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

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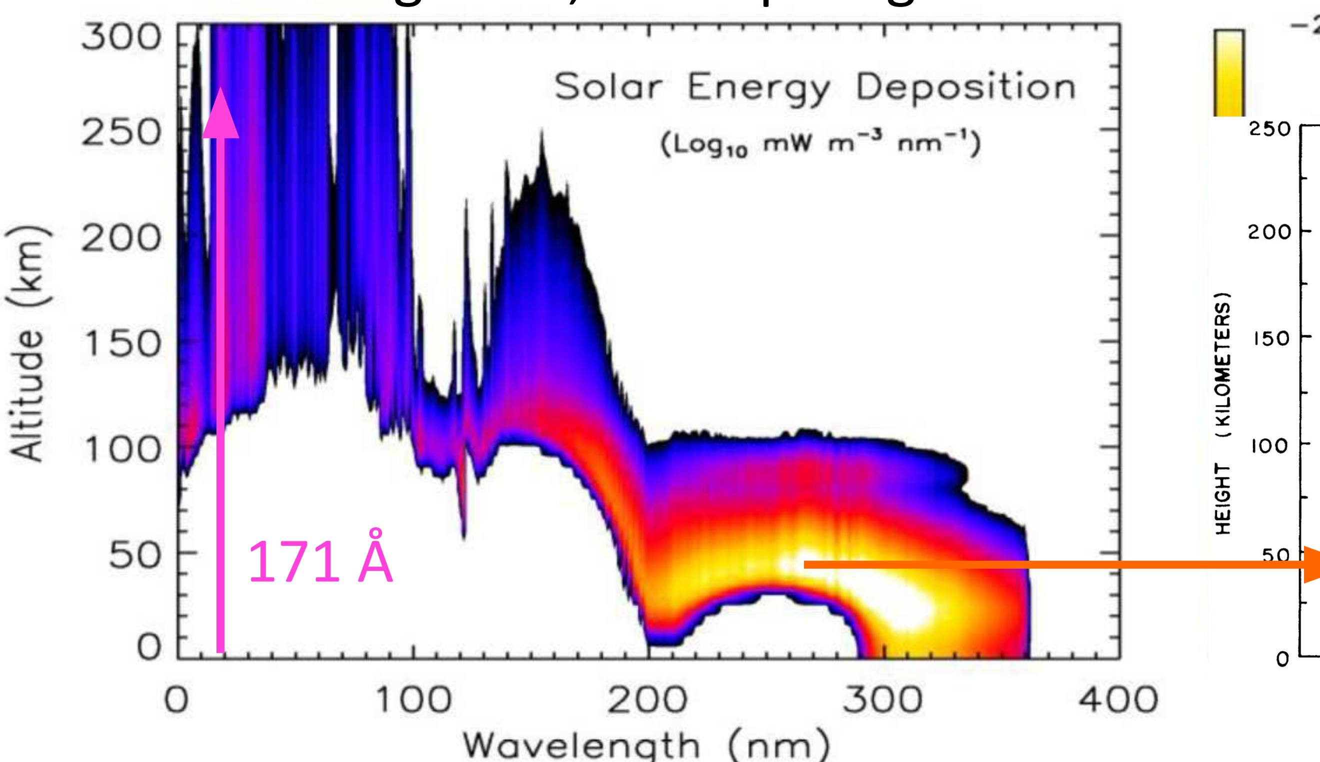
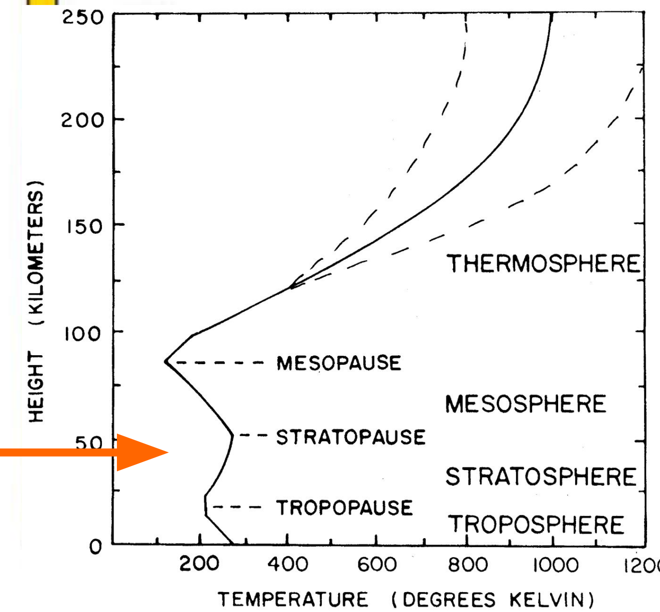
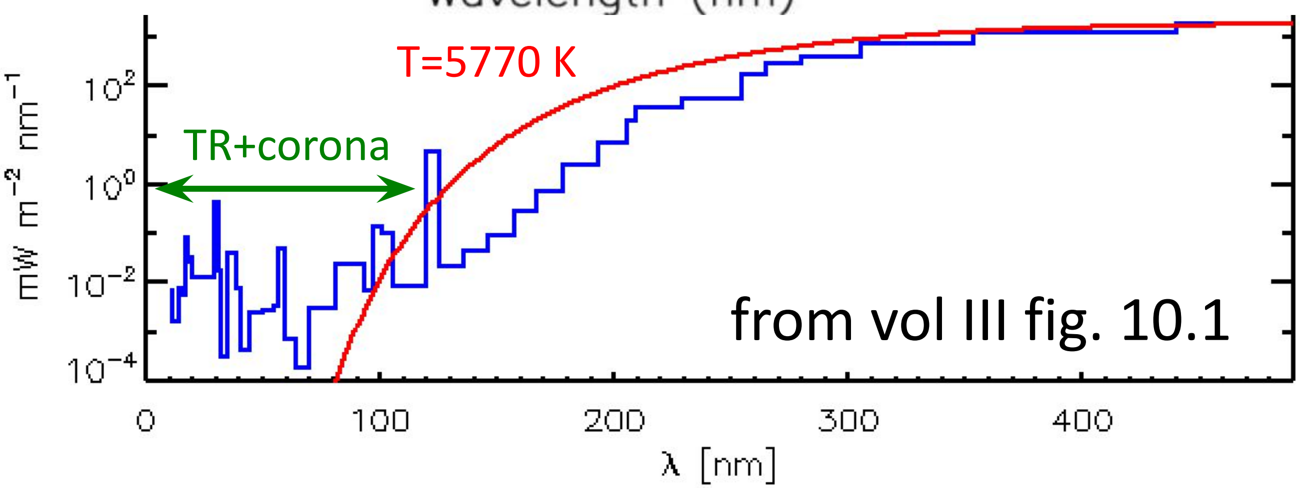
Review & Activities

vol. III fig. 13.3; Principia fig. 2.4

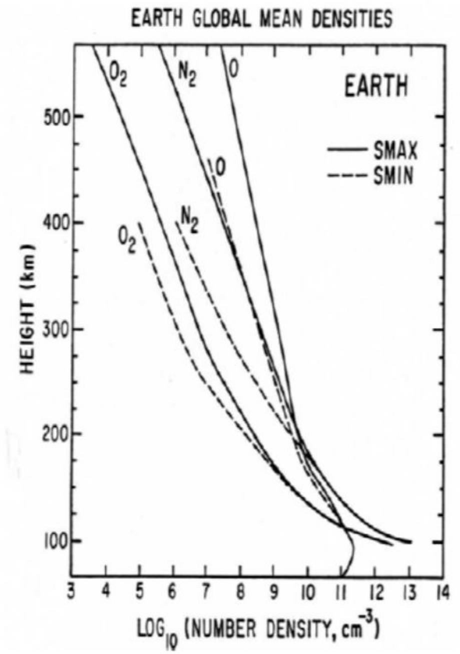


Solomon





Activity 17 (p. 32): The fact that concentrations of atomic nitrogen are not shown in Fig. 2.5 should make you wonder given that molecular nitrogen is the most common species in the troposphere. Why is atomic nitrogen rare in the upper atmosphere? Hint: compare the molecular binding energies of nitrogen, oxygen, and water.



Bond-dissociation energy:
https://en.wikipedia.org/wiki/Bond-dissociation_energy

	O-H in H_2O	O=O in O_2	C=O in CO_2	N≡N in N_2
eV/bond	5.15	5.15	5.51	9.79

Activity 9 (p. 21): Compute scale heights H_p in the Earth's atmosphere for molecular nitrogen (the dominant component) at a range of temperatures, and compare these with the value H_p for the atomic hydrogen-dominated gas in the solar photosphere, and for the CO_2-rich atmospheres of Venus and Mars. Use the data in Tables 2.1 and 2.3. Consider how the value of $H_p/R_\odot$ contributes to the appearance of the Sun as having a well-defined surface. Also, consider why neutral, atomic hydrogen dominates in the solar photosphere

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

Earth:

T = 300 K

$g = 10^3$ cm/s^2

particles = N_2

$m = 28\ m_p$

$= 3 \times 10^{-23}$ g

$H_p = 9$ km

T= 1450 K □ $H_p = 43$ km

Venus:

T = 740 K

g = 900 cm/s^2

particles = CO_2

$m = 44\ m_p$

$= 7 \times 10^{-23}$ g

$H_p = 15$ km

Solar photosphere:

T = 6000 K

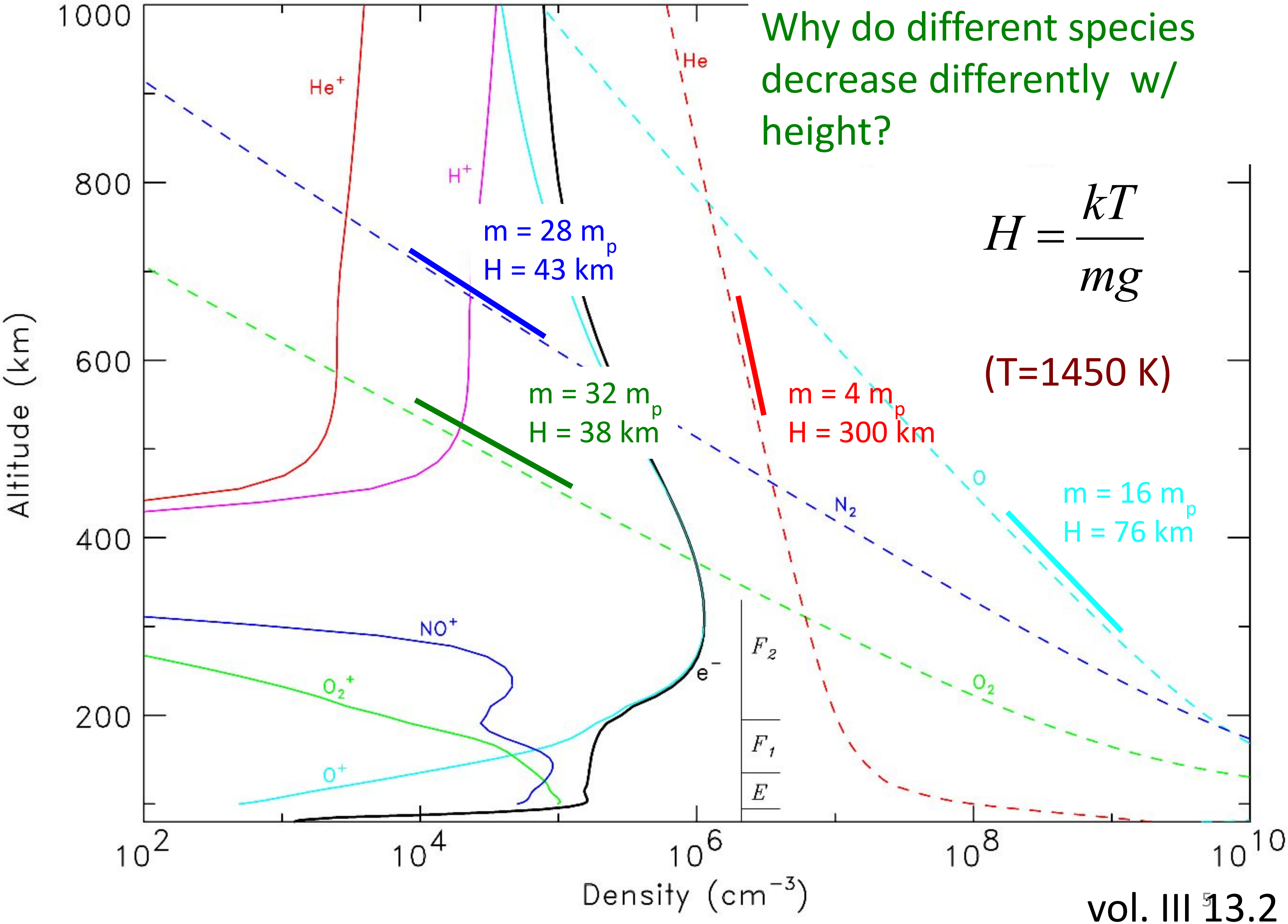
$g = 3 \times 10^4$ cm/s^2

particles = H atoms

$m = m_p = 2 \times 10^{-24}$ g

$H_p = 180$ km

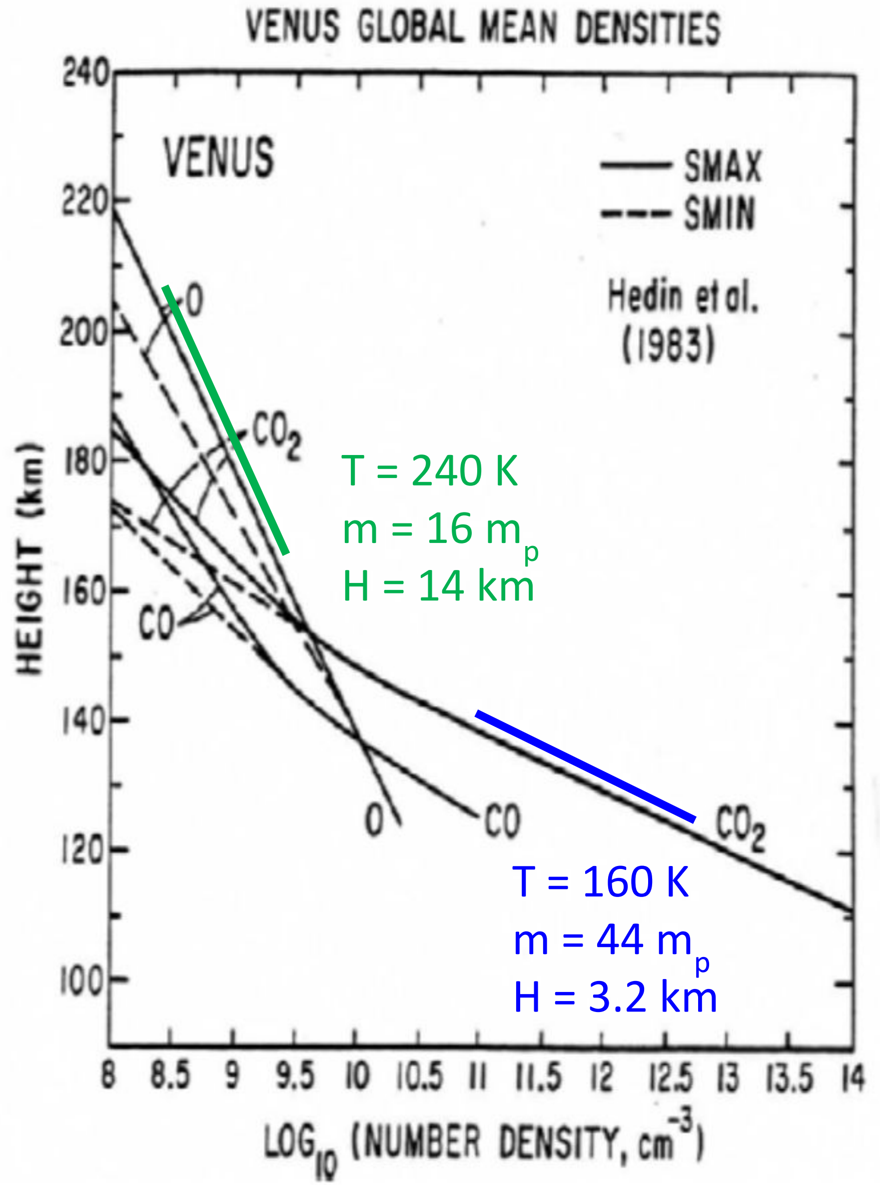
Why do different species decrease differently w/ height?

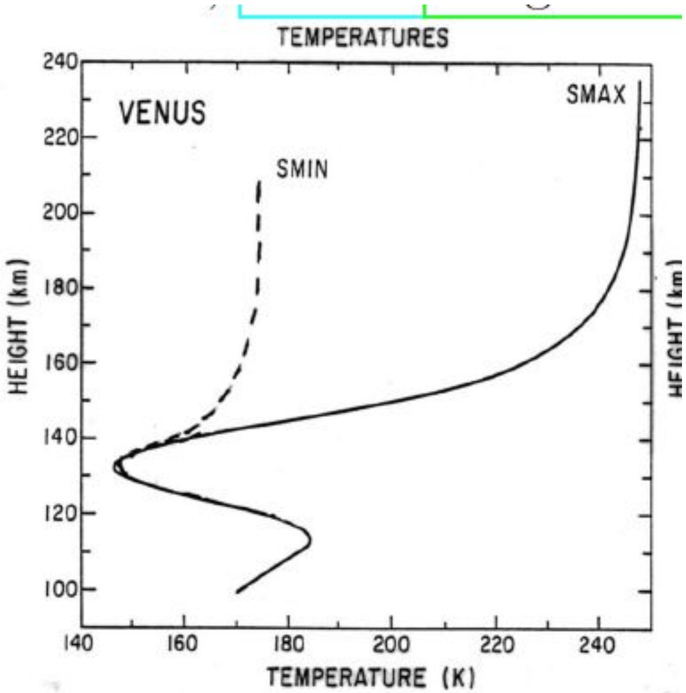


$$H = \frac{kT}{mg}$$

(T=1450 K)

vol. III 13.2





Venus:

g = 900 cm/s^2

How fuzzy is the solar limb

$H_\odot$ = 180 km

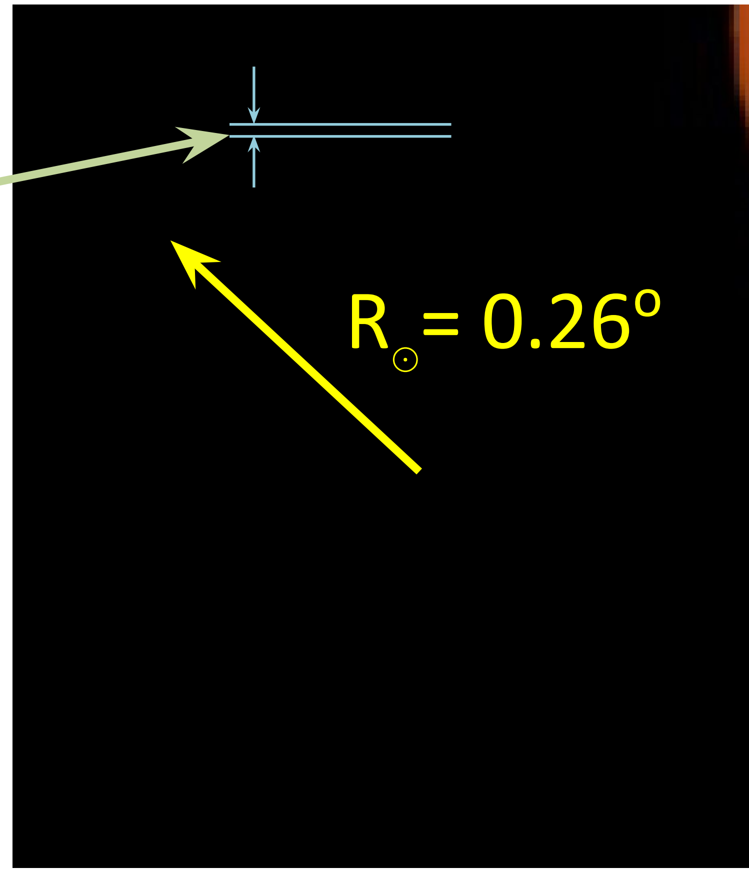
$$\propto e^{-r/H}$$

95% drop over

$\Delta r = 3\, H_\odot$ = 520 km

= 0.0007 $R_\odot$

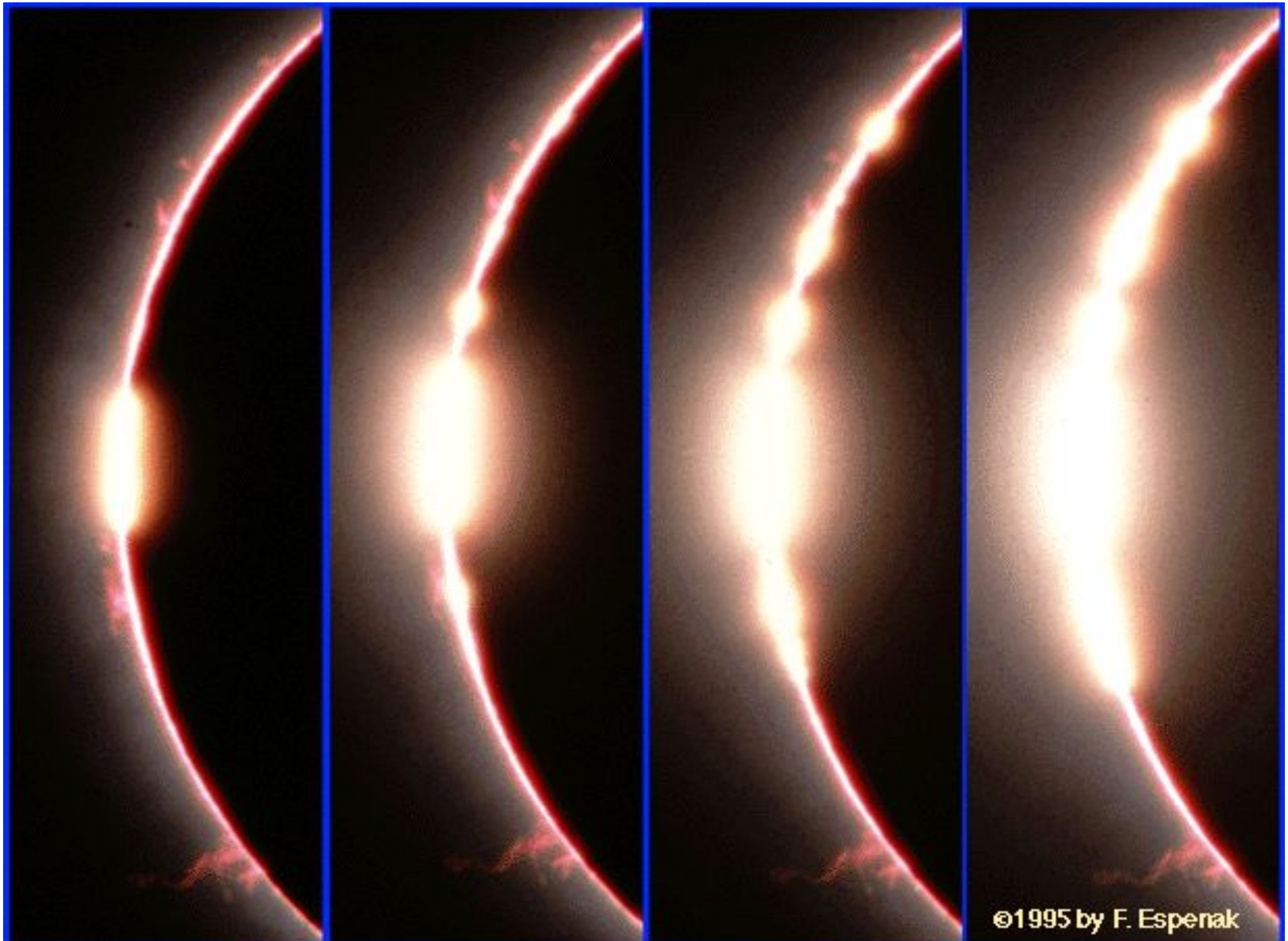
= 0.7 arcsecs



Resolving power:

Human eye (good): ~60 arcsec

Telescope on Earth: ~1 arcsec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$H_{cor} \gg H_{\odot} = 180$ km

either:

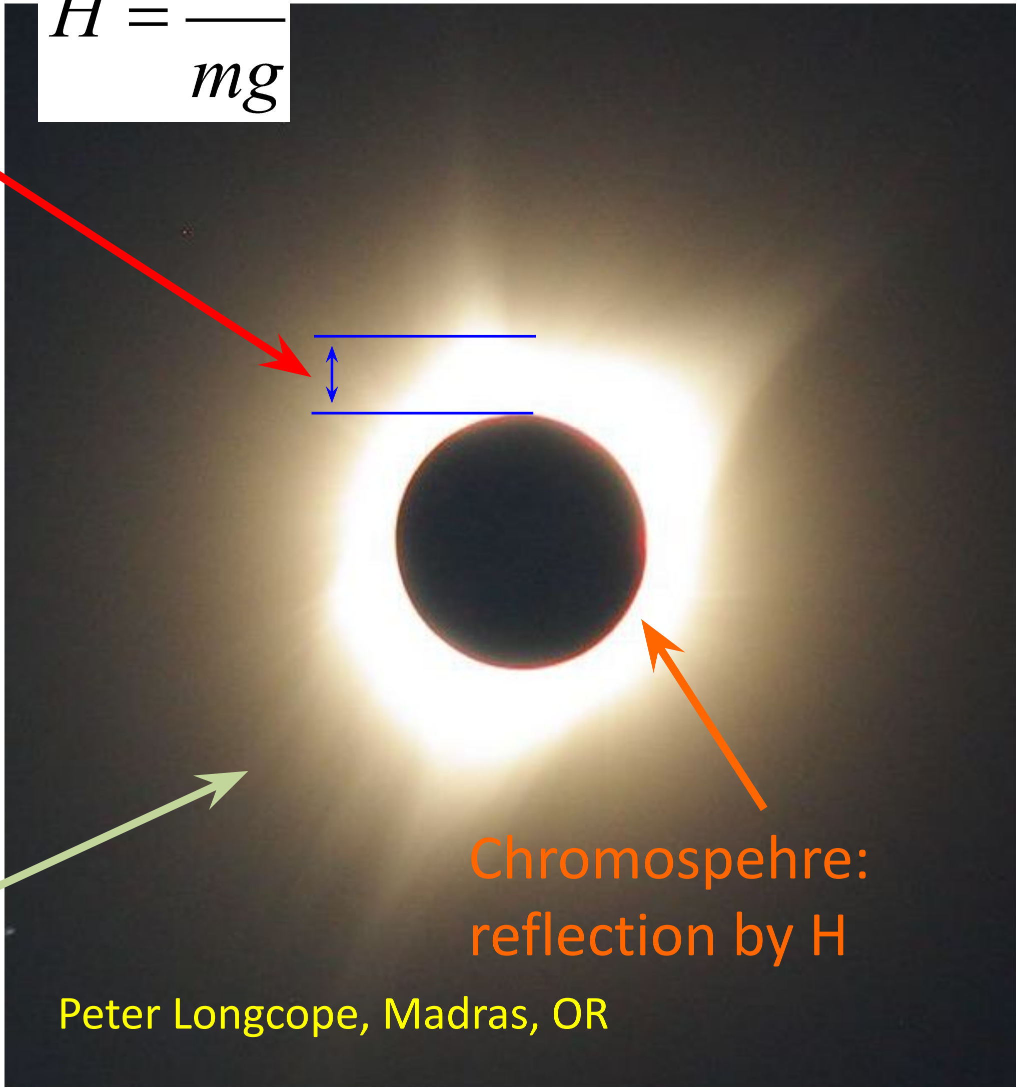
$m_{cor} \ll$ Hydrogen
(coronium?)

or

$T_{cor} \gg T_{\odot} = 6000$ K

white light:
no scattering
from H
□ too hot for atoms!

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



Activity 19 (p. 33): You can think of the optical depth as the mean number of absorbers within the cross-section along a photon's path from infinity to height h. The probability of suffering zero absorptions, and thus making it to h, is exp(-τ). The intensity at h is then an integral from infinity over the expected number of absorptions along the way. Combine that with Eq. (2.18) to derive Eqs. (2.19) and (2.20).

show:

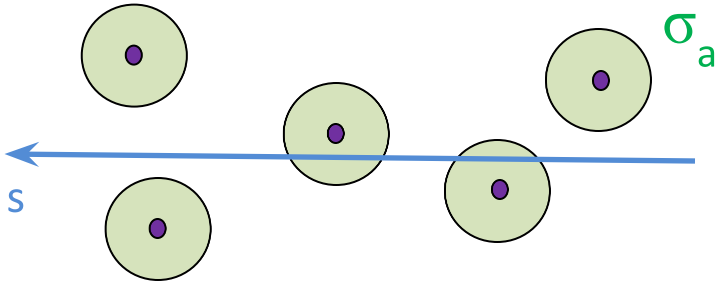
$$\tau = \sigma_\mathrm{a} n(h) \frac{H_p(h)}{\cos(\chi)}, \qquad (2.19)$$

use:

$$q = \sigma_\mathrm{a} I(h) n(h) \eta_\mathrm{i}, \qquad (2.18)$$

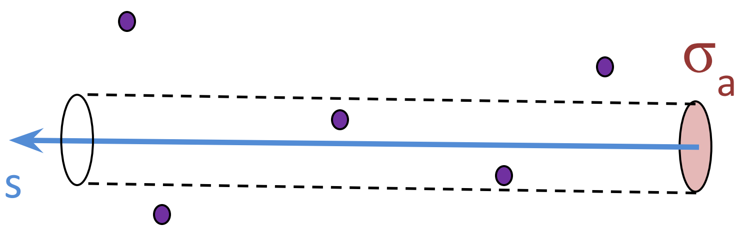
to derive:

$$q(h) = I_\infty \exp\left[-\sigma_\mathrm{a} n(h) \frac{H_p(h)}{\cos(\chi)}\right] \eta_\mathrm{i} \sigma_\mathrm{a} n(h).$$



Compute number N of absorbers (cross section σ_a) the line passes through

same answer as:



Compute number N of centers included in a cylinder w/ cross section σ_a

local # density of centers

Answer on average: $$\langle N \rangle = \int \sigma_a \, n(s) \, ds = \tau$$

Poisson: the probability of including **exactly N** centers

$$p_N = \frac{\tau^N}{N!} e^{-\tau} \quad .$$

survival ⇔ N=0 absorptions

This occurs with probability $p_0 = e^{-\tau}$

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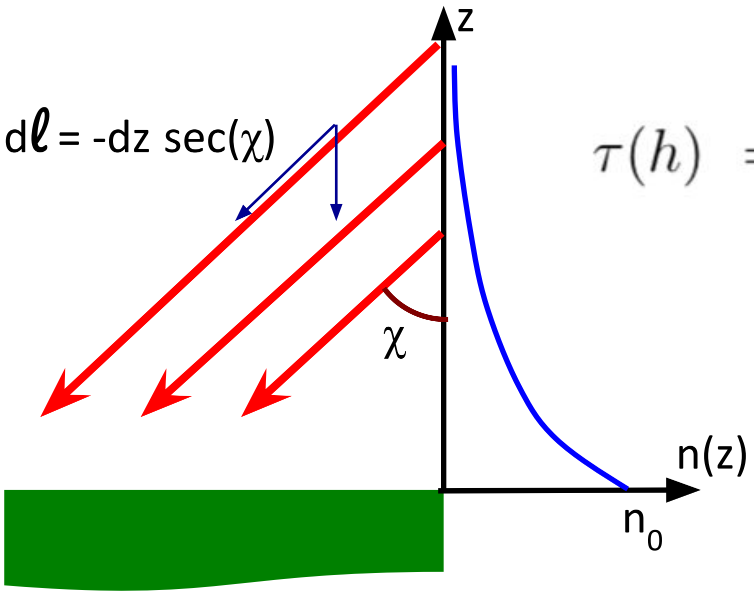
Fate of a photon

w/ absorption x-section σ

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

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

τ=1 □ 1 absorber: mean-free path



$$\tau(h) = \int_h^\infty \sigma_a\, n(z)\, \frac{dz}{\cos\chi}$$

$$= \frac{\sigma_a}{\cos\chi} \int_h^\infty n(z)\, dz = \frac{\sigma_a}{\cos\chi} \frac{p(h)}{g\,\bar{m}}$$

$$\frac{p(h)}{H_p(h)} = -\frac{dp}{dz} = g\,\rho(h) = g\,\bar{m}\, n(h)$$

$$\tau = \sigma_a n(h) \frac{H_p(h)}{\cos(\chi)},$$

Fate of a photon

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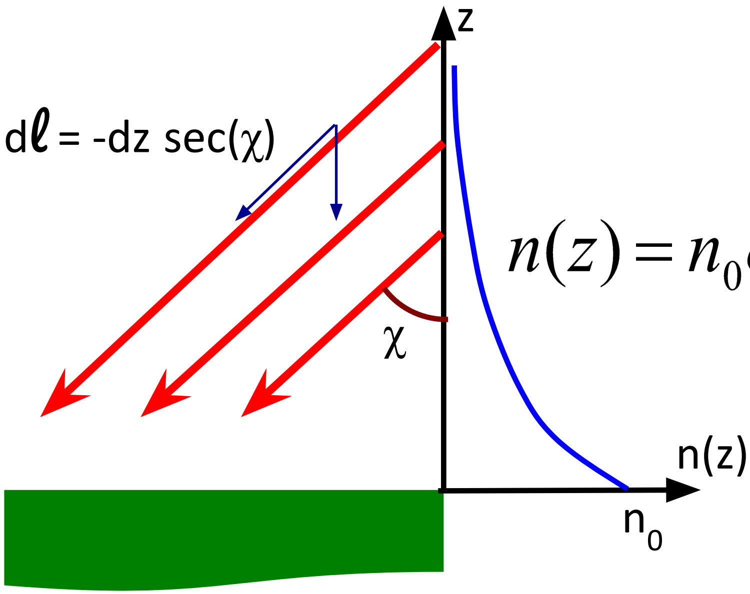


$$n(z) = n_0 e^{-z/H}$$

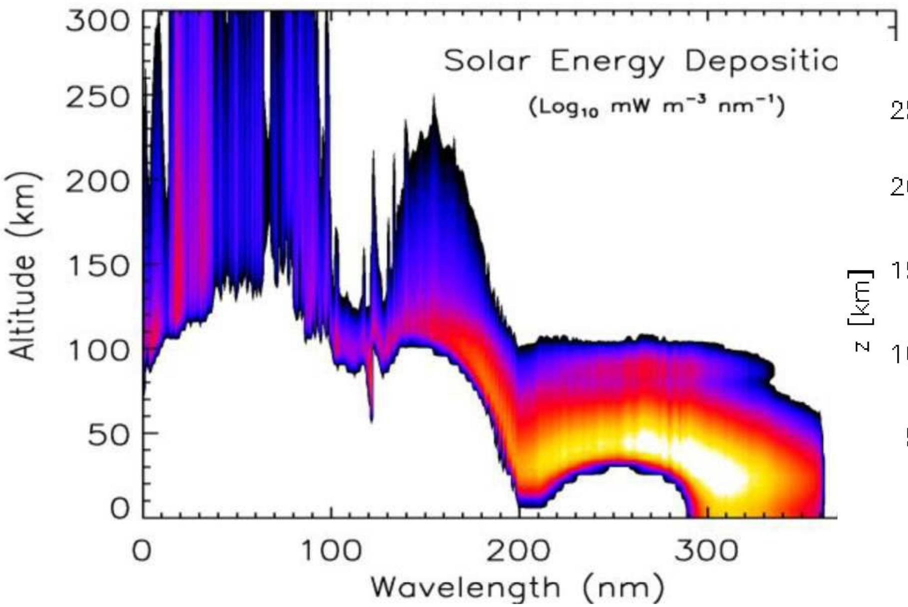
$$\tau(z) = \int_z^{\infty} \sigma n(z')\sec(\chi)\, dz'$$

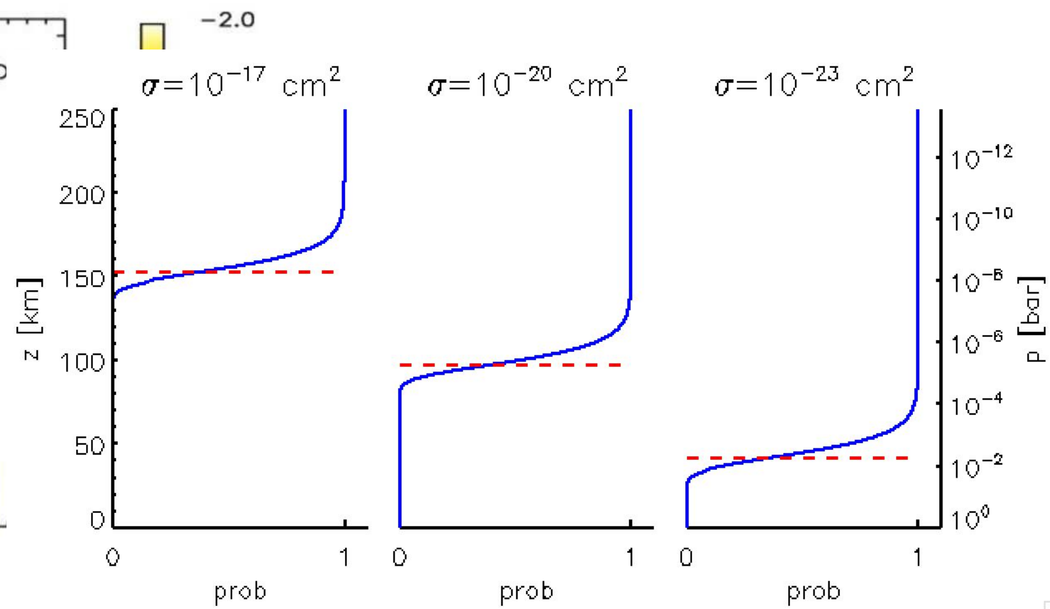
$$= \sigma n_0 \sec(\chi) \int_z^{\infty} e^{-z'/H}\, dz'$$

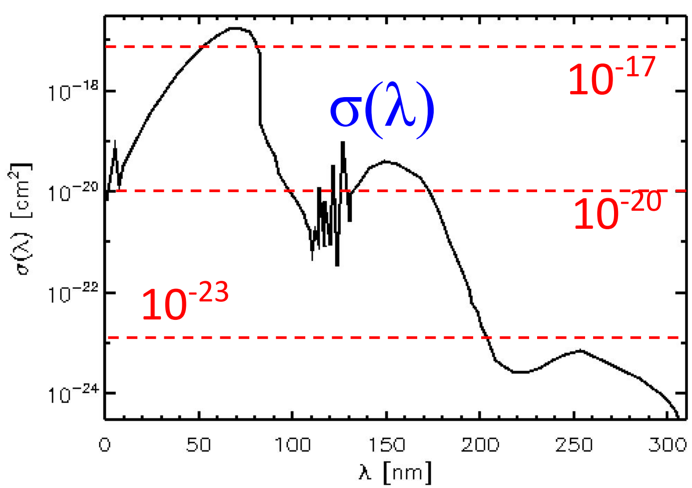
$$\tau(z) = \sigma n_0 H \sec(\chi)\, e^{-z/H} = e^{-(z-z_{\tau 1})/H}$$

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

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







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

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

Prob. of surviving to h:

$$P(h) \;=\; e^{-\tau(h)}$$

$$\tau(h) \;=\; \int_h^\infty \sigma_a\, n(s)\, ds$$

Energy flux @ h:
∝ # surviving

$$I(h) \;=\; I_\infty\, e^{-\tau(h)}$$

$$q(h) \;=\; \sigma_a\, n(h)\eta_i\, I(h) \;=\; \sigma_a\, n(h)\eta_i\, I_\infty\, e^{-\tau(h)}$$

$$\tau = \sigma_\mathrm{a} n(h) \frac{H_p(h)}{\cos(\chi)},$$

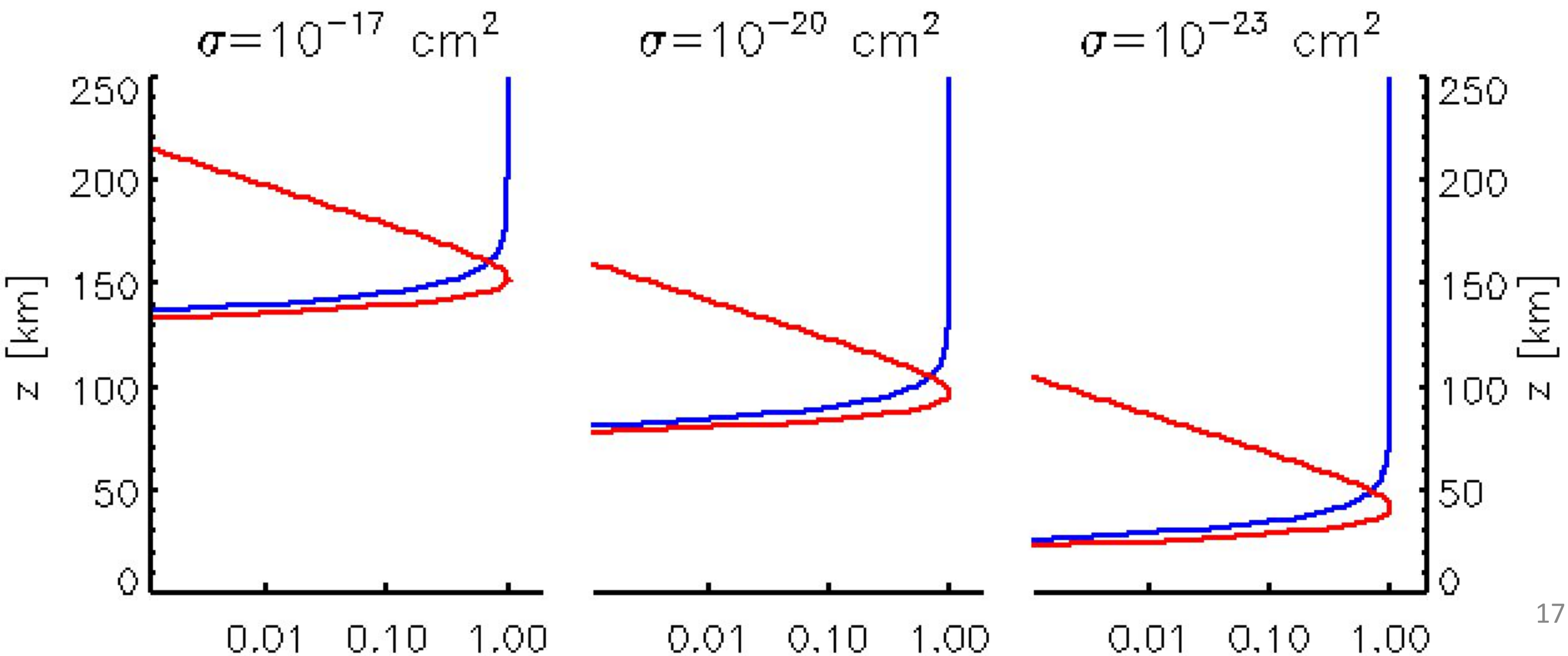
$$q(h) = I_\infty \exp\left[-\sigma_\mathrm{a} n(h) \frac{H_p(h)}{\cos(\chi)}\right] \eta_\mathrm{i} \sigma_\mathrm{a} n(h).$$

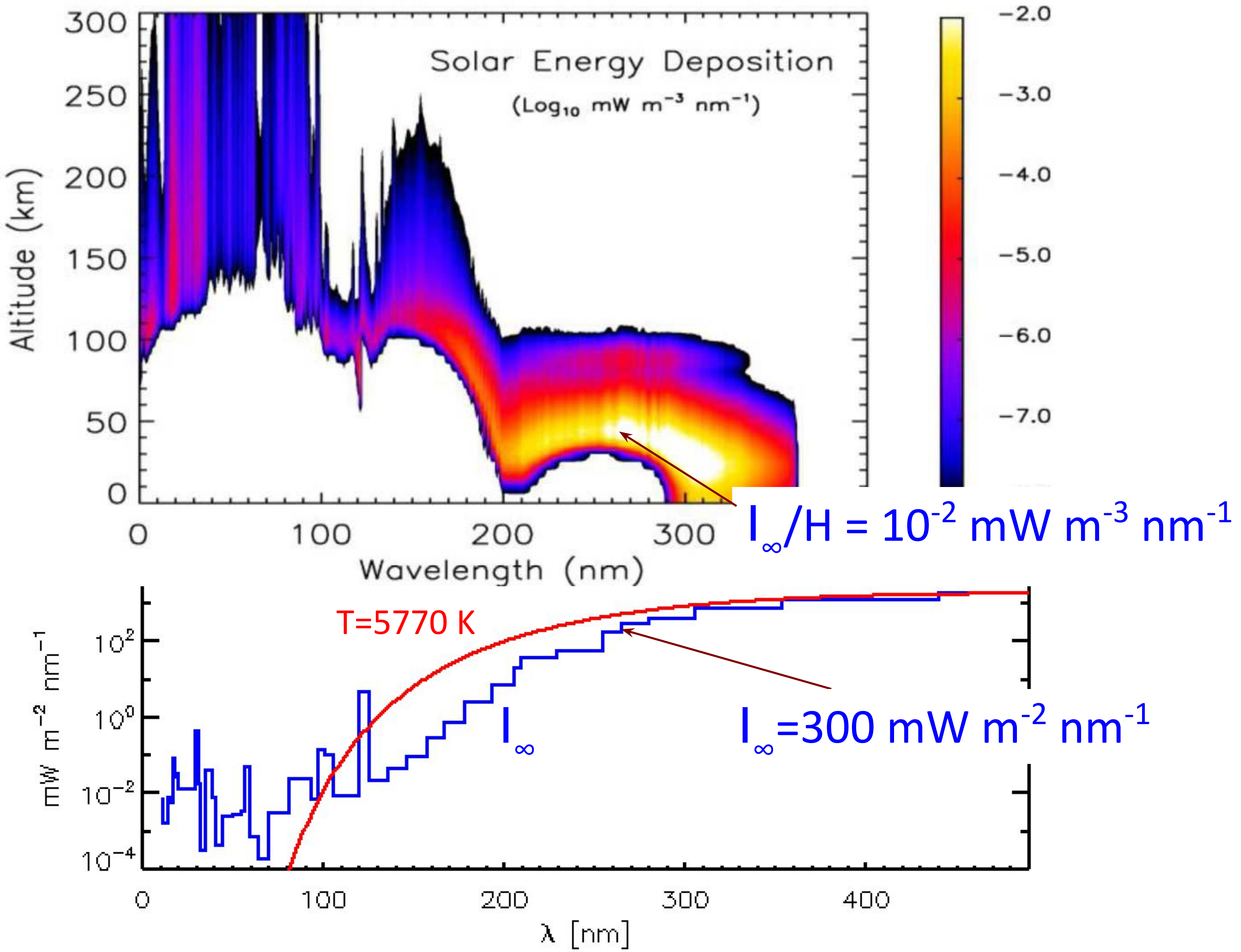
Radiation intensity & heating

$$q(h) = I_\infty \exp\left[-\sigma_a n(h) \frac{H_p(h)}{\cos(\chi)}\right] \eta_i \sigma_a n(h).$$

$$= \frac{I_\infty}{H_p} \exp\left[-e^{-(z-z_1)/H_p} - \frac{(z-z_1)}{H_p}\right] \eta_i$$

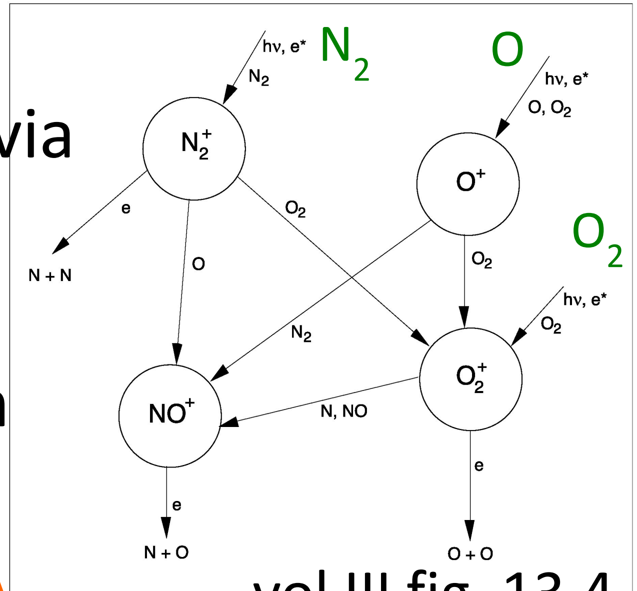
Chapman layer

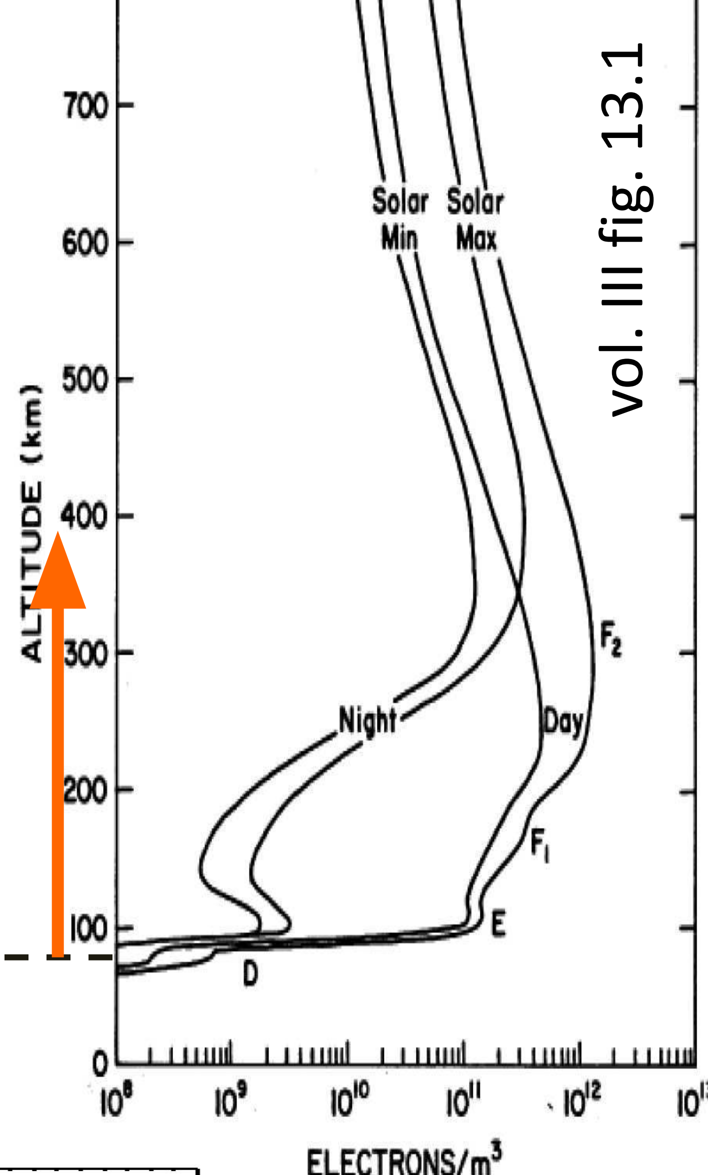


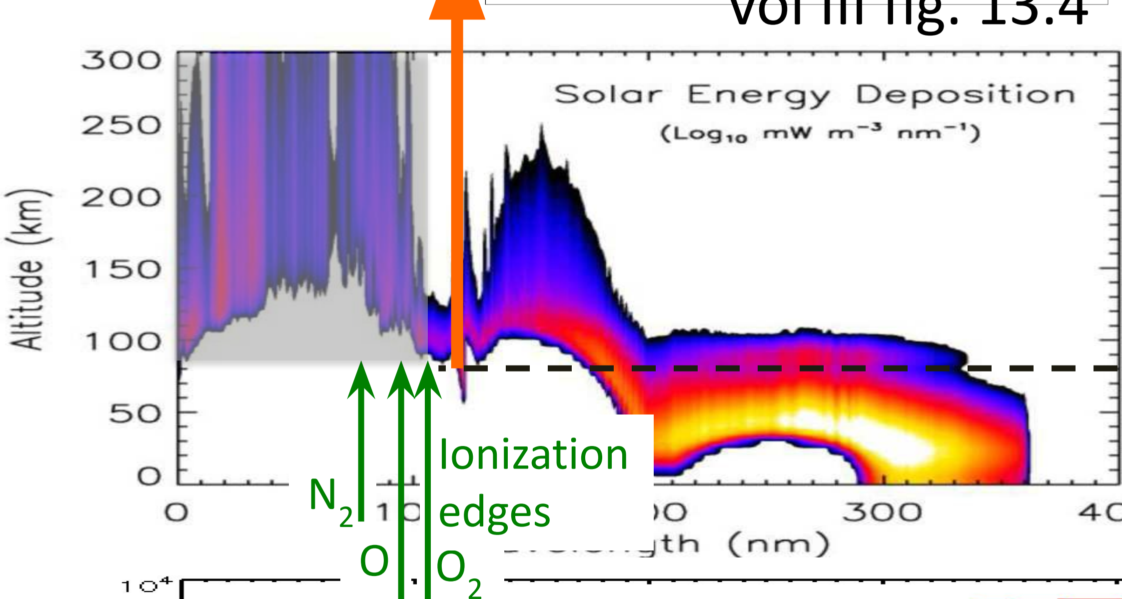


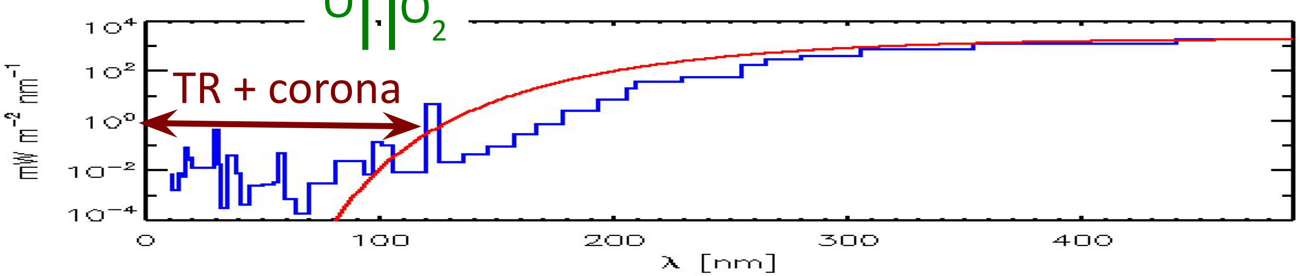
Solar Energy Deposition
(Log_{10} mW m^{-3} nm^{-1})
Altitude (km)
Wavelength (nm)
$I_\infty/H = 10^{-2}$ mW m^{-3} nm^{-1}
T=5770 K
I_∞
I_∞=300 mW m^{-2} nm^{-1}
mW m^{-2} nm^{-1}
λ [nm]

Absorption via ionization creates ion/electron pairs









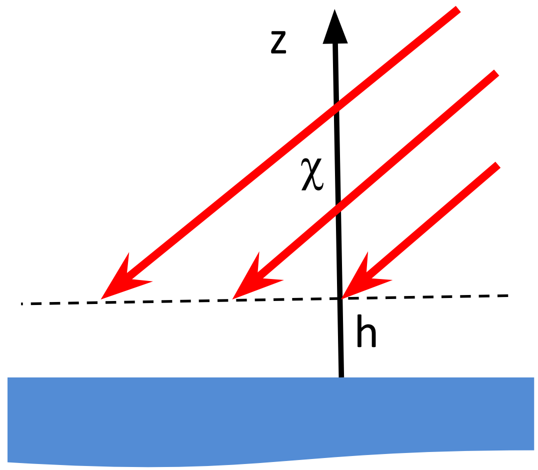
Common Physics

optical depth $$\tau(h) = \int_h^\infty \sigma_a \, n(z) \, \frac{dz}{\cos\chi}$$

Planetary atmospheres:

$e^{-\tau(h)}$ = probability of photon surviving **to** height z = *h* after **originating** at z = ∞

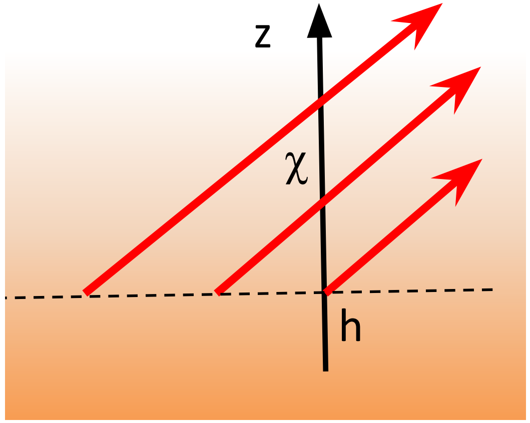
$\tau = 1$ identifies average point of **death**



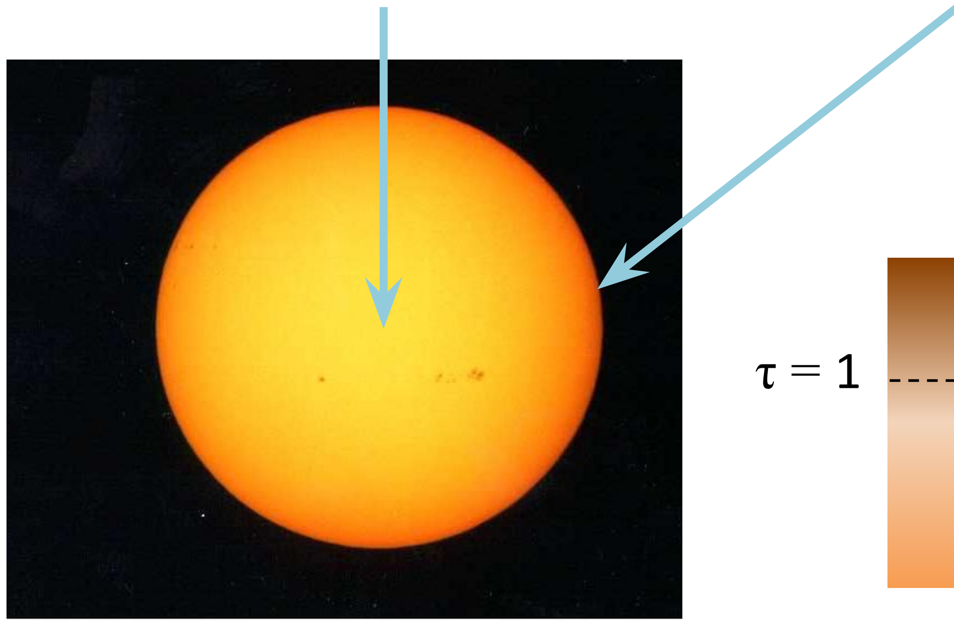
Stellar atmospheres:

$e^{-\tau(h)}$ = probability of photon surviving **to** z = ∞ after **originating** at height z = *h*

$\tau = 1$ identifies average point of **birth**
(among photons reaching ∞)

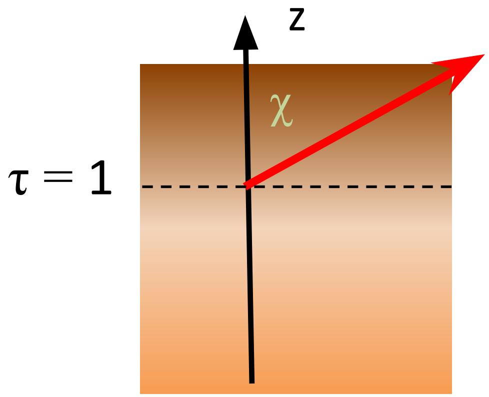


Activity 18 (p. 33): Optical depth is an integral over absorption along a line of sight, and thus as useful for incoming as for outgoing radiation. Explain why the layers contributing most to the light from the solar photosphere are geometrically higher as you look away from disk center. What can you infer about the stratification of the solar atmosphere from the fact that the Sun (emitting close to black-body radiation over much of the optical spectrum) is brightest near disk center, darkening towards the limb?



Limb darkening tells us that temperature decreases with height in the solar atmosphere

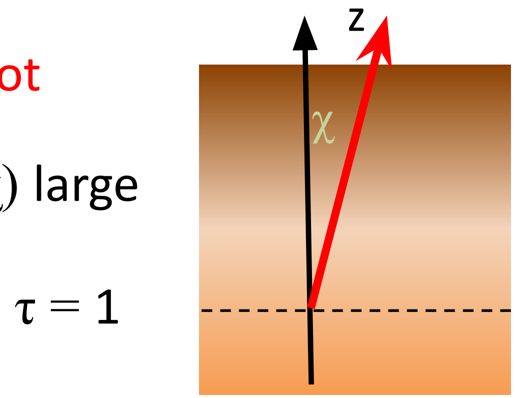
dark □ cold



cos(χ) small

bright □ hot

cos(χ) large



$$\tau = \sigma_{\rm a} n(h) \frac{H_p(h)}{\cos(\chi)},$$

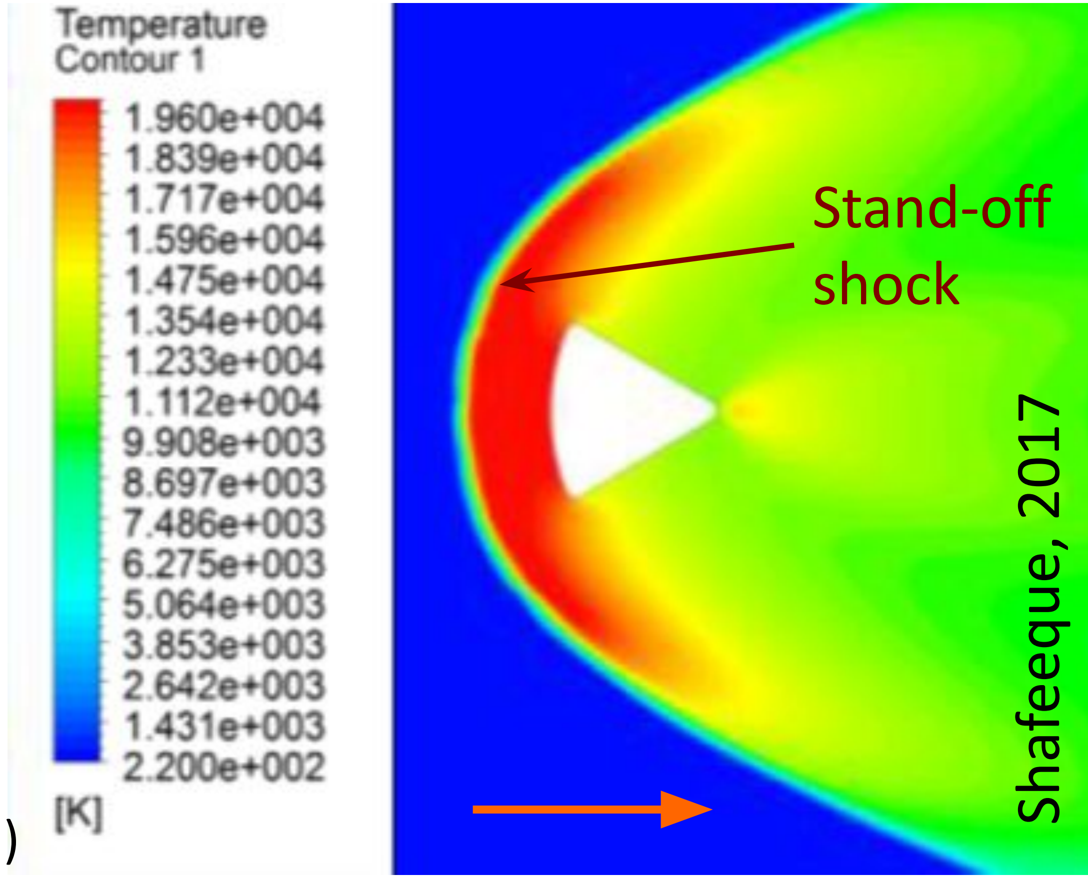
Shocks

Supersonic ($u_1/c_{s,1}>1$) flow encounters **obstacle**:

1. shock slows flow ($u_2 < u_1$)
2. shock heats fluid ($c_{s,2} > c_{s,1}$)

– flow kinetic energy is partly converted to thermal energy

 Makes flow **subsonic** ($u_2/c_{s,2}<1$) so it can go around obstacle



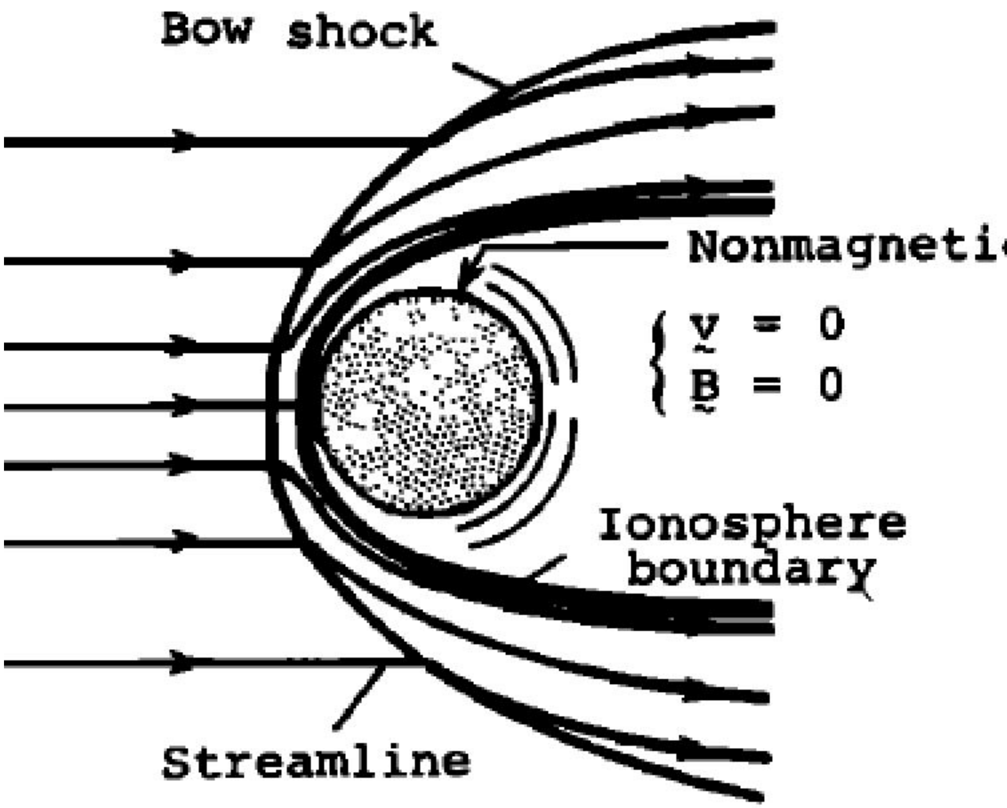
$u_1 = v_{esc} = 11$ km/s

$M = u_1/c_{s,1} = 33$

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

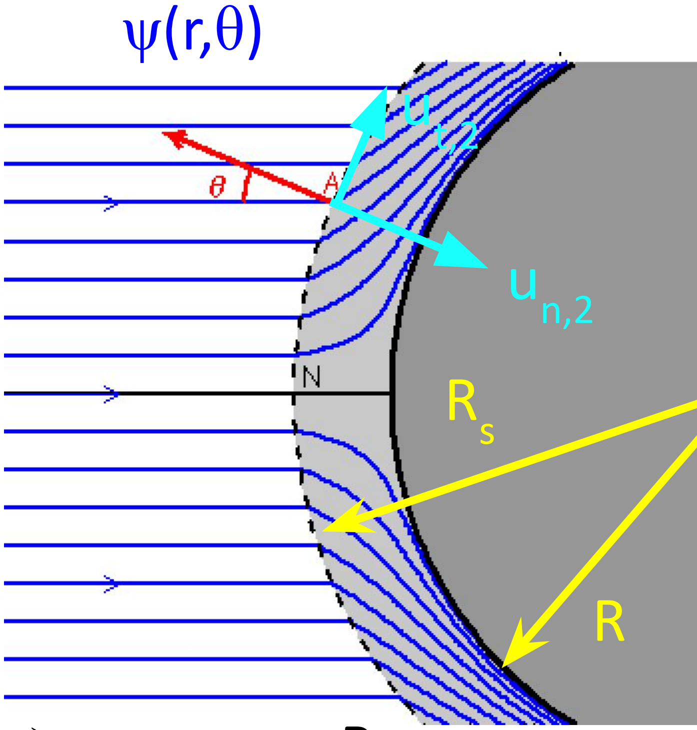


Simple picture of bow shock

- 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

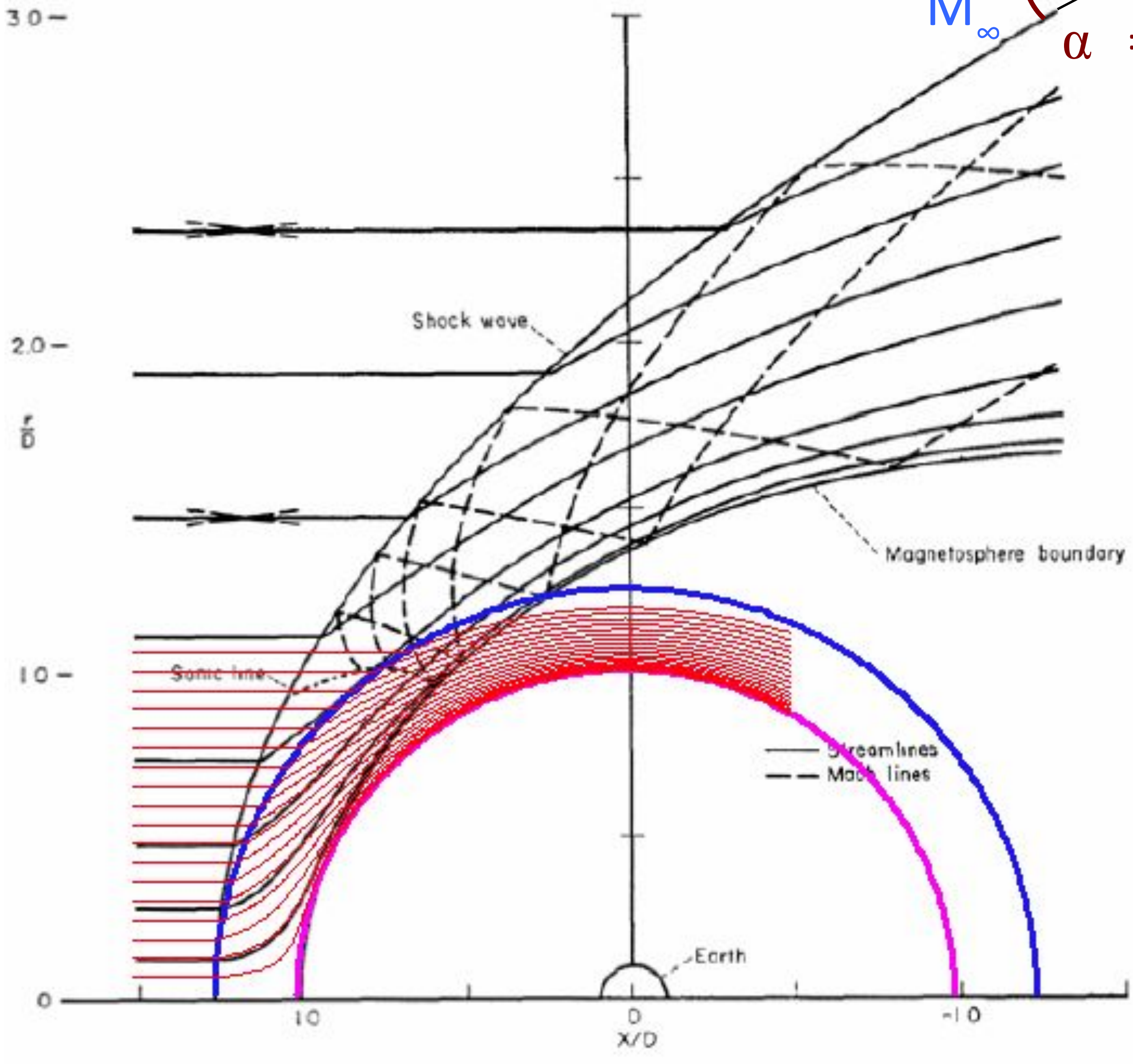


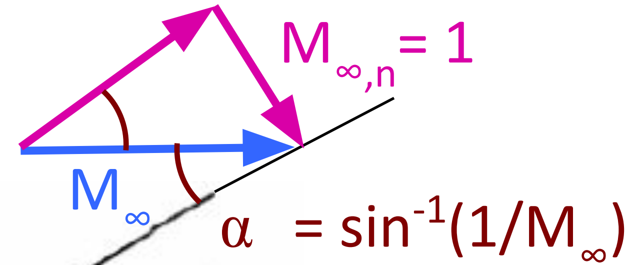
- $u_{n,2} = u_{n,1}/4$, $u_{t,2} = u_{t,1}$

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

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

Numerical solution
from Spreiter *et al.* 1966





Weak shock
far down
stream

Activity 65 (p. 134): Use Eqs. (5.2) and (5.8-5.12) to show that in the case of a strong shock (in which the thermal energy of the solar wind upstream of the bow shock can be ignored) the temperature just downwind of the bow shock is given by $(3m_p/32k)v_{sw}^2$ for a wind speed of v_{sw} and that the density contrast across the shock is a factor of 4 (show that is true anywhere along the shock).

Use this to estimate the angle from the upwind direction out to which the flow remains supersonic just inside the shock front (remembering that the transverse component of the velocity is unaffected by the shock).

$$\{\rho \mathbf{v} \cdot \hat{\mathbf{e}}_\perp\} = 0 \ , \tag{5.2}$$

$$\left\{\rho v_\perp^2 + p + \frac{B_\parallel^2}{8\pi}\right\} = 0 \tag{5.8}$$

$$\left\{\rho \mathbf{v}_\parallel v_\perp - \frac{\mathbf{B}_\parallel B_\perp}{4\pi}\right\} = 0 \tag{5.9}$$

$$\left\{\left(\frac{1}{2}\rho v^2 + \frac{\gamma p}{\gamma - 1} + \frac{B^2}{4\pi}\right) v_\perp - (\mathbf{v} \cdot \mathbf{B})\frac{B_\perp}{4\pi}\right\} = 0 \tag{5.10}$$

$$\{B_\perp\} = 0 \tag{5.11}$$

$$\{\mathbf{v}_\perp \times \mathbf{B}_\parallel + \mathbf{v}_\parallel \times \mathbf{B}_\perp\} = \mathbf{0} \ . \tag{5.12}$$

Activity 65 (p. 134): Use Eqs. (5.2) and (5.8-5.12) to show that in the case of a strong shock (in which the thermal energy of the solar wind upstream of the bow shock can be ignored) the temperature just downwind of the bow shock is given by $(3m_p/32k)v_{sw}^2$ for a wind speed of v_{sw} and that the density contrast across the shock is a factor of 4 (show that is true anywhere along the shock).

β >> 1

$$\left\{\rho v_\perp^2 + p + \frac{B_\parallel^2}{8\pi}\right\} = 0 \qquad (5.8)$$

$$\rho_{\rm sw}\, v_{\rm sw}^2 \;+\; p_{\rm sw} \;=\; \rho_2\, v_2^2 \;+\; p_2 \;=\; \rho_2\, v_2^2 \;+\; \frac{k_b}{(m_p/2)}\,\rho_2\, T_2$$

$$T_2 \;=\; \frac{m_p}{2k_b}\left[\frac{\rho_{\rm sw}}{\rho_2}\, v_{\rm sw}^2 \;-\; v_2^2\right] \;=\; \frac{m_p}{2k_b}\left[\frac{1}{4}\, v_{\rm sw}^2 \;-\; \frac{1}{16}\, v_{\rm sw}^2\right] \;=\; \frac{3m_p}{32k_b}\, v_{\rm sw}^2$$

Use this to estimate the angle from the upwind direction out to which the flow remains supersonic just inside the shock front (remembering that the transverse component of the velocity is unaffected by the shock).

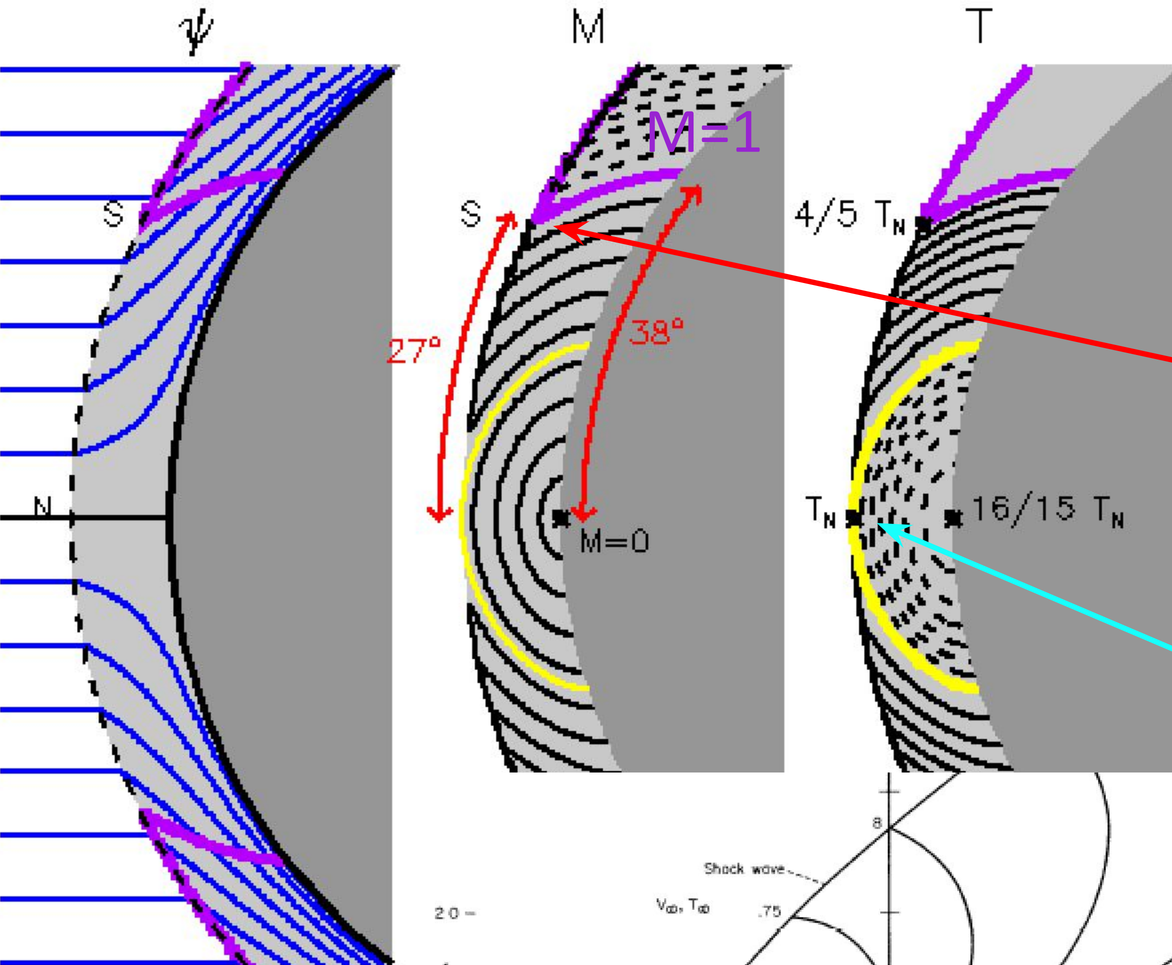
$$\frac{k_b T_2}{m_p} = \frac{3}{32} v_{\mathrm{sw},\perp}^2$$

$$c_{s,2}^2 = \frac{5 k_b T_2}{3(m_p/2)} = \frac{5}{16} v_{\mathrm{sw},\perp}^2 = 5\, v_{2,\perp}^2$$

remains supersonic:

$$v_{\mathrm{sw},\parallel}^2 = v_{2,\parallel}^2 > \frac{4}{5} c_{s,2}^2 = 4\, v_{2,\perp}^2 = \frac{1}{4} v_{\mathrm{sw},\perp}^2$$

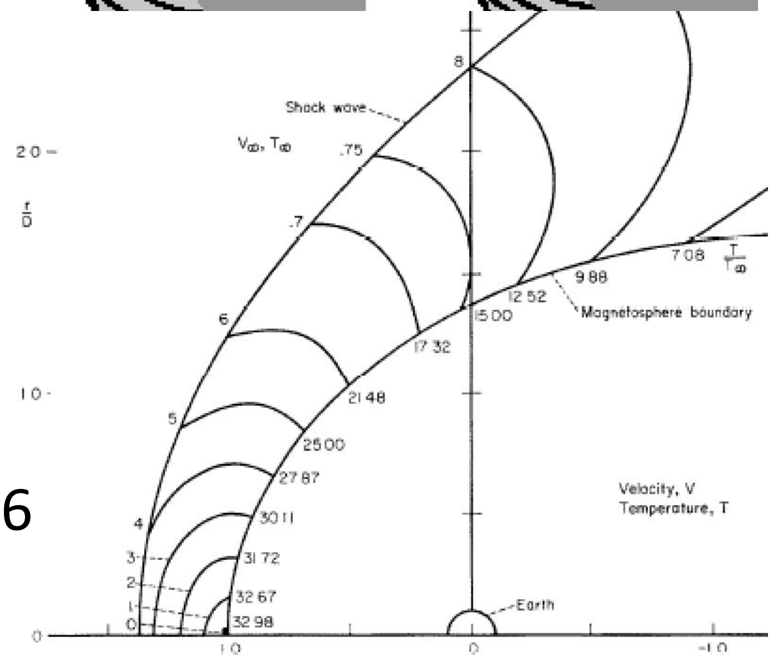
$$\tan(\theta_{\mathrm{sw}}) = \frac{v_{\mathrm{sw},\parallel}}{v_{\mathrm{sw},\perp}} > \frac{1}{2} \qquad \theta_{\mathrm{sw}} > 27^\circ$$



$$\tan(\theta_{sw}) = \frac{v_{sw,\parallel}}{v_{sw,\perp}} > \frac{1}{2}$$

$$\theta_{sw} > 27^\circ$$

$$\frac{3m_p}{32k_b} v_{sw}^2$$



Spreiter
et al. 1966

Activity 66 (p. 135): What is the expression for the temperature of the gas at the stagnation point on the magnetopause assuming that the flow continues adiabatically after the shock (i.e., that it conserves the sum of bulk kinetic and thermal energies)? What is the value for v_{sw} = 800 km/s.

$$\frac{1}{2}v^2 + \frac{5}{2}\frac{p}{\rho} = \frac{1}{2}v^2 + \frac{5}{2}\frac{k_b}{(m_p/2)}T = \text{const.}$$

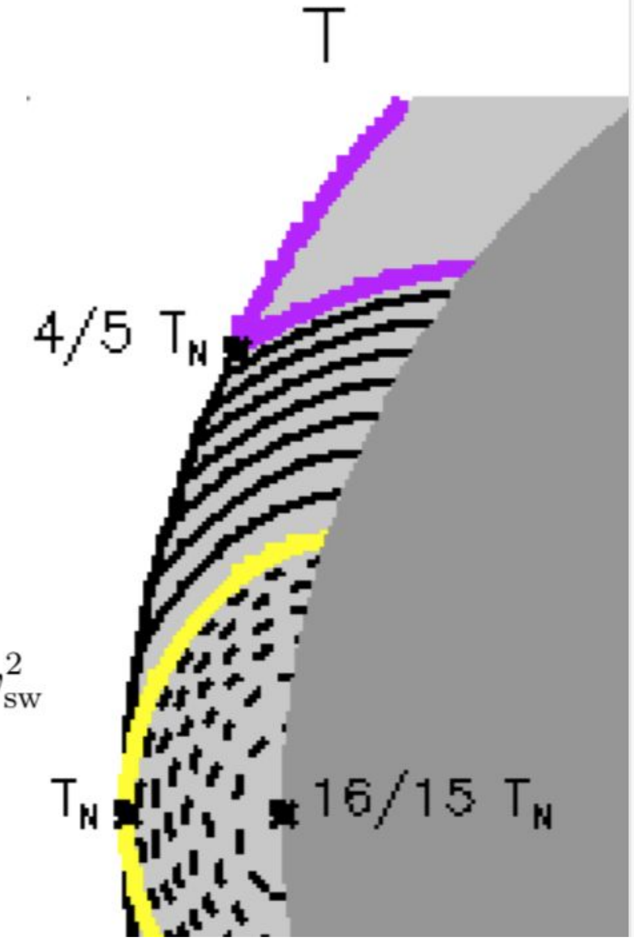
$$= \frac{1}{32}v_{\text{sw}}^2 + 5\frac{k_b}{m_p}T_N = 0 + 5\frac{k_b}{m_p}T_s$$

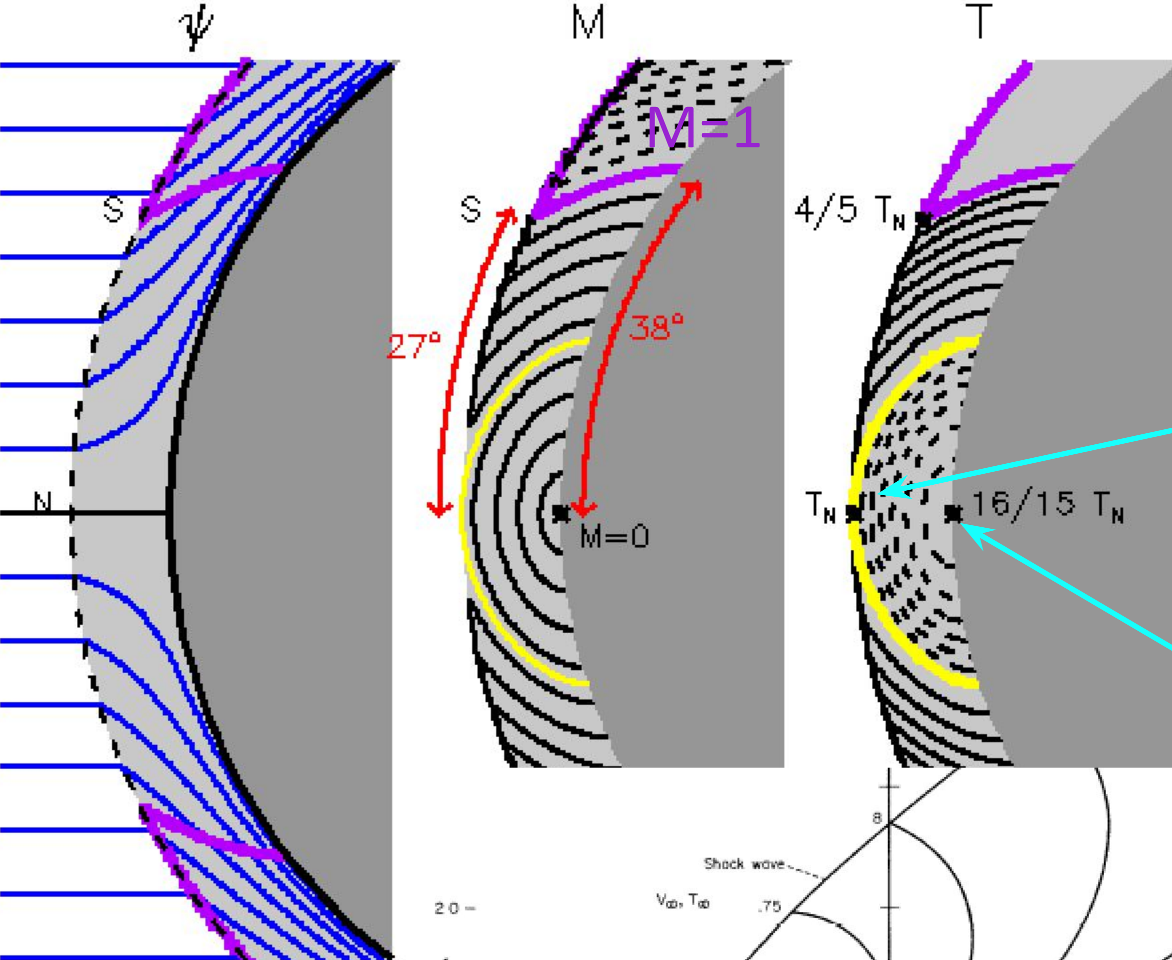
$$5\frac{k_b}{m_p}T_s = \frac{1}{32}v_{\text{sw}}^2 + 5\cdot\frac{3}{32}v_{\text{sw}}^2 = \frac{1}{2}v_{\text{sw}}^2$$

$$T_s = \frac{1}{10}\frac{m_p}{k_b}v_{\text{sw}}^2 = \frac{16}{15}T_N$$

$$\frac{3m_p}{32k_b}v_{\text{sw}}^2$$

$$0.1\,(1.2 \times 10^{-8})\,(8 \times 10^{7})^2 = 7.7 \times 10^{6}\ \text{K}$$





Shock partially therm-alizes flow KE of SW:

- N normal)

$$\frac{3m_p}{32k_b}v_{\rm sw}^2$$

- Stagnation point

$$T_s = \frac{1}{10}\frac{m_p}{k_b}v_{\rm sw}^2 = \frac{16}{15}T_N$$

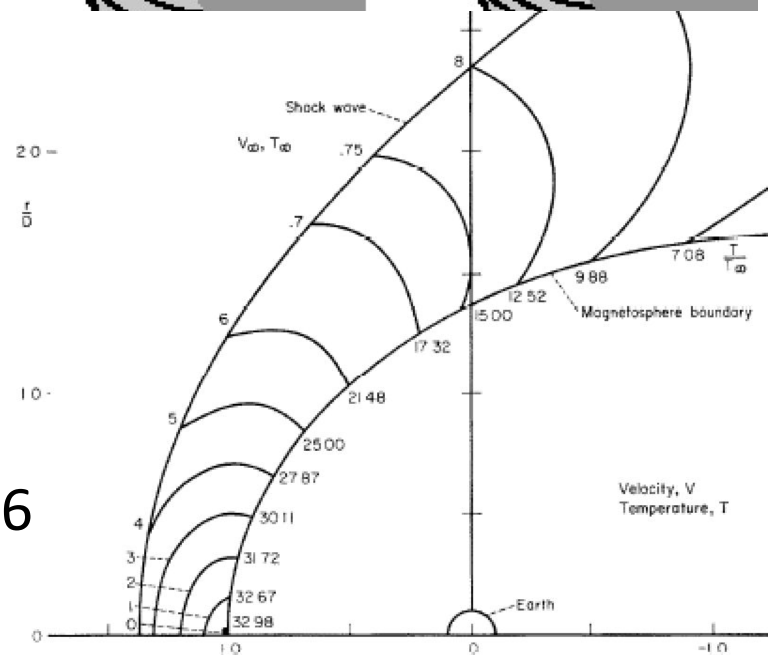
u_∞ = 800 km/s

T_N = 7.2 MK

T_s = 7.8 MK

- pressure

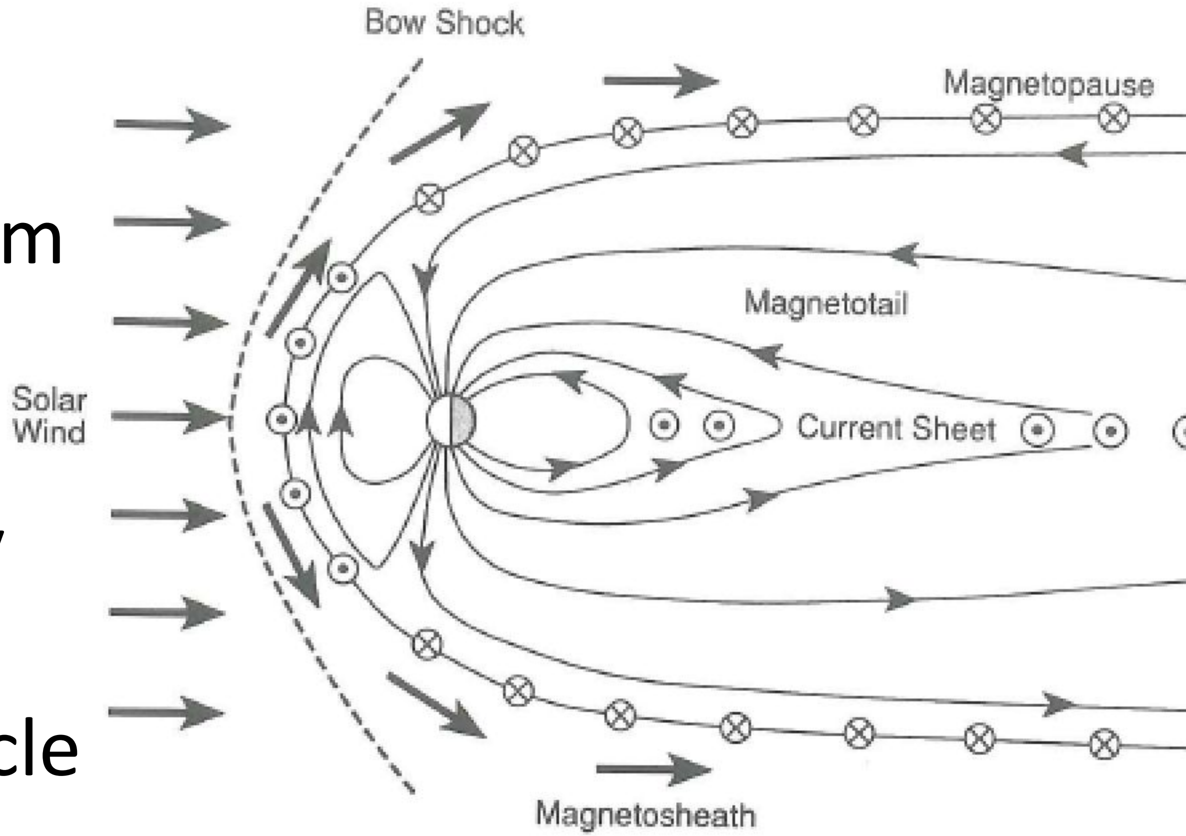
$$p_s = \frac{4}{5}\rho_\infty u_\infty^2$$



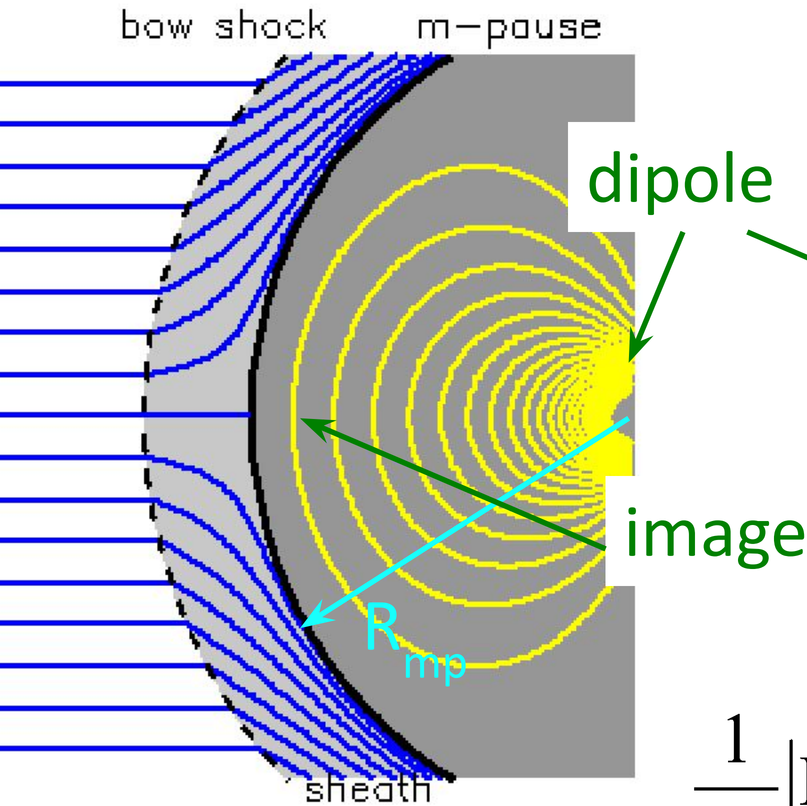
Spreiter *et al.* 1966

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

$$R_{\rm mp} = \frac{(\xi \mu_{\rm p})^{1/3}}{(8\pi \rho_{\rm sw} v_{\rm sw}{}^2)^{1/6}} \qquad (5.22)$$

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

Earth: $B_\oplus = 0.3$ G

steady slow wind: $\rho_{sw} = 10^{-23}$ g/cm^3, $u_{sw} = 400$ km/s

$$R_{mp} = 0.875\ (\ 0.09\ /\ 1.6 \times 10^{-8}\ )^{1/6}\ R_\oplus = 11.7\ R_\oplus$$

steady fast wind: $\rho_{sw} = 10^{-23}$ g/cm^3, $u_{sw} = 800$ km/s

$$R_{mp} = 0.875\ (\ 0.09\ /\ 6.4 \times 10^{-8}\ )^{1/6}\ R_\oplus = 9.3\ R_\oplus$$

Acitivity 68 (p. 135): With the fastest recorded solar-wind gusts at v_{sw} = 2500 km/s, what is the required plasma density to push the magnetopause to within geosynchronous orbit according to Eq. (5.22)?

$$R_{\mathrm{mp}} = \frac{(\xi \mu_{\mathrm{p}})^{1/3}}{(8\pi \rho_{\mathrm{sw}} v_{\mathrm{sw}}{}^2)^{1/6}} \qquad (5.22)$$

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

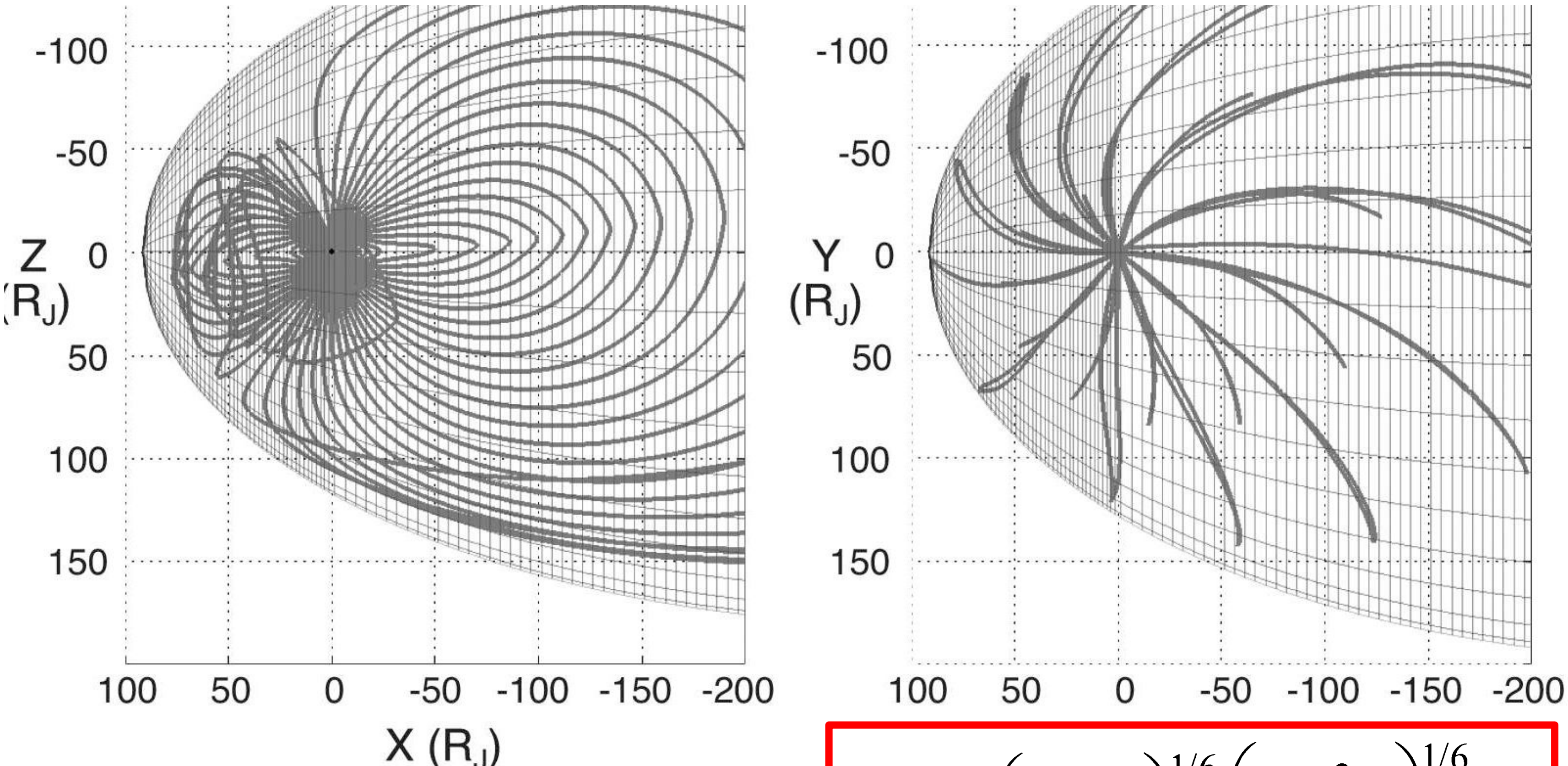
geosynchronous orbit (P=24 h *vs.* 1.5 h @ $R_\oplus$)

$$R_{gs} = (24/1.5)^{2/3} R_\oplus = 6.3 R_\oplus$$

u_{sw} = 2500 km/s from statement

$$\rho_{sw} = 0.45 (0.09 / 6.2 \times 10^{16}) (6.3)^{-6}$$
$$= 10^{-23} \text{ g/cm}^3 = m_p \times 6 \text{ cm}^{-3}$$

Other planets… same story



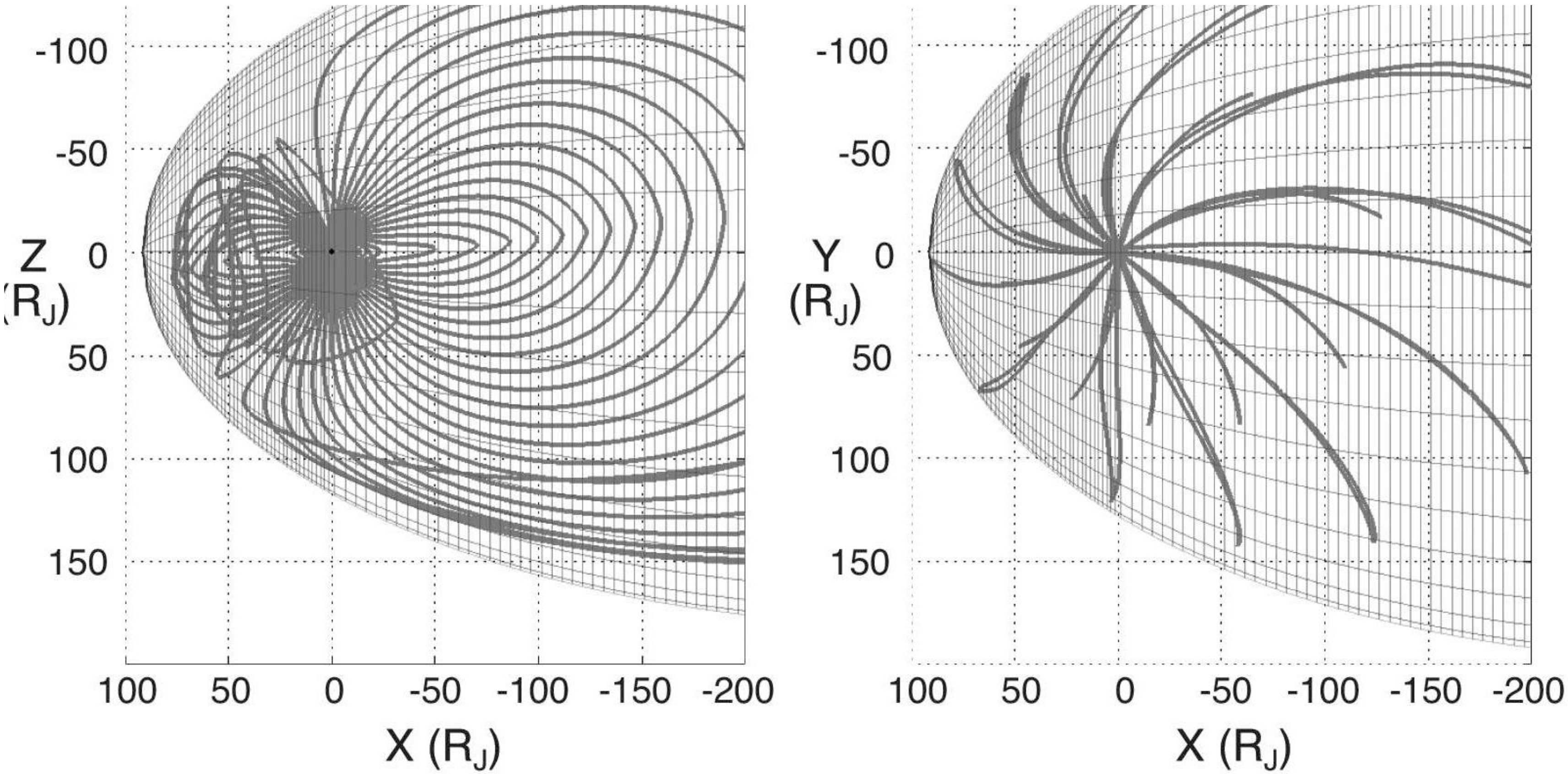
vol. I fig. 13.6

$B_J \sim 15\ B_\oplus \sim 5$ G

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

Q: how do u_∞ & ρ_∞ @ Jupiter compare to @ Earth?

Other planets… same story



vol. I fig. 13.6

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

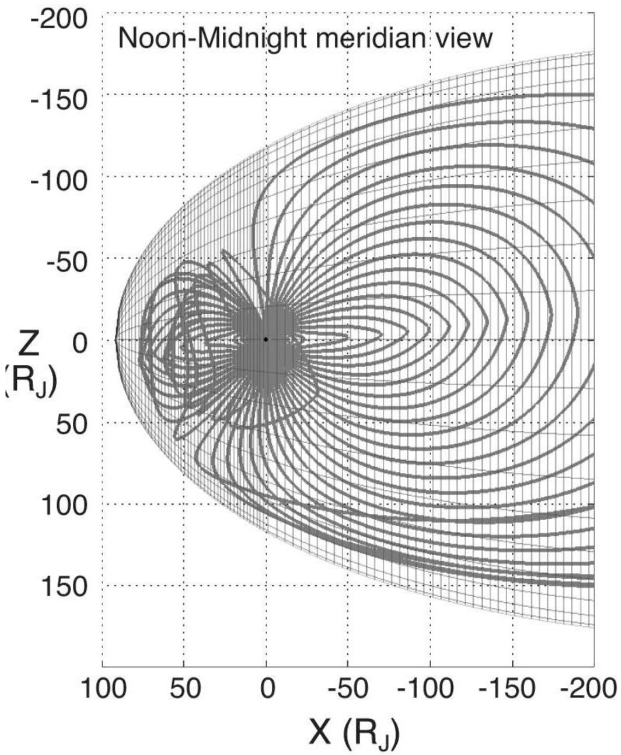
□ Jupiter's magnetopause:

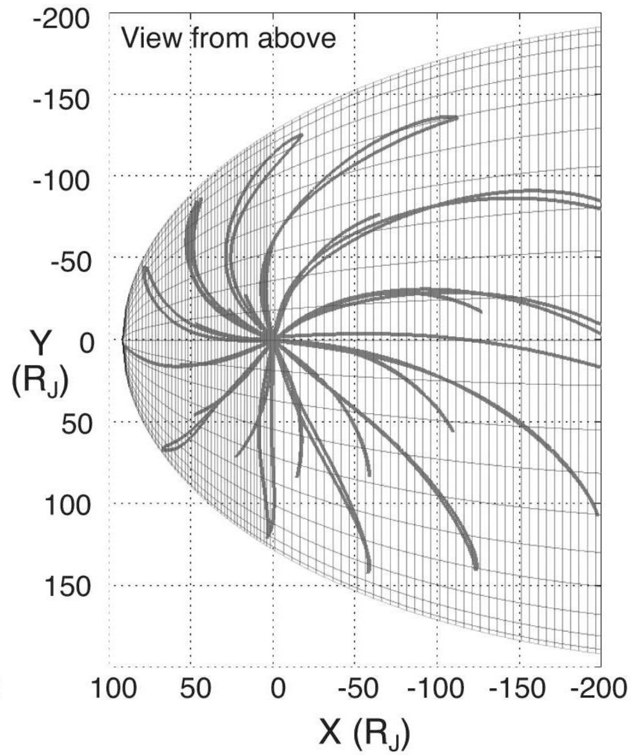
$R_{mp,J} \sim 50\ R_J = 3.5 \times 10^{11}$ cm

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

Activity 74 (p. 145): Many so-called 'hot Jupiters' have been found among the exoplanet population: giant planets that orbit very close to their parent stars. What would the estimated magnetopause distance $R_{CF;hJ}$ be if Jupiter were orbiting the present-day Sun at 0.05AU?

For a younger Sun (see Ch. 12) the solar wind would have been stronger, pushing $R_{CF;hJ}$ to below the orbital radius of Ganymede; describe what that would mean for this 'hot-Ganymede' moon?





Activity 74 (p. 145): Many so-called 'hot Jupiters' have been found among the exoplanet population: giant planets that orbit very close to their parent stars. What would the estimated magnetopause distance $R_{CF;hJ}$ be if Jupiter were orbiting the present-day Sun at 0.05AU?

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

$B_J \sim 15\ B_\oplus \sim 5$ G ; $\rho_\infty \sim (20)^2\ \rho_{\infty,\oplus} \sim 4 \times 10^{-21}$ g/cm^3

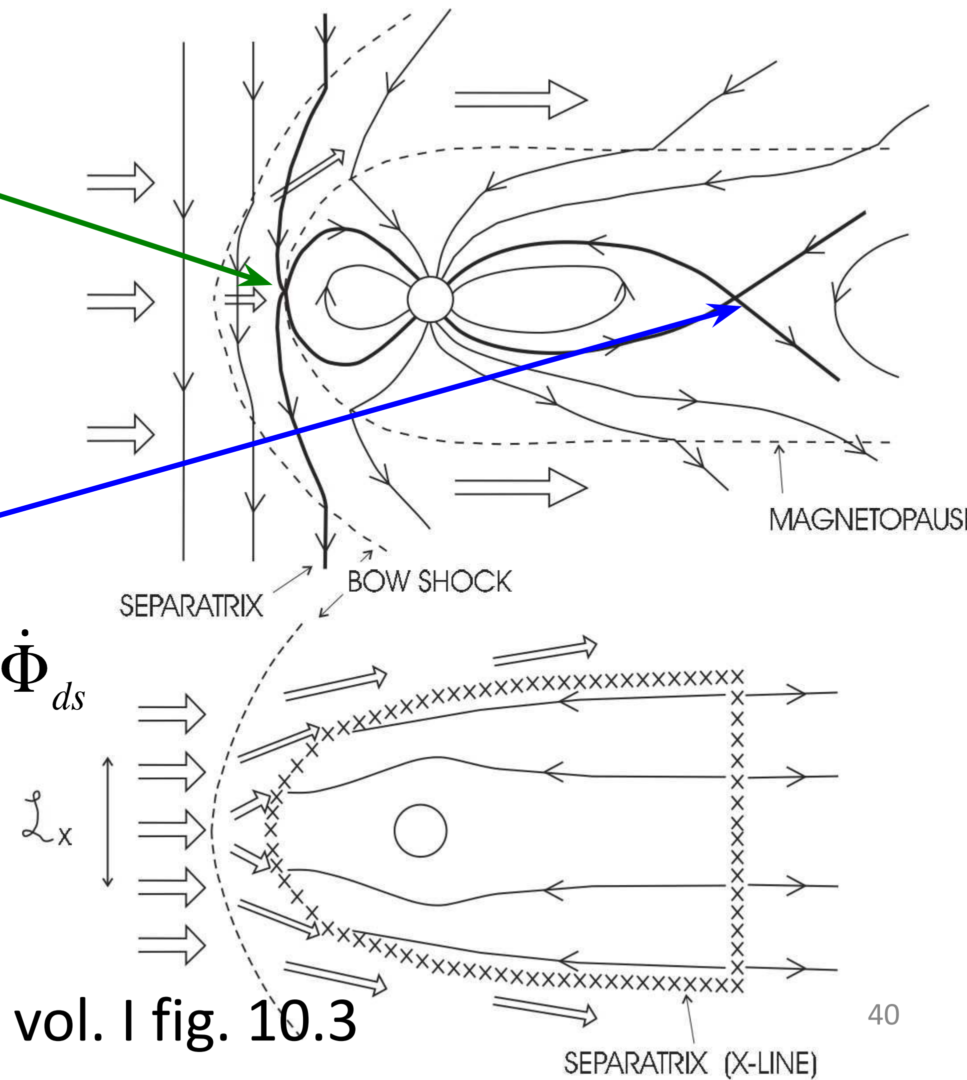
$u_\infty \sim 400$ km/s $= 4 \times 10^7$ cm/s

$R_{mp} = 0.875\ (25 / 6.4 \times 10^{-6})^{1/6}\ R_\oplus = 11\ R_J$

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

Reconnection with SW field (consider southward IMF)

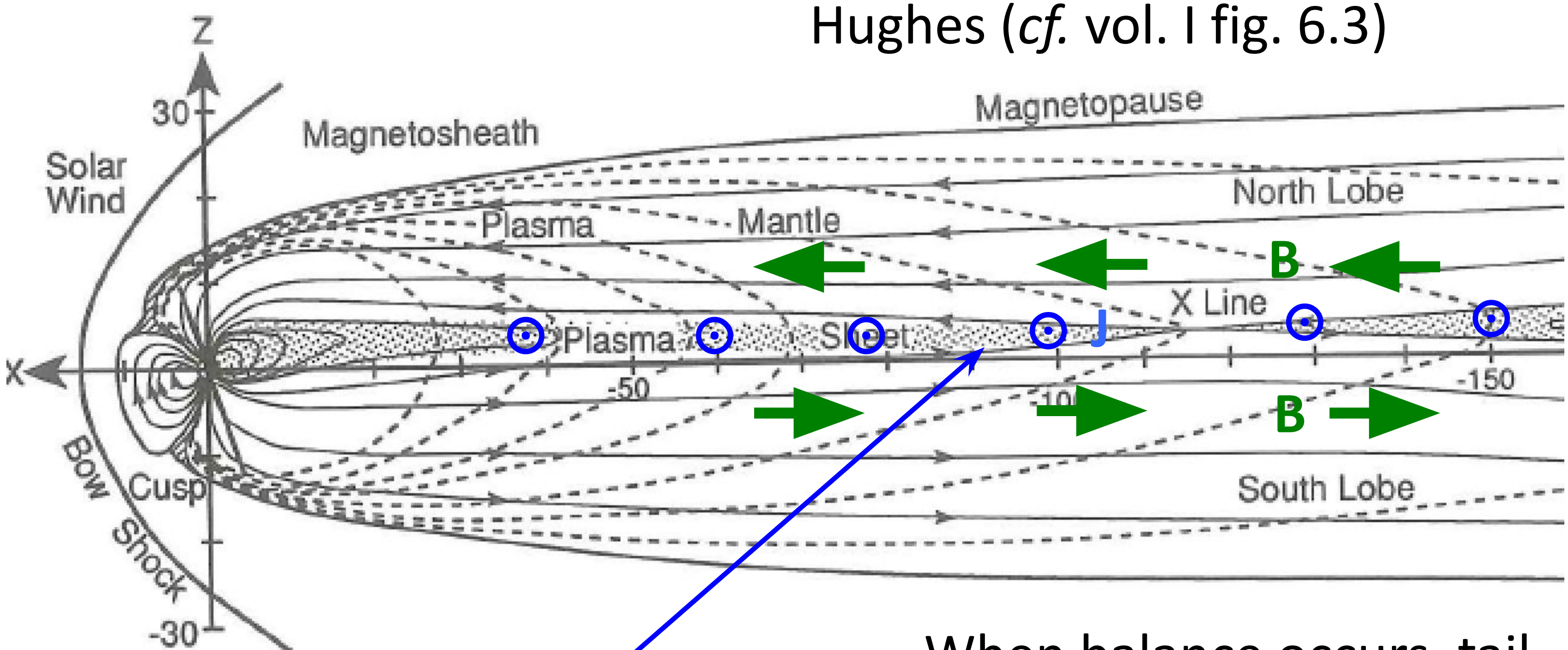
- Creates "open" flux connected to poles @ $\dot{\Phi}_{ds}$
- SW sweeps flux downstream – into **magnetotail**
- Steady state only when reconnection in tail "closes" flux at rate $\dot{\Phi}_n = -\dot{\Phi}_{ds}$
- Requires long & strong **neutral sheet** in magnetotail



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

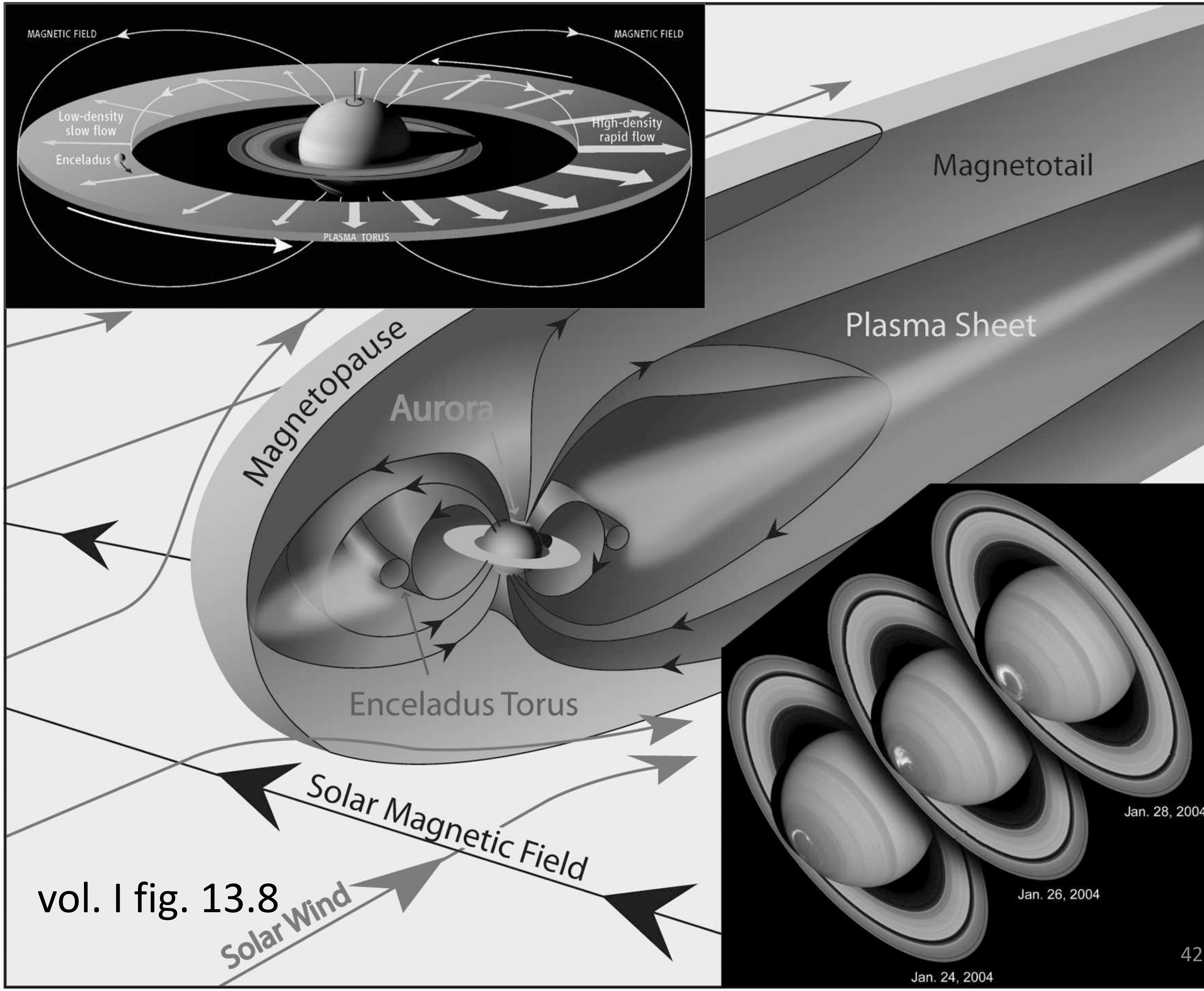
When balance occurs, tail…

- … has some length

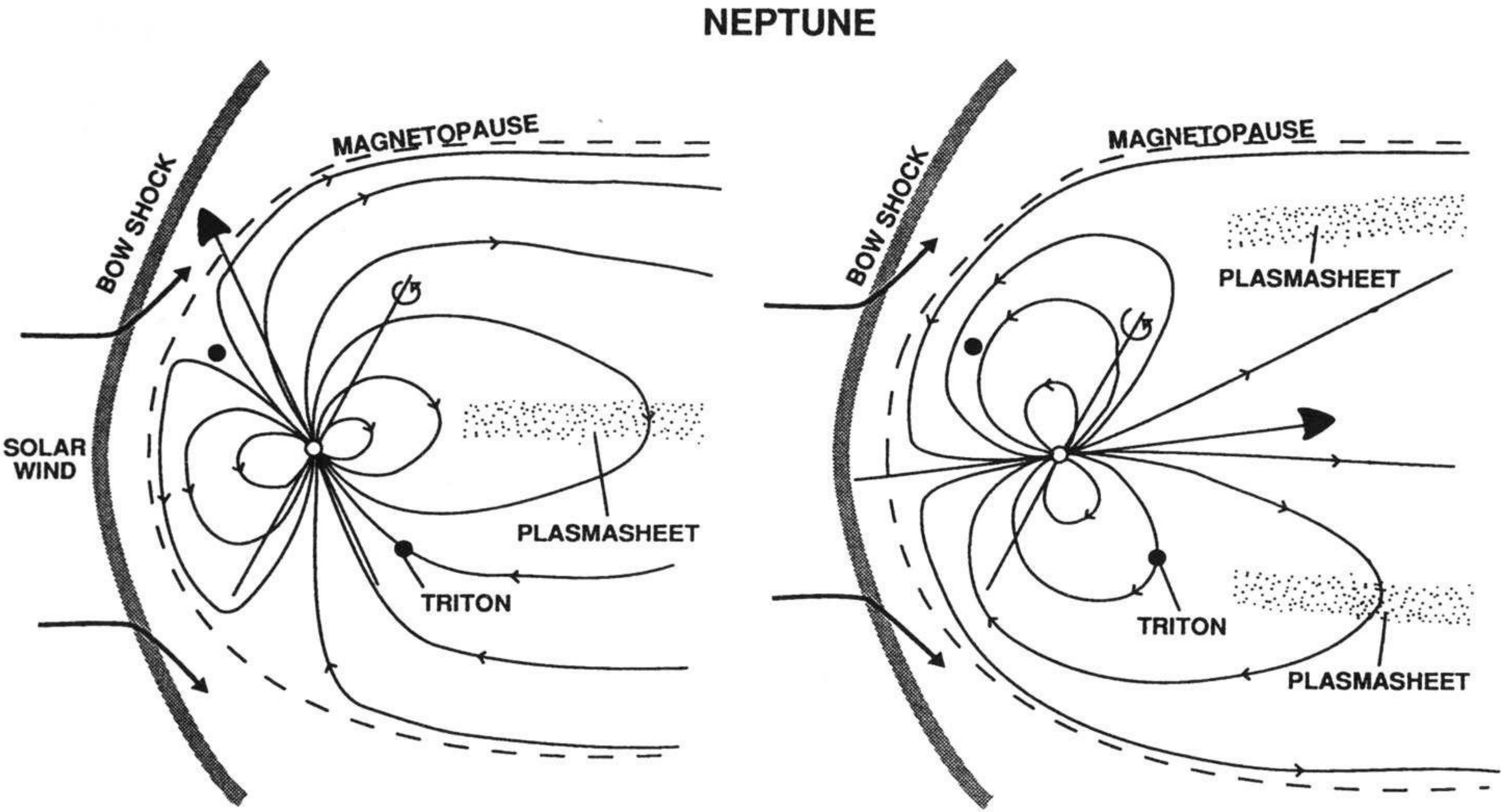
$$L_t \gg R_{mp}$$

- … has some open flux

$$\Phi_t$$

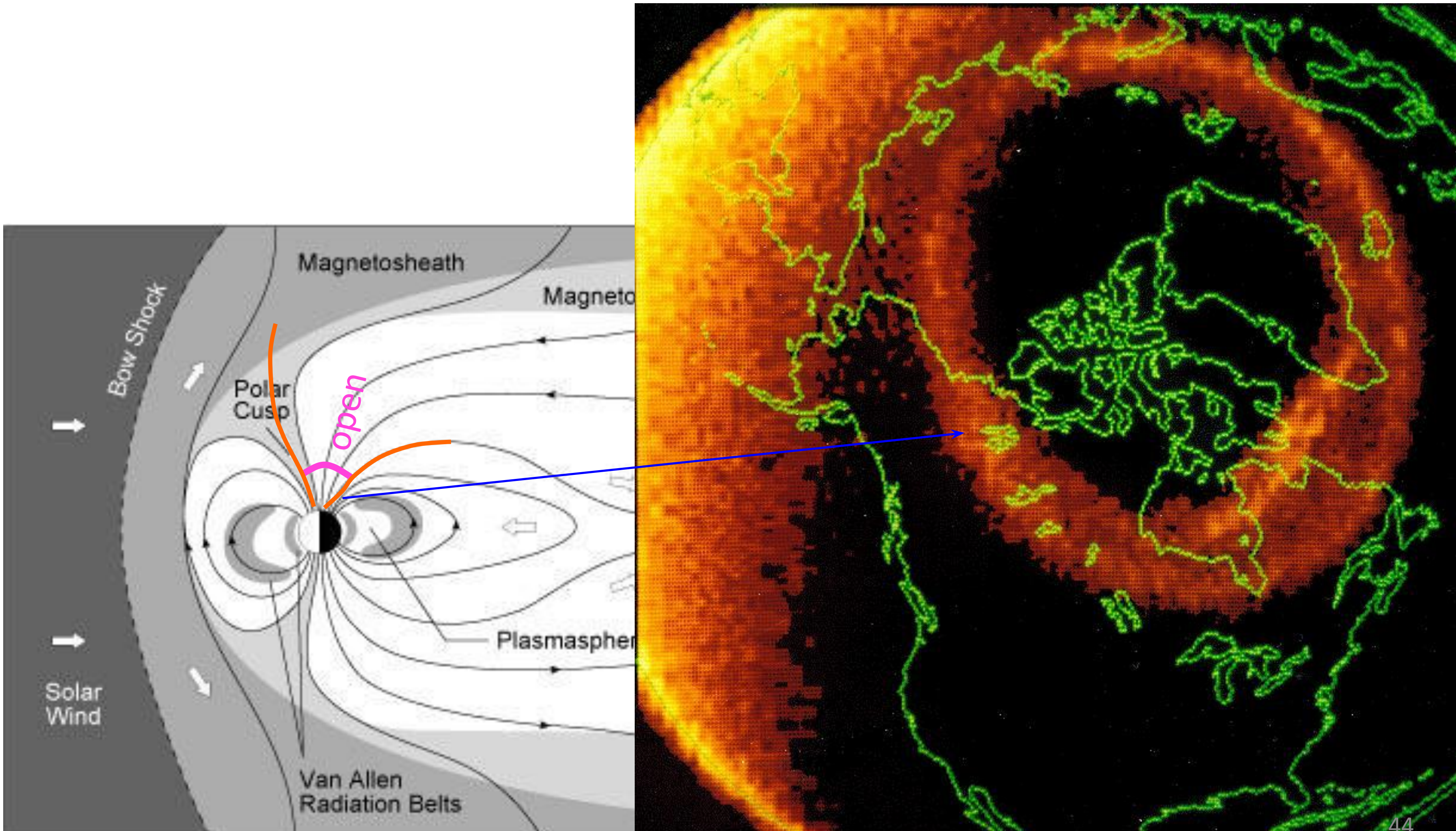

MAGNETIC FIELD
MAGNETIC FIELD
Low-density slow flow
Enceladus
High-density rapid flow
PLASMA TORUS
Magnetotail
Plasma Sheet
Magnetopause
Aurora
Enceladus Torus
Solar Magnetic Field
Solar Wind
Jan. 28, 2004
Jan. 26, 2004
Jan. 24, 2004

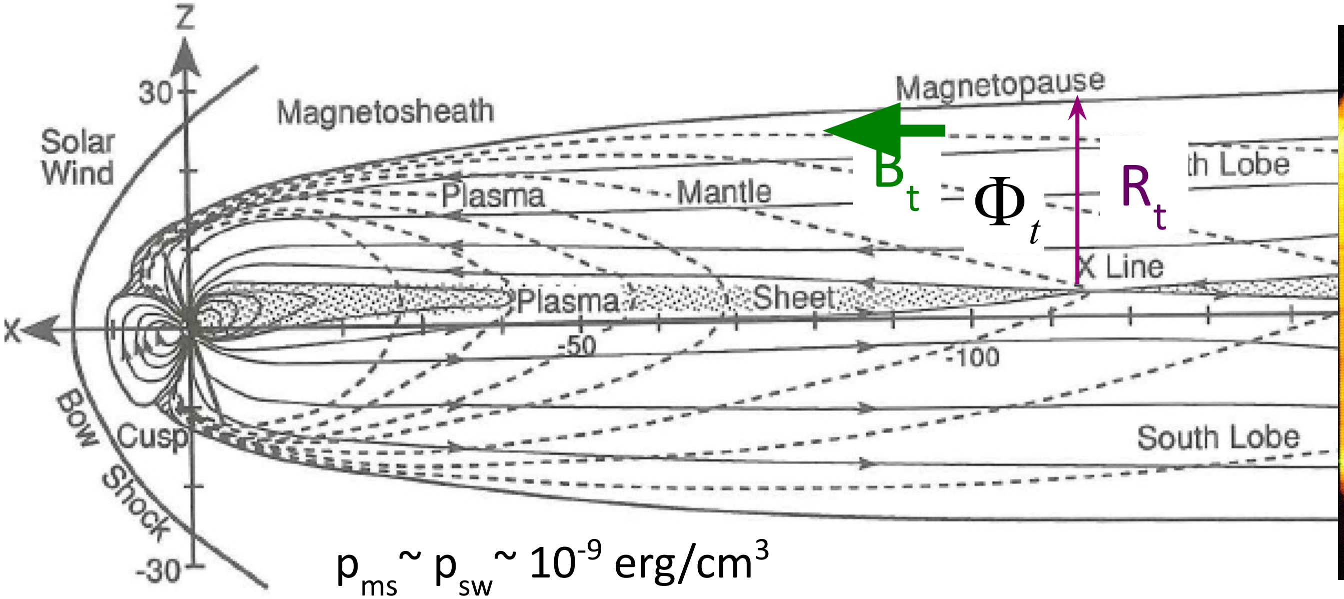
vol. I fig. 13.8

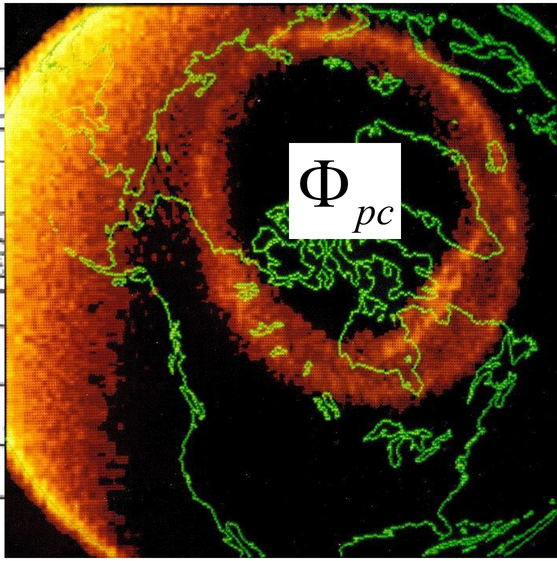


vol. I fig. 13.10

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:

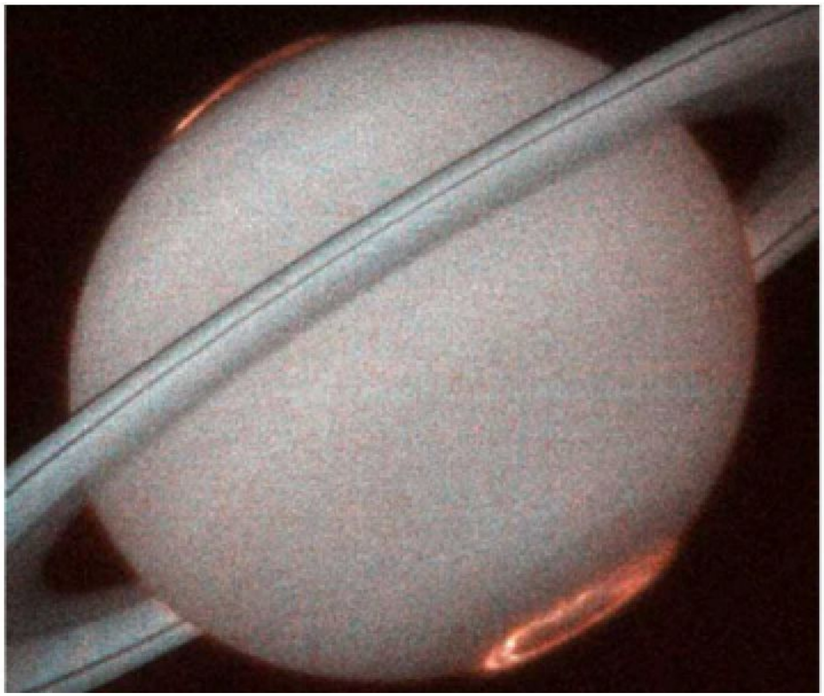
$$\frac{1}{8\pi} B_t^2 = \frac{1}{2\pi^3} \frac{\Phi_t^2}{R_t^4} = \frac{1}{2\pi}\left(\frac{R_\oplus}{R_t}\right)^4 \theta_{pc}^4 B_{np}^2$$

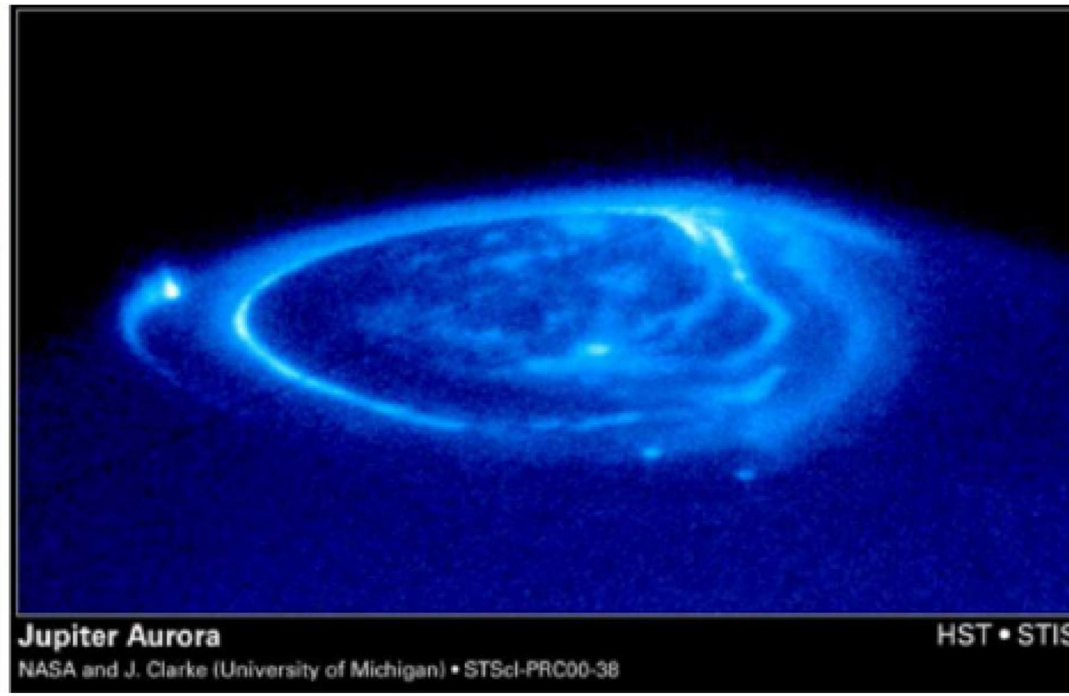
Pressure balance @ m-pause:

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

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

Other auroral ovals





vol. I fig. 2.9

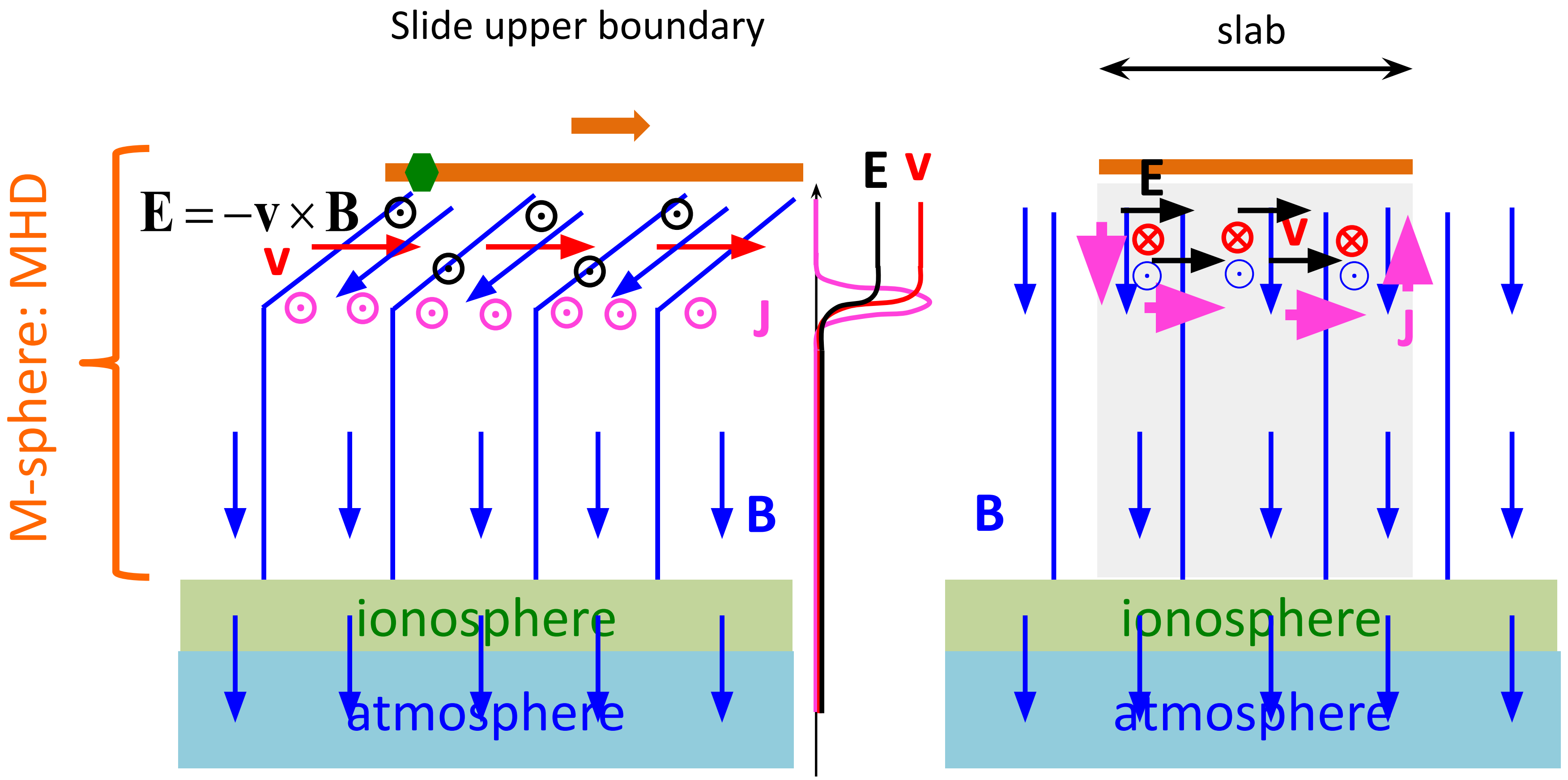
Convection: magnetosphere meets ionosphere

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

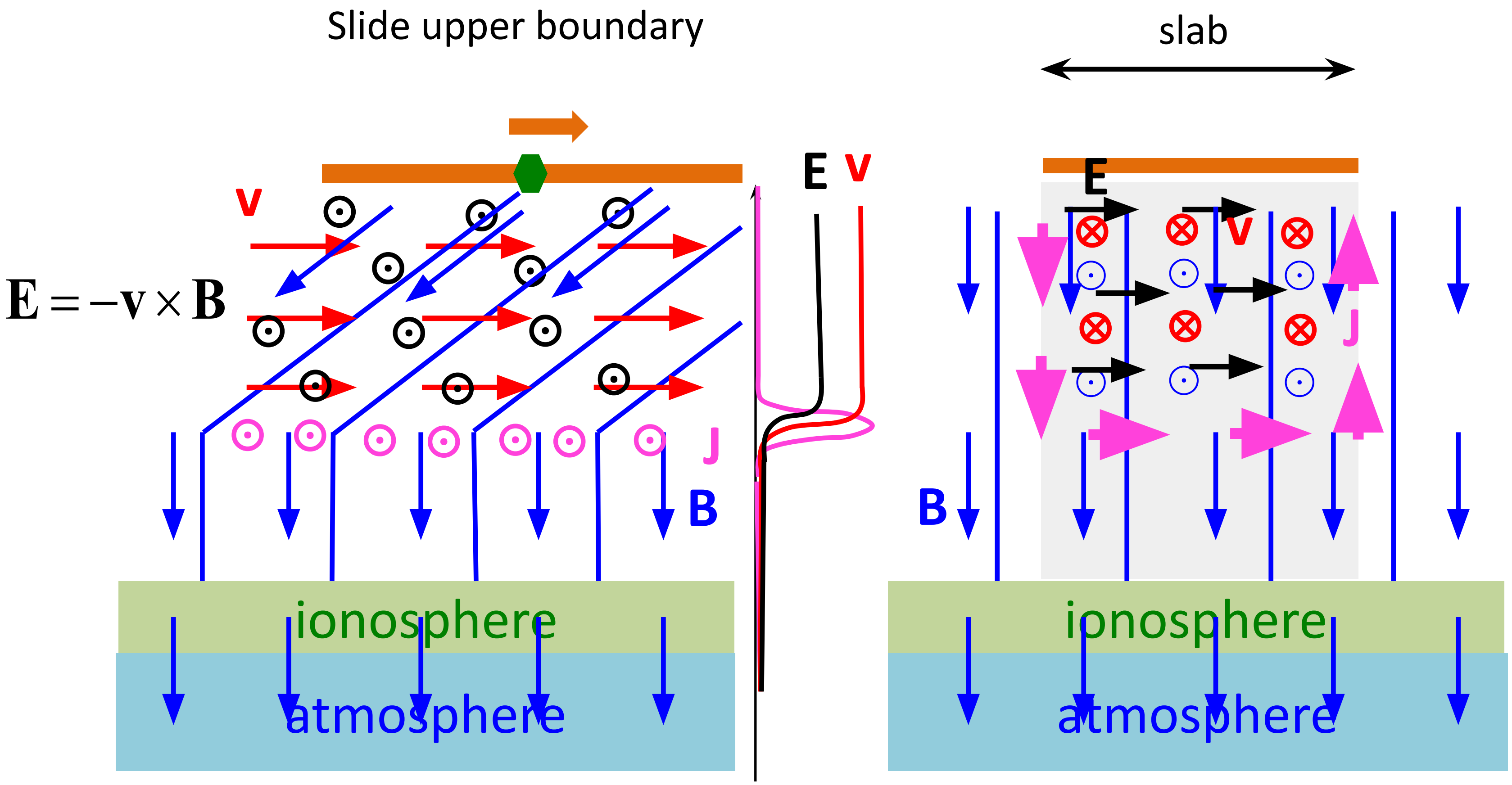
BUT: atmosphere & solid crust are insulators – field lines are **imaginary** there

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

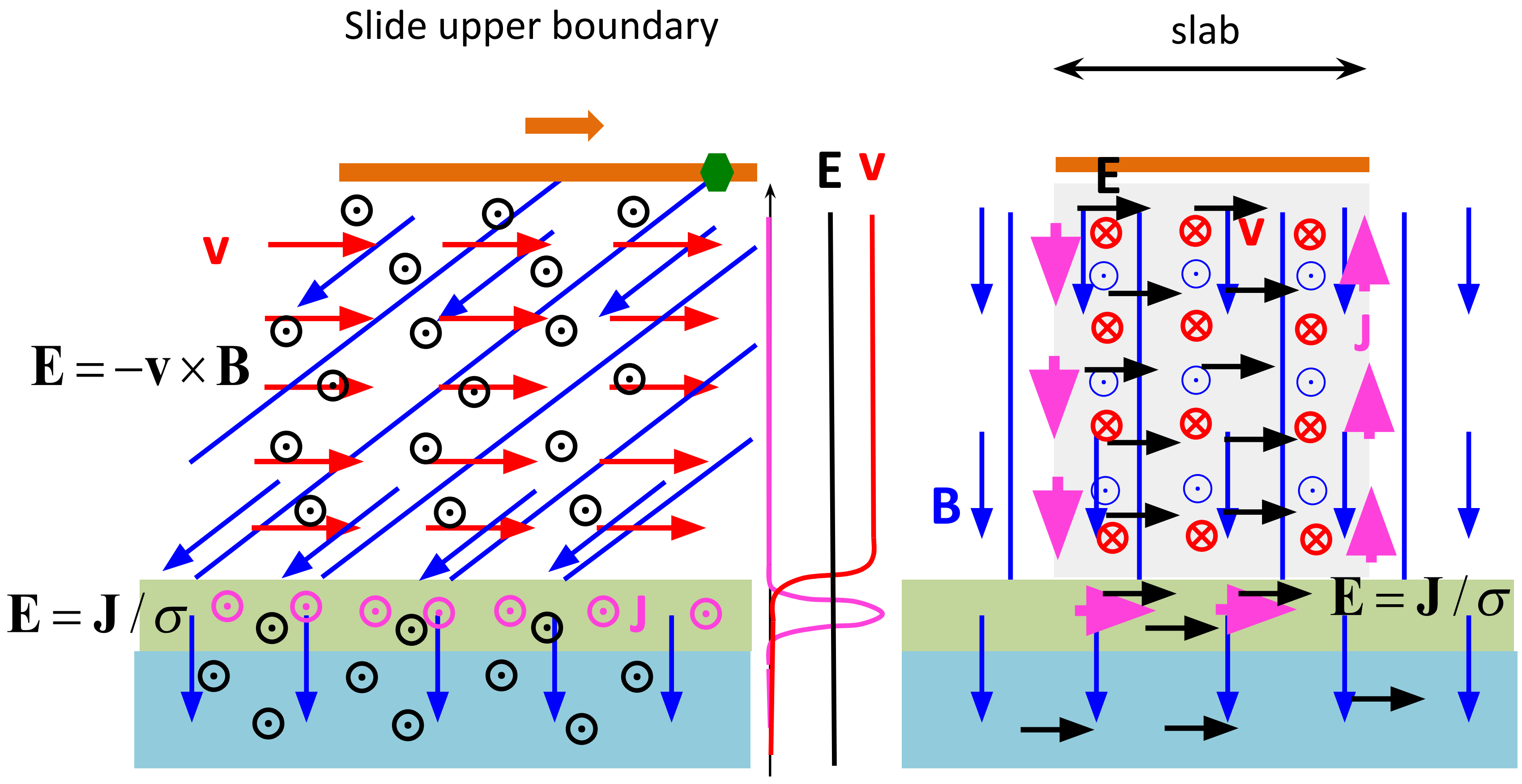
Example of how the motions meet



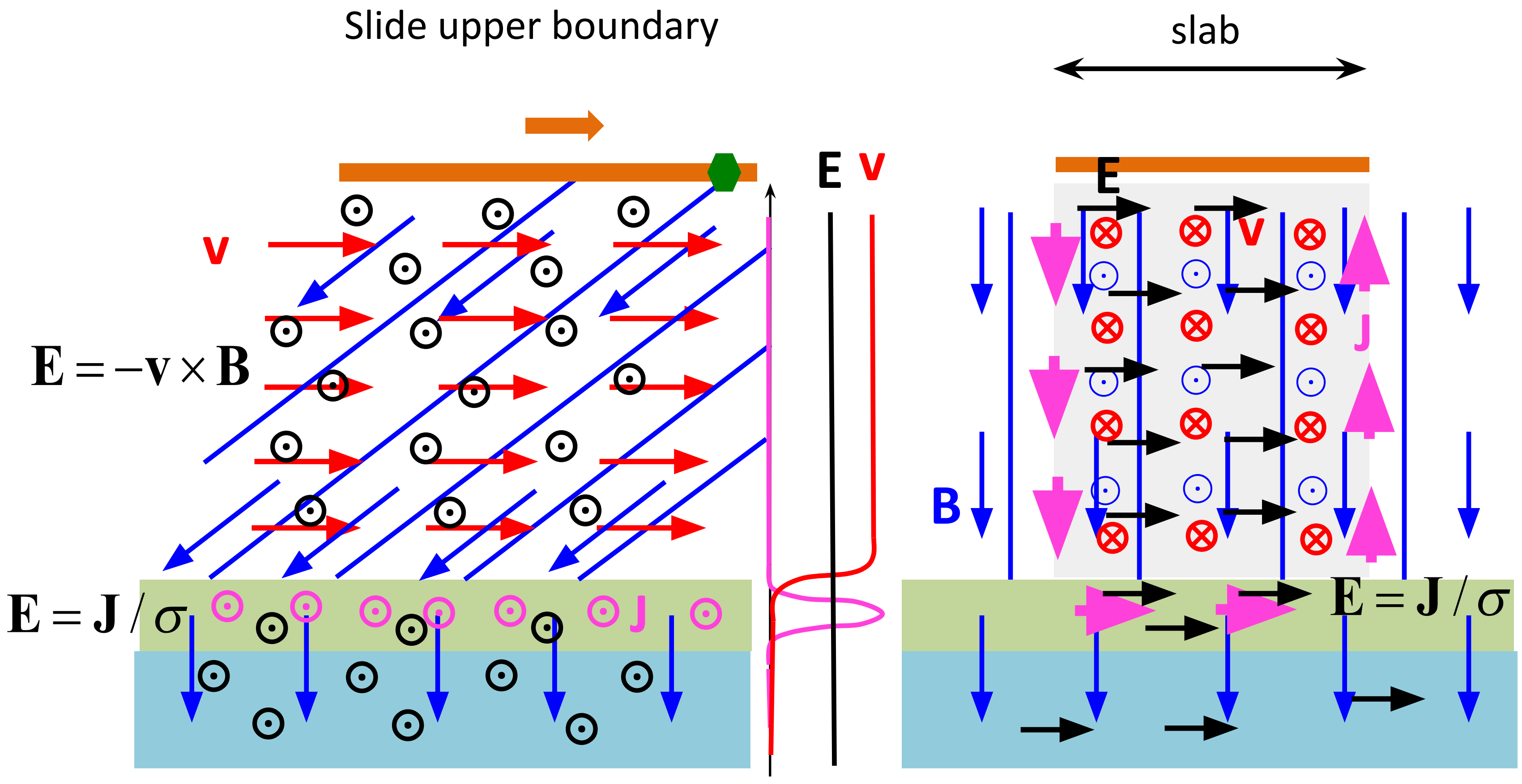
Example of how the motions meet



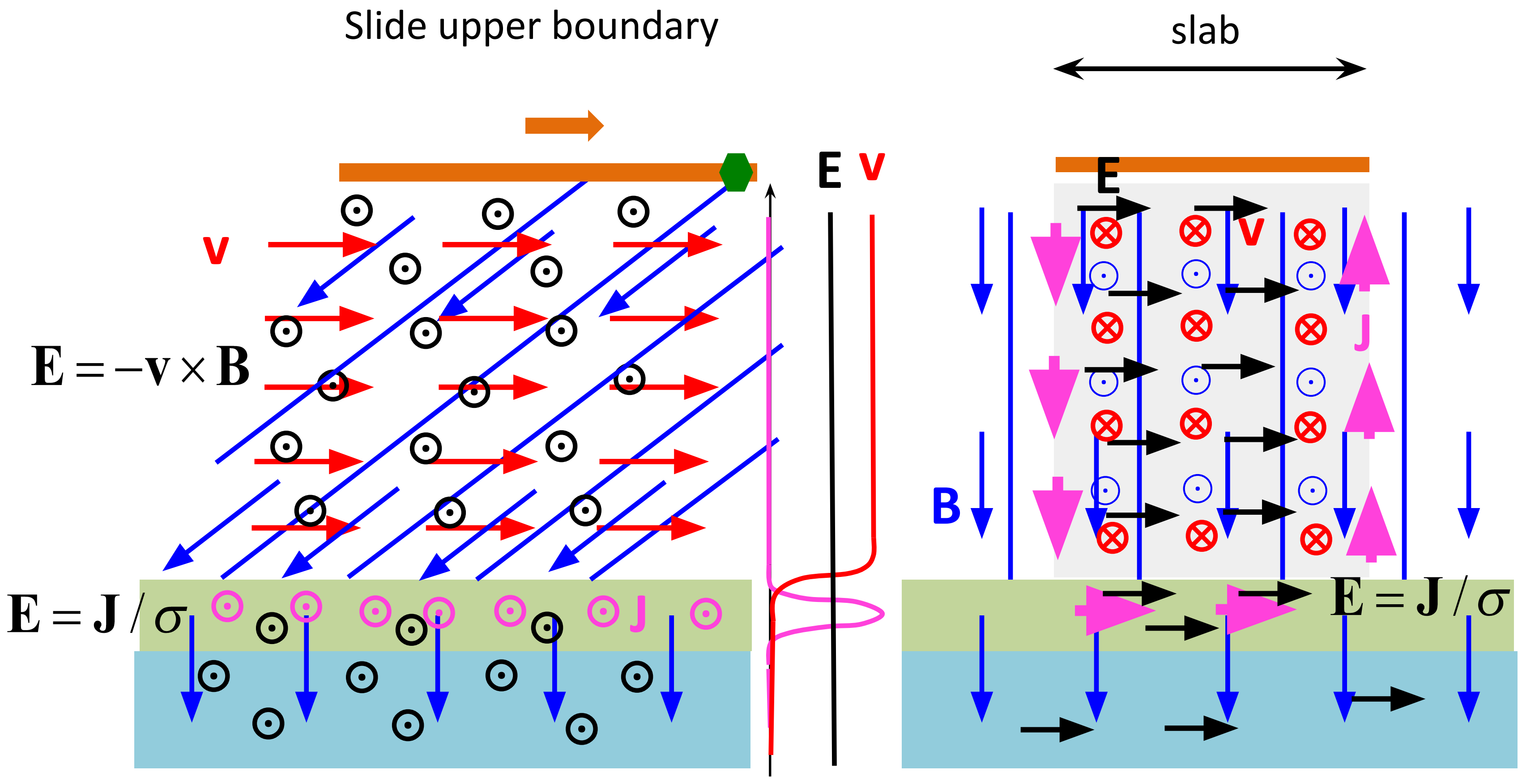
Example of how the motions meet



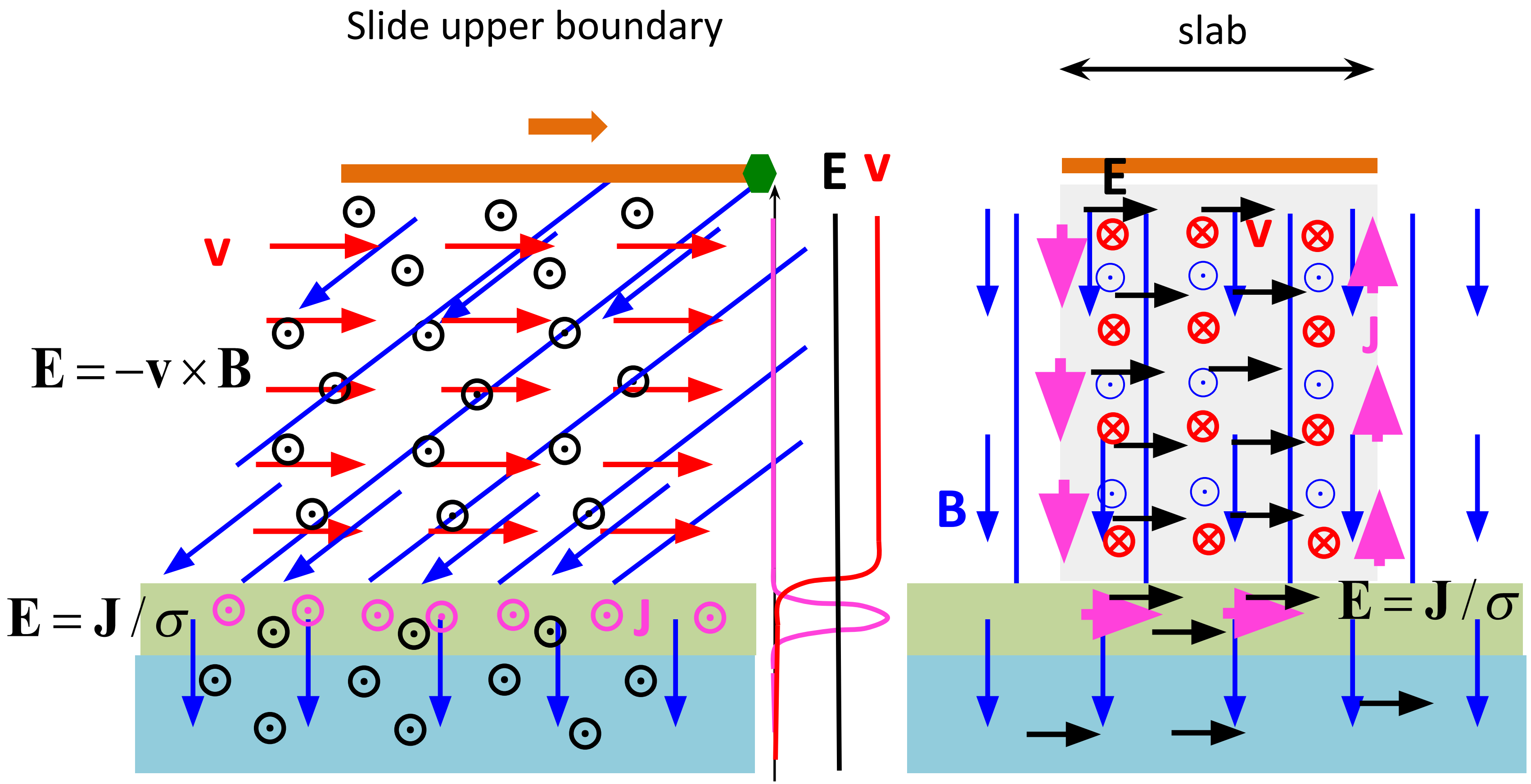
Example of how the motions meet



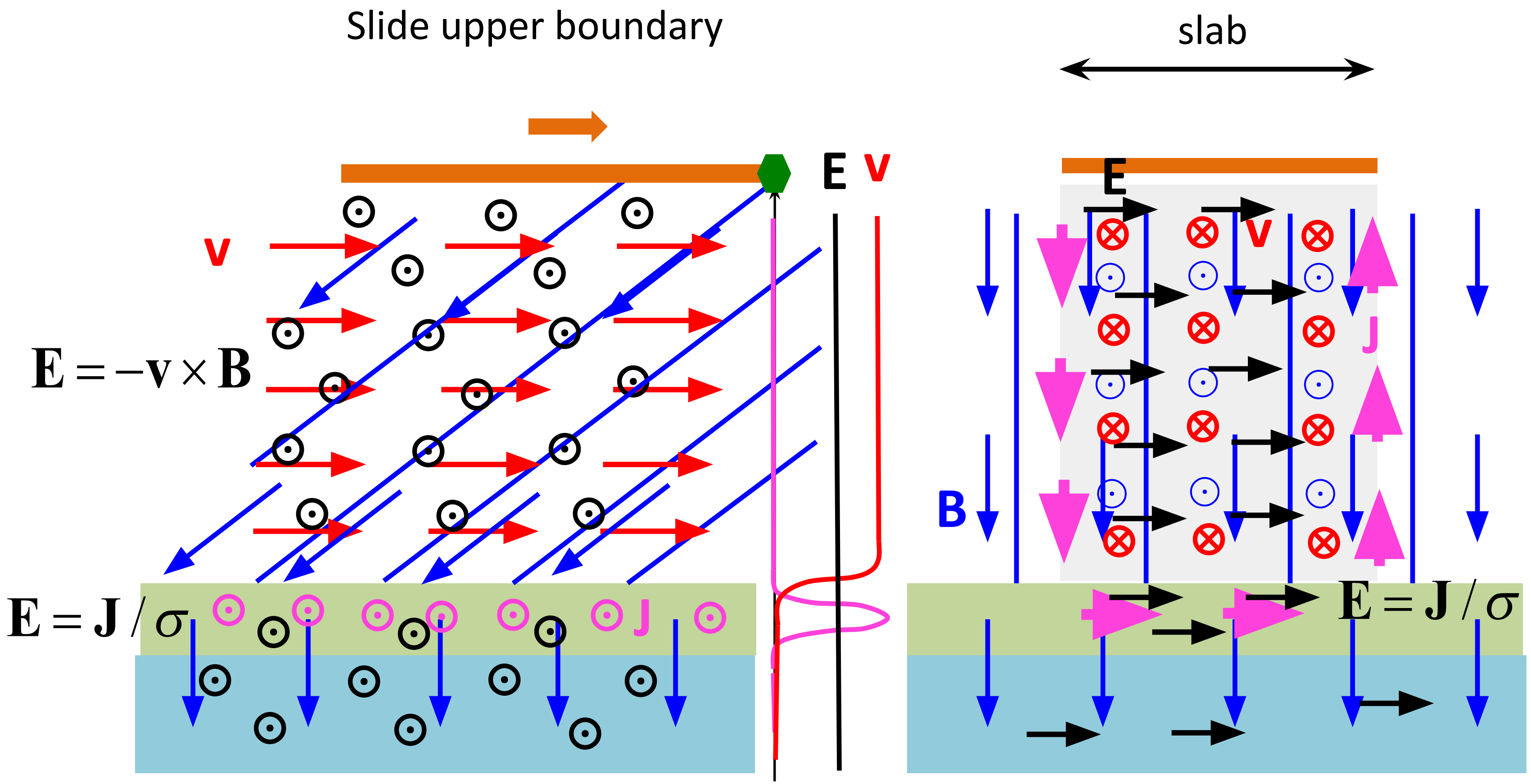
Example of how the motions meet



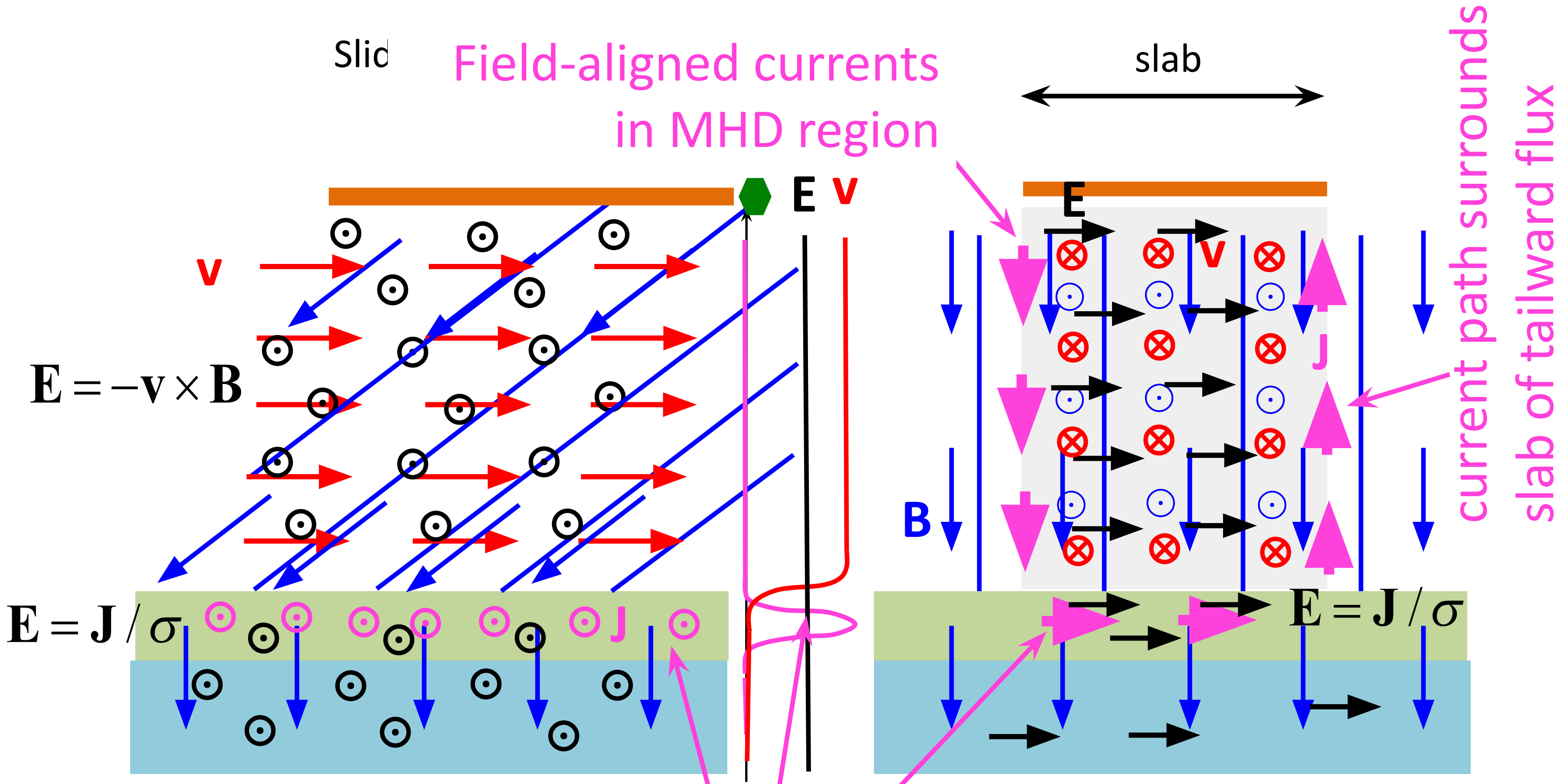
Example of how the motions meet



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

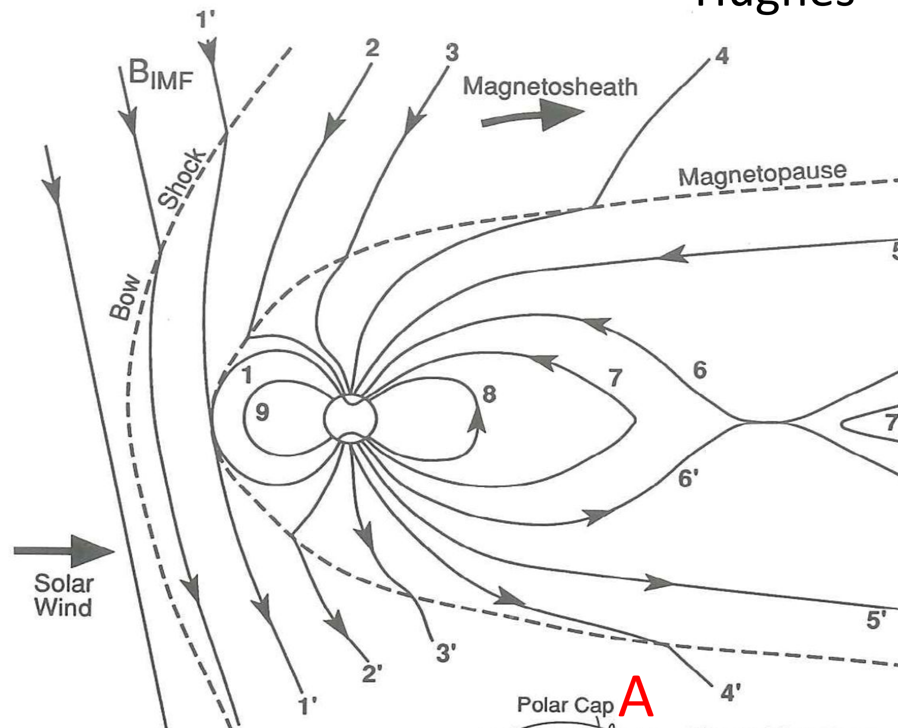
MHD motions drag footpoints across polar caps and back around to day side

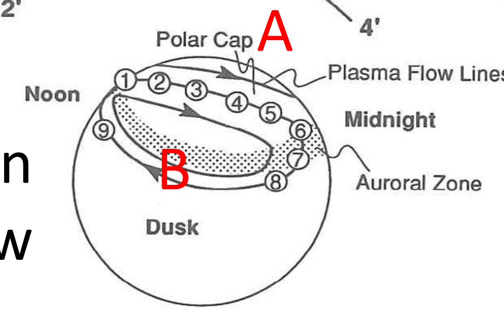
Integrate* **E** across polar cap:

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

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

Hughes



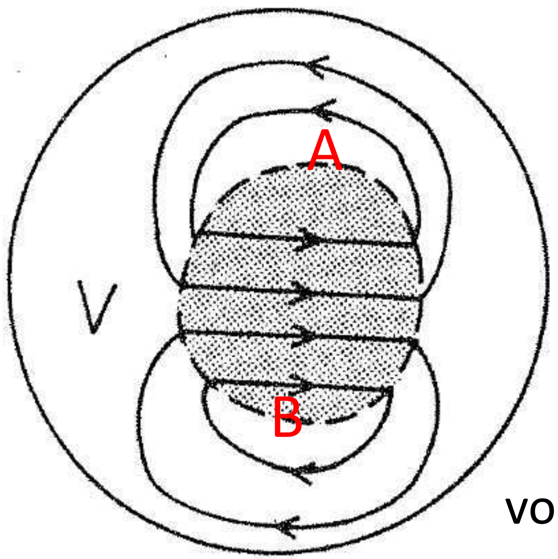


Convection flow

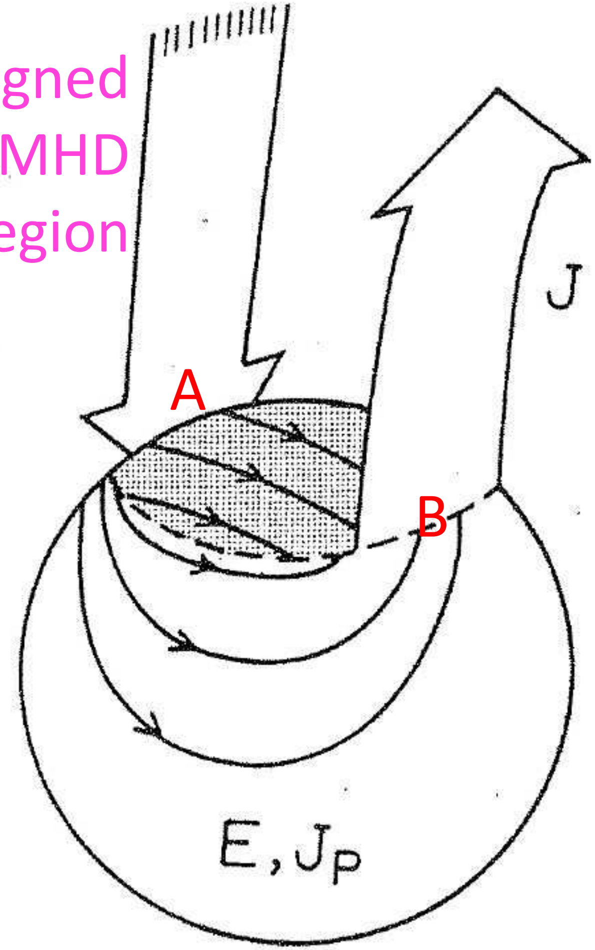
* use MKS here

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

Convection flow



Field-aligned currents in MHD region



vol. I fig. 10.5

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