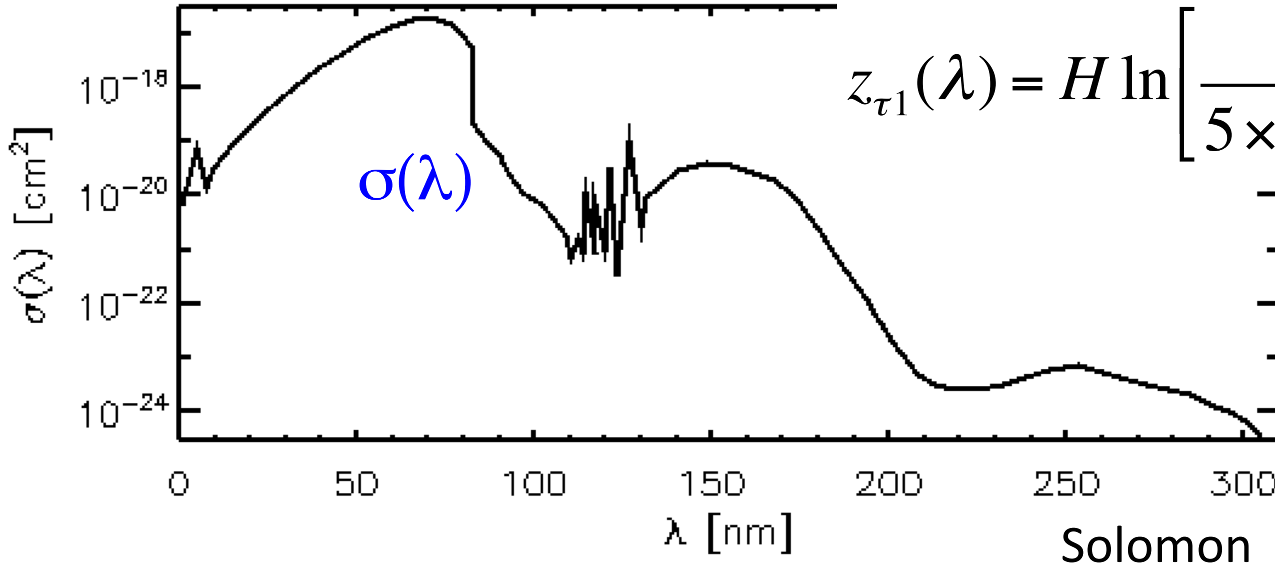
$$e^{z_{\tau 1}/H} = \sigma n_0 H \sec(\chi) = \frac{\sigma n_0 kT}{\bar{m}g}\sec(\chi) = \sigma \frac{p_0}{\bar{m}g}\sec(\chi) = \frac{\sigma}{\sigma_0}\sec(\chi)$$

$$\sigma_0 = \frac{\bar{m}g}{p_0} = \frac{5\times 10^{-23}\,\mathrm{g}\cdot 980\,\mathrm{cm/s^2}}{10^6\,\mathrm{erg/cm^3}} = 5\times 10^{-26}\,\mathrm{cm}^2$$

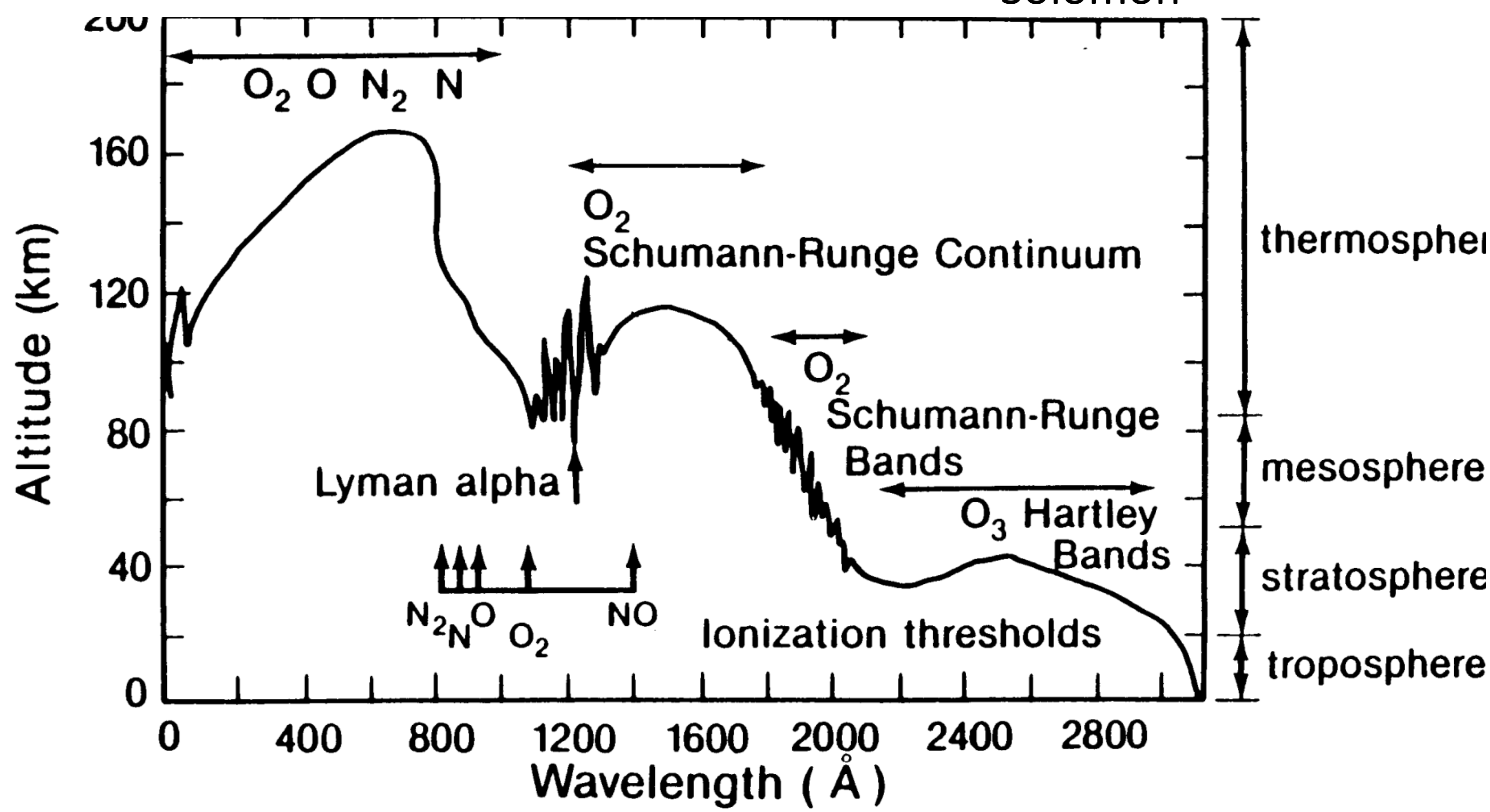


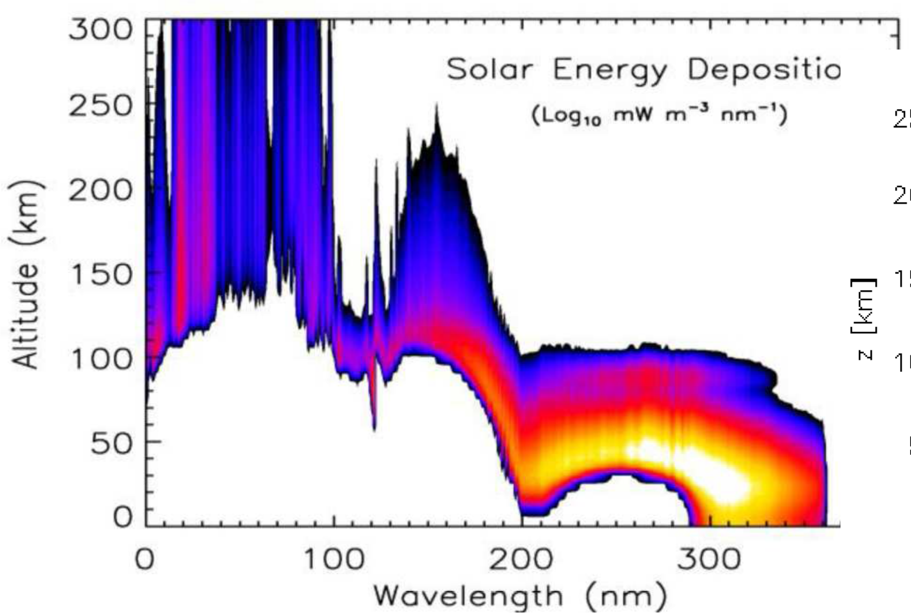
$$P(z) = e^{-\tau(z)} = \exp\left[-e^{-(z-z_{\tau 1})/H}\right]$$

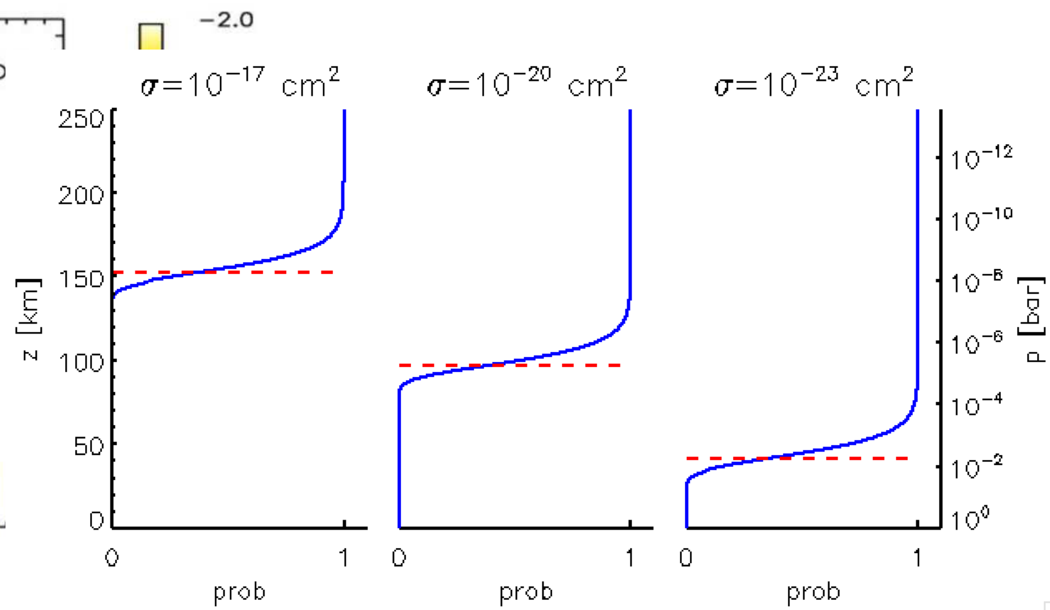
$$z_{\tau 1}(\lambda) = H \ln\left[\frac{\sigma(\lambda)}{5\times10^{-26}\,\mathrm{cm}^2}\right]$$

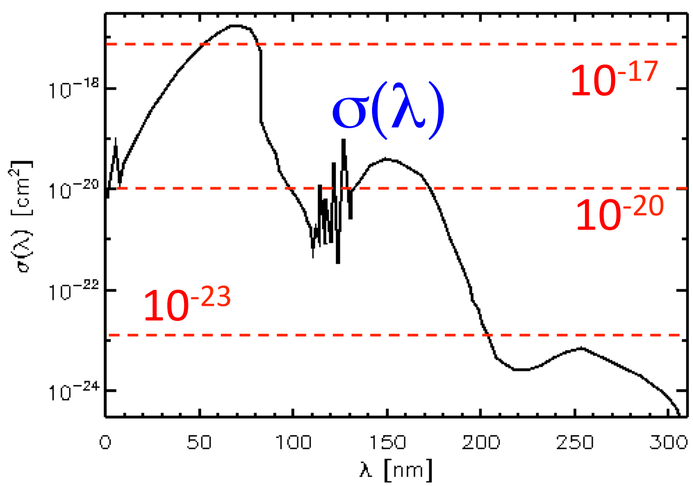


Solomon









$$P[z(\lambda)] = \exp\left[-e^{-[z - z_{\tau 1}(\lambda)]/H} \right]$$

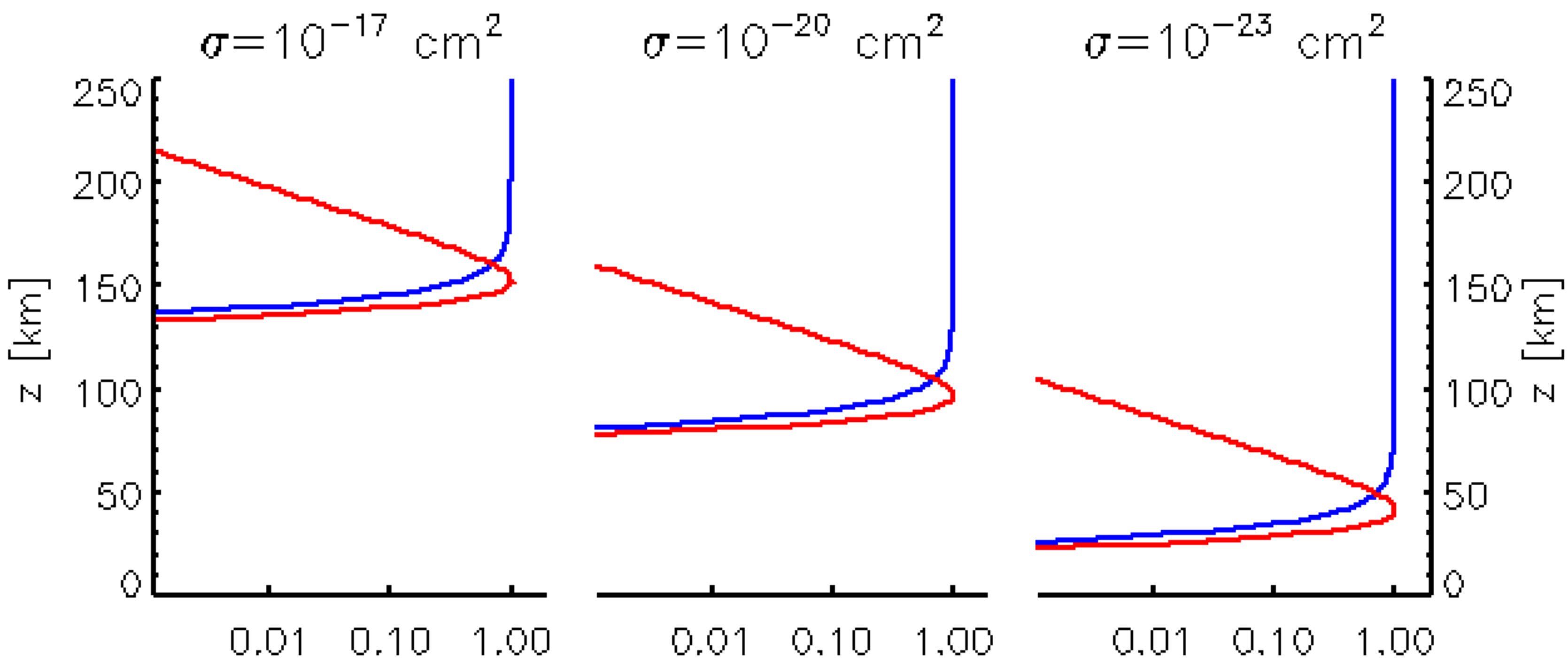
$$z_{\tau 1}(\lambda) = H \ln\left[\frac{\sigma(\lambda)}{5 \times 10^{-26}\,\mathrm{cm}^2} \right]$$

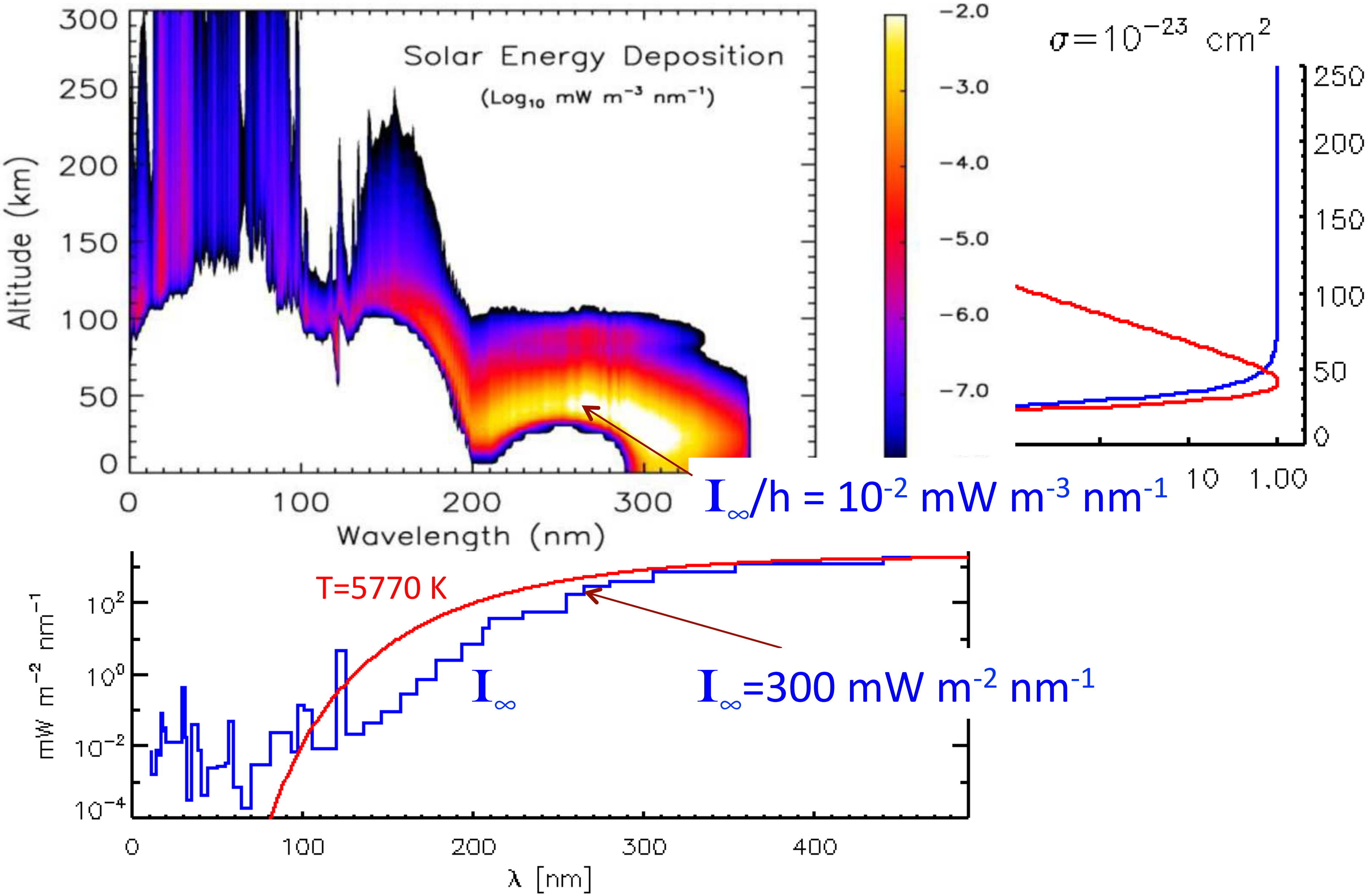
Radiation intensity & heating

Energy flux: $I(z) = I_\infty P(z) = I_\infty \exp\left[-e^{-(z-z_{\tau 1})/H} \right]$

Energy deposition: $\dfrac{dI}{dz} = \dfrac{I_\infty}{H} \exp\left[-e^{-(z-z_{\tau 1})/H} - \dfrac{z - z_{\tau 1}}{H} \right]$

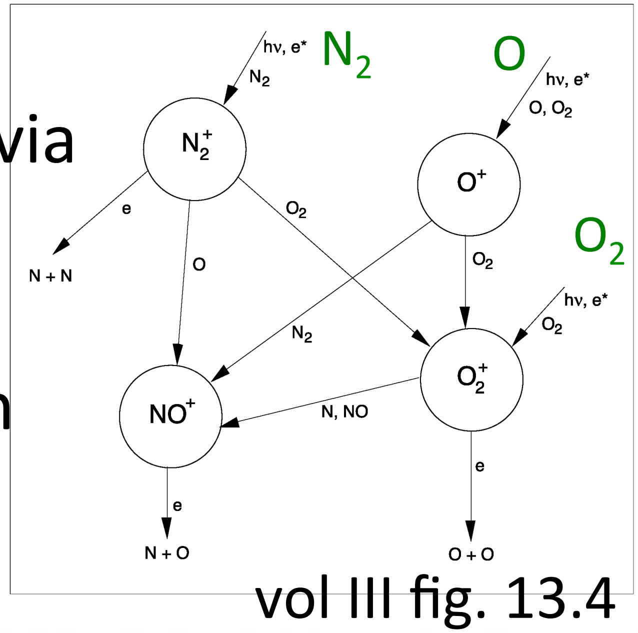
Chapman layer

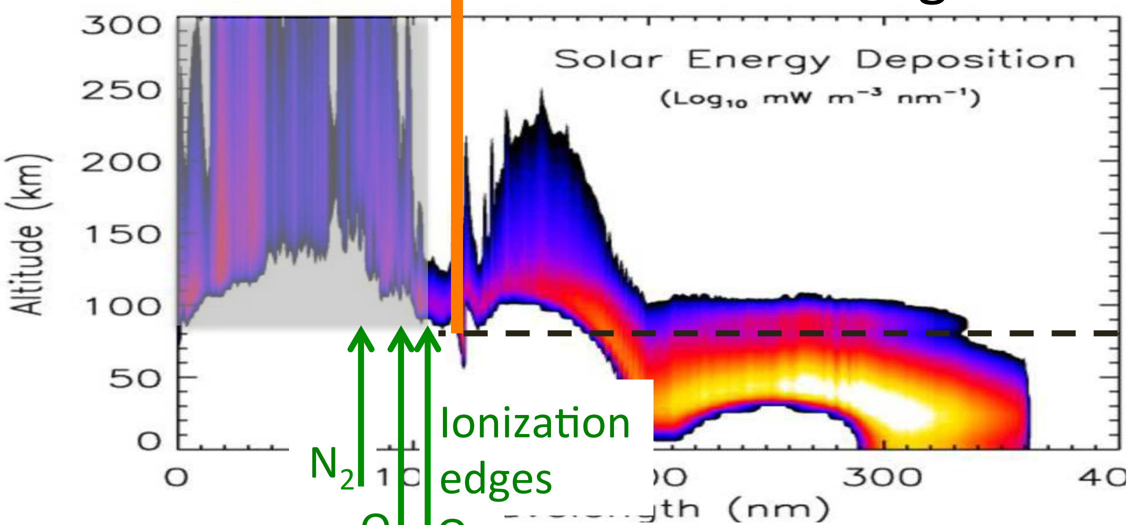


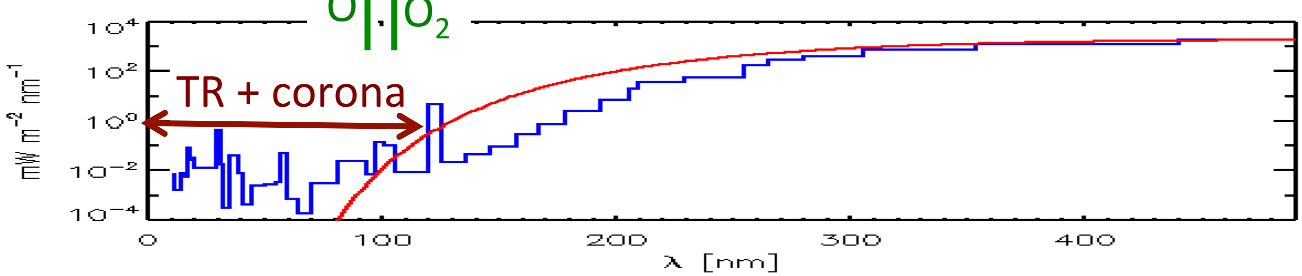


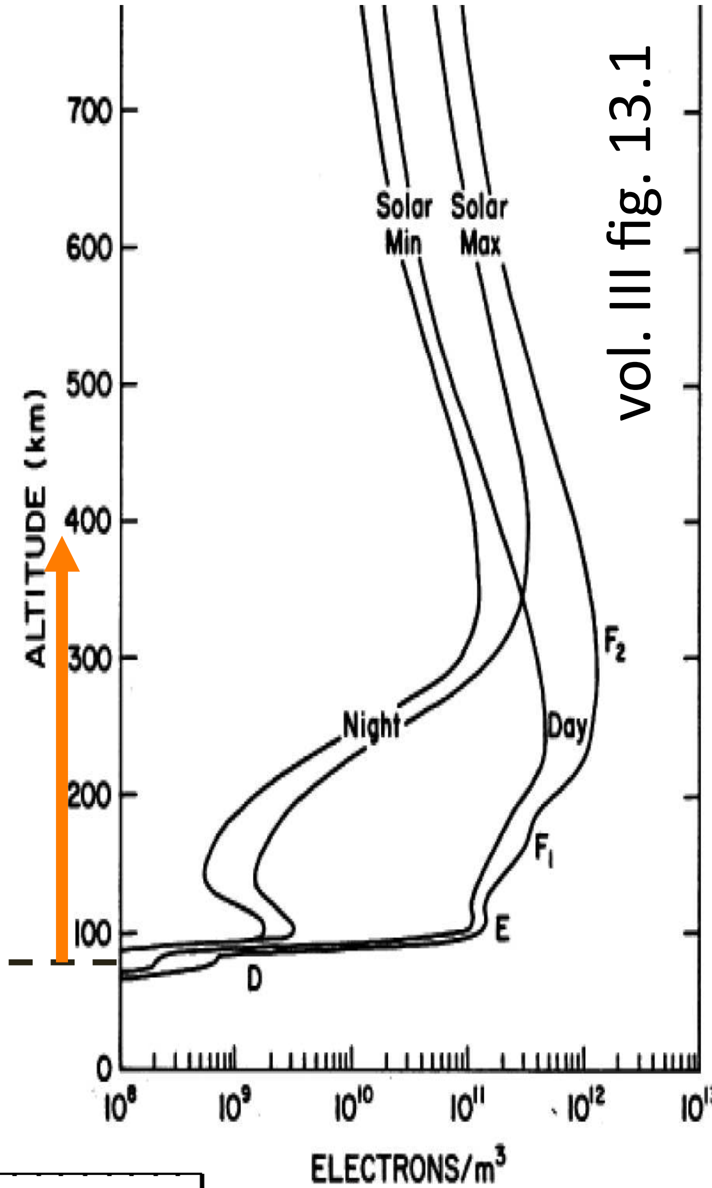
Solar Energy Deposition
(Log10 mW m-3 nm-1)
Altitude (km)
Wavelength (nm)
σ=10-23 cm2
I∞/h = 10-2 mW m-3 nm-1
T=5770 K
I∞
I∞=300 mW m-2 nm-1
mW m-2 nm-1
λ [nm]

Absorption via ionization creates ion/electron pairs







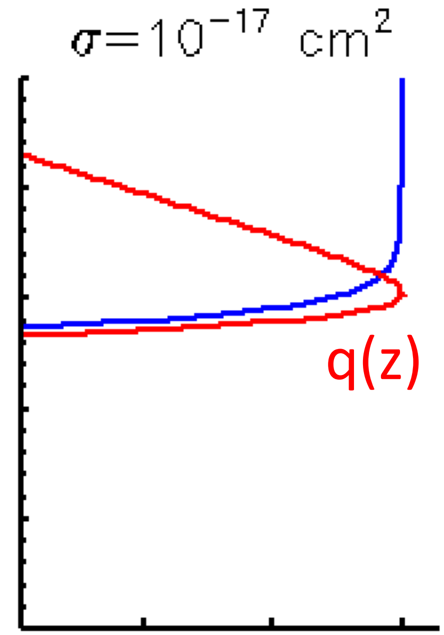


Rate of photo-ionization (per volume)

= Electron production rate:

$$q(z) = \sigma_{\text{ion}} n(z)\, F(z) = \sigma_{\text{ion}} n(z)\, F_\infty P(z)$$

$$= \sigma_{\text{ion}} n_0 F_\infty \exp\left[-e^{-(z-z_{\tau 1})/H} - \frac{z}{H} \right]$$



Electron destruction by recombination with +'ve ions @ rate

$$L = \alpha\, n_e n_i \approx \alpha\, n_e^2$$

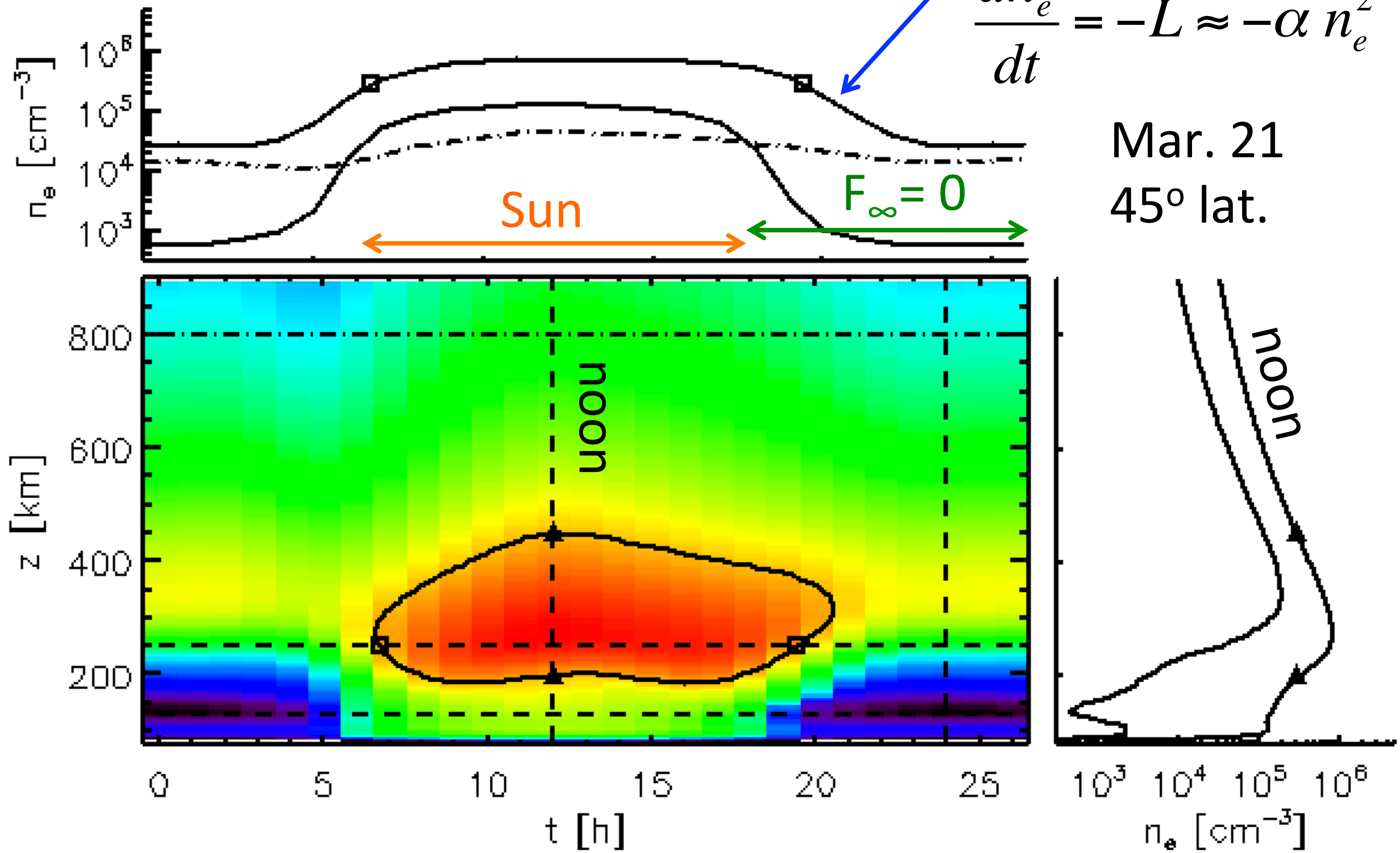
Assuming neutrality

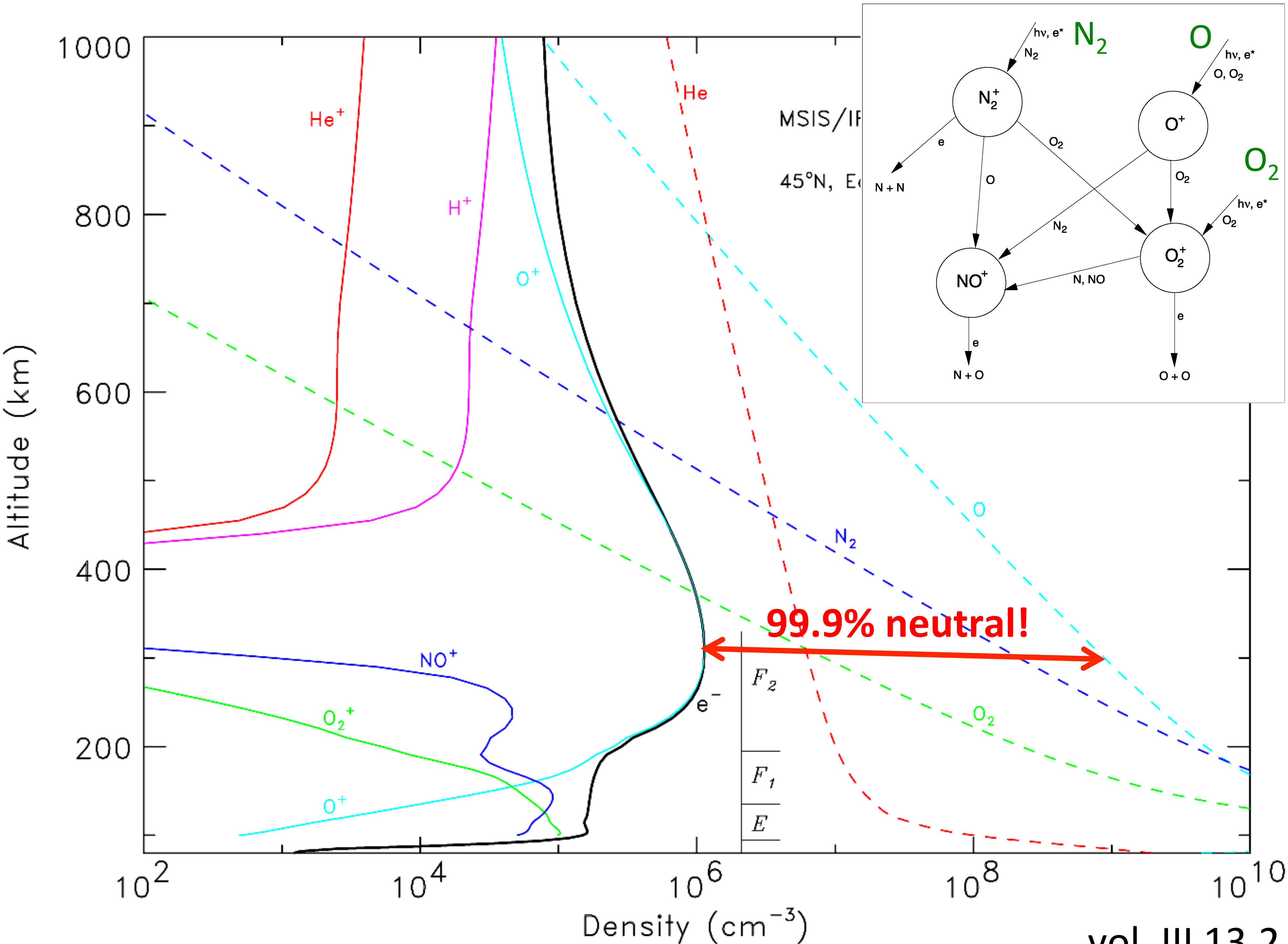
Production balances destruction: q=L

$$n_e(z) = \sqrt{\frac{q(z)}{\alpha(z)}}$$

Production shut off
– recombination removes electrons

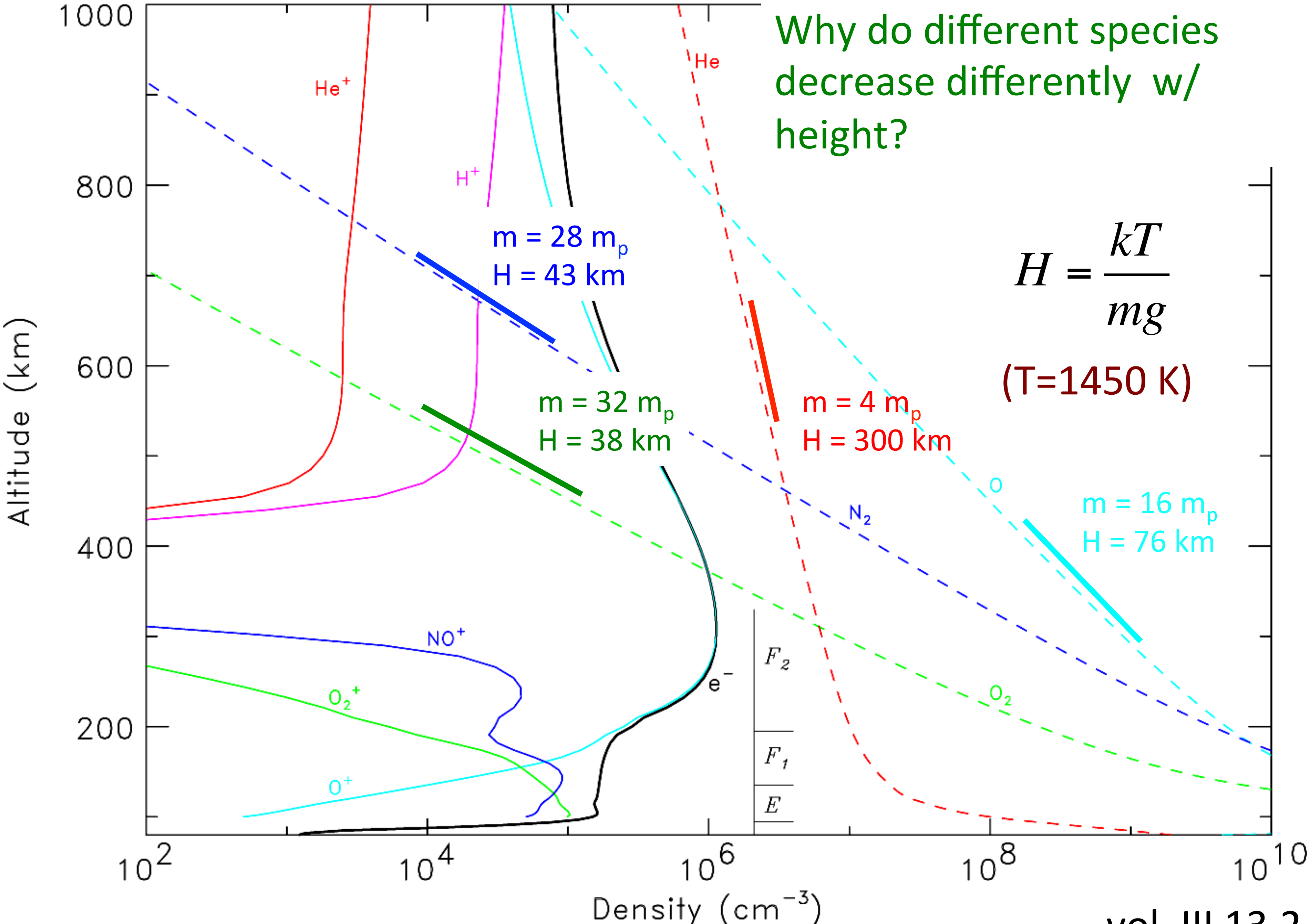
$$\frac{dn_e}{dt} = -L \approx -\alpha\, n_e^2$$




Altitude (km)
1000
800
600
400
200
Density (cm^{-3})
10^2
10^4
10^6
10^8
10^{10}
He$^+$
H$^+$
O$^+$
He
MSIS/IF
45°N, E
O
N_2
O_2
NO$^+$
O_2^+
O$^+$
e$^-$
F_2
F_1
E
99.9% neutral!
N_2
O
O_2
hν, e*
N_2^+
O$^+$
NO$^+$
O_2^+
e
N + N
N + O
O + O
O, O_2
N, NO

vol. III 13.2

Why do different species decrease differently w/ height?



$$H = \frac{kT}{mg}$$

(T=1450 K)

vol. III 13.2

Ionospheric plasma

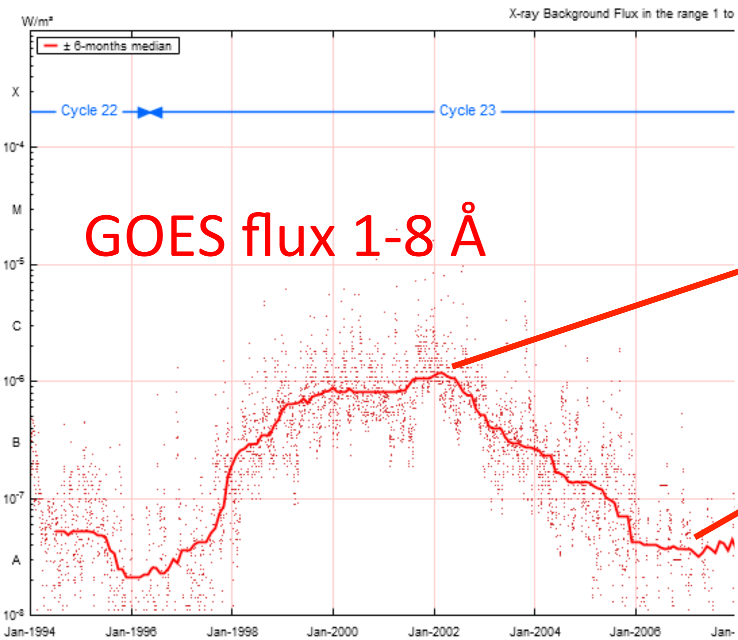
- ions/e^- form plasma – conducting fluid
- Neutrals: separate fluid
- Continual creation/destruction couples fluids
  – created ``drag force'' between them

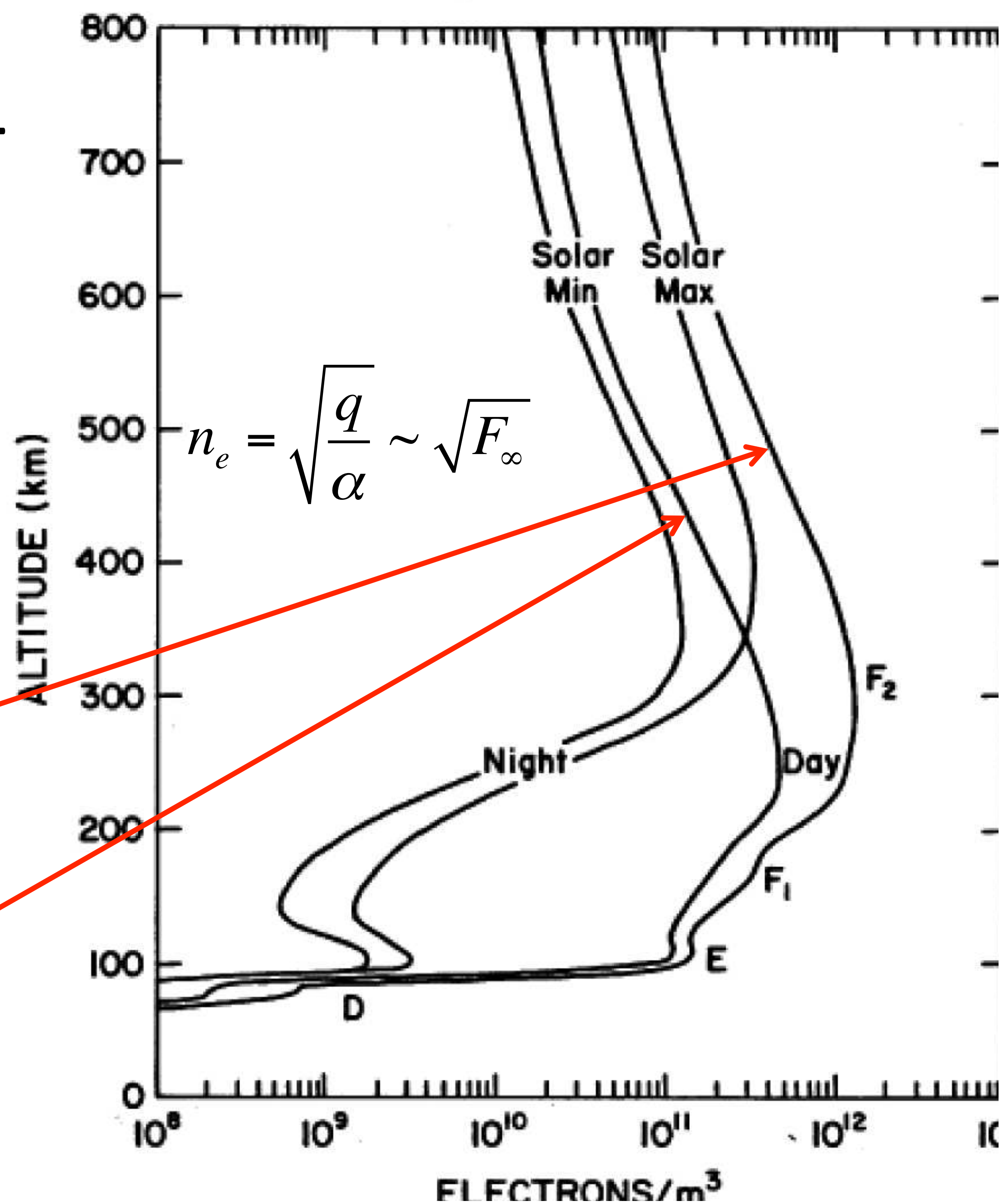
A plasma with electron density n_e (cm^{-3}) screens out E fields w/ f < its plasma frequency

$$f_p = \sqrt{\frac{e^2 n_e}{\pi m_e}} = 10^4\,\mathrm{Hz}\ n_e^{1/2}$$

Q: what is the lowest freq. solar radio emission we can observe from the ground?

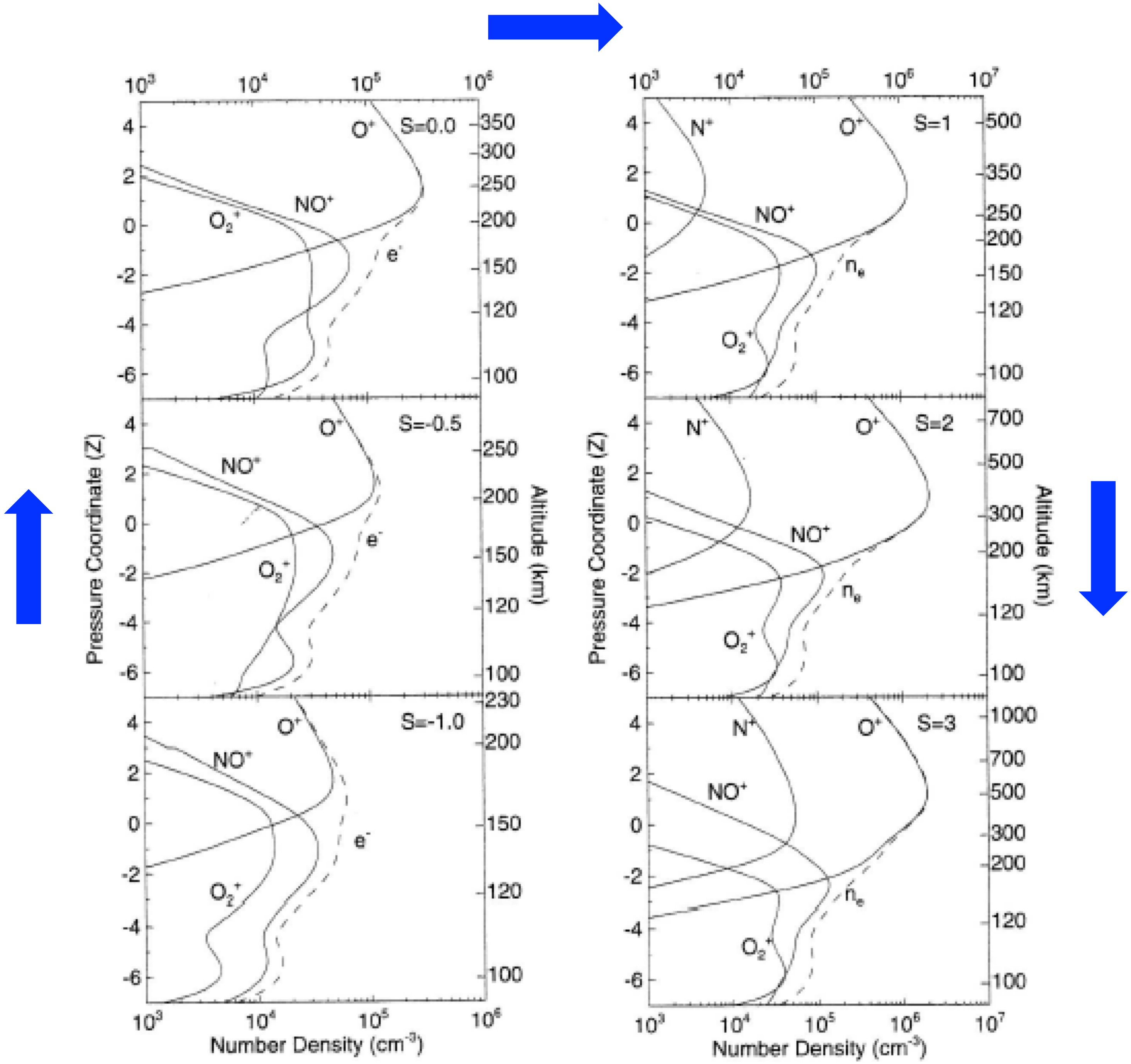
Corona varies – ionosphere varies





$$n_e = \sqrt{\frac{q}{\alpha}} \sim \sqrt{F_\infty}$$

increasing coronal flux

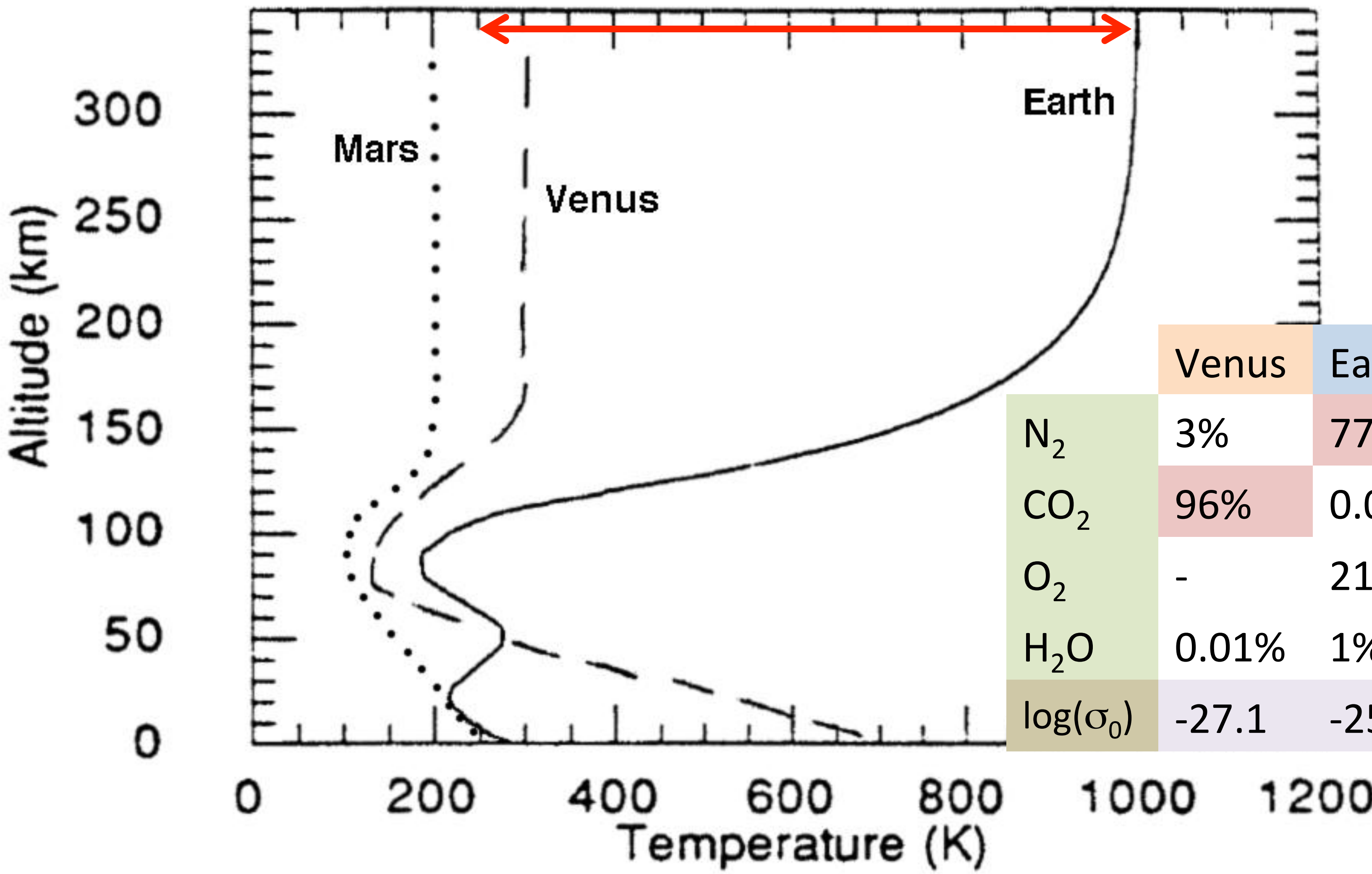


vol. III 14.4

Other planets… other atmospheres

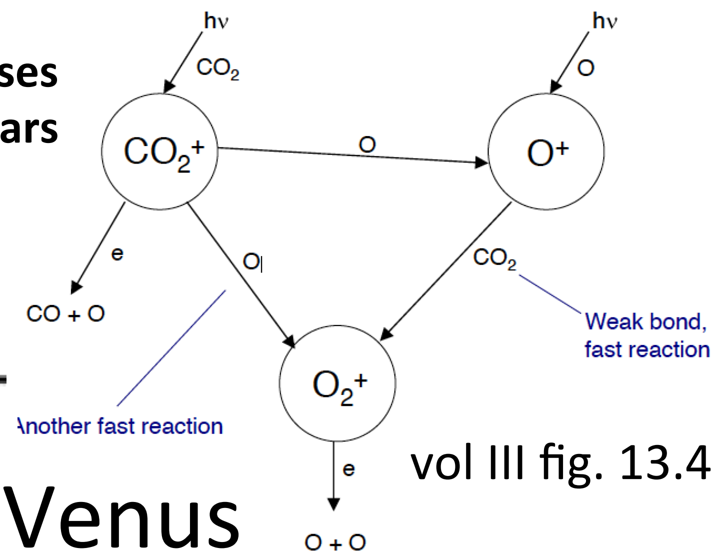
Why is Earth's thermosphere so hot?

Solomon



	Venus	Earth	Mars
N_2	3%	77%	3%
CO_2	96%	0.03%	95%
O_2	-	21%	-
H_2O	0.01%	1%	-
$\log(\sigma_0)$	-27.1	-25.3	-23.4

Principal Ionization Processes on Venus & Mars

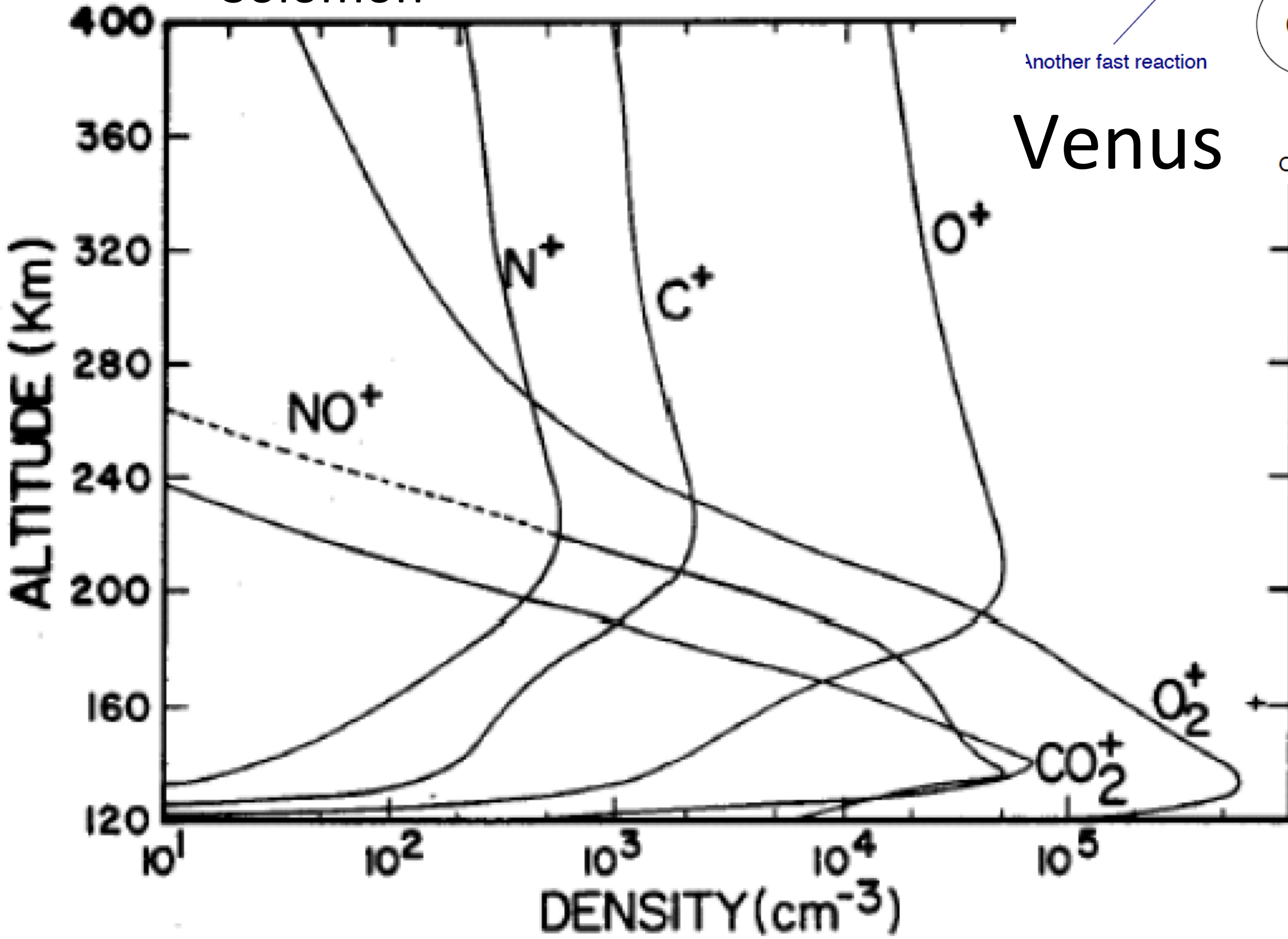


vol III fig. 13.4

Venus

Solomon

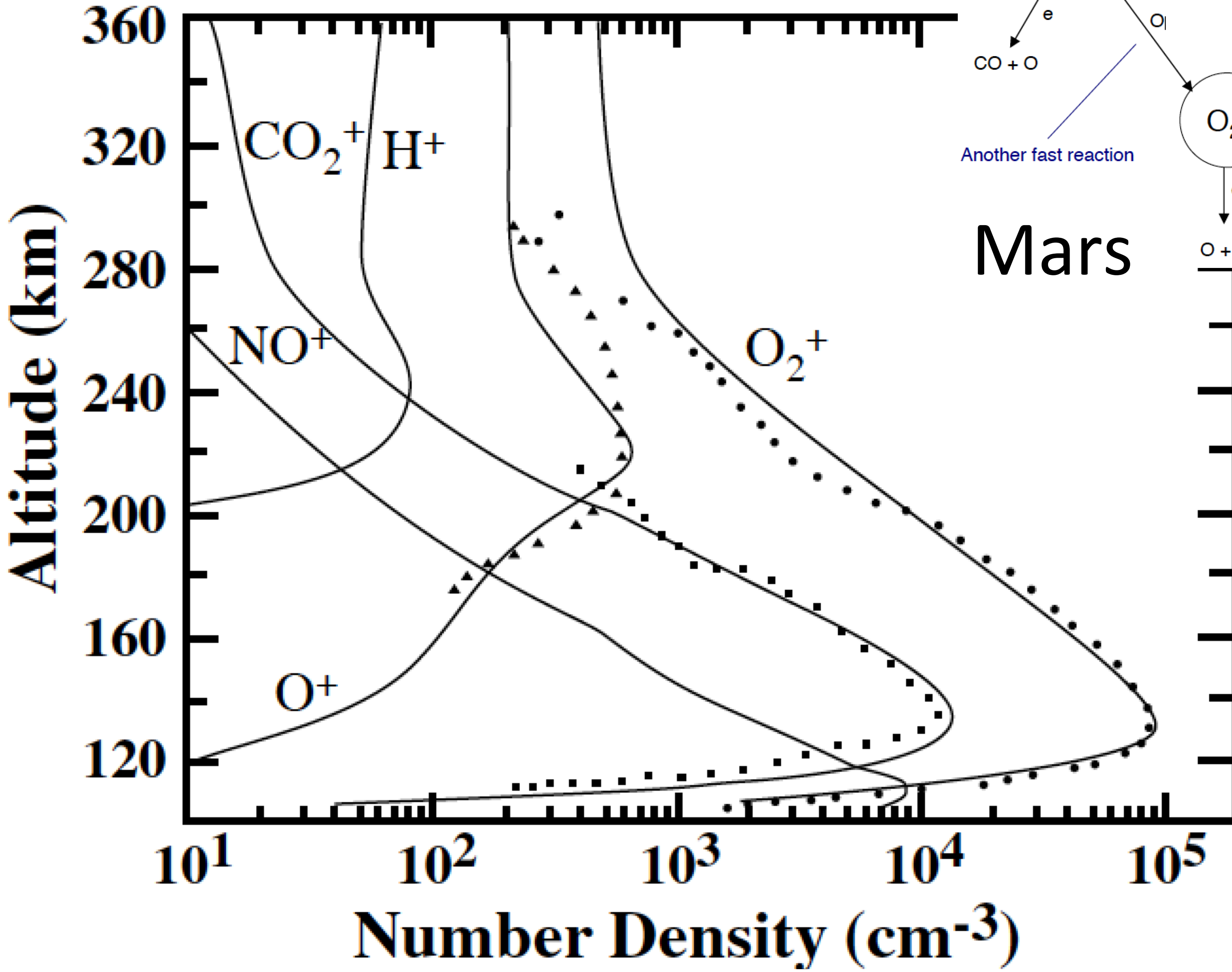
$\chi=60^o$

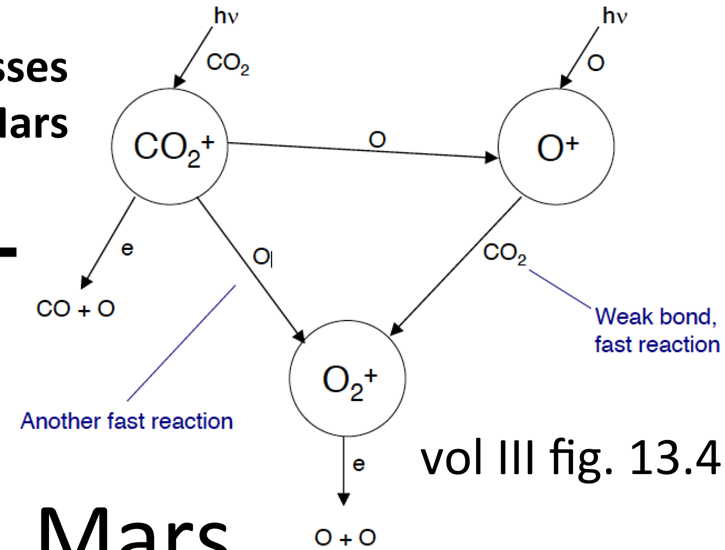


	Venus
N_2	3%
CO_2	96%
O_2	-
H_2O	0.01%

Principal Ionization Processes on Venus & Mars

vol III fig. 13.6





vol III fig. 13.4

Mars

	Mars
N_2	3%
CO_2	95%
O_2	-
H_2O	-

Say I discover an exoplanet – Dana-I

It is a Jupiter-size gas giant orbiting fairly close (1 AU) to its star: a B-type star

($M = 10\ M_\odot$, $T_s = 20{,}000K$, $L = 10^4\ L_\odot$)

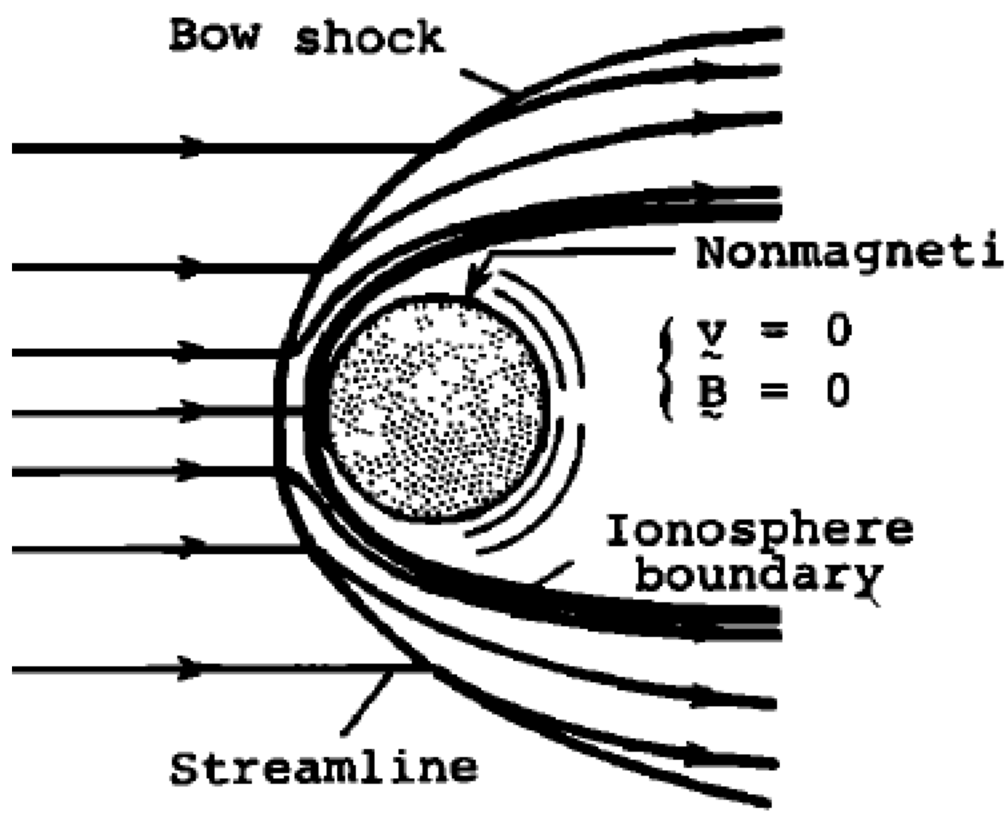
Q: Is it likely that Dana-I has an ionosphere?

Q: What if the host star were a much cooler M-type star?

Venus or Mars

- No dynamo – no **B**
- Ionosphere ➔ conducting bdry
- SW– w/ **B** – can't penetrate
- Supersonic flow deflected by obstacle
- Bow shock forms

Spreiter & Stahara 1980



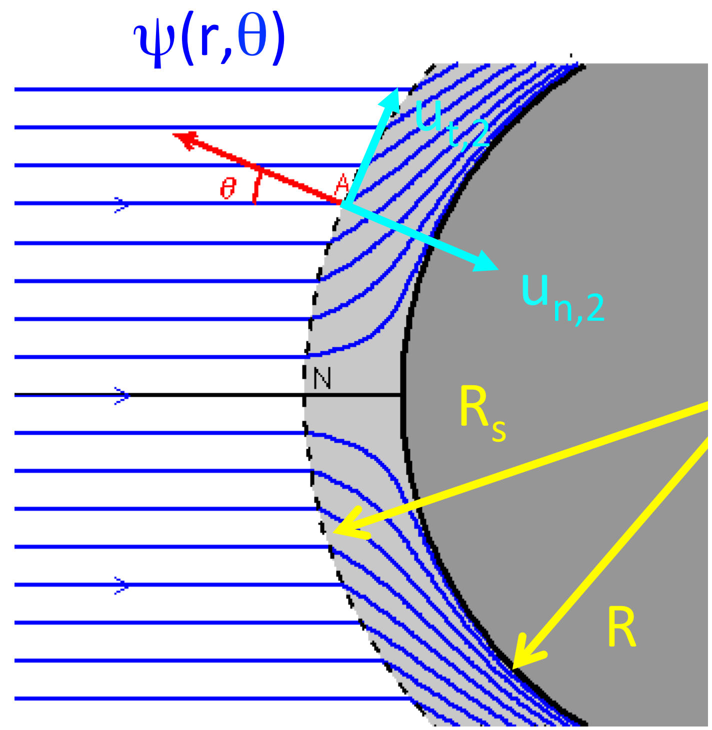
Simple picture of bow shock

- Ignore pressure from SW **B**
- SW: $u_\infty/c_{s,\infty}$, ρ_∞, $M_\infty \gg 1$
- Standing shock ~ sphere radius= R_s
- Post-shock flow
  - v. ubsonic – $M \ll 1$
  - ➔ ~ incompressible w/ $u_r(R) = 0$

$$\mathbf{u} = \nabla\psi \times \nabla\phi$$

$$\psi(r,\theta) = C\left(\frac{r^4}{R^4} - \frac{R^2}{r^2}\right)\sin^2\theta$$

Lighthill 1957



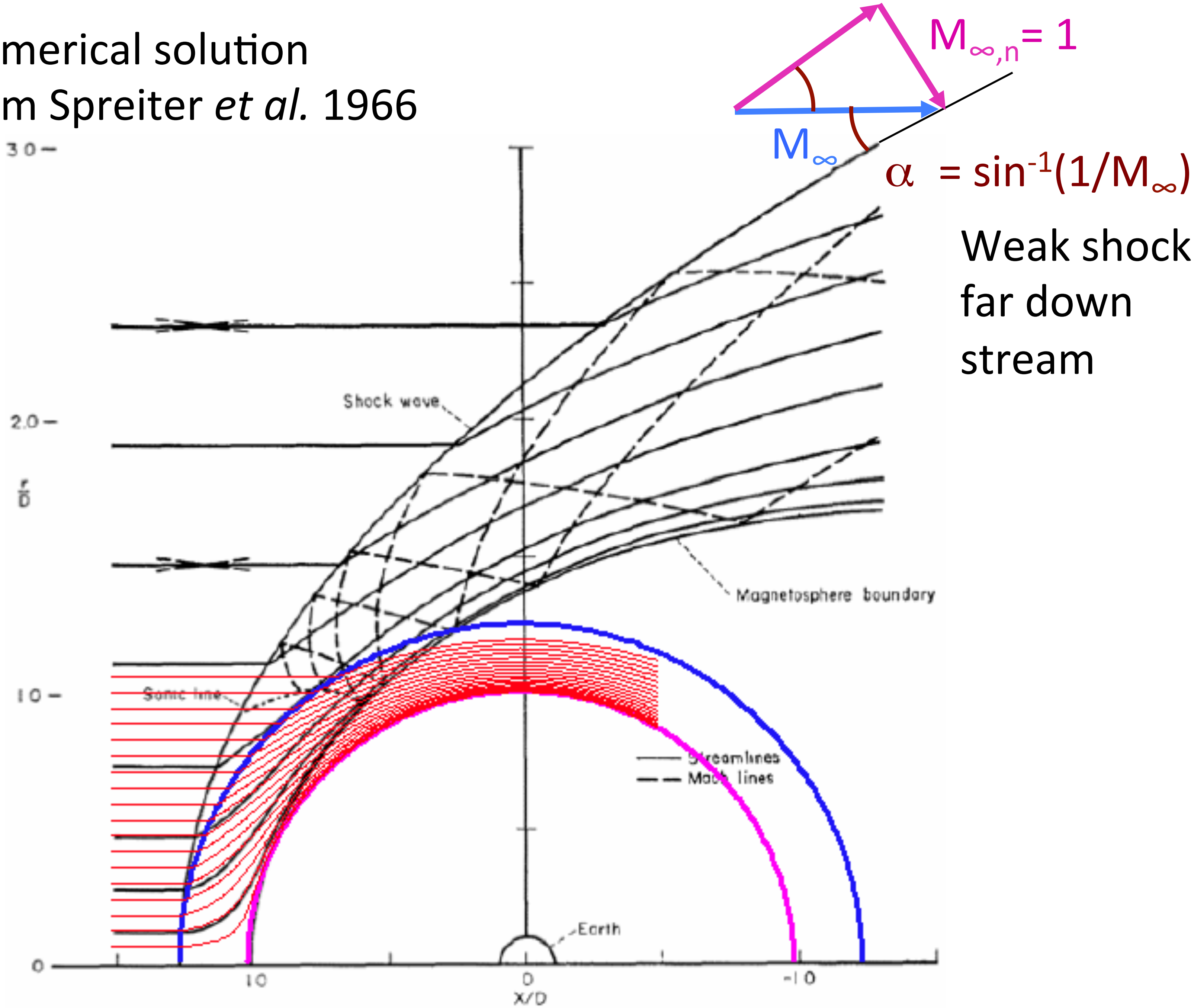
Bow shock

- $u_{n,2} = u_{n,1}/4$, $u_{t,2} = u_{t,1}$

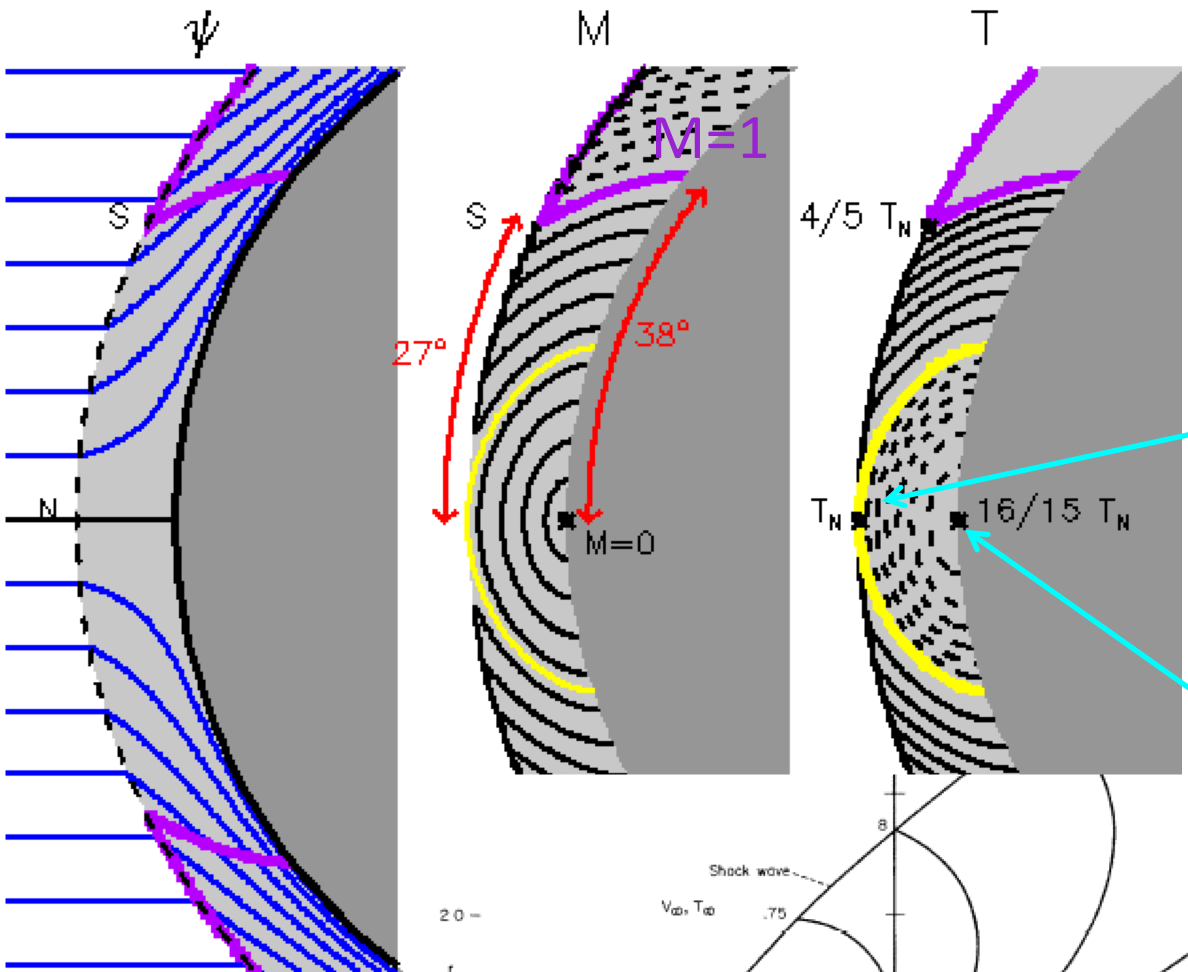
$$\frac{u_{r,2}}{\cos\theta} = 2\frac{CR_s^2}{R^4}\left(1 - \frac{R^5}{R_s^5}\right) = -\frac{1}{4}u_\infty \qquad \frac{u_{\theta,2}}{\sin\theta} = -\frac{CR_s^2}{R^4}\left(4 + \frac{R^5}{R_s^5}\right) = u_\infty$$

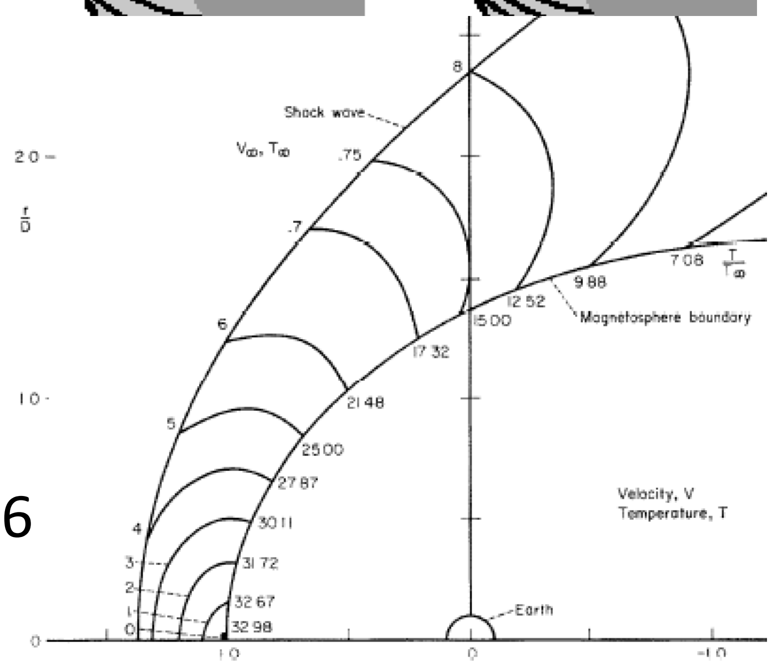
$$R_s = \left(\frac{3}{2}\right)^{2/5} R = 1.18\,R$$

Numerical solution
from Spreiter *et al.* 1966



Weak shock far down stream





Spreiter *et al.* 1966

Shock partially therm-alizes flow KE of SW:

- Nose point (normal)

$$T_N = \frac{3}{8} \cdot \frac{\frac{1}{2} m u_\infty^2}{k_B}$$

- Stagnation point

$$T_s = \frac{16}{15} T_N = \frac{2}{5} \cdot \frac{\frac{1}{2} m u_\infty^2}{k_B}$$

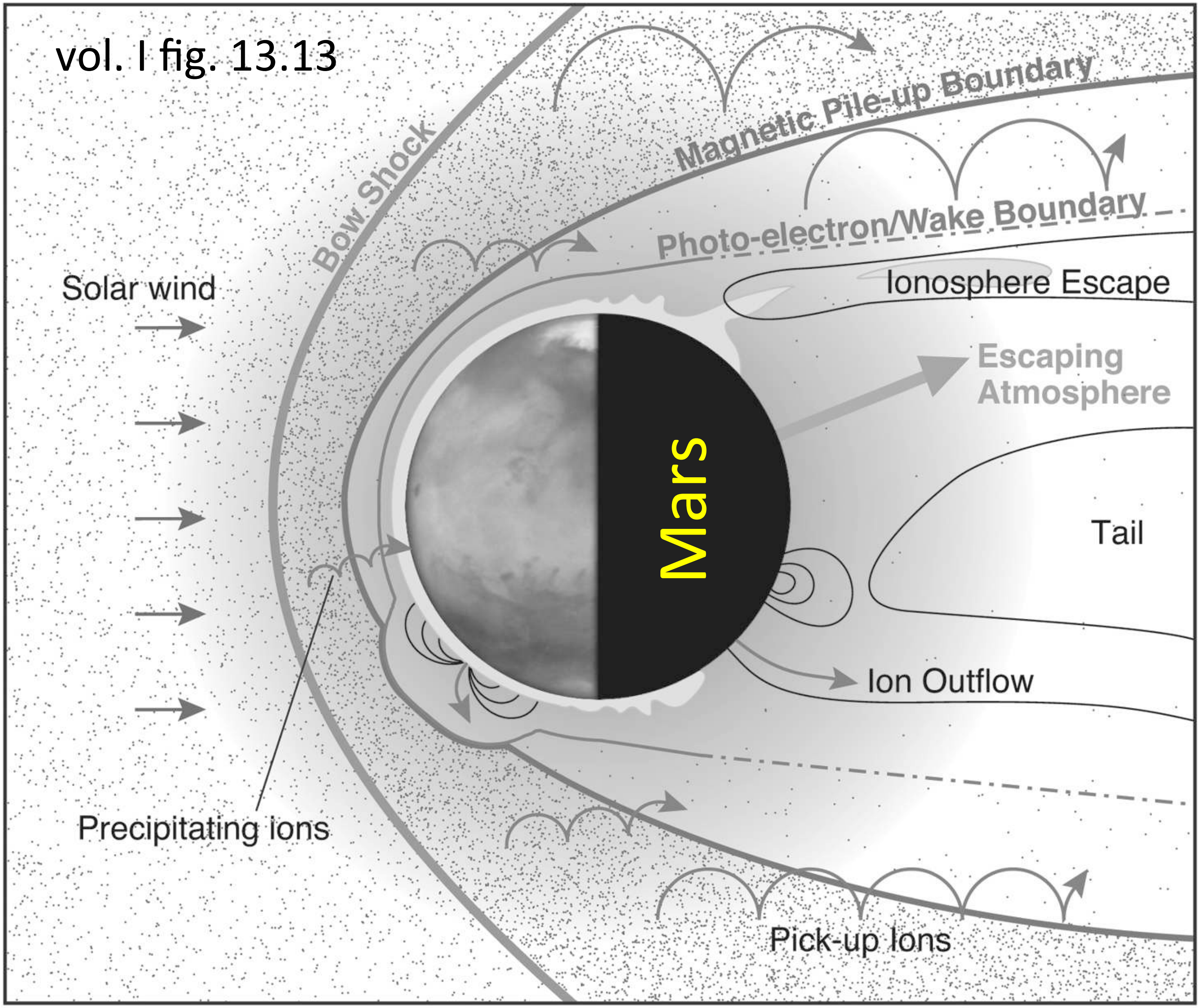
u_∞ = 400 km/s

➔ T_N = 3.6 MK

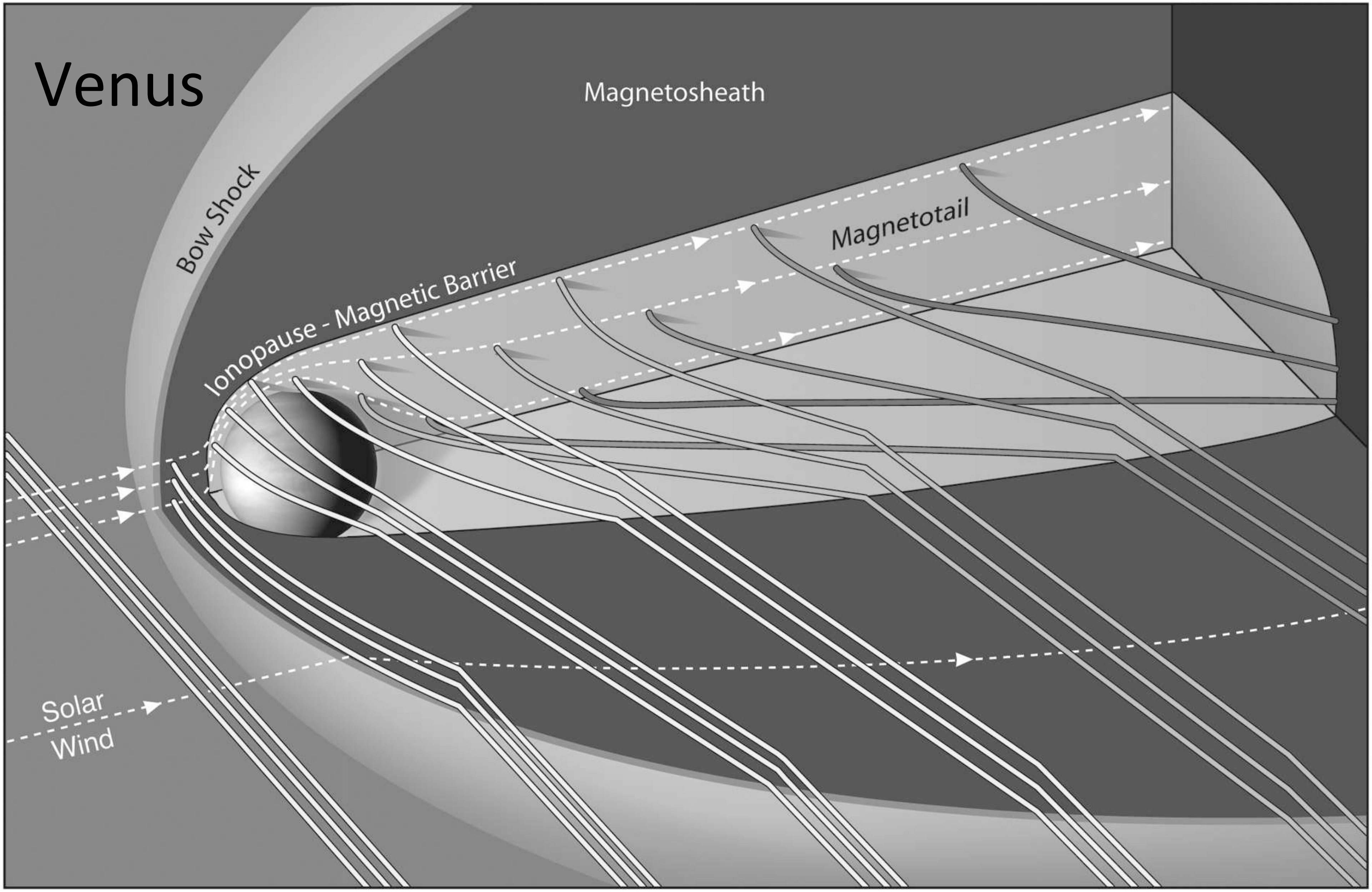
➔ T_s = 3.8 MK

- pressure

$$p_s = \frac{4}{5} \rho_\infty u_\infty^2$$



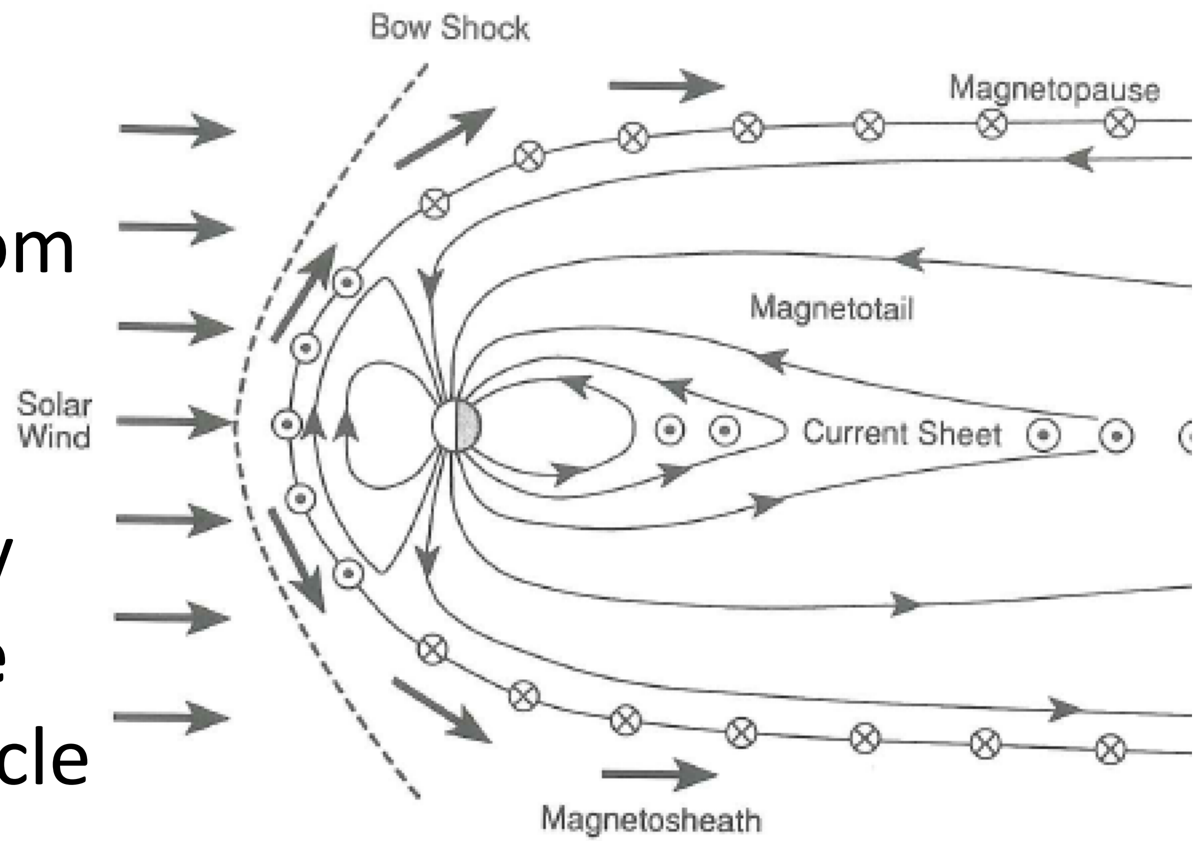
vol. I fig. 13.13
Bow Shock
Magnetic Pile-up Boundary
Photo-electron/Wake Boundary
Ionosphere Escape
Solar wind
Escaping
Atmosphere
Mars
Tail
Ion Outflow
Precipitating ions
Pick-up Ions



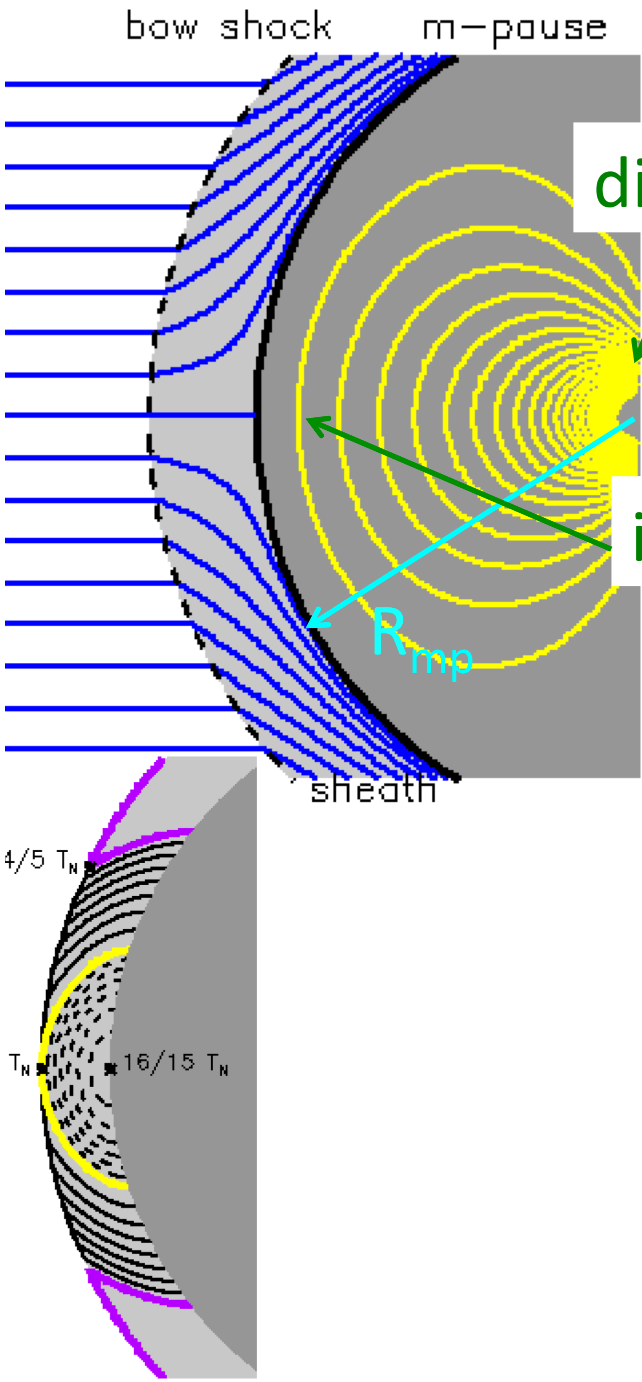
vol. I fig. 13.12

Wind @ Magnetized Planets
Earth, Jupiter, Saturn, …

- Planetary **B** prevents SW from reaching ionosphere
- SW deflected by **magnetosphere**
- "squishy" obstacle



Hughes (*cf.* vol. I fig. 10.1)



Shock & sheath: similar to before

- Stagnation point (SP) @ $r=R_{mp}$
- Plasma pressure: $p_s = \frac{4}{5}\rho_\infty u_\infty^2$
- Inside ($r < R_{mp}$): $\mathbf{B} = -\nabla \chi$

$$\chi(r,\theta) = \frac{B_\oplus R_\oplus^3}{R_{mp}^2}\left(\frac{R_{mp}^2}{r^2} + \frac{2r}{R_{mp}}\right)\cos\theta$$

- Magnetic pressure @ SP

$$\frac{1}{8\pi}\left|\mathbf{B}(R_{mp},0)\right|^2 = \frac{1}{8\pi}\left(\frac{1}{R_{mp}}\frac{\partial \chi}{\partial \theta}\right)^2 = \frac{9R_\oplus^6}{8\pi R_{mp}^6}B_\oplus^2$$

- Ignore inner plasma – balance

$$R_{mp} = \left(\frac{45}{32\pi}\right)^{1/6}\left(\frac{B_\oplus^2}{\rho_\infty u_\infty^2}\right)^{1/6} R_\oplus$$

Chapman-Ferraro Distance

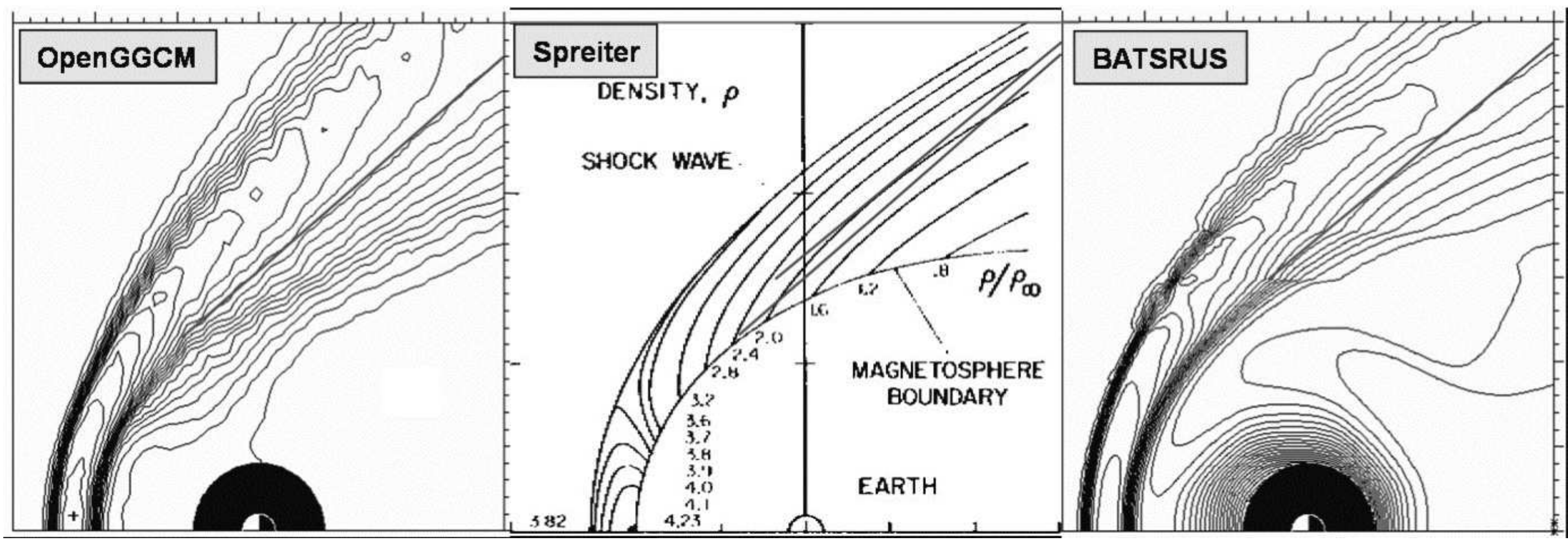
Intuition break

$$R_{mp} = \left(\frac{45}{32\pi}\right)^{1/6}\left(\frac{B_{\oplus}^2}{\rho_{\infty}u_{\infty}^2}\right)^{1/6} R_{\oplus} \sim 12\ R_{\oplus}$$

$\rho_{sw} = 10^{-23}$ g/cm
$u_{sw} = 400$ km/s

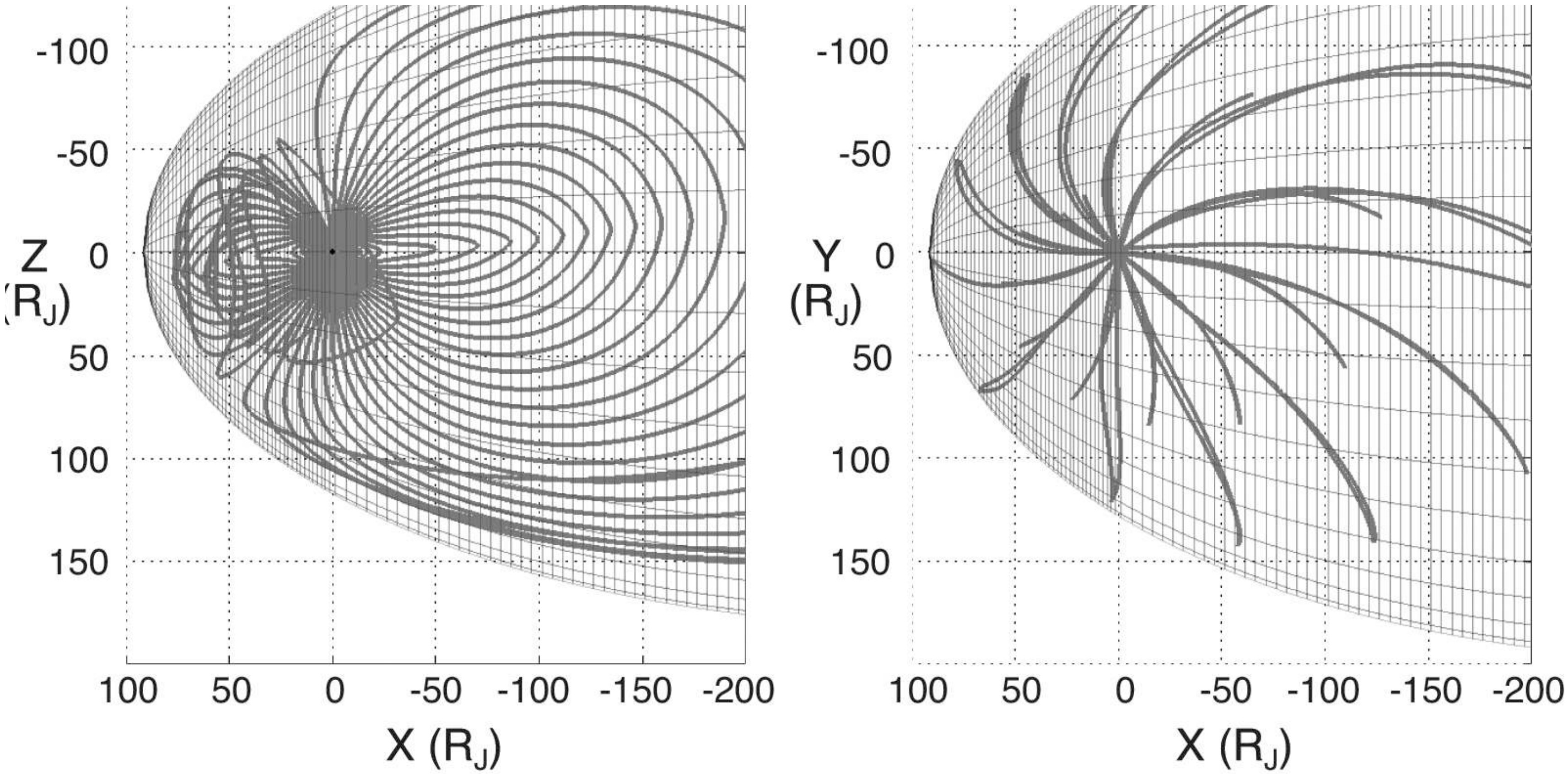
- At what distance do geostationary satellites orbit?
- Is the moon inside or outside the magnetopause?
- What happens to R_{mp} during fast SW: $u_{sw} = 800$ km/s

Similar picture from high-powered codes



vol. I fig. 11.2

Other planets… same story



vol. I fig. 13.6

$B_J \sim 15\ B_\oplus \sim 5$ G ; $\rho_\infty \sim 0.04\ \rho_{\infty,\oplus}$

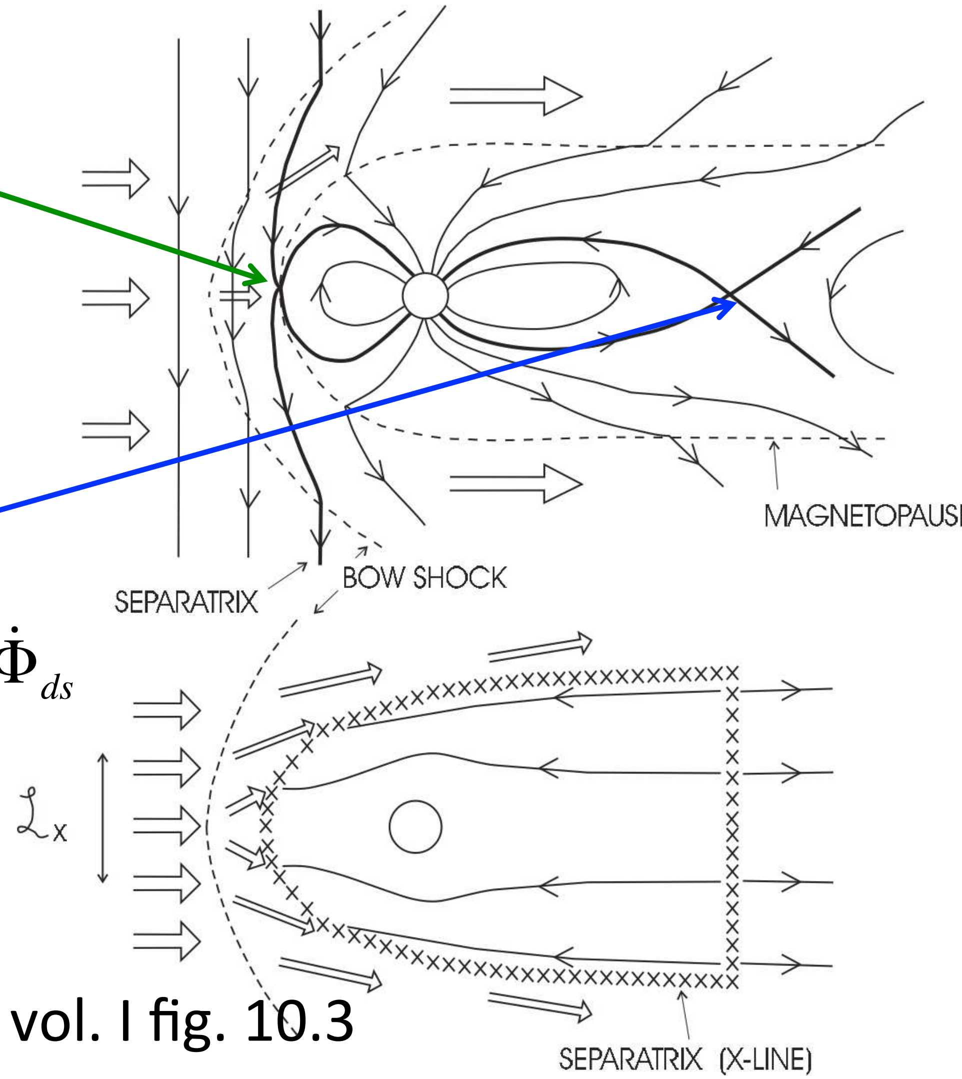
➔ Jupiter's magnetopause:

$R_{mp,J} \sim 50\ R_J = 3.5 \times 10^{11}$ cm

But not all of Earth's field stays confined to m-sphere

Reconnection with SW field (consider southward IMF)

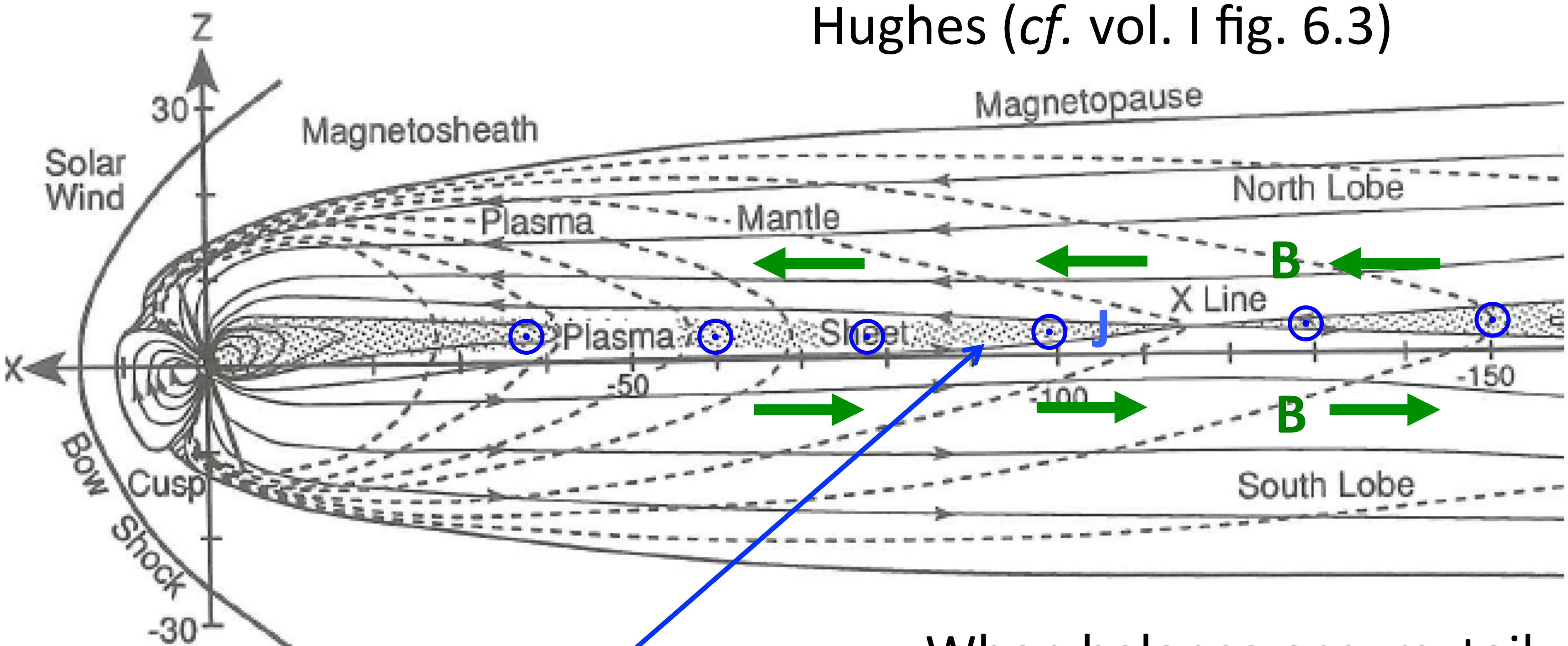
- Creates "open" flux connected to poles @ $\dot{\Phi}_{ds}$
- SW sweeps flux downstream – into **magnetotail**
- Steady state only when reconnection in tail "closes" flux at rate $\dot{\Phi}_{n} = -\dot{\Phi}_{ds}$
- Requires long & strong **neutral sheet** in magnetotail



vol. I fig. 10.3

But not all of Earth's field stays confined to m-sphere

Hughes (*cf.* vol. I fig. 6.3)

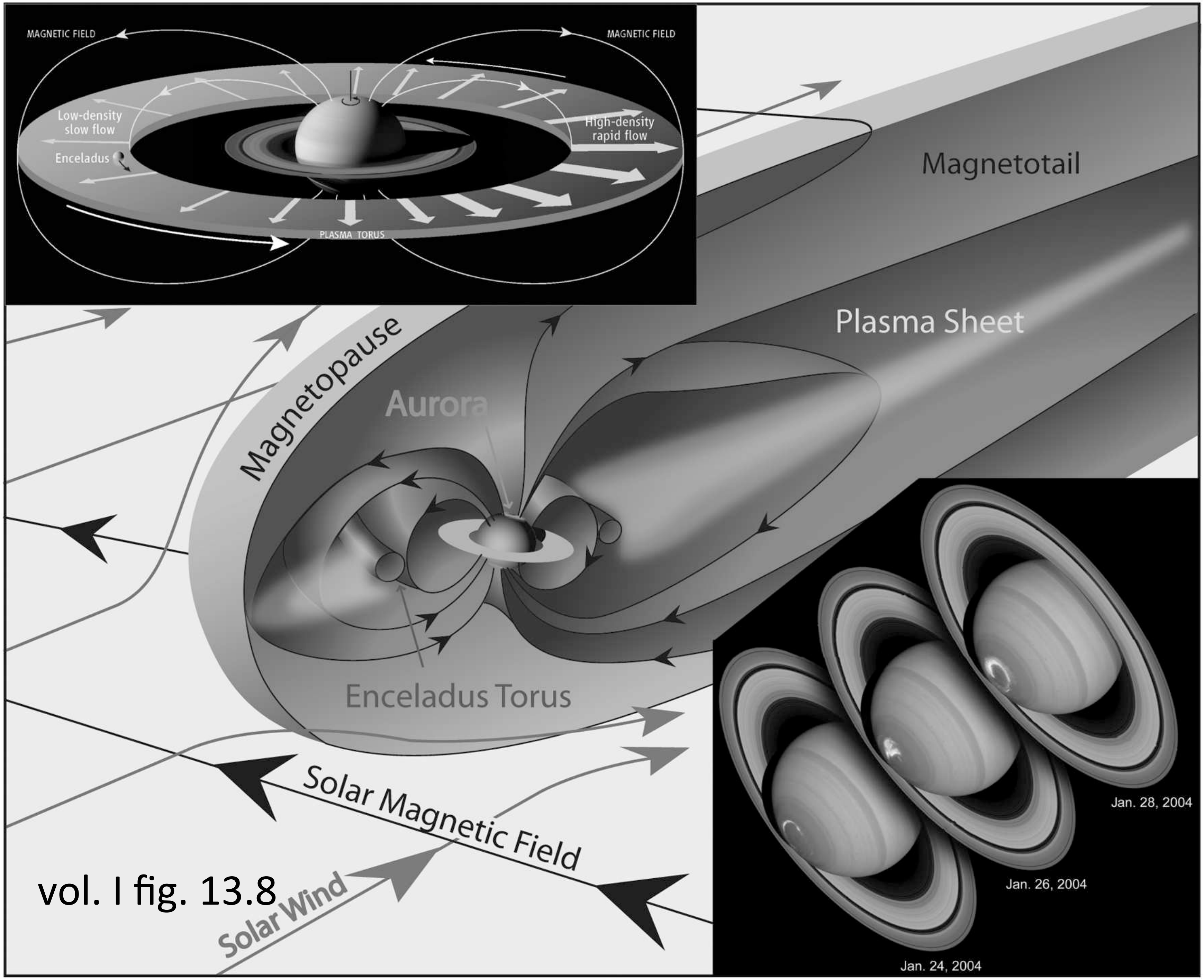


"closes" flux at rate $\dot{\Phi}_n = -\dot{\Phi}_{ds}$

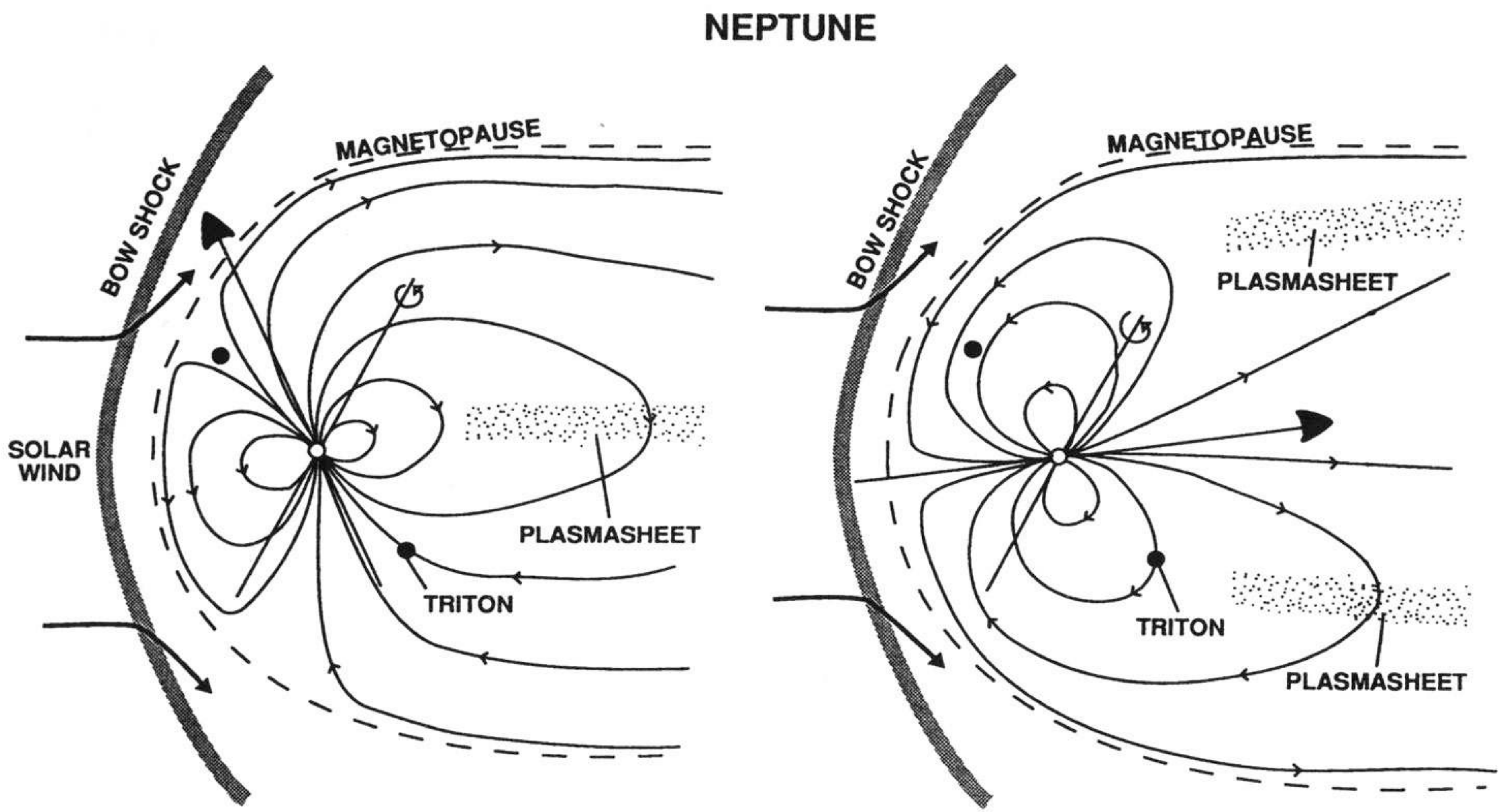
- Requires long & strong **neutral sheet** in magnetotail

When balance occurs, tail…

- … has some length $L_t \gg R_{mp}$
- … has some open flux Φ_t

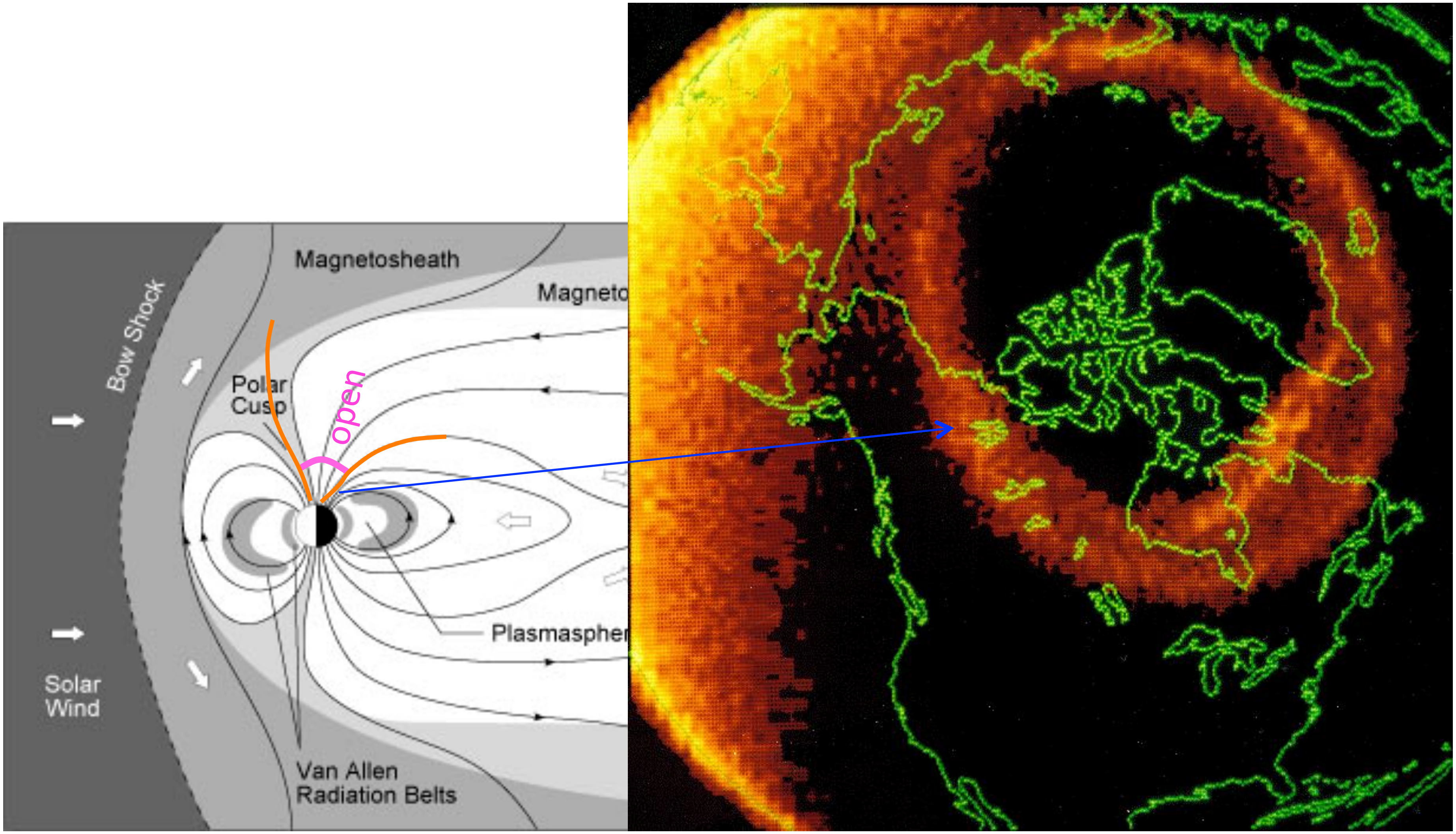

MAGNETIC FIELD
MAGNETIC FIELD
Low-density
slow flow
High-density
rapid flow
Enceladus
PLASMA TORUS
Magnetotail
Plasma Sheet
Magnetopause
Aurora
Enceladus Torus
Solar Magnetic Field
Solar Wind
Jan. 28, 2004
Jan. 26, 2004
Jan. 24, 2004

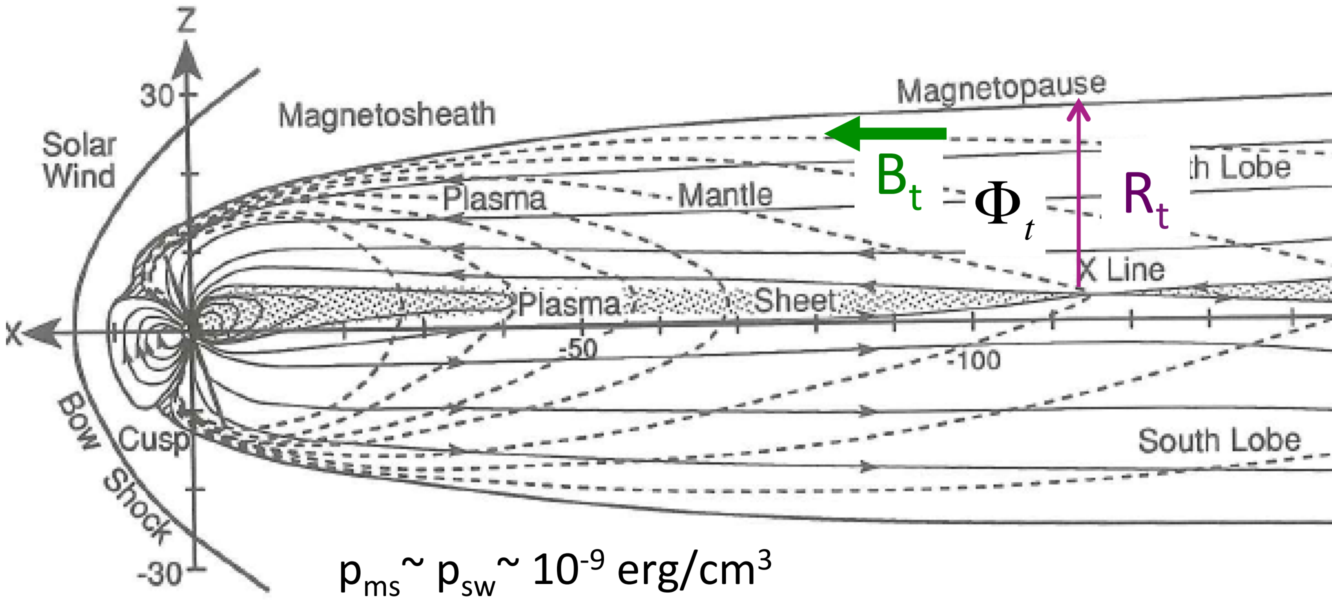
vol. I fig. 13.8

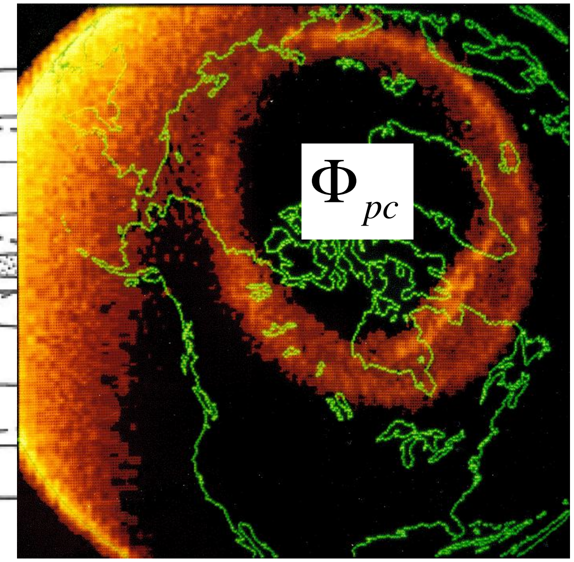


vol. I fig. 13.10

closed/open boundary maps down to "auroral oval"







$p_{ms} \sim p_{sw} \sim 10^{-9}$ erg/cm^3

$$\Phi_t = \Phi_{pc} = \pi\left(R_\oplus \sin\theta_{pc}\right)^2 B_{np} \sim \pi R_\oplus^2 \theta_{pc}^2 B_{np} \sim 10^{17}\,\mathrm{Mx}$$

$$\Phi_t = \frac{\pi}{2} R_t^2 B_t$$

mag. pressure In tail:

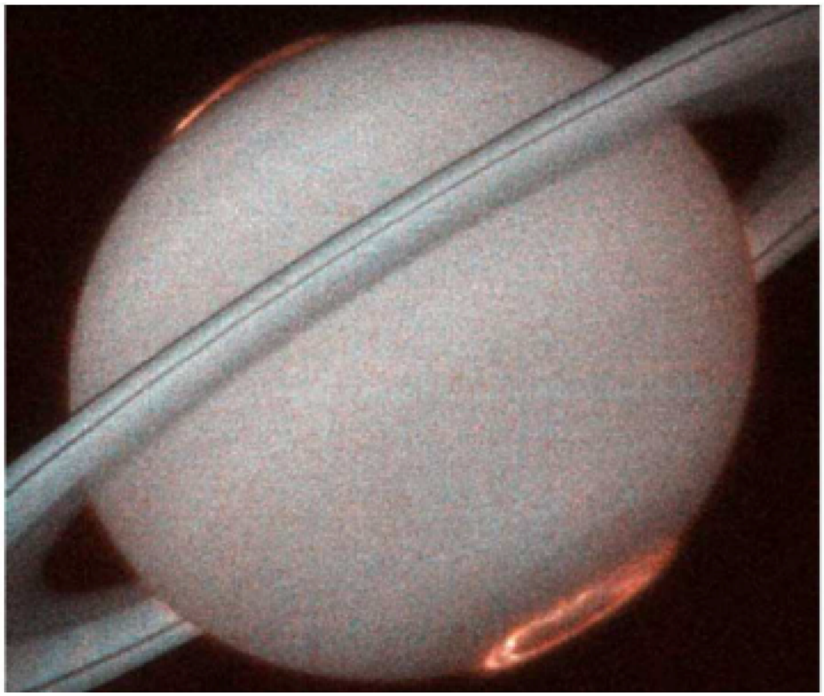
$$\frac{1}{8\pi} B_t^2 = \frac{1}{2\pi^3}\frac{\Phi_t^2}{R_t^4} = \frac{1}{2\pi}\left(\frac{R_\oplus}{R_t}\right)^4 \theta_{pc}^4 B_{np}^2$$

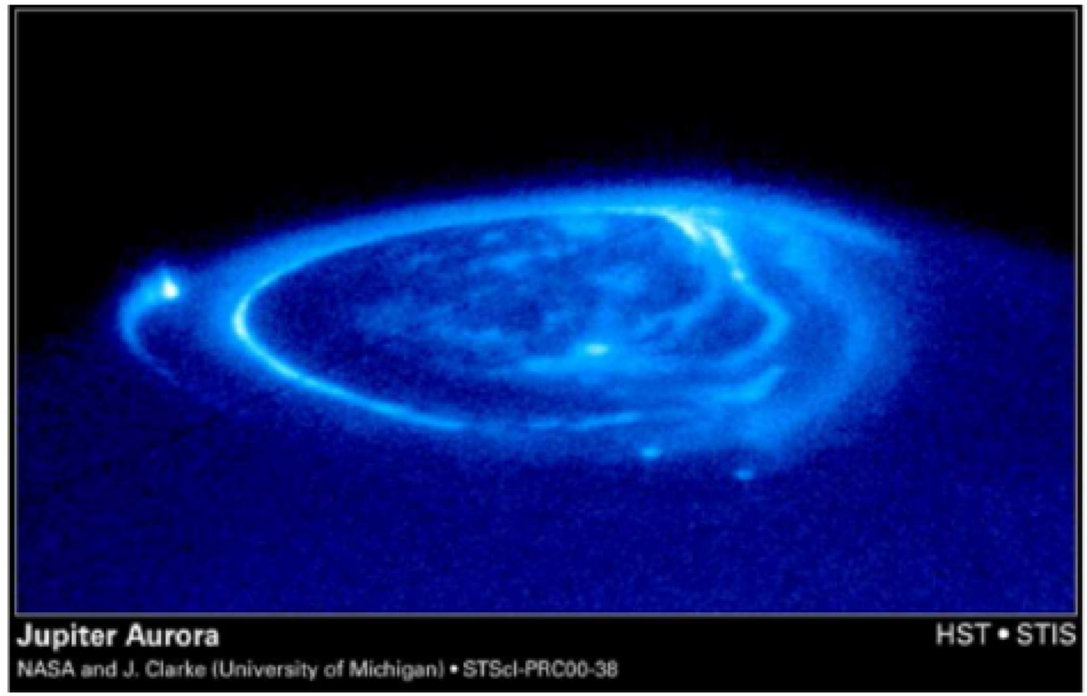
Pressure balance @ m-pause:

$$\frac{R_t}{R_\oplus} = (2\pi)^{-1/4}\frac{B_{np}^{1/2}}{p_{sw}^{1/4}}\theta_{pc} \sim 25$$

$B_t \sim 10^{-4}$ G ~ 10 nT

Other auroral ovals

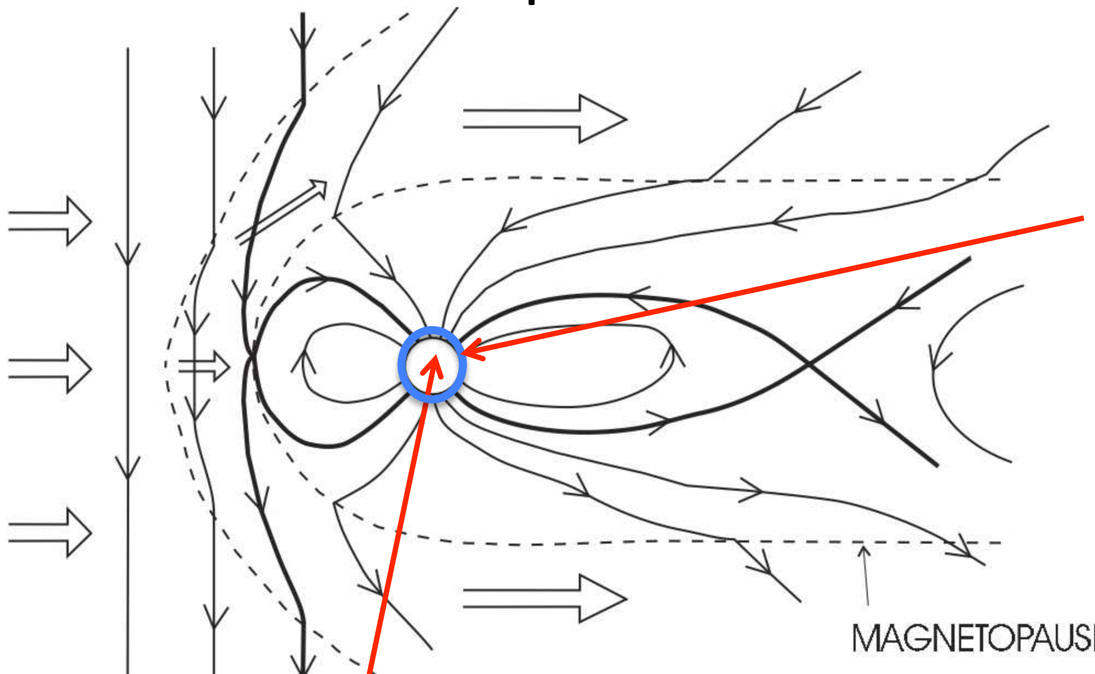




vol. I fig. 2.9

Convection: magnetosphere meets ionosphere

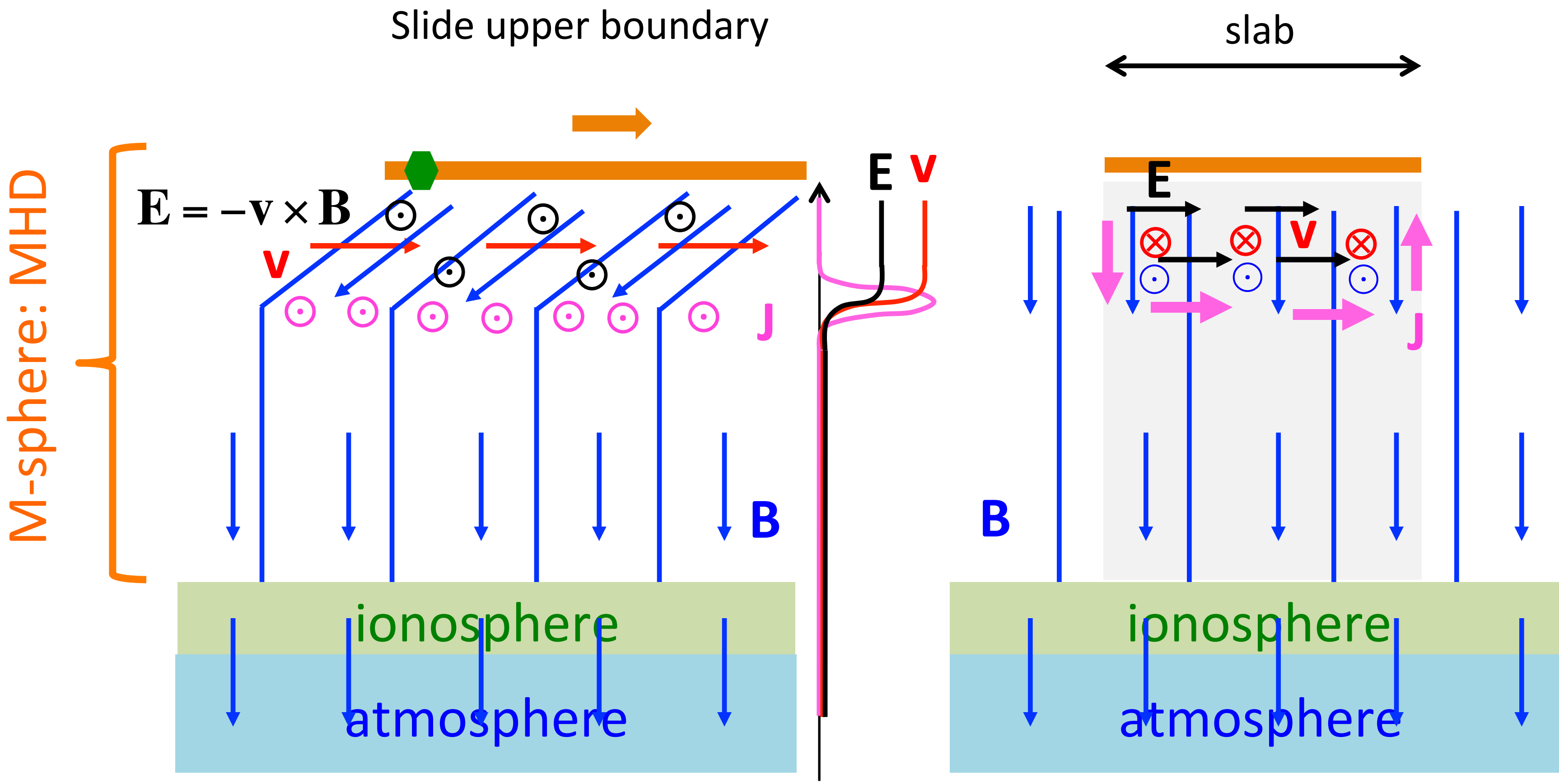
field lines are frozen to M-spheric plasma.
motion sweeps filed lines back



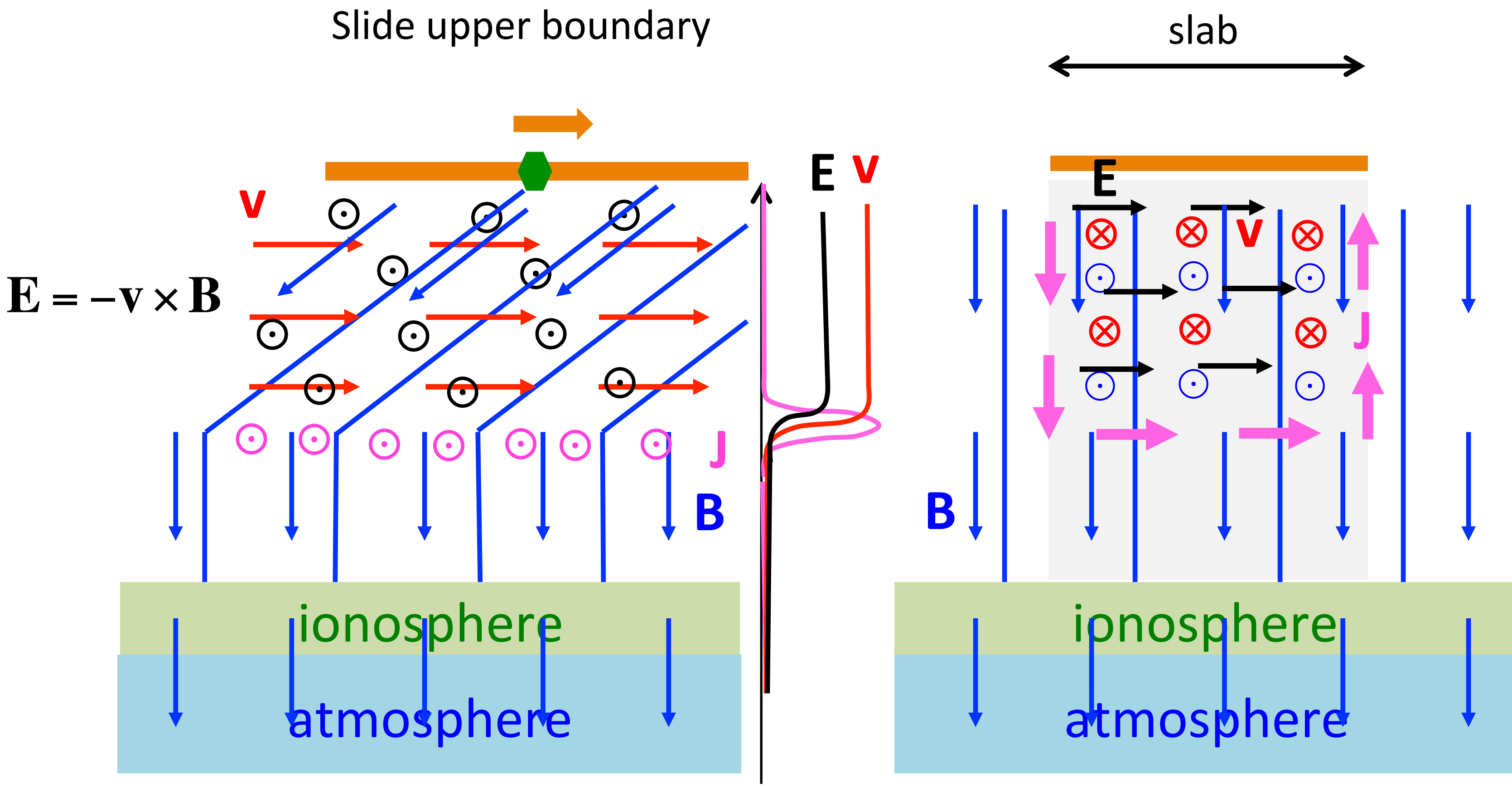
BUT: atmosphere & solid crust are insulators – field lines are **imaginary** there

Objection: field lines are also frozen into liquid core – ends cannot be moved

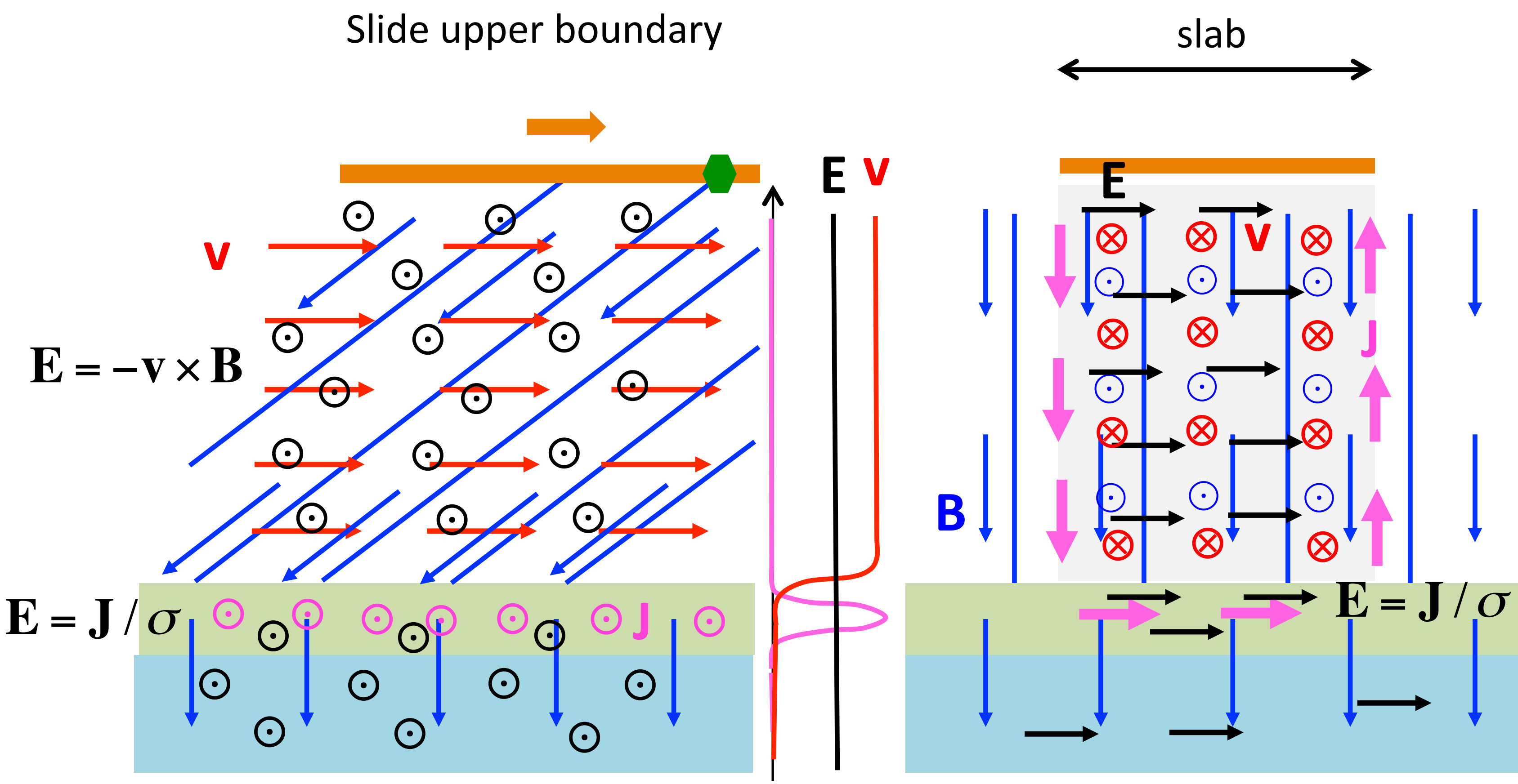
Example of how the motions meet



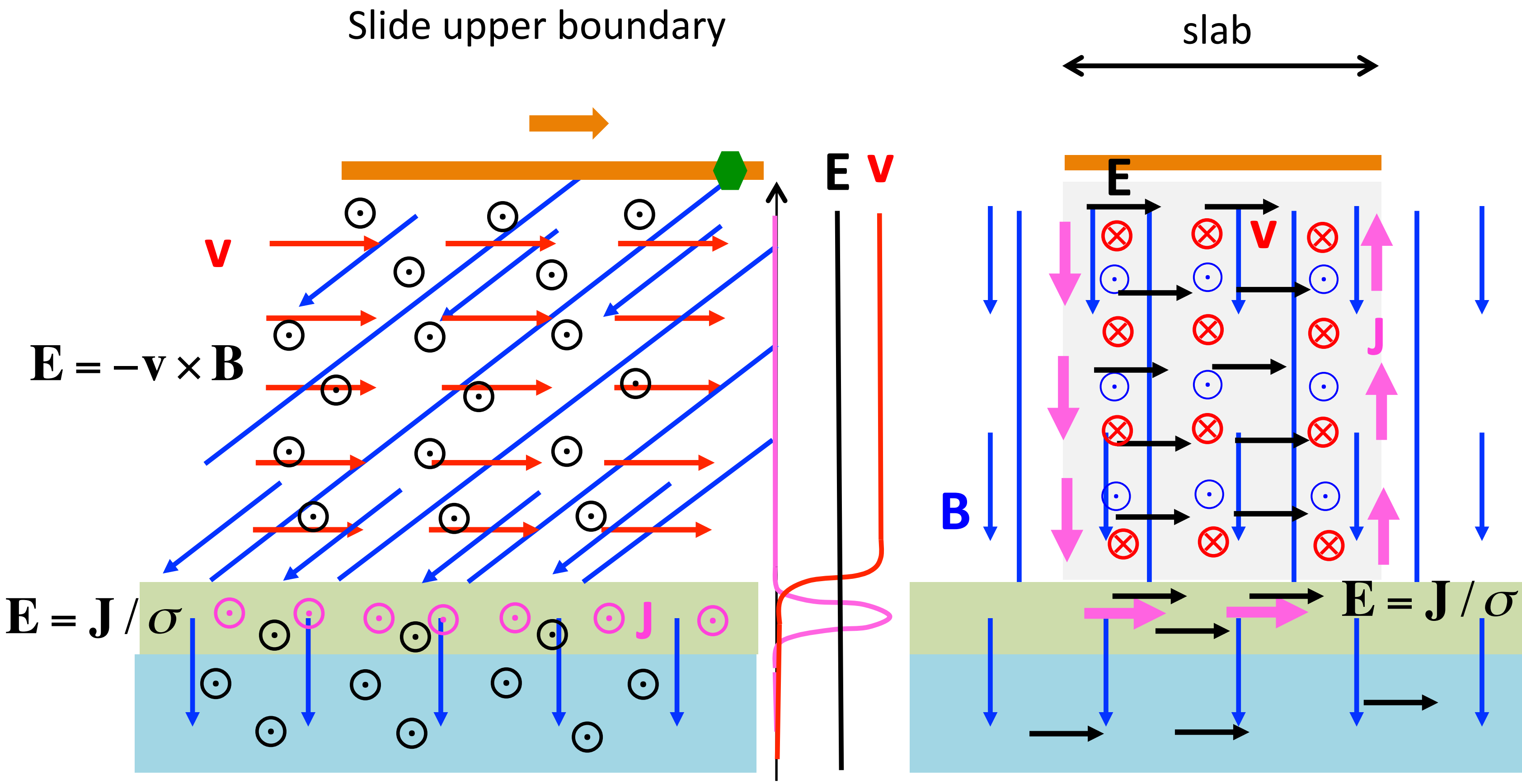
Example of how the motions meet



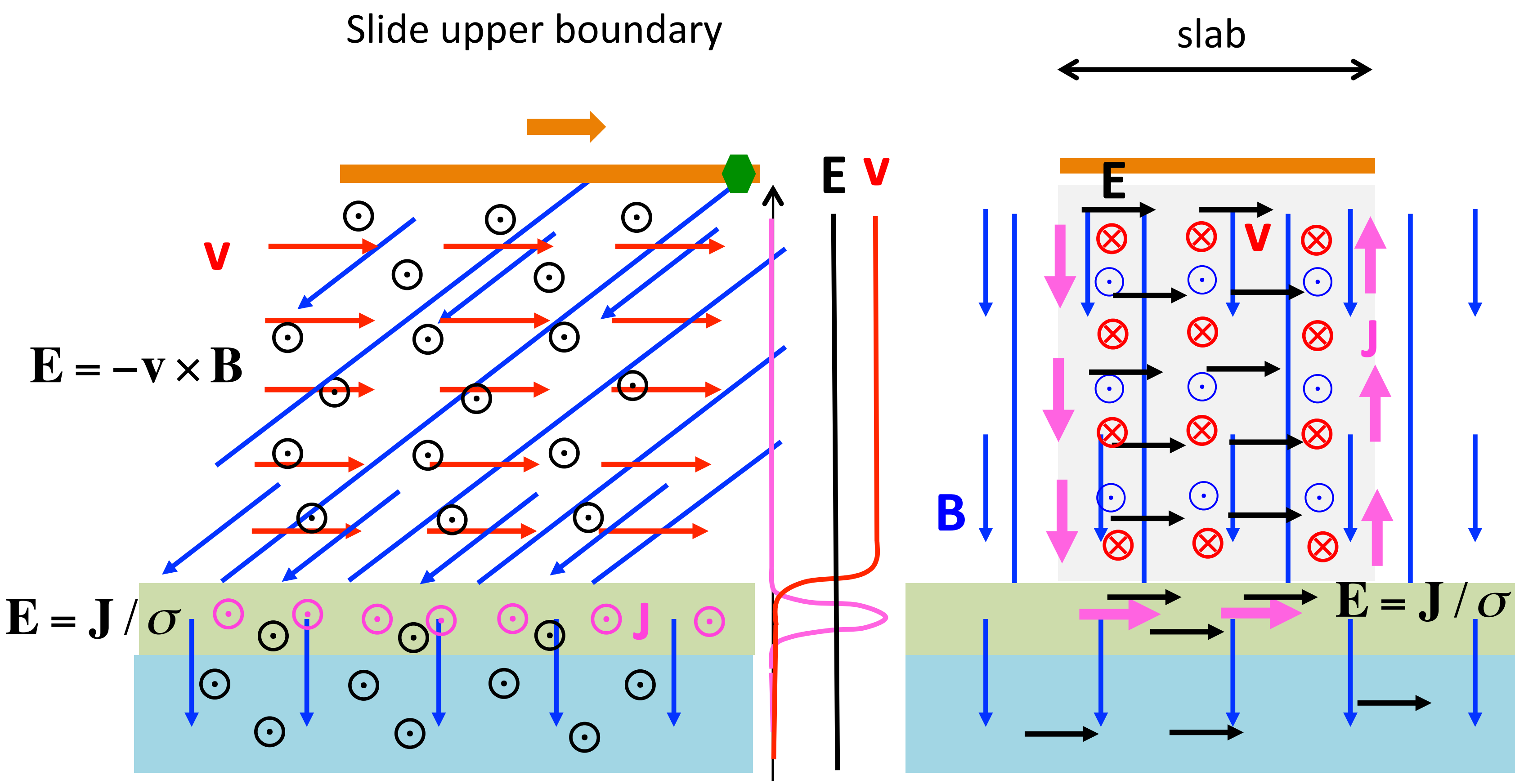
Example of how the motions meet



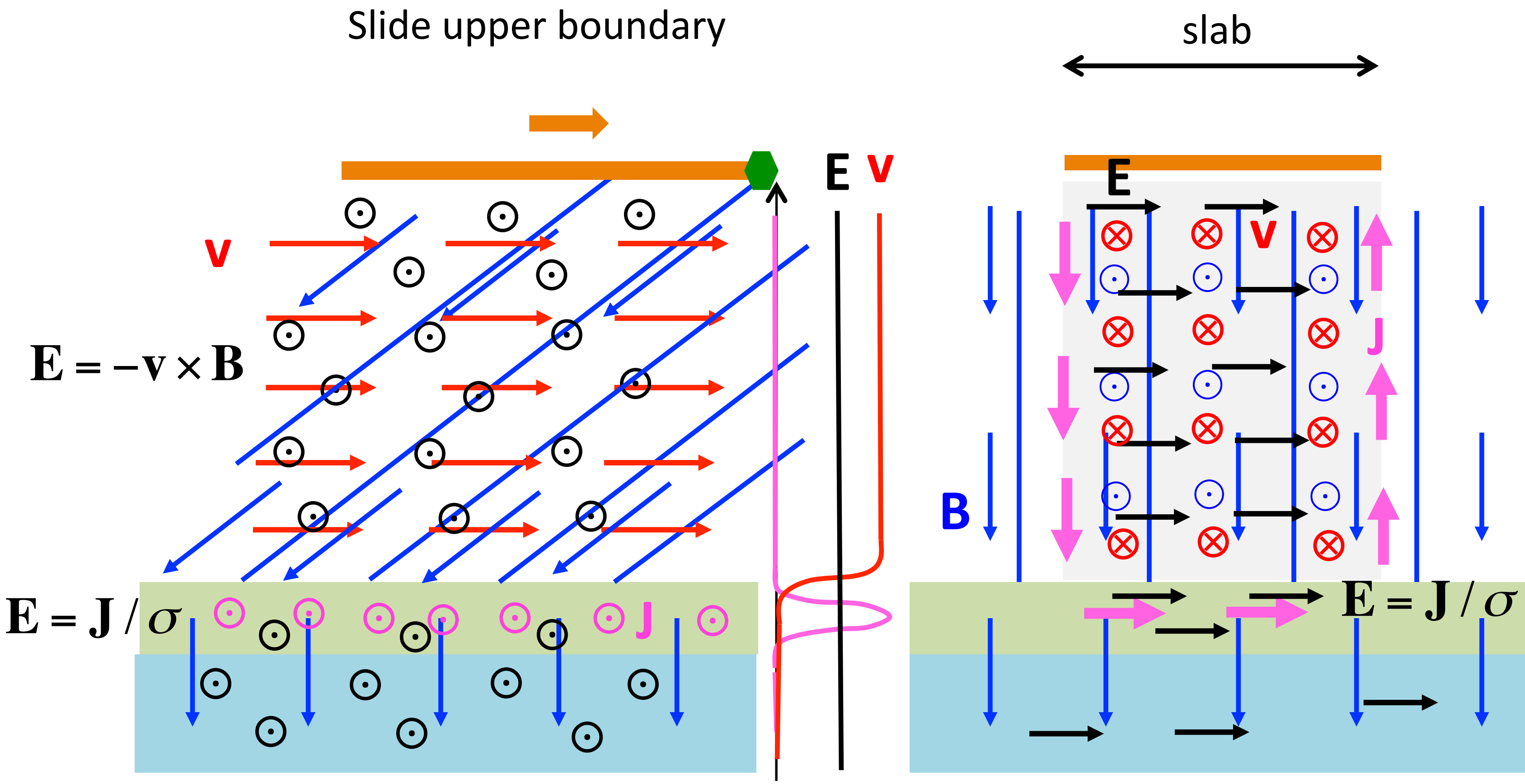
Example of how the motions meet



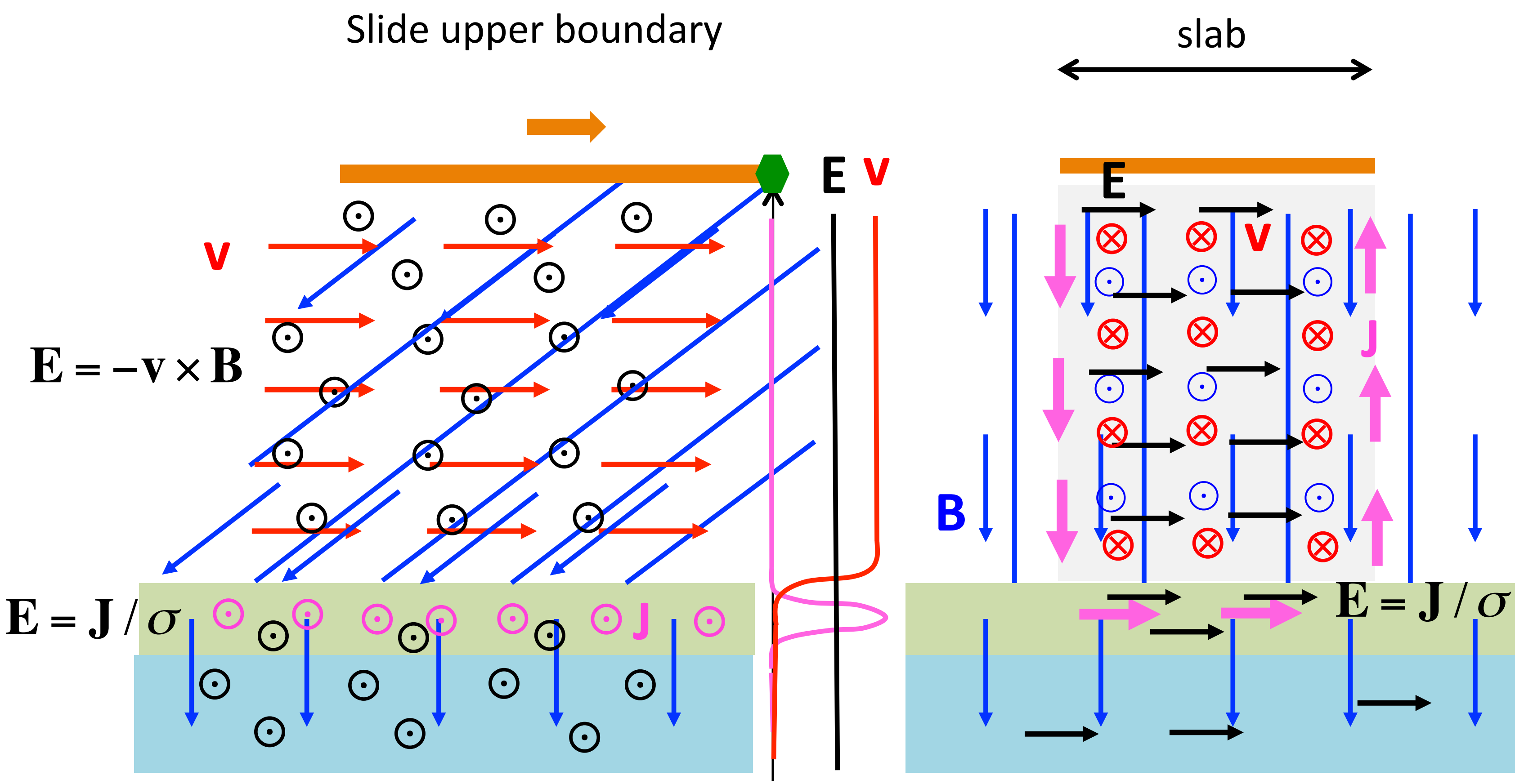
Example of how the motions meet



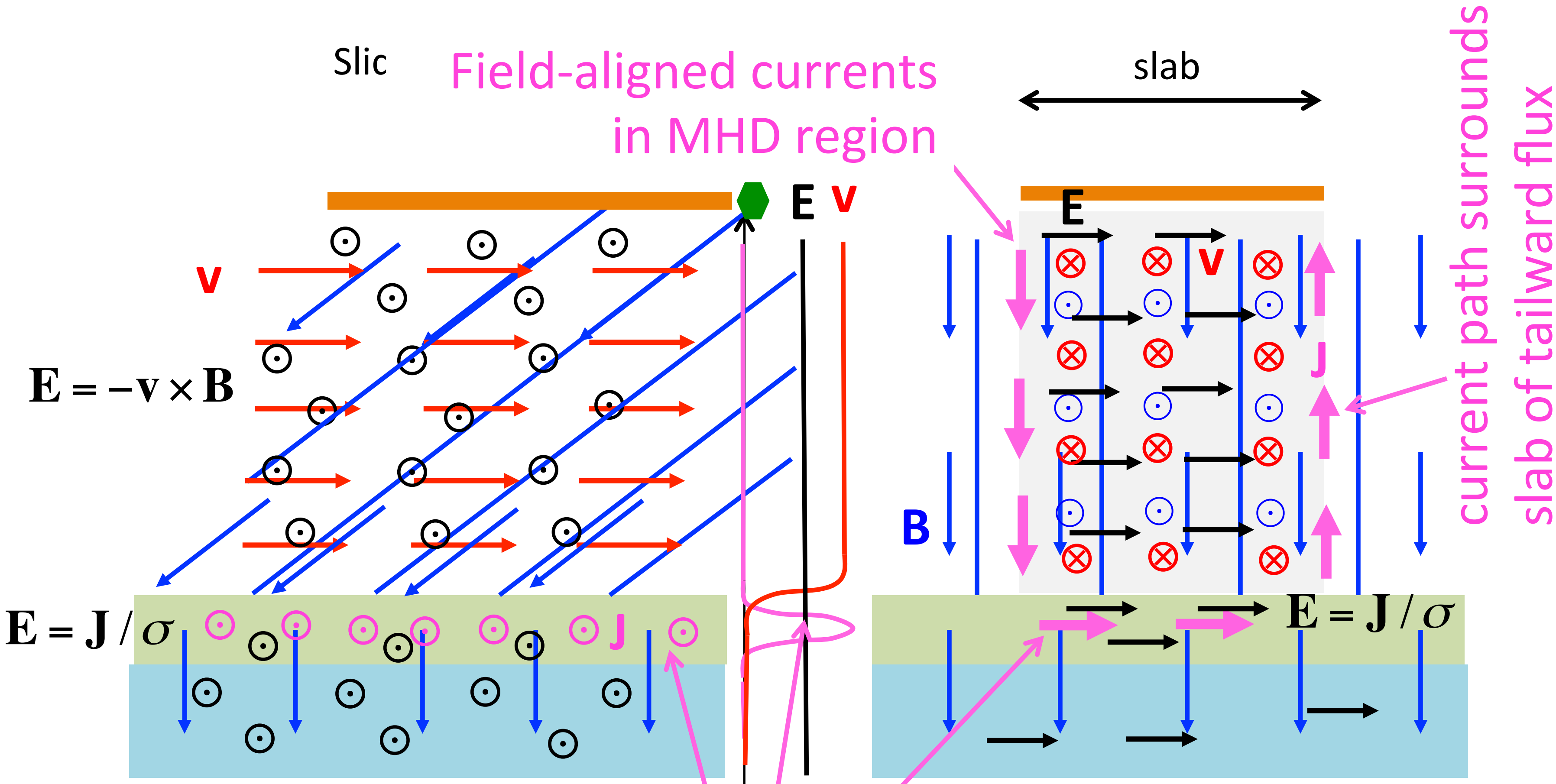
Example of how the motions meet



Example of how the motions meet



Example of how the motions meet



MHD Field line motion creates
current in ionosphere – accompanied by **E**

Convection: magnetosphere meets ionosphere

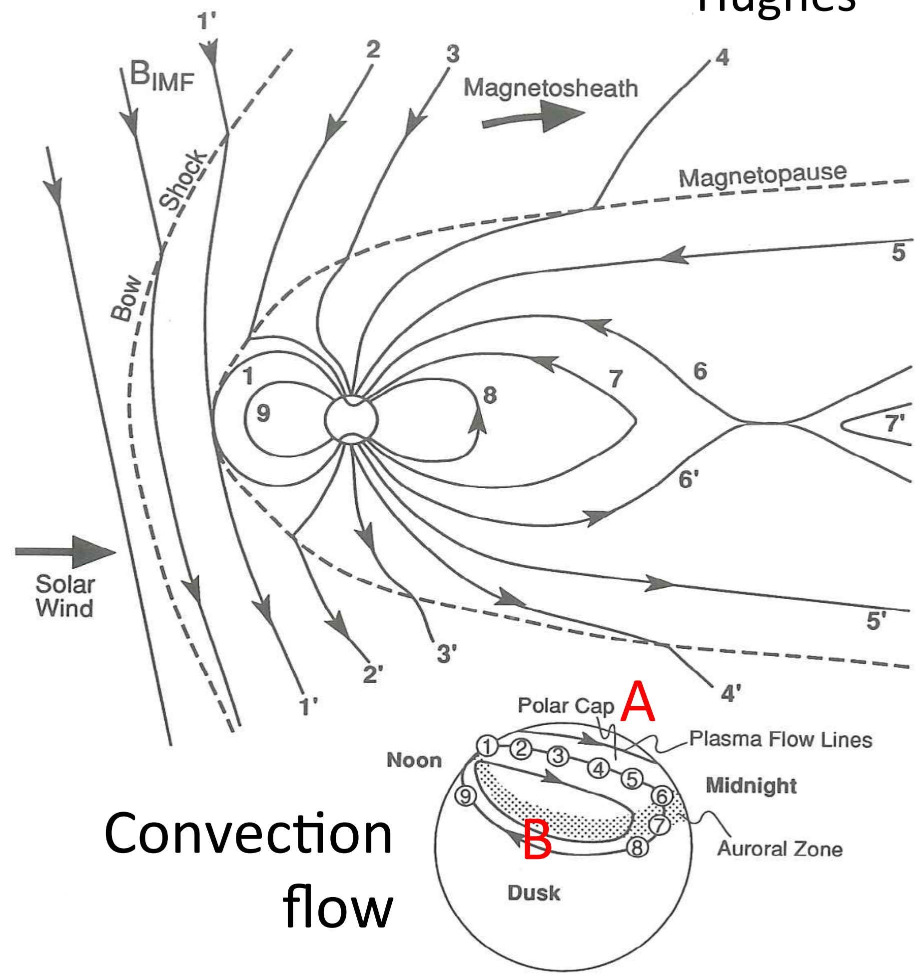
Hughes

MHD motions drag footpoints across polar caps and back around to day side

Integrate* **E** across polar cap:

$$\int_A^B \mathbf{E}\cdot d\mathbf{l} = \varphi_{pc} = \dot{\Phi}_{ds}$$

Really an EMF – but called "cross polar cap potential"

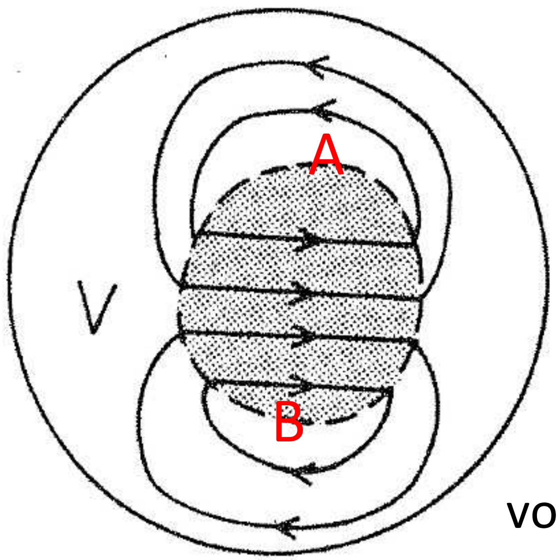


Convection flow

* use MKS here

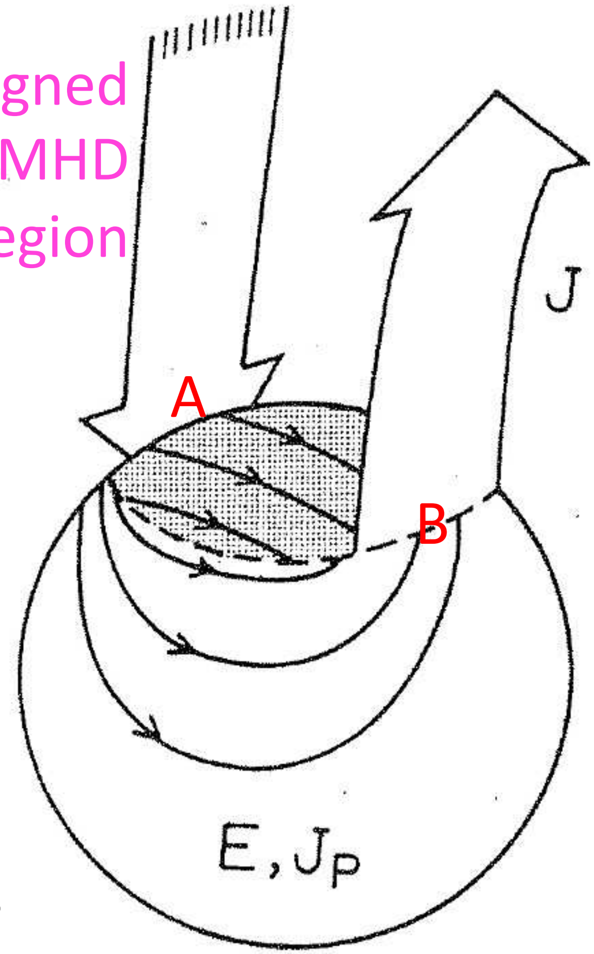
$$\int_A^B \mathbf{E} \cdot d\mathbf{l} = \varphi_{pc} = \dot{\Phi}_{ds}$$

Convection flow



vol. I fig. 10.5

Field-aligned currents in MHD region



ϕ_{pc} = 50 kV

= 5 × 10^{12} Mx/s

recycle in Φ_t in ~ 5 hours

Summary

- Ionospheres created by EUV & X-rays from Sun's TR and corona
- Diminish during night – lower during solar minimum
- SW deflected by ionospheres of unmagnetized planets (Venus & Mars)
- SW deflected by magnetospheres
- Magnetotail created by reconnection with solar wind magnetic field