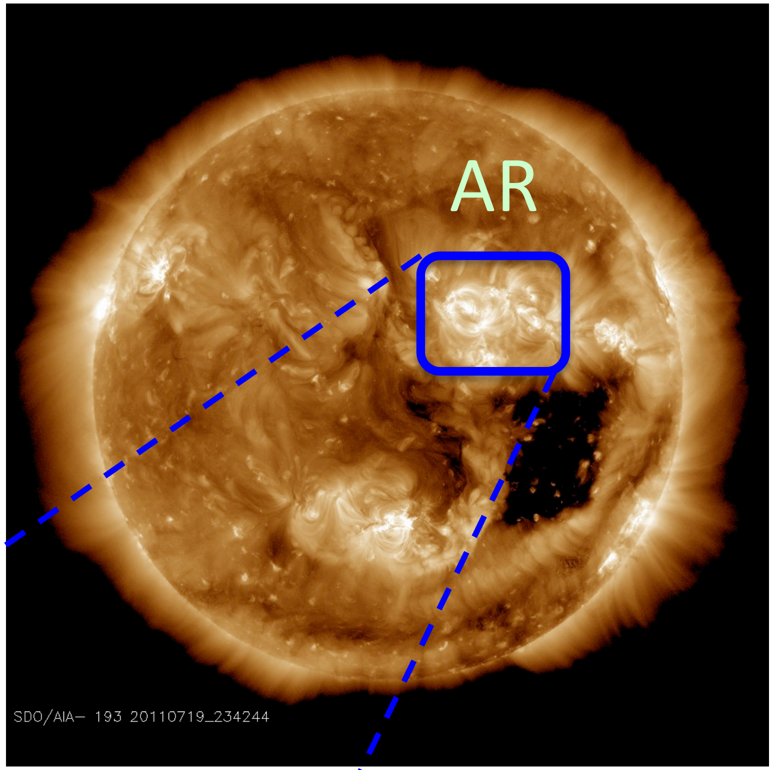
Q: Why does the Sun have a Corona? A Wind?

Dana Longcope
Montana State University

Review & Activities based on original talk

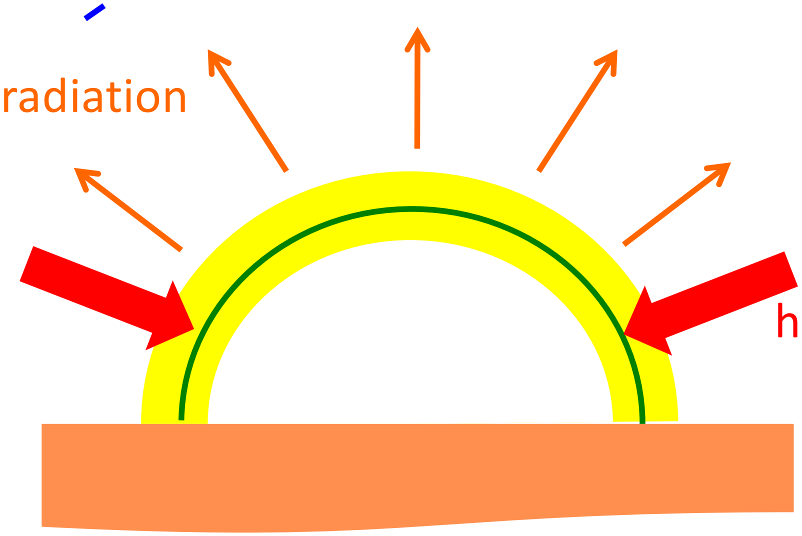
B large enough to restrict plasma motion: only along field lines



0d picture: balance between heat & radiation @ fixed pressure

Radiative losses per volume:
Vol. I: Eq. (8.6)
Principia (9.1)

$$\boxed{n_e n_H}\Lambda(T) = p^2 \frac{\Lambda(T)}{k_b^2 T^2}$$



Activity 122 (p. 243): Eq. (9.1) contains a product of electron and hydrogen densities, but hydrogen is fully ionized at coronal temperatures and thus has no spectral lines that can be excited through collisions with electrons. Why is it acceptable to express it this way?

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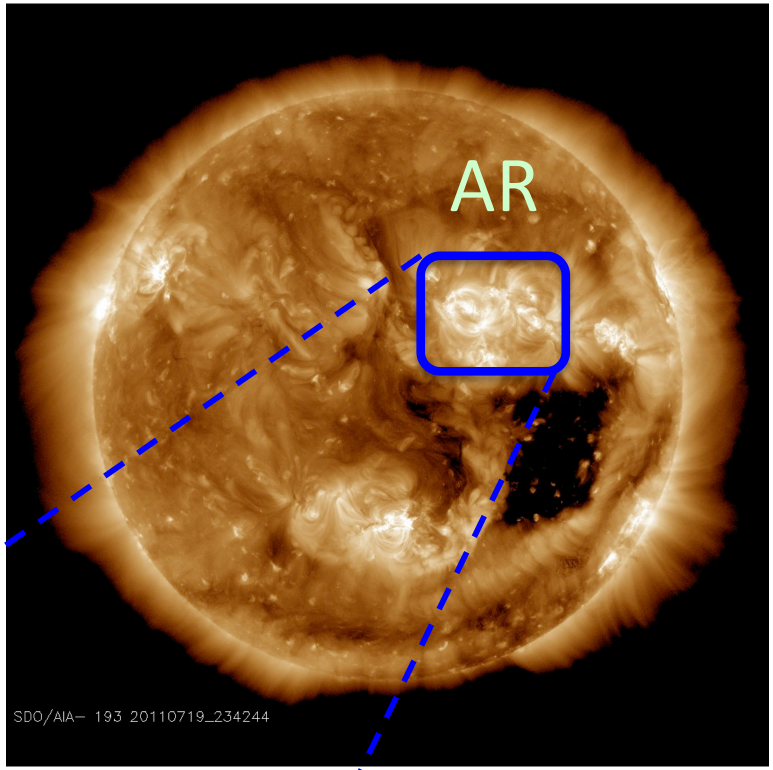

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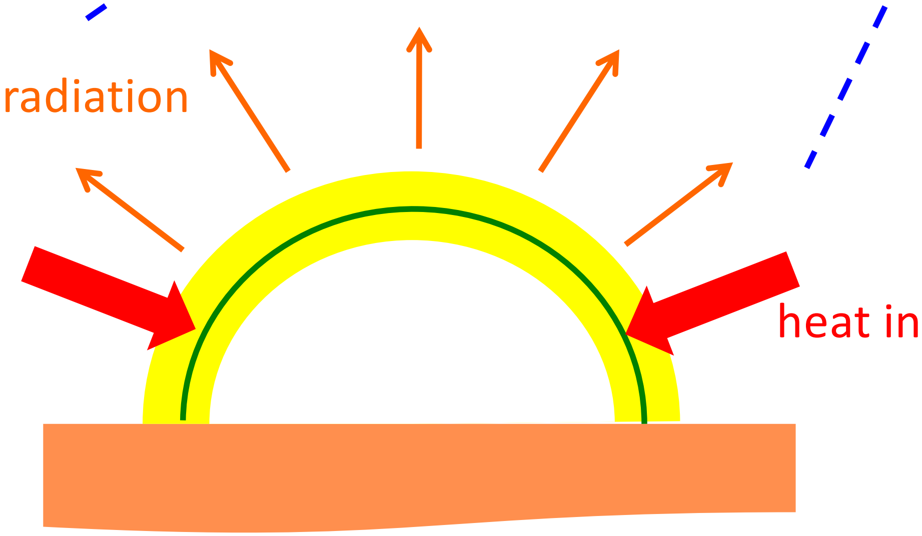
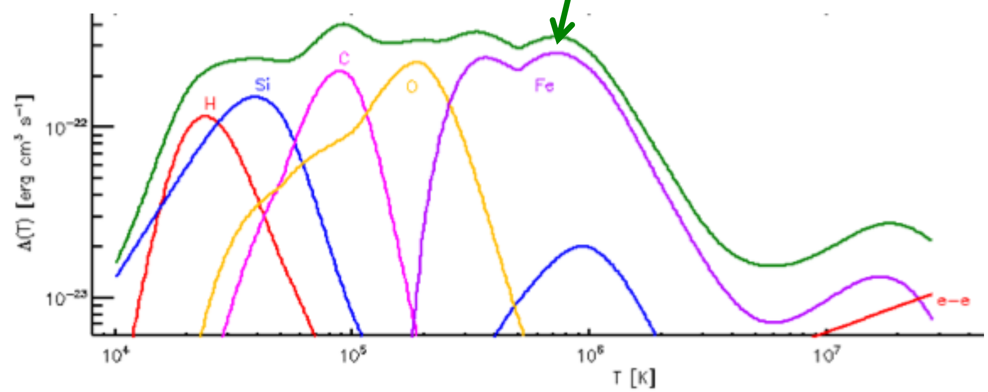
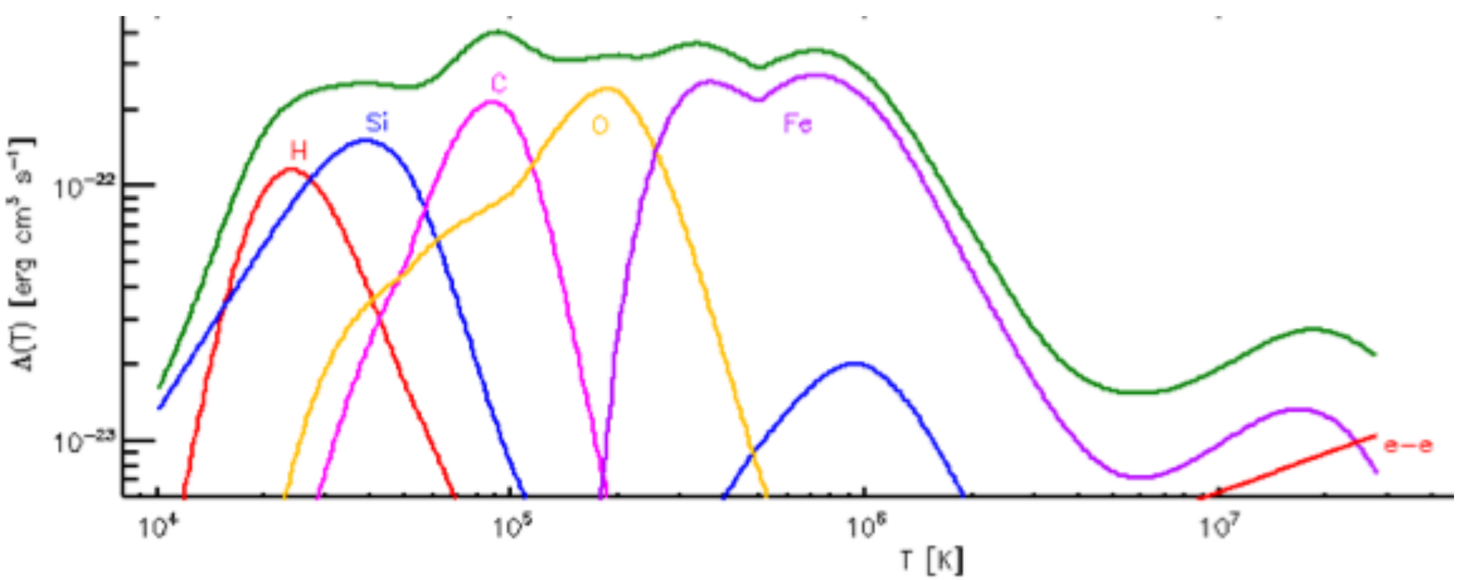




Activity 121 (p. 243): The processes of electromagnetic radiation from a plasma involve three fundamentally distinct processes: bound-bound, free-bound (radiative recombination), and free-free (Bremsstrahlung) emission. **The Sun's coronal emission, caused by collisions of ions with thermal electrons, is dominated the first,** except for flares when the last is also important; why?

➔ Which ions are typically strong contributors to the coronal X-ray and EUV emission from an active region at ~ 3MK? Hint: combine elemental abundances with ionization energies (such as given by *). For this rough estimate, ignore oscillator strengths for the transitions involved. For the solar corona under most conditions, the dominant radiative losses are from C, N, O (below about 0.5 MK), and Fe (above about 0.5 MK).

https://en.wikipedia.org/wiki/Ionization_energies_of_the_elements_(data_page)

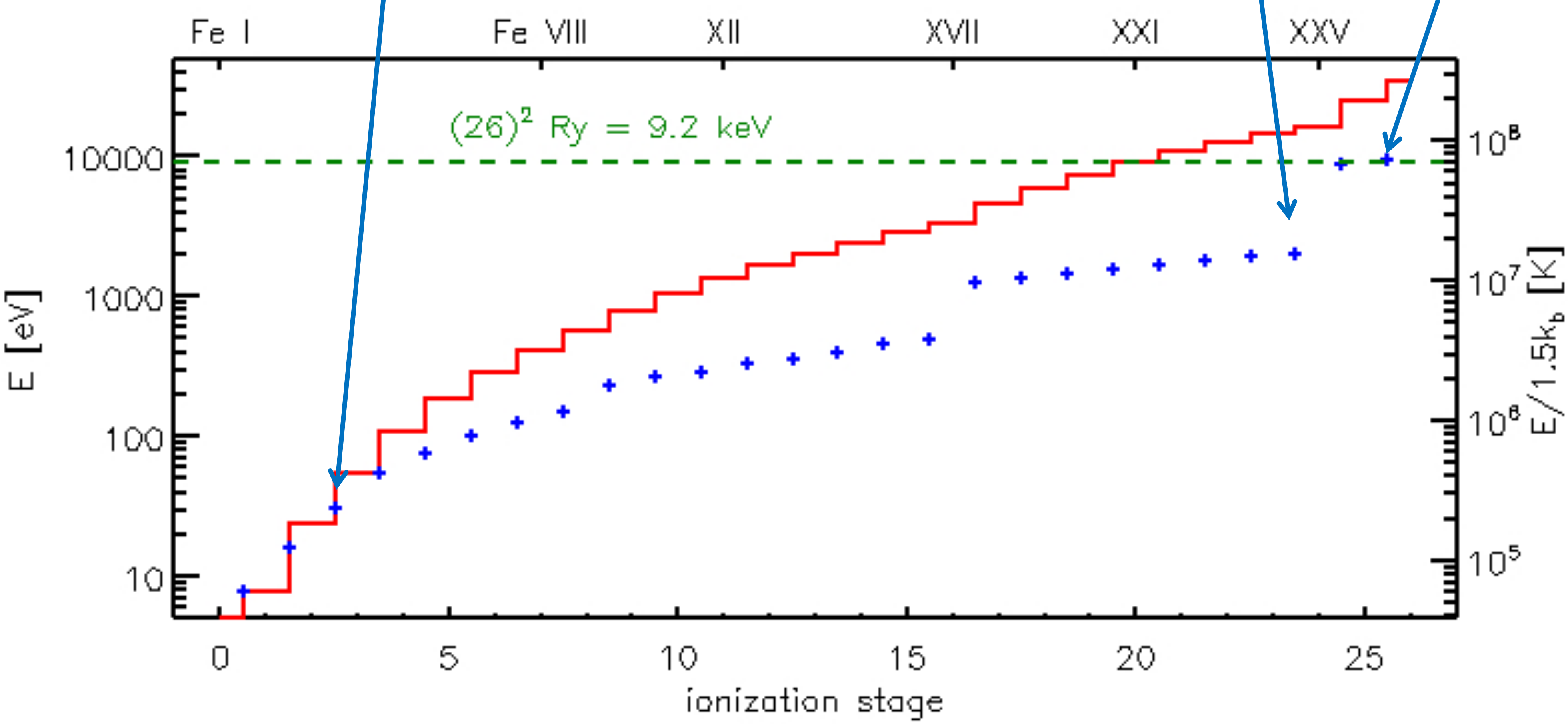


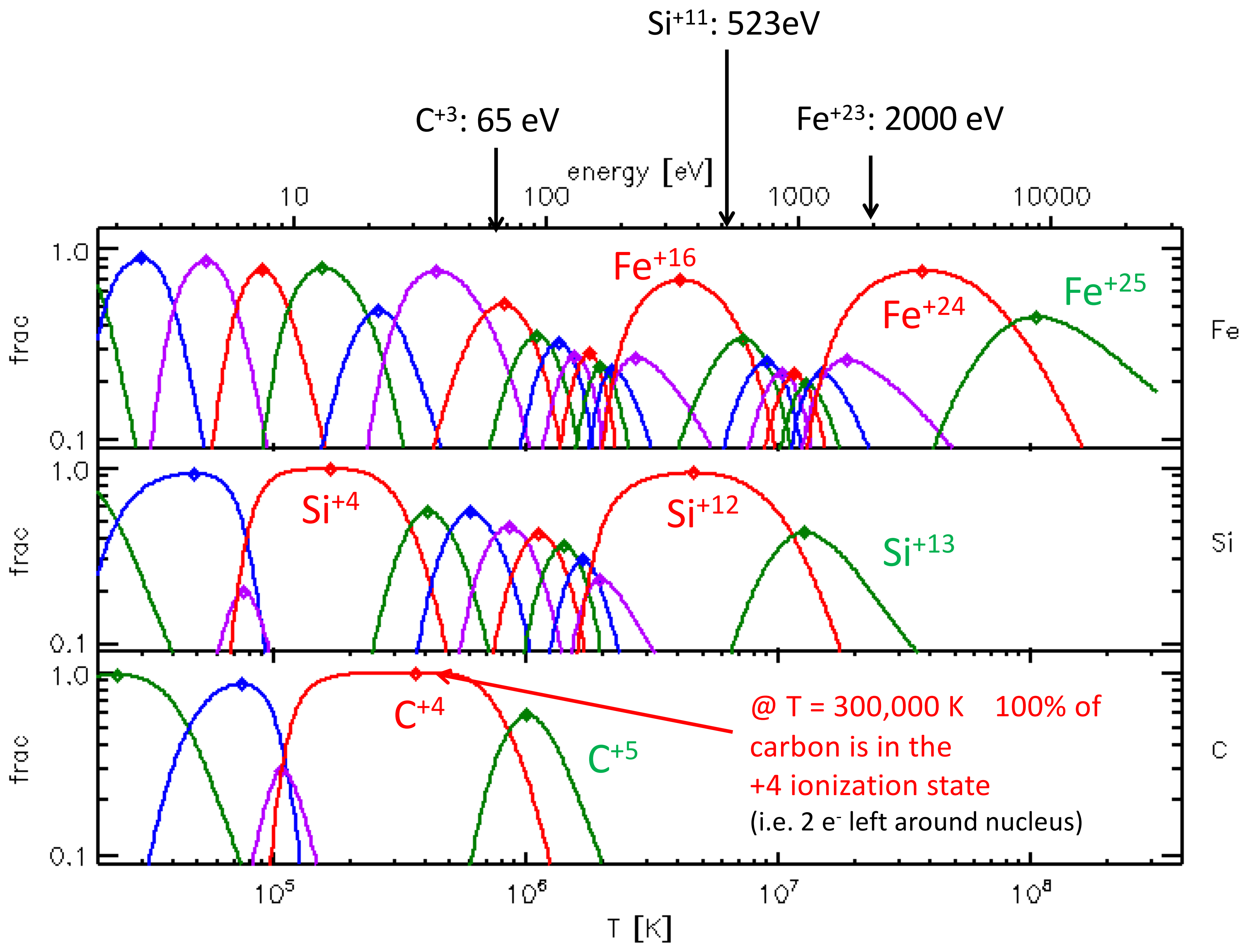
Fe^{+2}

26 Fe iron							
use	**762.5**	**1561.9**	**2957**	**5290**	**7240**	**9560**	**1**
WEL	762.5	1561.9	2957	5290	7240	9560	1
CRC	7.9024	16.1878	30.652	54.8	75.0	99.1	1

Fe^{+23} Fe^{+25}

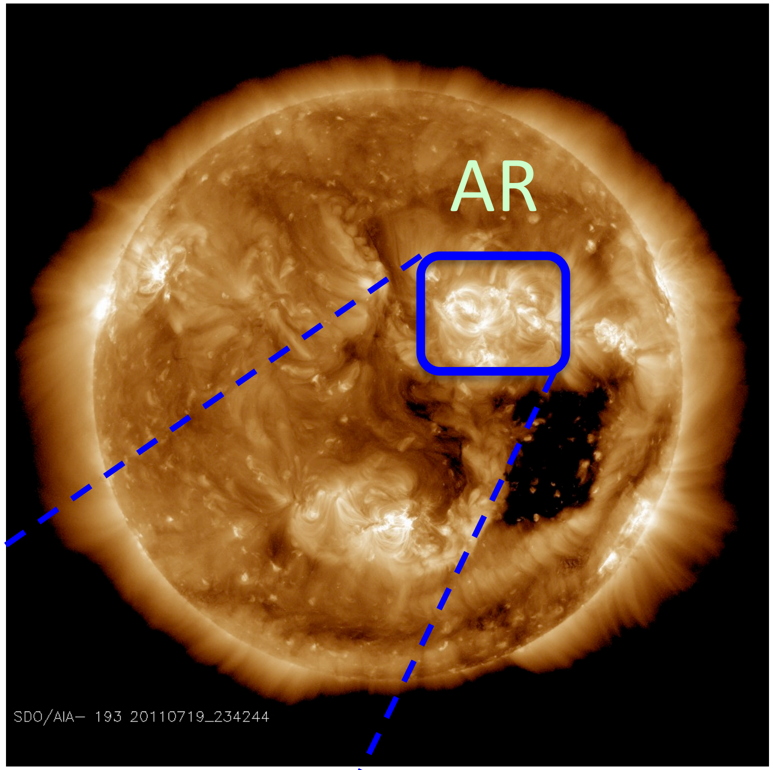
3600	**188100**	**195200**	**851800**	**895161**
99	1950	2023	8828	9277.69

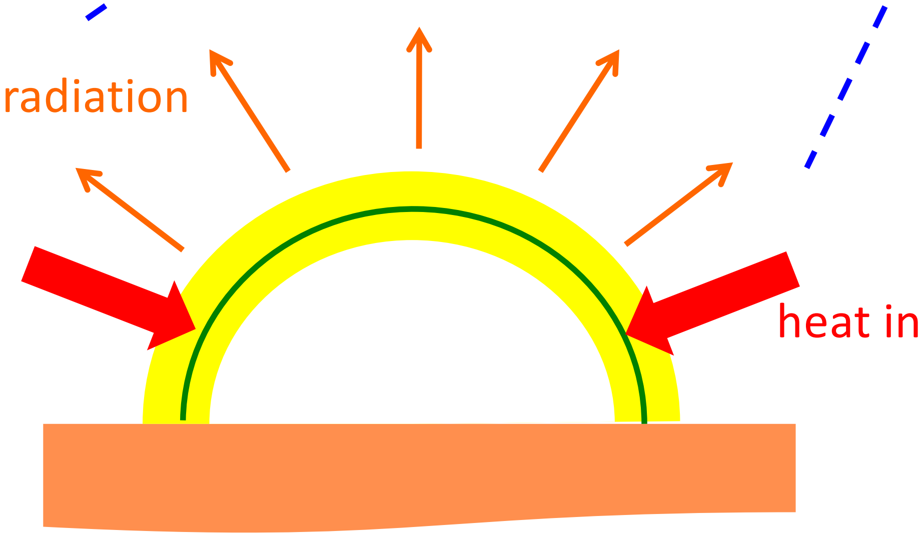




Si+11: 523eV
C+3: 65 eV
Fe+23: 2000 eV
energy [eV]
10
100
1000
10000
1.0
0.1
frac
Fe+16
Fe+24
Fe+25
Fe
Si+4
Si+12
Si+13
Si
C+4
C+5
C
@ T = 300,000 K 100% of carbon is in the +4 ionization state
(i.e. 2 e- left around nucleus)
10^5
10^6
10^7
10^8
T [K]

B large enough to restrict plasma motion: only along field lines





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balance between heat & radiation @ fixed pressure

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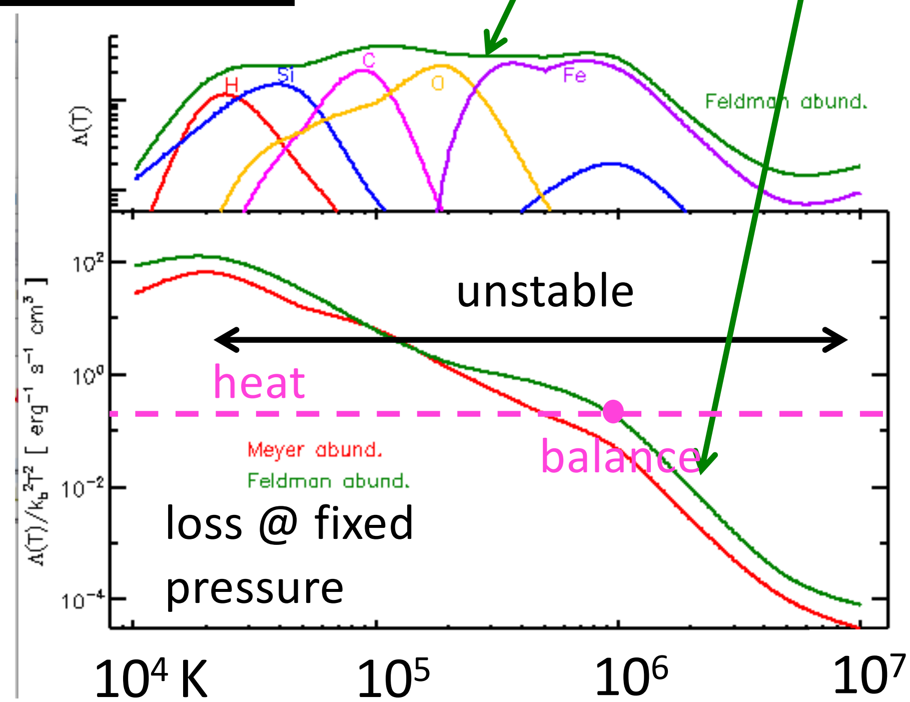
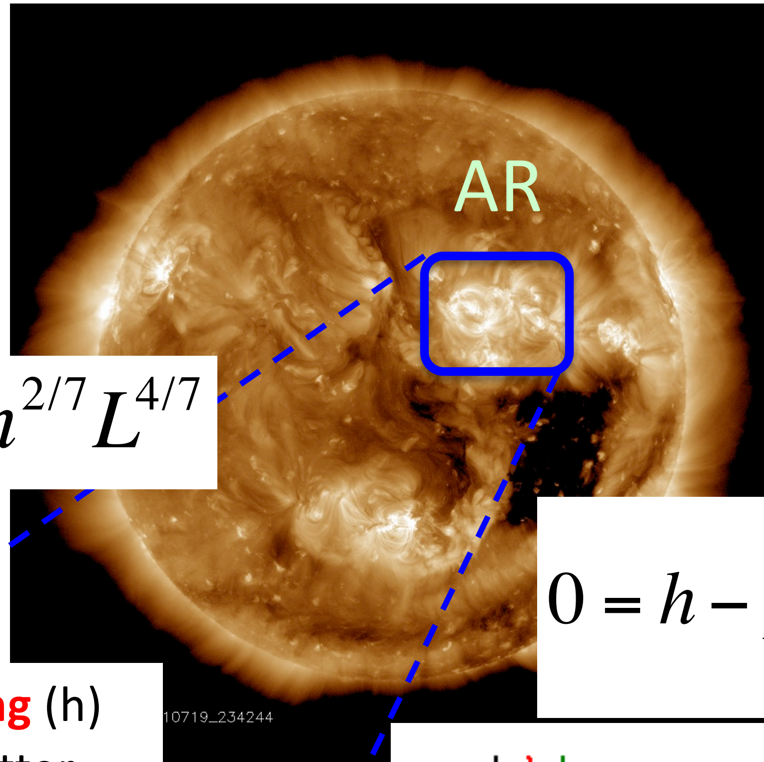


balance:
(RTV)

$$p \sim h^{6/7} L^{5/7}$$

$$T_{\max} \sim (pL)^{1/3} \sim h^{2/7} L^{4/7}$$

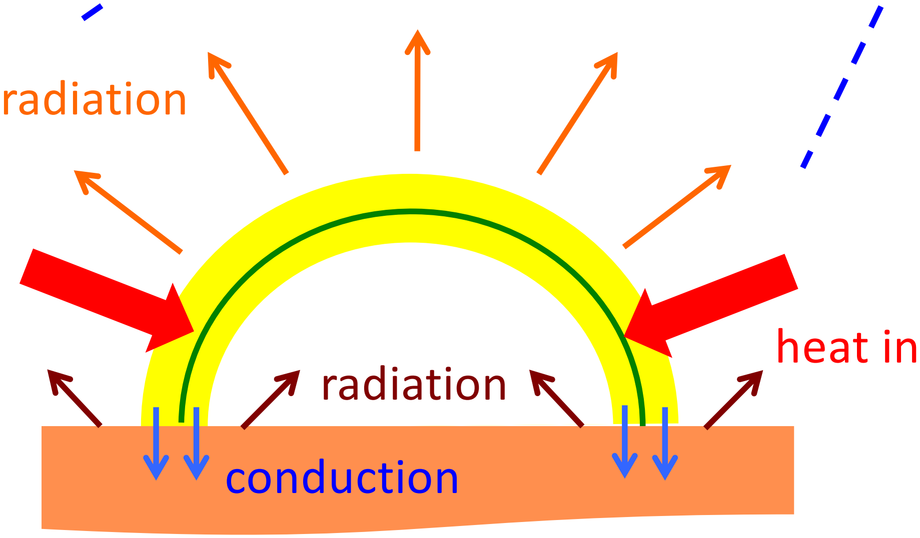
$$I \sim n_e^2 \sim h^{8/7} L^{2/7}$$

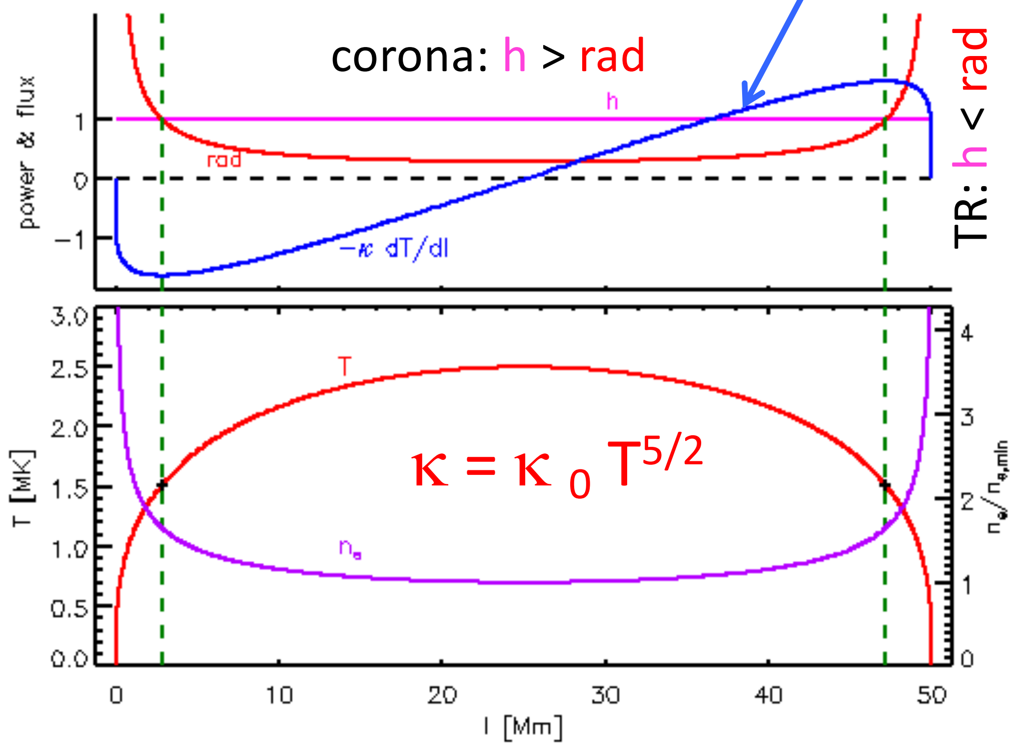


Need 1d:
include thermal
conduction to
move heat to
chromosphere

$$0 = h - p^2 \frac{\Lambda(T)}{k_B^2 T^2} + \frac{\partial}{\partial \ell}\left(\boxed{\kappa \frac{\partial T}{\partial \ell}}\right)$$

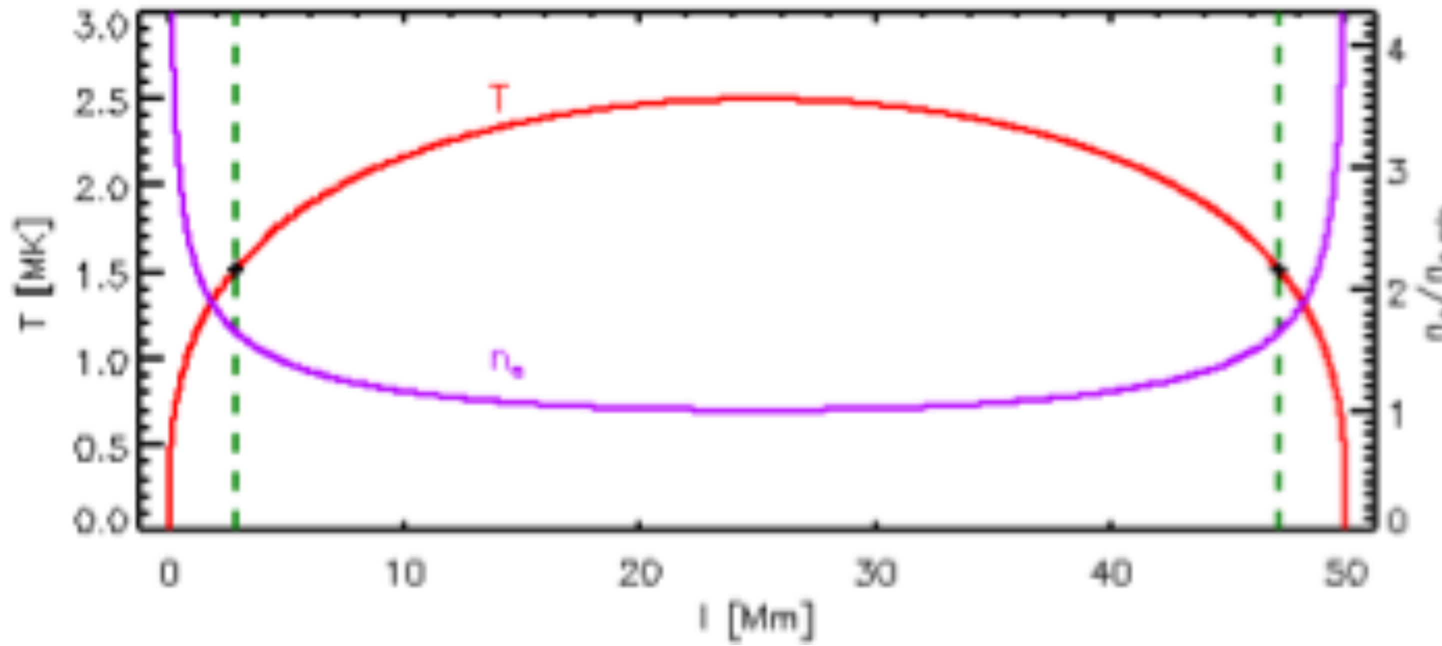
more heating (h)
➔ little hotter
much brighter





Activity 123 (p. 245): Use Eq. (9.4) to estimate typical volumetric heating rates (i.e. ε_{heat}) for … an active region (with coronal field strengths of order 200 G, loop-top temperatures of ~ 3 MK, and loop half lengths L $\simeq$ 15 × 10^9 cm). Compare [this] to the thermal energies also estimated from Eq. (9.4) and also compare plasma to field pressures (i.e., compute values of plasma-β).

$$T_{\mathrm{a},6} \approx 2.8(n_{\mathrm{a},10}L_9)^{1/2} \quad ; \quad T_{\mathrm{a},6} \approx 7.3(\epsilon_{\mathrm{heat}}L_9^2)^{2/7}, \tag{9.4}$$



Extra for later today: what are $T_{a,6}$ and $n_{a,10}$ when the heating rate ε_{heat} in the active region loop increases by × 10^4? On which does this have a larger effect?

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$$\varepsilon = L_9^{-2}\,(T_6/7.3)^{7/2} = (15)^{-2}\,2^{-7/2} = 4 \times 10^{-4}\ \text{erg cm}^{-3}\ \text{s}^{-1}$$

$$n_{10} = L_9^{-1}\,(T_6/2.8)^2 = (15)^{-1}\,1^2 = 0.067$$

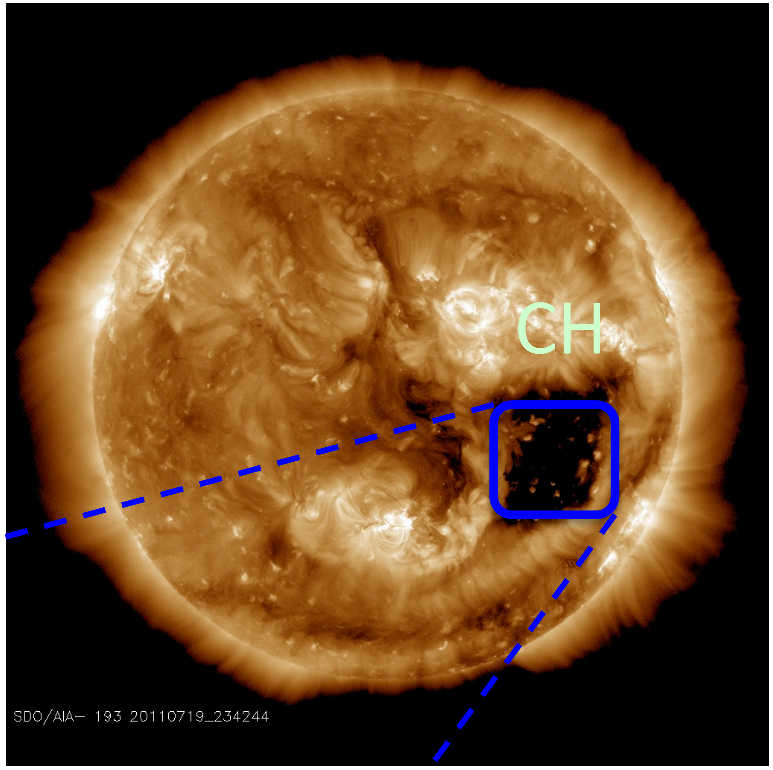
$$\Rightarrow\ n_e = 7 \times 10^8\ \text{cm}^{-3}$$

$$e = 3\,n_e\,k_b T = 3\,(7 \times 10^8)\,(4 \times 10^{-10}) = 0.9\ \text{erg cm}^{-3}$$

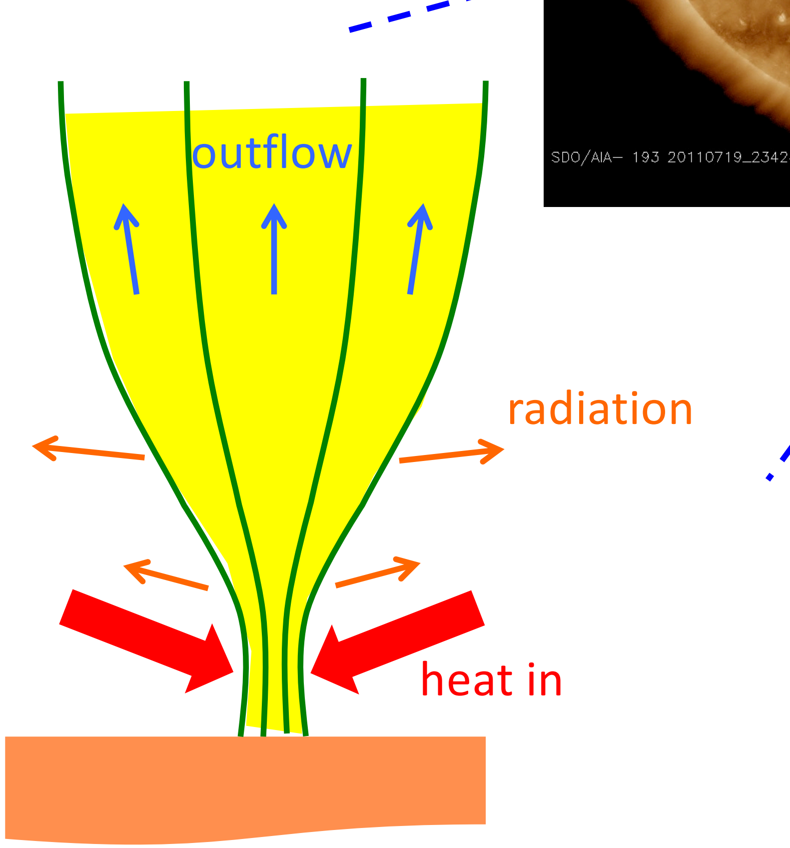
$$e/\varepsilon = 0.9/(4 \times 10^{-4}) = 2.2 \times 10^3\ \text{s} = 36\ \text{min}$$

$$F = L_9\,\varepsilon = L_9^{-1}\,(T_6/7.3)^{7/2} = 6 \times 10^6\ \text{erg cm}^{-2}\ \text{s}^{-1}$$

B large enough to restrict plasma motion: only along field lines



Wind: from open flux



specific enthalpy

$$\boxed{w(\rho) \propto \frac{\gamma}{\gamma - 1}\rho^{\gamma-1}}$$

Advective energy loss –

$$\tfrac{1}{2}\rho\mathbf{v}v^2 + \rho\mathbf{v}\boxed{w(\rho)}$$

>> radiative loss

$$\frac{1}{v}\frac{\mathrm{d}v}{\mathrm{d}r}\left\{v^2 - \frac{2kT}{m_\mathrm{p}}\right\} = \left\{\frac{4kT}{m_\mathrm{p} r} - \frac{GM_\odot}{r^2}\right\} \qquad (2.10)$$

$$\frac{d}{dr}\left\{\frac{v^2}{2} - \frac{2k_bT}{m_p}\ln(v)\right\} = \frac{d}{dr}\left\{\frac{2k_bT}{m_p}\ln(r^2) + \frac{GM_\odot}{r}\right\}$$

because
dT/dr = 0

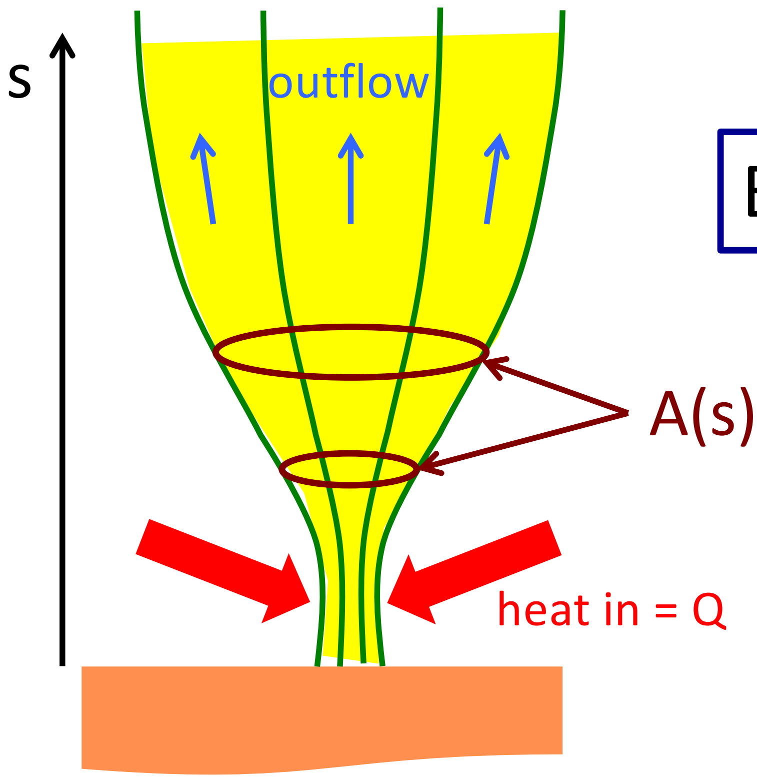
$$\frac{d}{dr}\left\{\frac{v^2}{2} - \frac{2k_bT}{m_p}\ln(vr^2) - \frac{GM_\odot}{r}\right\} = 0 = \frac{d}{dr}\left\{\frac{v^2}{2} + \frac{2k_bT}{m_p}\ln(\rho) - \frac{GM_\odot}{r}\right\}$$

kinetic

potential

Bernoulli's law:

specific enthalpy



$$w = \int^p \frac{dp'}{\rho(p')} = \frac{2k_bT}{m_p}\int^\rho \frac{d\rho'}{\rho'} = \frac{2k_bT}{m_p}\ln(\rho)$$

$$\frac{1}{v}\frac{\mathrm{d}v}{\mathrm{d}r}\left\{v^2 - \frac{2kT}{m_\mathrm{p}}\right\} = \left\{\frac{4kT}{m_\mathrm{p}r} - \frac{GM_\odot}{r^2}\right\} \tag{2.10}$$

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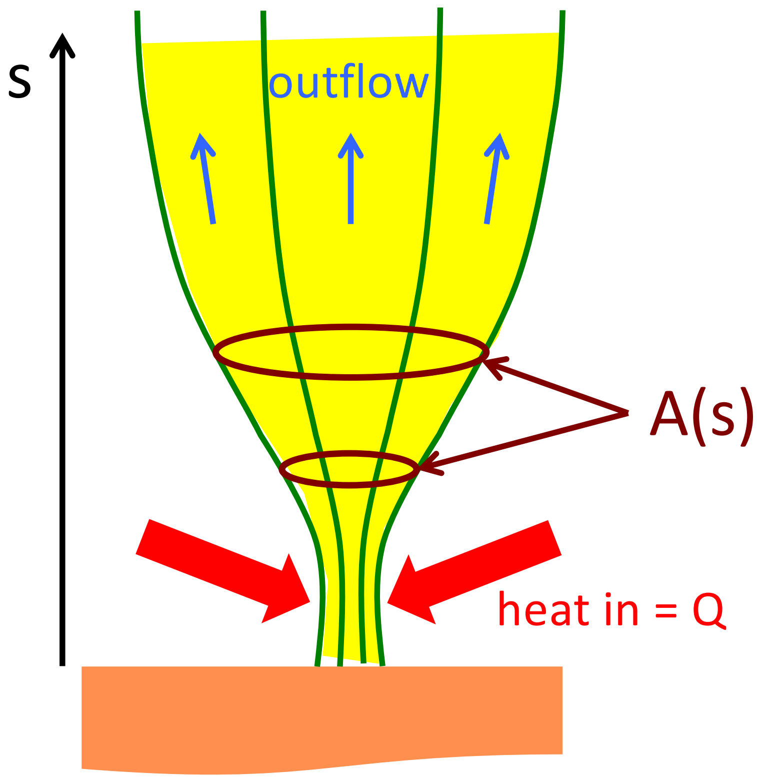
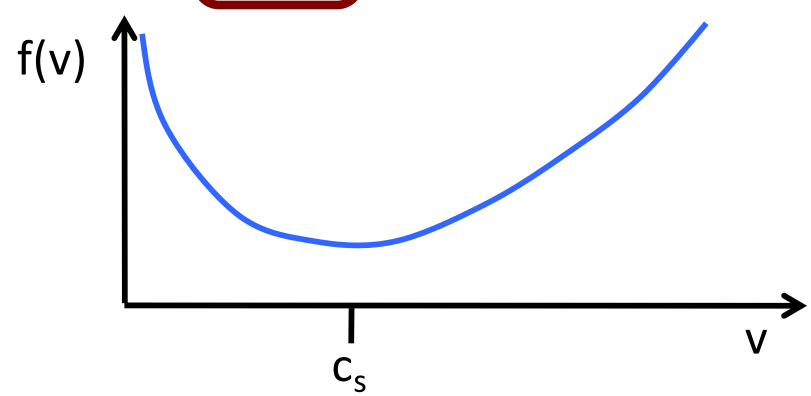
$f(v) = v^2/2 - c_s^2 \ln(v)$

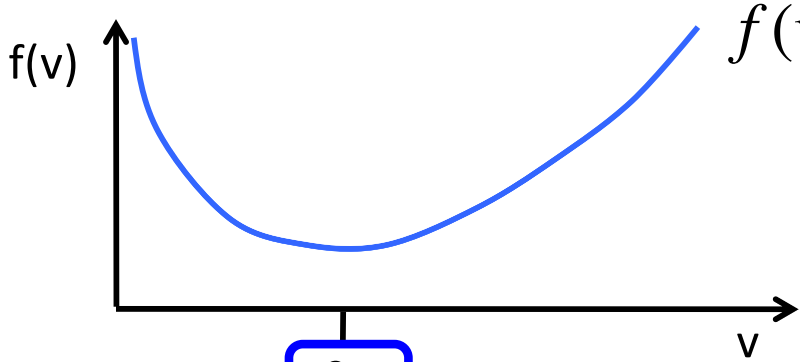
$- g(r) = c_s^2 \ln(A) - \Psi(r)$



$$\rightarrow \boxed{\tfrac{1}{2}v^2 - c_s^2 \ln(v)} - c_s^2 \ln[A(s)] + \Psi(s) = \text{const.}$$

$$= \boxed{f(v)} + g(s) = \text{const.}$$





$$f(v) = \tfrac{1}{2}v^2 - c_s^2 \ln(v)$$

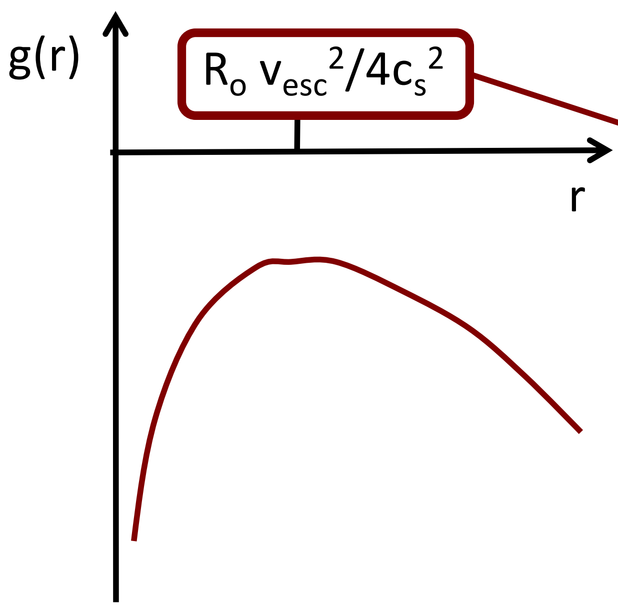
$$F(v,r) = f(v) + g(r) = \frac{Q}{\dot{M}} = \text{const.}$$

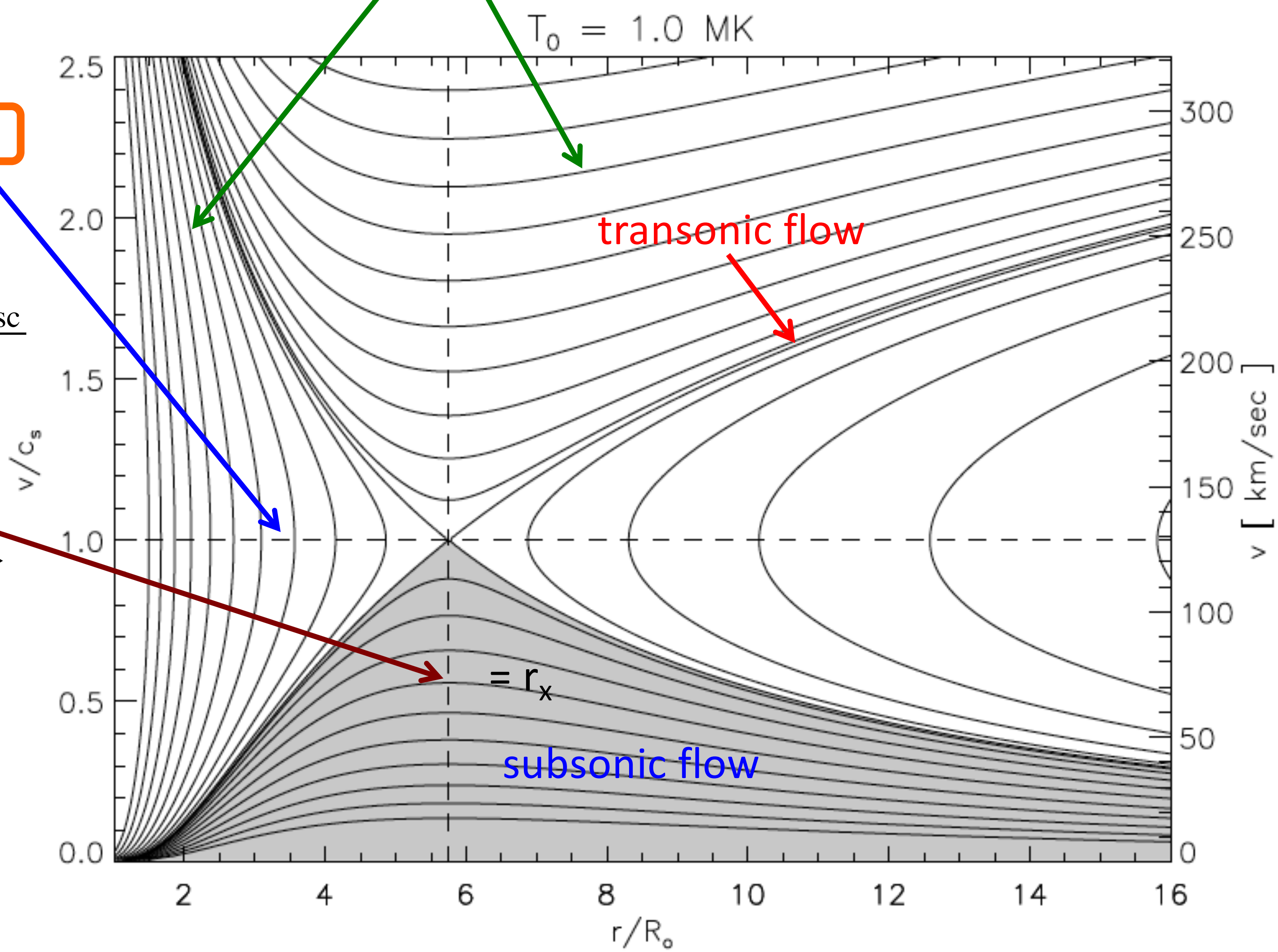
tube:

$\boxed{\text{cone}}$ w/ $\boxed{\text{vertical axis}}$

$\boxed{A(s) \sim s^2}$ $\boxed{s = r}$

$$g(r) = -2c_s^2 \ln(r) - \frac{R_o v_{esc}^2}{2r}$$



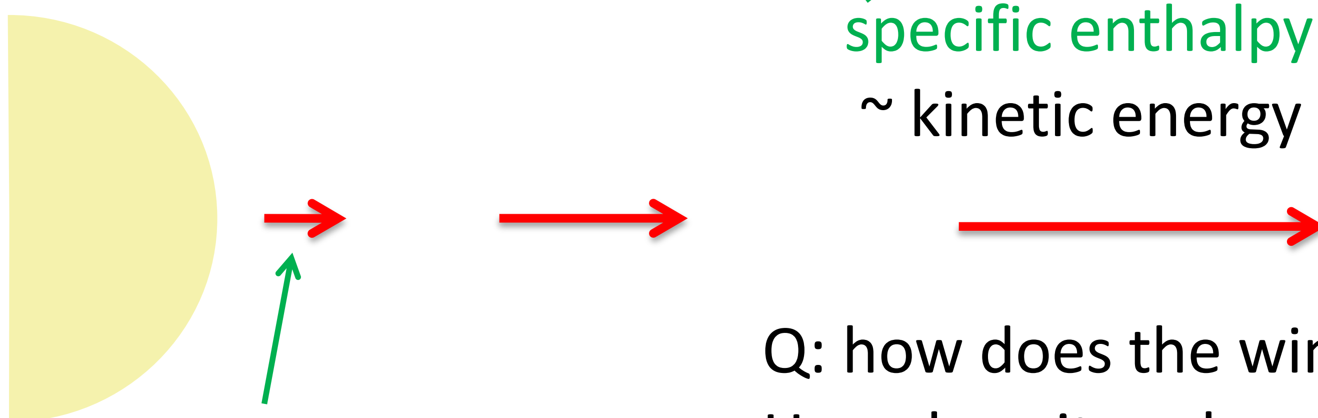


Activity 14 (p. 24): What powers the solar wind in the basic model discussed here? To see the answer, rewrite Eq. (2.10) to an energy equation with the terms for the kinetic and potential energy in the Sun's gravitational field, plus a term that reflects the work done by the expanding gas both geometrically and by acceleration; the energy for that expansion in the isothermal approximation is provided by the thermal conduction by the electron population…

Bernoulli's law: $v^2/2 + w + \Psi(r)$ = constant

specific enthalpy ~ c_s^2

~ kinetic energy of particles



Q: how does the wind escape?

How does it end up going faster?

$c_s \sim 150$ km/s

$v \sim 0$

$\Psi(R) = -\,v_{esc}^2/2$; $v_{esc} \sim 600$ km/s

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$$\frac{d}{dr}\left(\frac{v^2}{2}\right) - \frac{2k_bT}{m_p}\frac{d}{dr}\ln(v) = \frac{2k_bT}{m_p}\frac{d}{dr}\ln(r^2) + \frac{d}{dr}\left(\frac{GM_\odot}{r}\right)$$

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$$\frac{d}{dr}\left\{\frac{v^2}{2} - \frac{GM_\odot}{r}\right\} = \frac{2k_bT}{m_p}\frac{d}{dr}\ln(vr^2) = p\,\frac{d}{dr}\left(\frac{1}{\rho}\right)$$

kinetic potential -work = p dV/dr = -de/dr + dQ/dr

$$\frac{d}{dr}\left\{\frac{v^2}{2} + e - \frac{GM_\odot}{r}\right\} = \frac{dQ}{dr} = T\frac{ds}{dr}$$

heating NB: de/dr = 0

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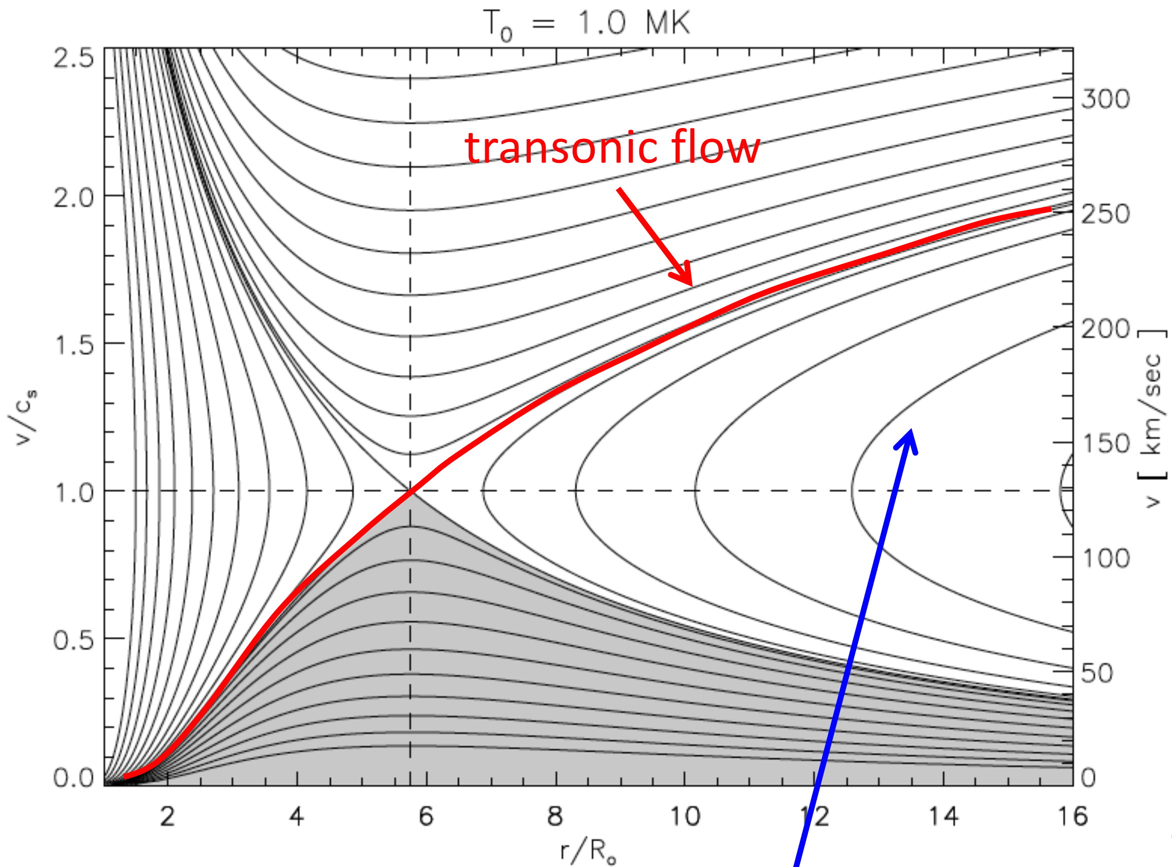
because dT/dr = 0

$$\frac{d}{dr}\left\{\frac{v^2}{2} + e - \frac{GM_\odot}{r}\right\} = \frac{dQ}{dr} = T\frac{ds}{dr}$$

heating

Q: how can I easily see that heat (i.e. entropy) must be added to the wind to keep T constant?

A: ds/sr = 0 ➔ $T \sim \rho^{\gamma-1} = \rho^{2/3}$ will decrease moving outward



Activity 14 continued (p. 24):
… The real-world solar wind is not isothermal, certainly not far from the Sun (compare the coronal temperatures in Table 2.3 with near-Earth wind properties in Table 2.4), and moreover is provided some additional power (in the form of heating and pressure) by waves and turbulence.

far from Sun

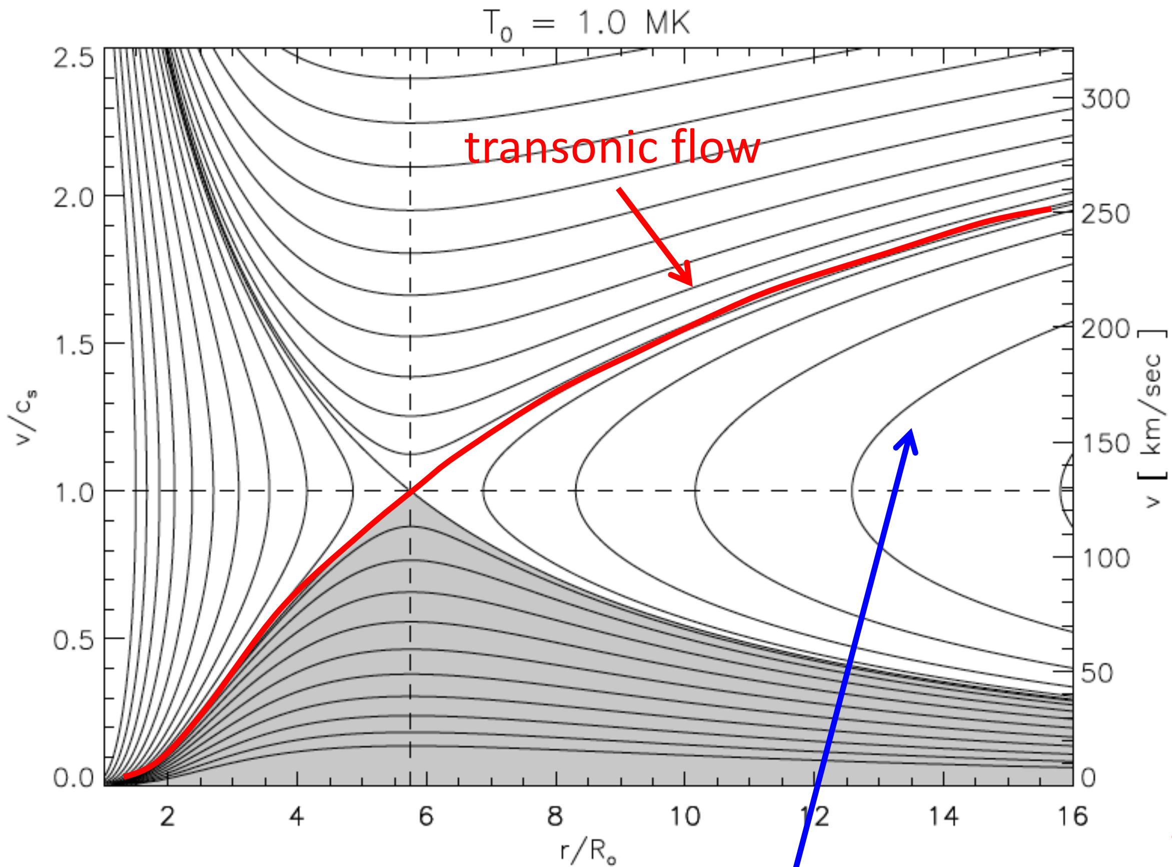
Bernoulli's law: $v^2/2 + w + \Psi(r)$ = constant

hypersonic:

$v >> c_s$

➔ $v \sim$ constant $\quad \frac{\mathrm{d}}{\mathrm{d}r}(\rho v 4\pi r^2) = 0 \quad$ ➔ $\rho \sim r^{-2}$

adiabatic ($ds/dr=0$) ➔ $T \sim \rho^{2/3} \sim r^{-4/3}$



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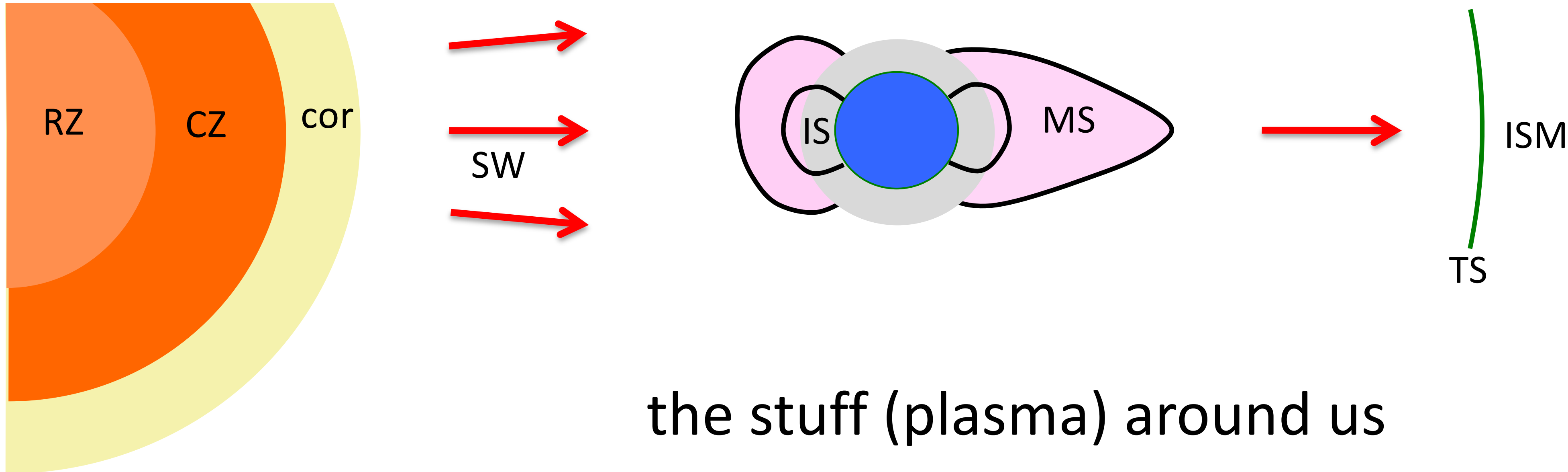
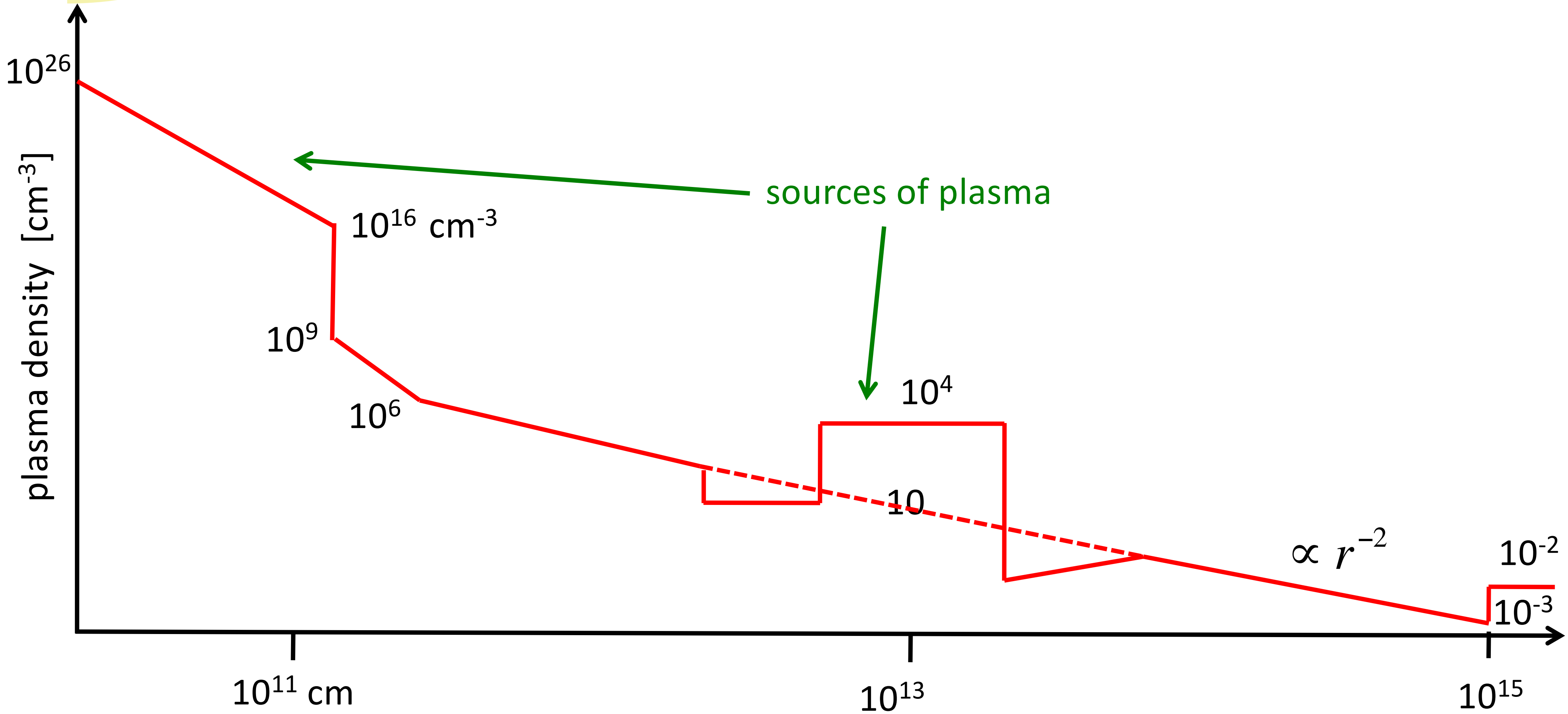
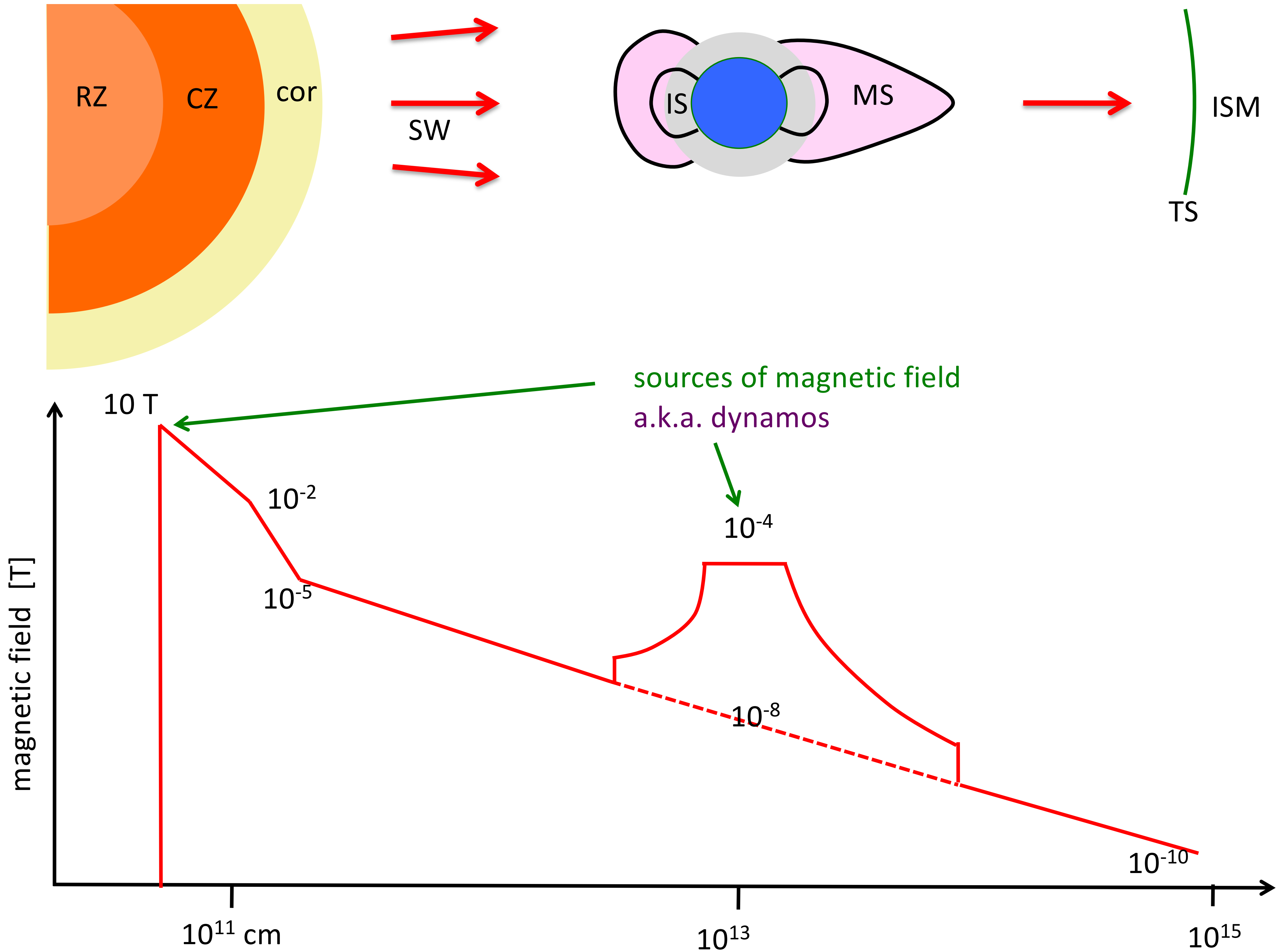


the stuff (plasma) around us





RZ
CZ
cor
SW
IS
MS
ISM
TS
sources of magnetic field
a.k.a. dynamos
10 T
10^{-2}
10^{-5}
10^{-4}
10^{-8}
10^{-10}
magnetic field [T]
10^{11} cm
10^{13}
10^{15}

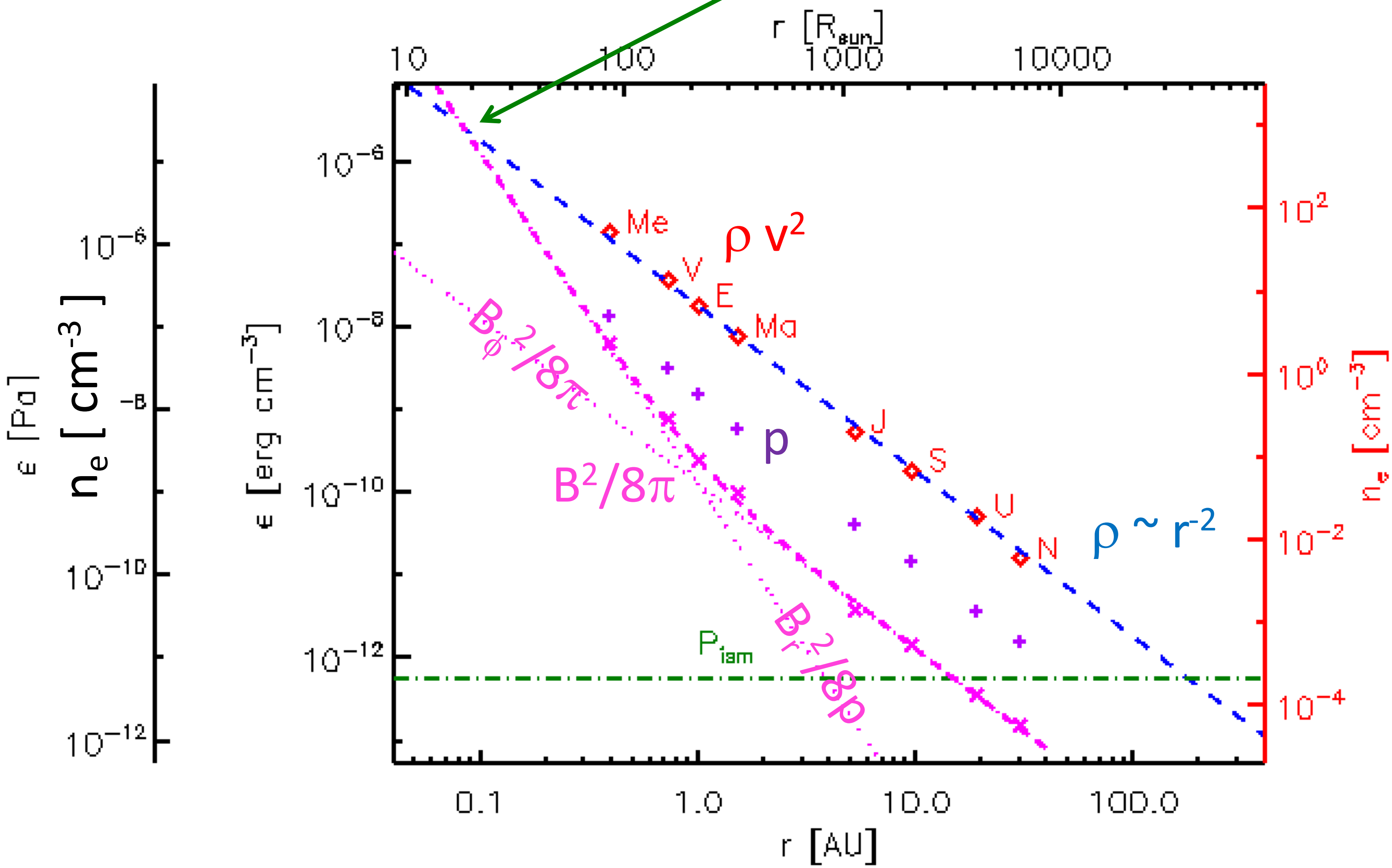
Activity 37 (p. 71): Make comparisons of energy densities for the solar wind as in Sec. 3.5.2 at other bodies in the Solar System (using Table 5.2). Why comparisons of energy densities in planetary magnetic fields (Table 5.2) and in the surrounding solar wind are informative is discussed in Ch. 5. Why would you expect the ow energy density and the magnetic field energy density to be comparable at only a few solar radii from the Sun?

Table 5.2. *Properties of the solar wind near the planets [after Table H-I:13.2]. Plasma β values assume a solar-wind temperature of 1.5 MK.*

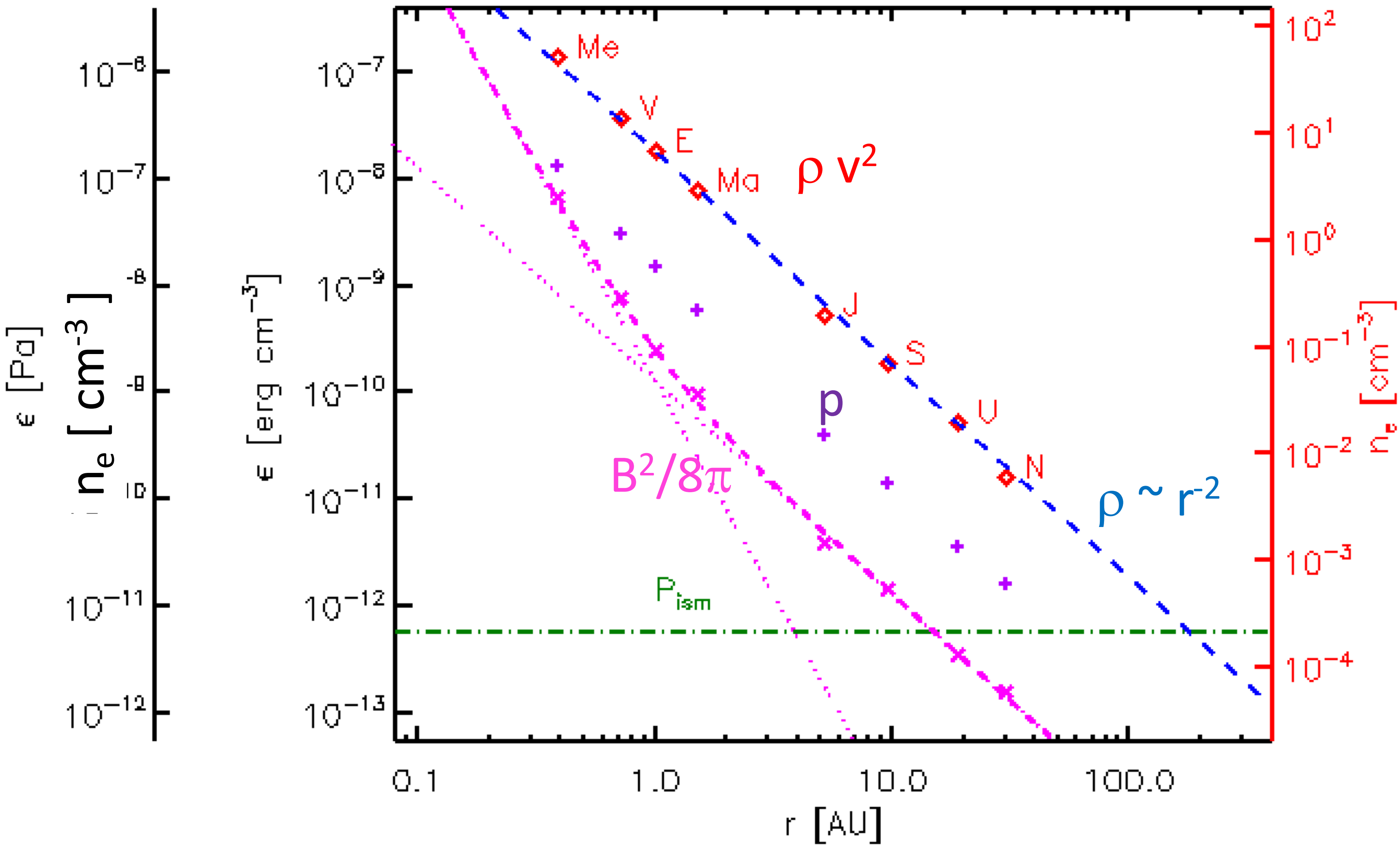
Planet	Distance d_{p} (AU) [a]	Solar wind density (cm^{-3})	B_{IMF} (μG) [c]	$\approx \beta$	$\approx v_{\mathrm{A}}$ (km/s)
Mercury	0.39	53	410	2	120
Venus	0.72	14	140	4	80
Earth	1	7[b]	80	6	70
Mars	1.52	3	50	6	60
Jupiter	5.2	0.2	10	10	50
Saturn	9.5	0.07	6	10	50
Uranus	19	0.02	3	10	50
Neptune	30	0.006	2	10	50

[a] 1 AU = $1.5\,10^8$ km; [b]tThe density of the solar wind fluctuates by about a factor of 5 about typical values of $\rho_{\mathrm{sw}} \sim (7\,\mathrm{cm}^{-3})/d_{\mathrm{p}}^2$; [c] mean values. [...]

Activity 37 (p. 71): Make comparisons of energy densities for the solar wind as in Sec. 3.5.2 at other bodies in the Solar System (using Table 5.2). Why comparisons of energy densities in planetary magnetic fields (Table 5.2) and in the surrounding solar wind are informative is discussed in Ch. 5. Why would you expect the flow energy density and the magnetic field energy density to be comparable at only a few solar radii from the Sun?

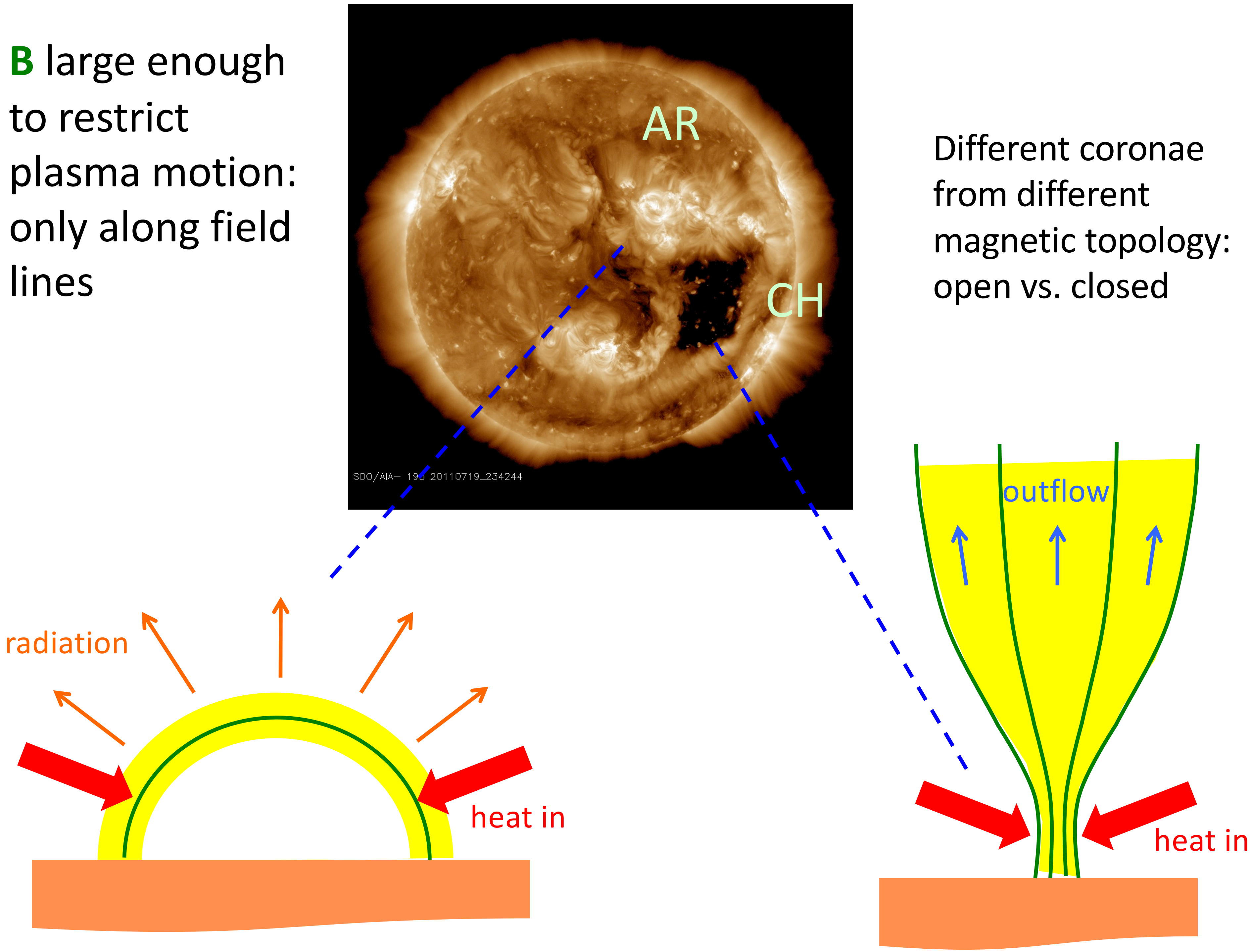


Activity 133 (p. 263): With average values for solar wind density and velocity (assuming a radial outflow at constant velocity and with a density as specified in Table 2.4), at what distance from the Sun does the solar wind dynamic pressure equal the interstellar total pressure for estimated values of $B_{LISM} \approx 3$ G, $T_{LISM} \approx 6500$ K, and $n_{p;LISM} \approx 0.06$ cm^{-3} and $n_{H;LISM} \approx 0.18$ cm^{-3} (see, e.g., Sect. H-IV:3.2)?



B large enough to restrict plasma motion: only along field lines

Different coronae from different magnetic topology: open vs. closed



Why are some field lines open & others closed?

Magnetic field dominates:
nothing capable of countering its force so…

$$(\nabla \times \mathbf{B}) \times \mathbf{B} = 0$$

$$\Rightarrow \boxed{\nabla \times \mathbf{B} = \alpha \mathbf{B}} \quad (i.e. \parallel \mathbf{B})$$

simplest version: $\alpha = 0$ (by fiat)

$$\Rightarrow \nabla \times \mathbf{B} = 0 \quad \Rightarrow \boxed{\mathbf{B} = -\nabla \chi}$$

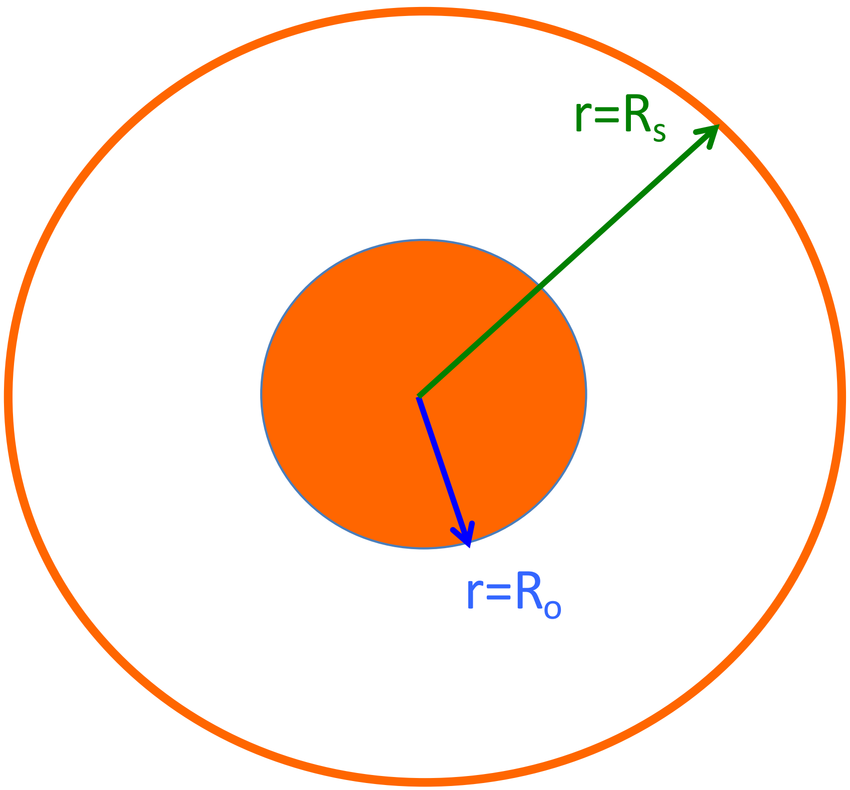
potential field
(cf. electrostatics)

$$\nabla \cdot \mathbf{B} = 0 \quad \Rightarrow \quad \nabla^2 \chi = 0$$

harmonic potential
(cf. electrostatics in vacuum)

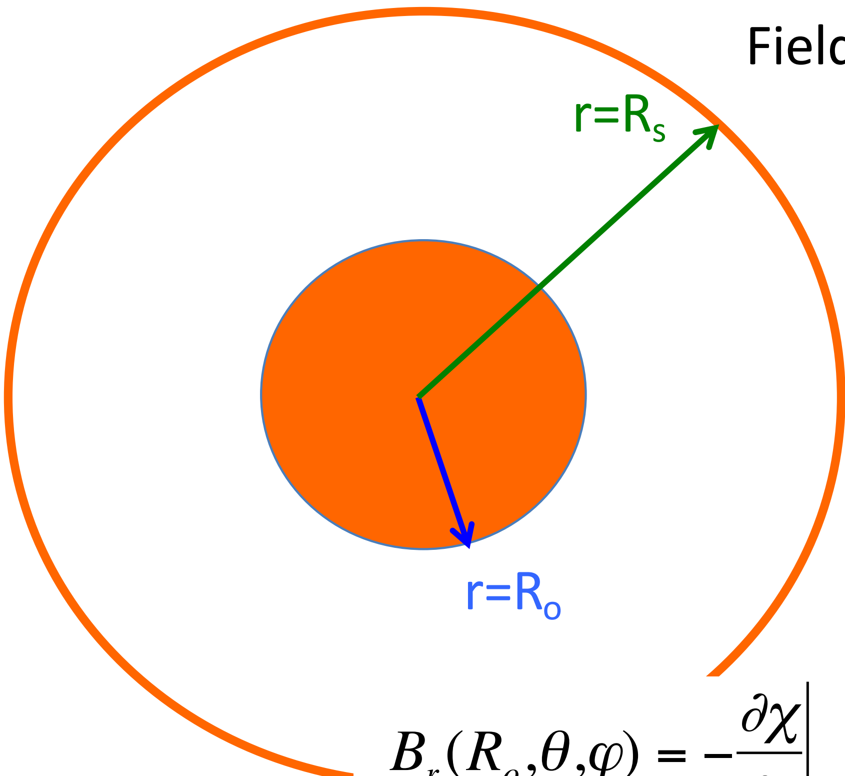
$$\mathbf{B} = -\nabla\chi \quad \& \quad \nabla^2\chi = 0$$

potential field outside sphere r=R_o



$$\mathbf{B} = -\nabla\chi \quad \& \quad \nabla^2\chi = 0$$

potential field outside sphere $r=R_o$



Field: purely radial @ $r=R_s$ (by fiat)

$$(B_\theta, B_\varphi) = 0 \quad \Rightarrow \quad \left(\frac{\partial\chi}{\partial\theta}, \frac{\partial\chi}{\partial\varphi}\right) = 0$$

$$\Rightarrow \quad \chi(R_s,\theta,\varphi) = 0$$

Dirichlet

$$\boxed{\chi(r,\theta,\varphi) = \sum_{\ell,m} A_{\ell,m}\left[\left(\frac{R_s}{r}\right)^{\ell+1} - \left(\frac{r}{R_s}\right)^{\ell}\right] Y_{\ell,m}(\theta,\varphi)}$$

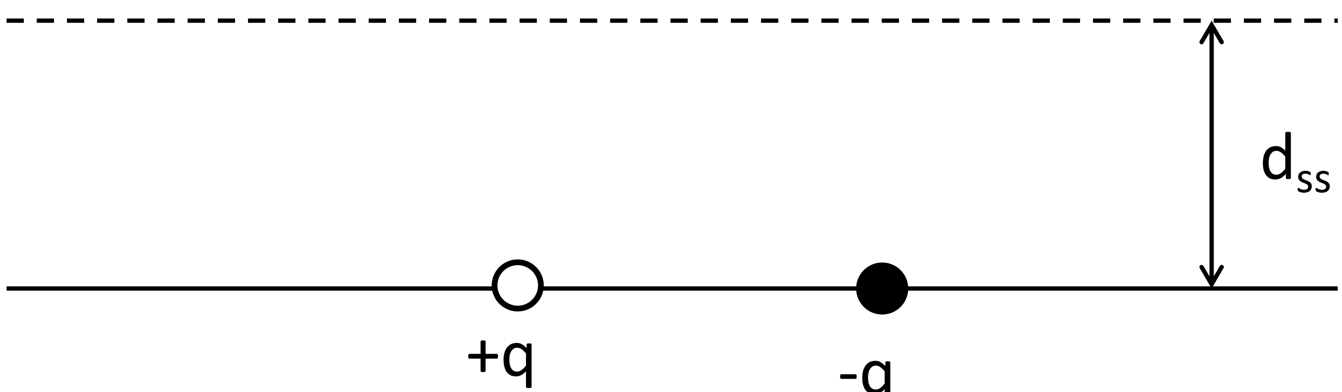
$$B_r(R_o,\theta,\varphi) = -\left.\frac{\partial\chi}{\partial r}\right|_{r=R_o}$$

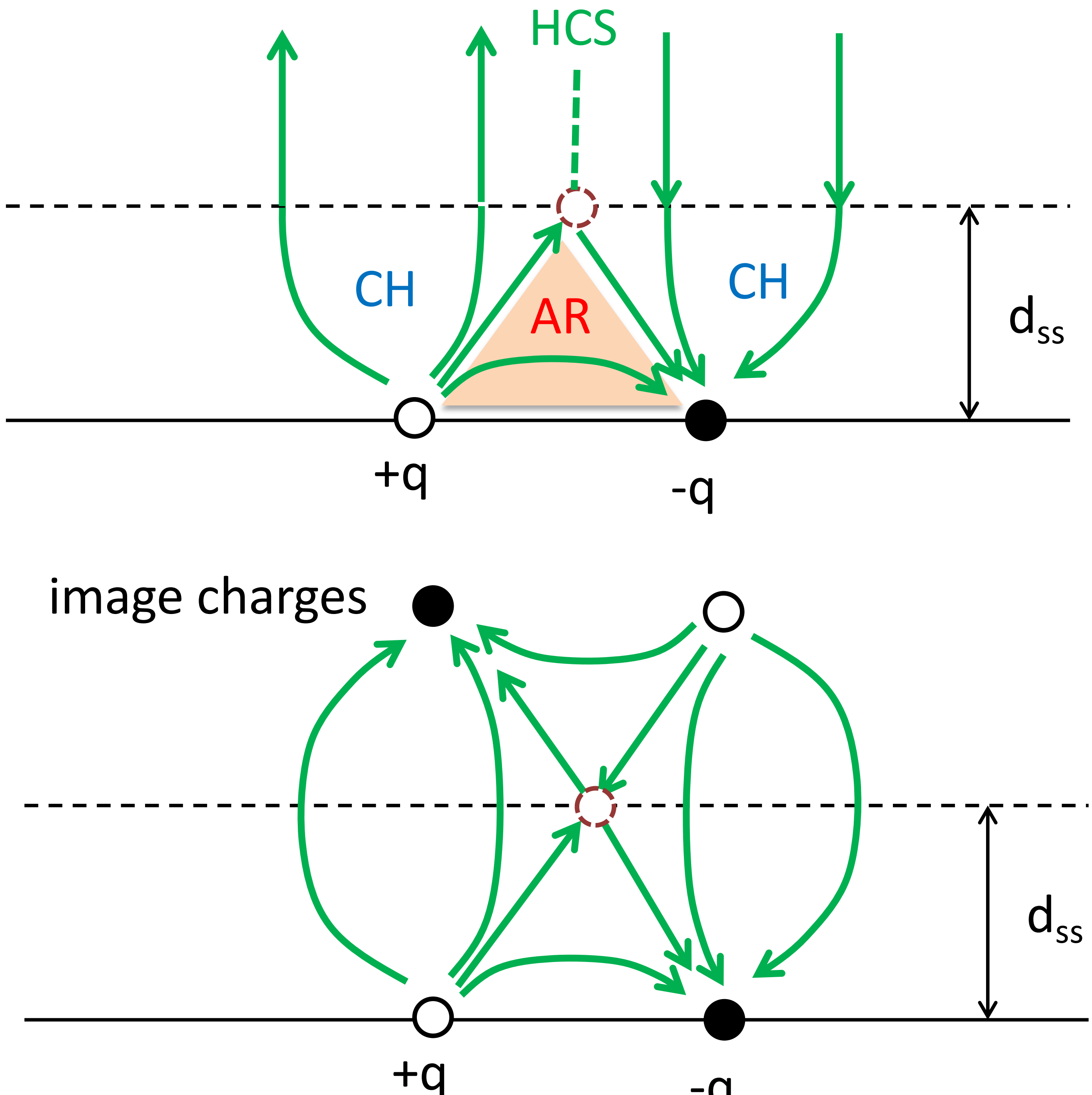
Observed (Neumann)

$$B_r(R_o,\theta,\varphi) = \sum_{\ell,m} \frac{A_{\ell,m}}{R_s}\left[(\ell+1)\left(\frac{R_s}{R_o}\right)^{\ell+2} + \ell\left(\frac{R_o}{R_s}\right)^{\ell-1}\right] Y_{\ell,m}(\theta,\varphi)$$

- Observe $B_r(\theta,\phi)$ @ photosphere
- decompose w/ spherical harmonics
- coeffs. ➔ $A_{l,m}$

Activity 62 (p. 124): The solar wind stretches the high-coronal magnetic field into the heliosphere into a roughly radial field below the Alfven radius. This enables an analogy with electrostatics: the field of electric charges placed above a perfect conductor can be computed by placing mirror charges opposite to the conducting surface, which then naturally has the electric field perfectly normal to the conducting surface. Analogously, in a magneto-static consideration above the spherical Sun, the magnetic field can be approximated by placing mirror 'charges' on a sphere at distance $d_{ss}^2/R_\odot$ which then has the field perfectly radial at d_{ss}. This is called the 'source surface model' … **For illustration, simplify the source-surface model by a 2-d sketch involving a line of charges and another of mirror charges**. Sketch the equivalent of the foundation of the heliospheric current sheet and examples of 'closed' field lines (the equivalent of coronal loops closing back onto the solar surface) and 'open' field lines (the equivalent of field stretched out into the heliosphere), at the base of which we find dark 'coronal holes' in X-ray images of the Sun.




HCS
CH
AR
CH
d_ss
+q
-q
image charges
d_ss
+q
-q

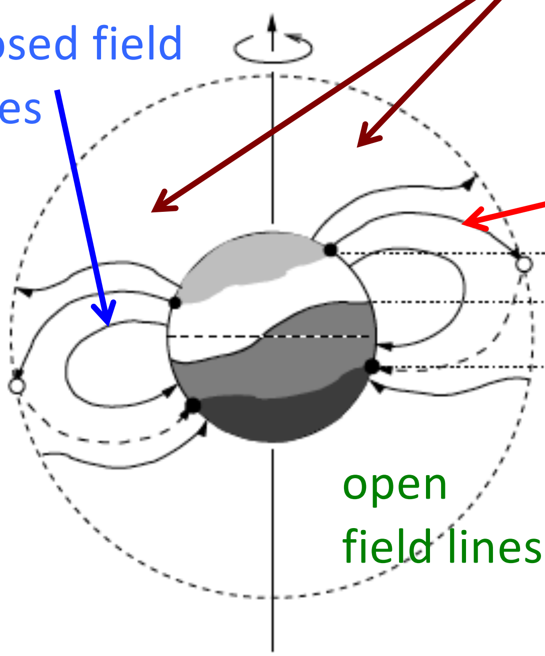
$$\chi(r,\theta,\varphi) = \underbrace{\sum_{\ell,m} A_{\ell,m}\left[\left(\frac{R_s}{r}\right)^{\ell+1} - \left(\frac{r}{R_s}\right)^{\ell}\right] Y_{\ell,m}(\theta,\varphi)}$$

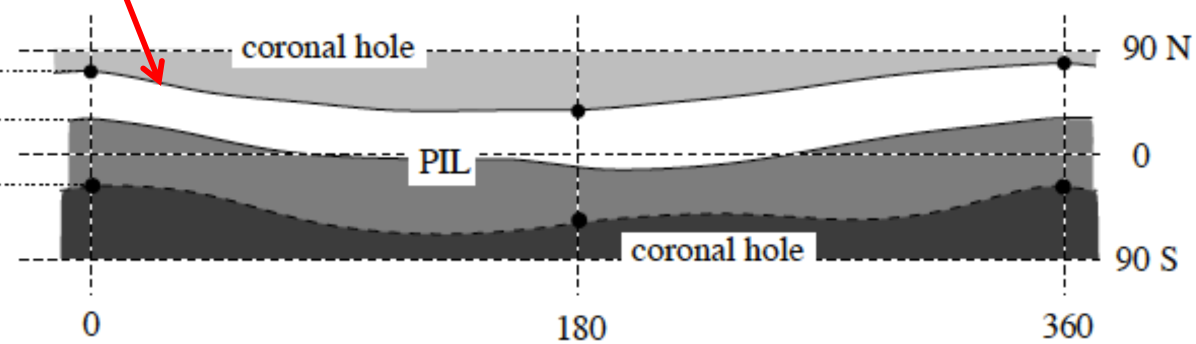
PFSS model

(potential field source surface)

closed field lines

Separatrix dividing open from closed





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open field lines

Solar wind flows from open field crossing $r=R_s$
… the `source’ of the wind
➔ the `source surface’

$B_r(\theta,\phi)$ ``measured’’ over entire sphere

- accumulate strips over 27-day rotation
- hope that not much changes
- fill in poles (somehow)
- decompose w/ spherical harmonics
- coeffs. ➔ $A_{l,m}$

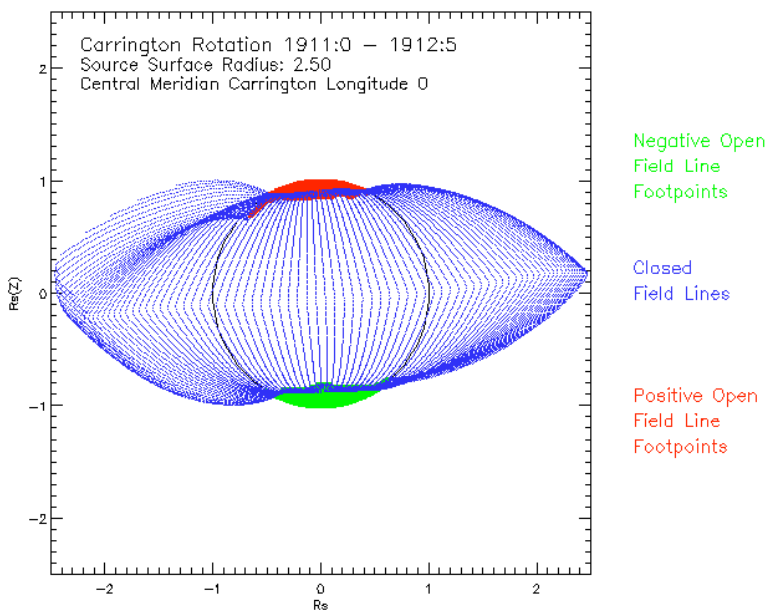
Assumptions of the PFSS

- No currents in coronal field (simplest equilibrium)

$$\nabla \times \mathbf{B} = 0 \qquad R_o < r < R_s$$

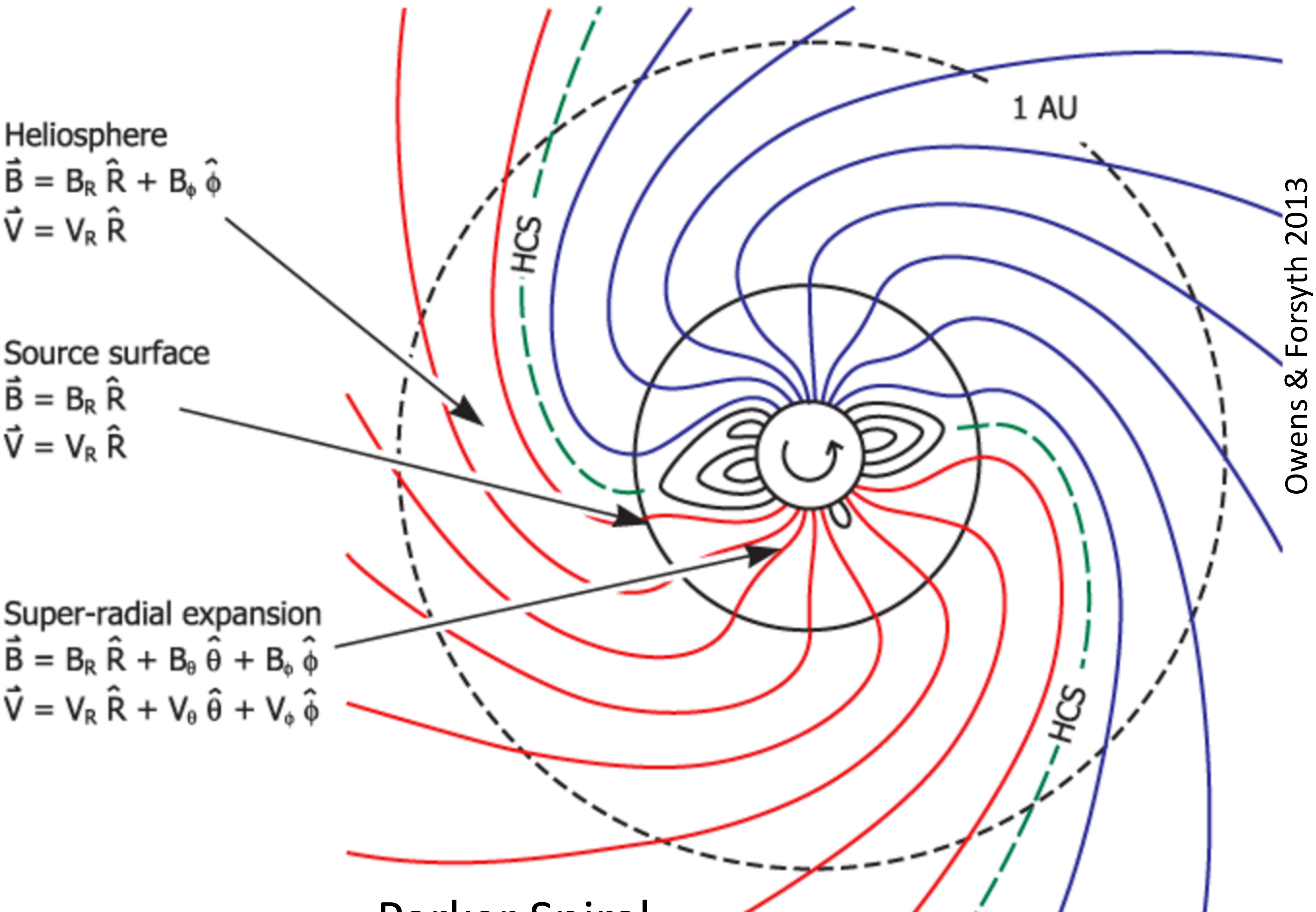
- Field becomes open (radial) @ fixed radius $r = R_s$

- Not much change during 27-day accumulation



➔ **Model** distinguishing open/closed coronal field

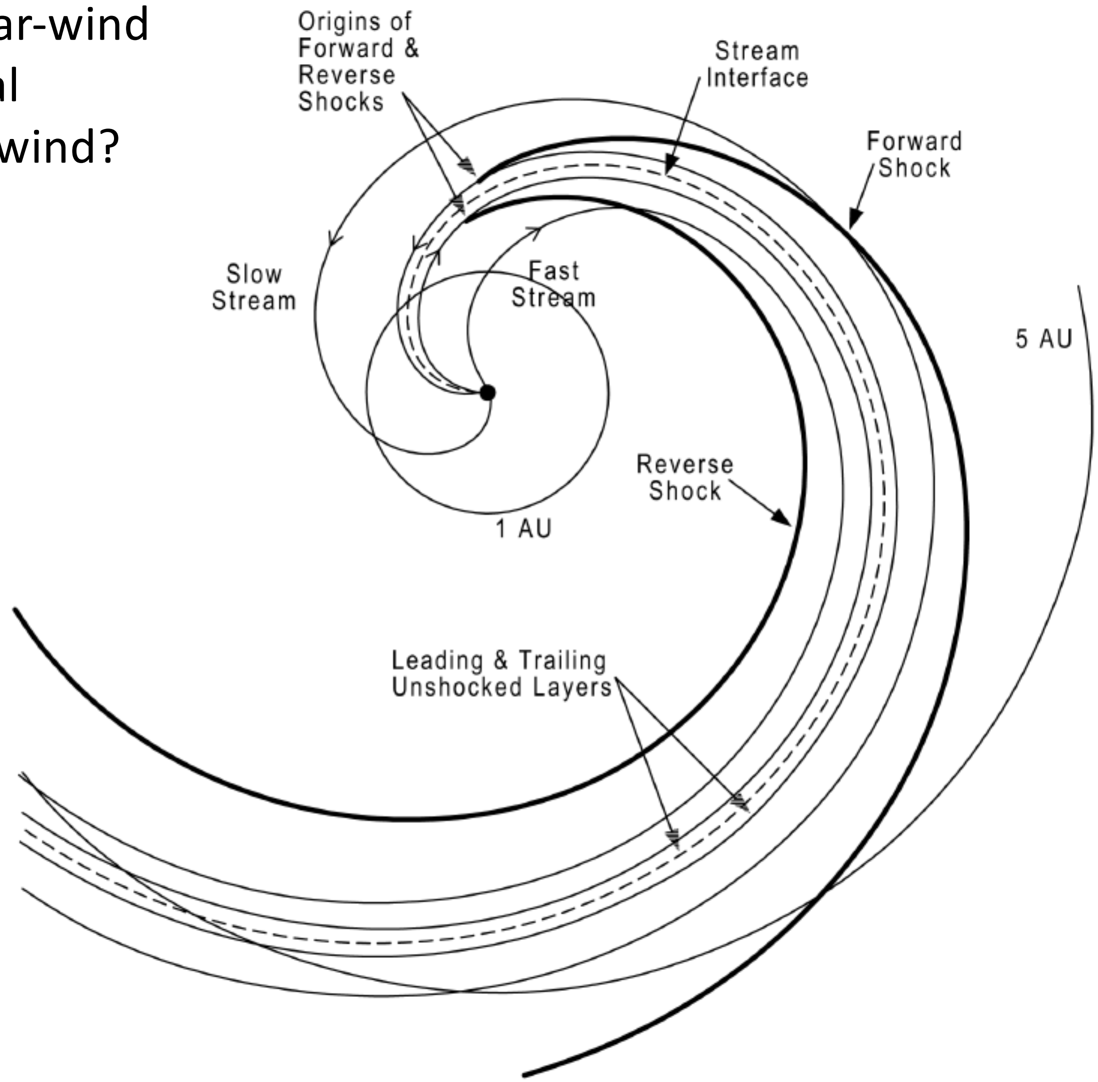
➔ Field **actually** open will be source of solar wind, less dense & dark in EUX & SXR



Parker Spiral

$$\text{for large } r: \; v_\phi \approx \frac{\Omega r_A^2}{r} \to 0\,;\; B_\phi \approx -\frac{B_r \Omega r}{v_r}, \tag{5.20}$$

Activity 61 (p. 122): At what distance from the Sun does the above solar-wind model have $|B_r| = |B_\phi|$ for typical values of the slow and fast solar wind?



$\Omega \approx 2\pi$ / (30 d)
$= 2.5 \times 10^{-6}$ rad/s

$v_r^{(s)} \approx 400$ km/s
$= 4 \times 10^{7}$ cm/s

$v_r^{(s)}/\Omega \approx 1.6 \times 10^{13}$ cm
$= 1$ AU

$v_r^{(f)} = 2\, v_r^{(s)}$

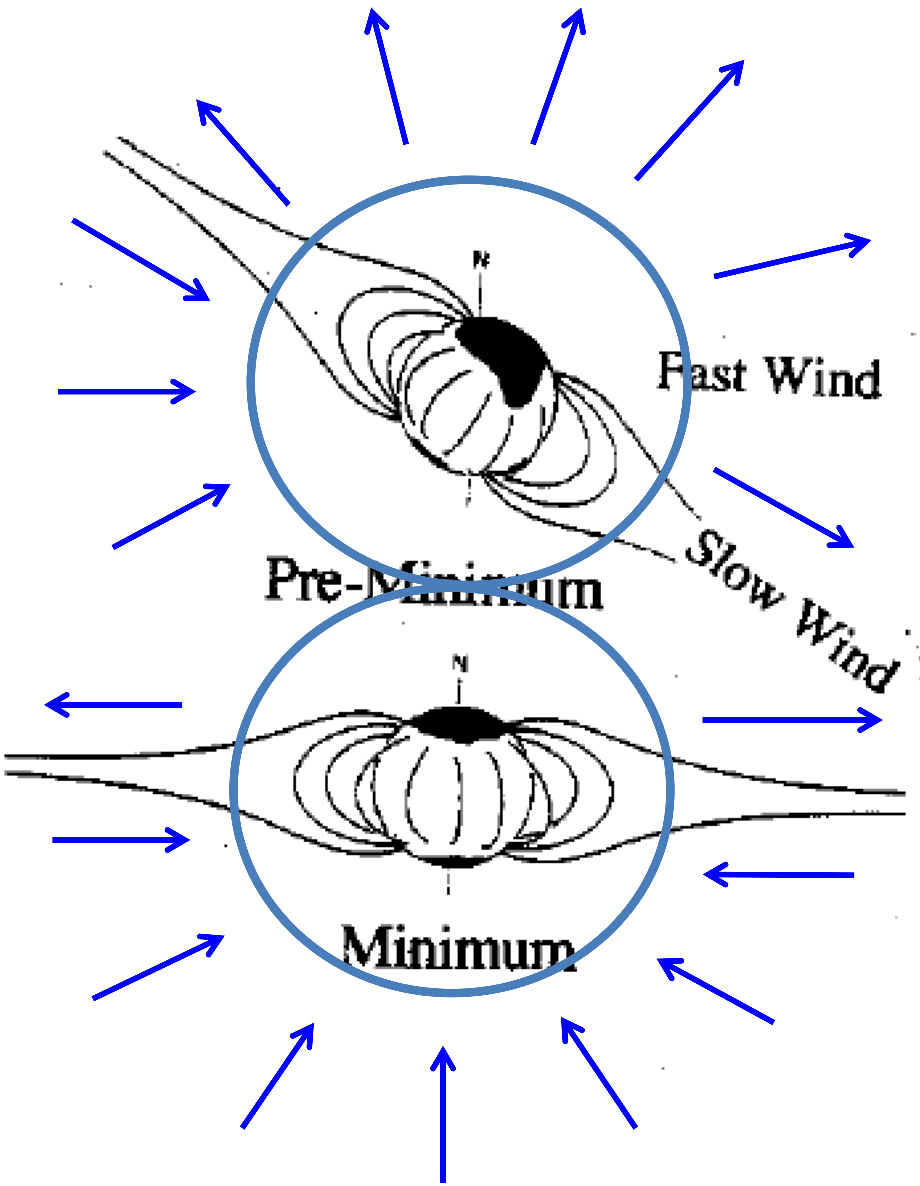
$v_r^{(f)}/\Omega = 2$ AU

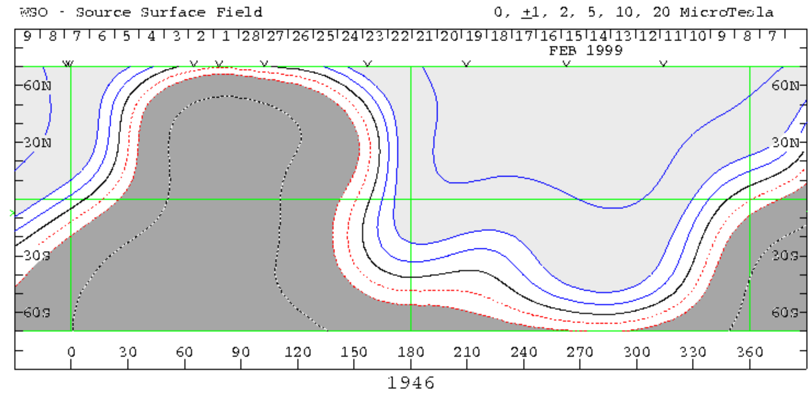
Historical interlude

Lord Kelvin once argued that it was impossible for magnetic distrurbances on the Sun to be responsible for geomagnetic activity on Earth (i.e. space weather should not occur). He did so using reasoning we continue to use all the time:

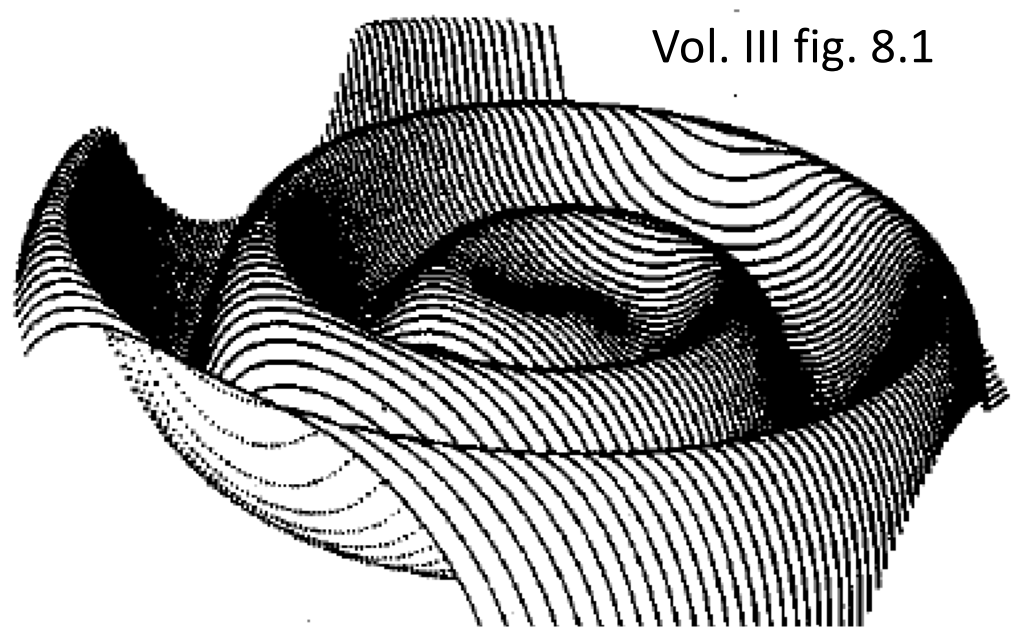
Magnetic field far away from currents will be dominated by the leading-order multipole – the dipole – which decreases with distance as $B \sim r^{-3}$. At this rate the field will be negligible at 1 AU.

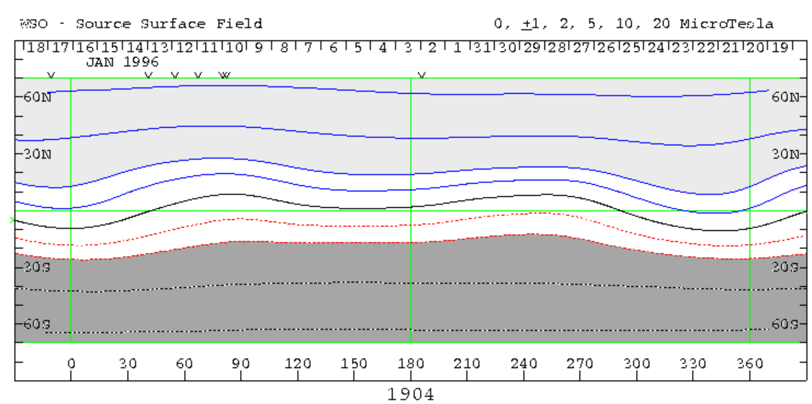
We have concluded above that $B_r \sim r^{-2}$ and $B_\phi \sim r^{-1}$ in clear contradiction of Kelvin's reasoning. What aspect of his argument is incorrect? What was he unaware of?



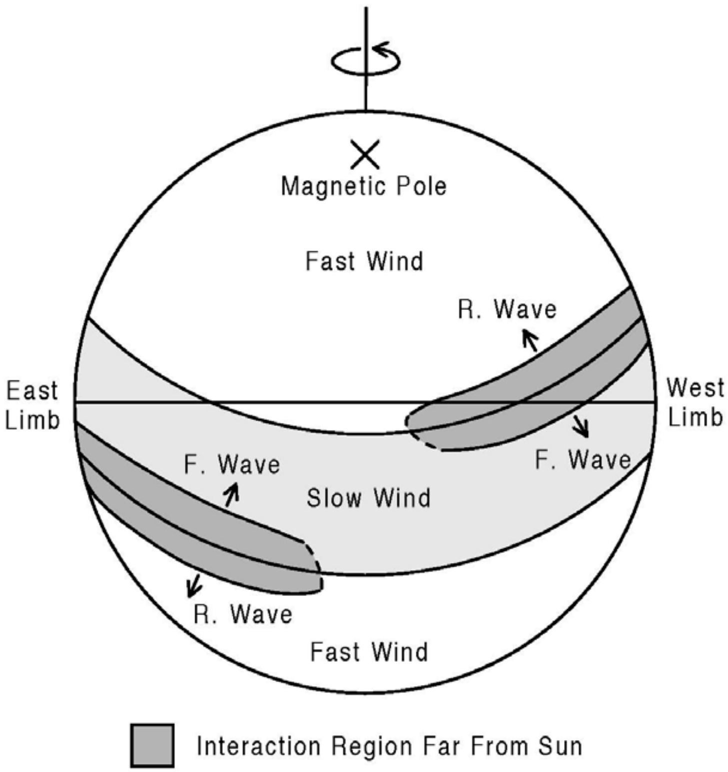


Vol. III fig. 8.1

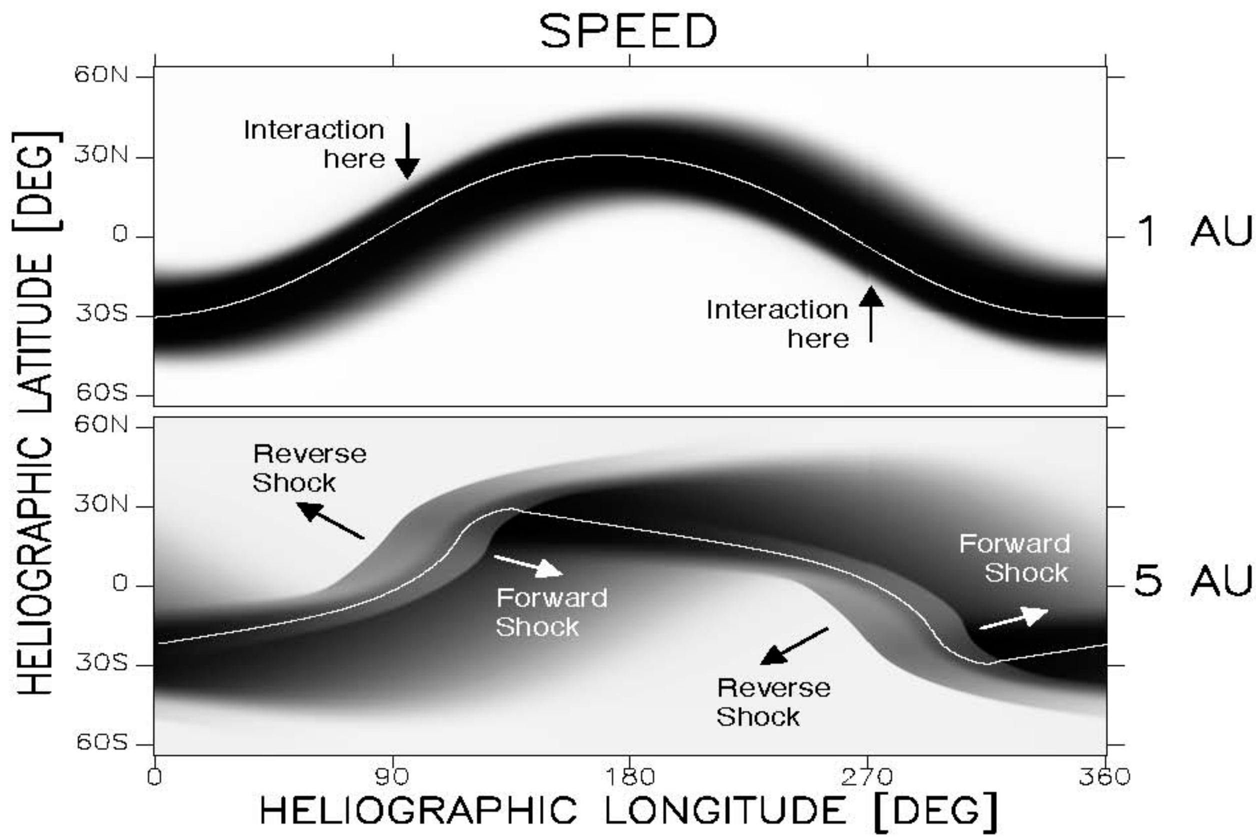




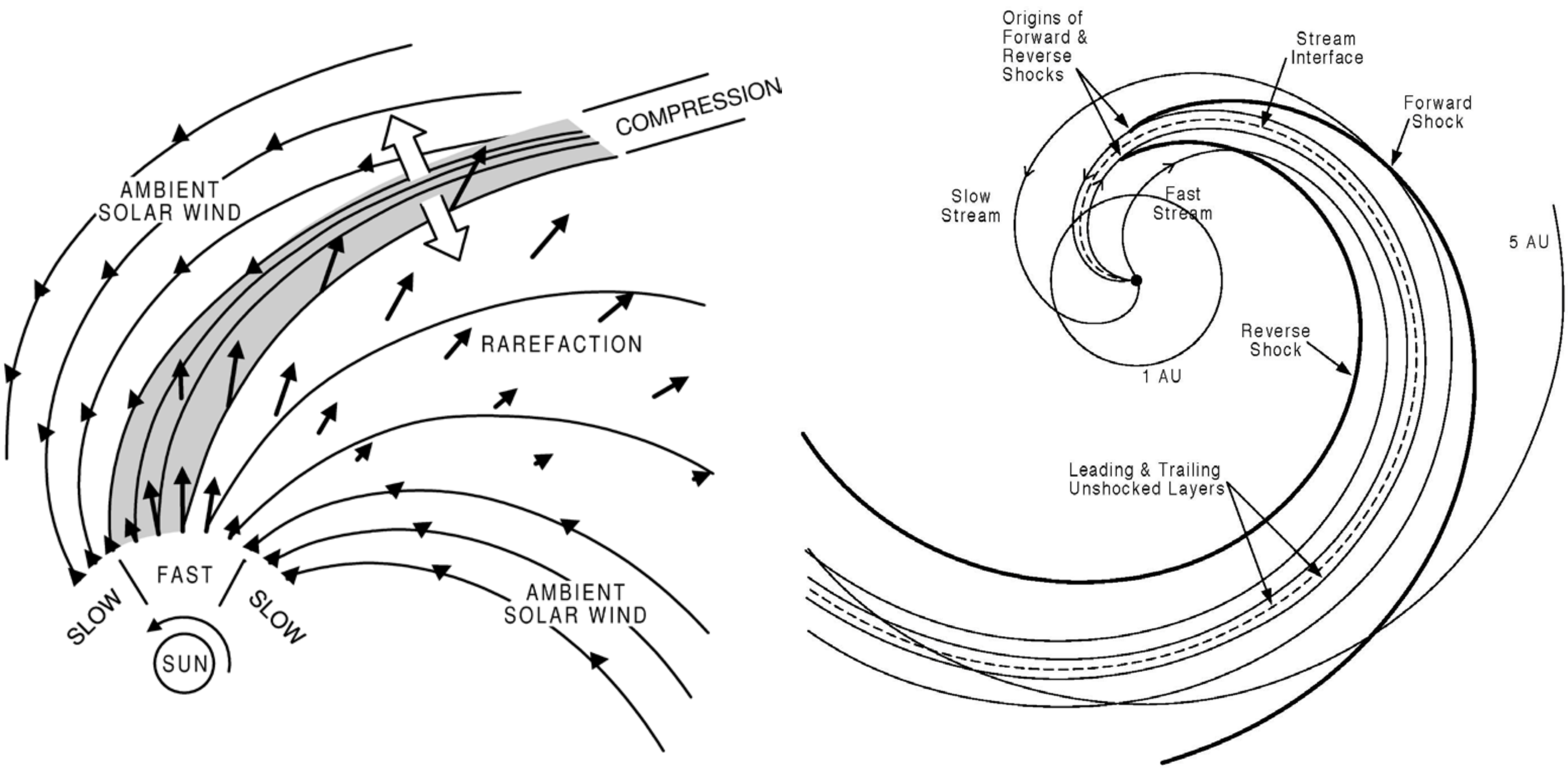
Effect of a ``warped" HCS



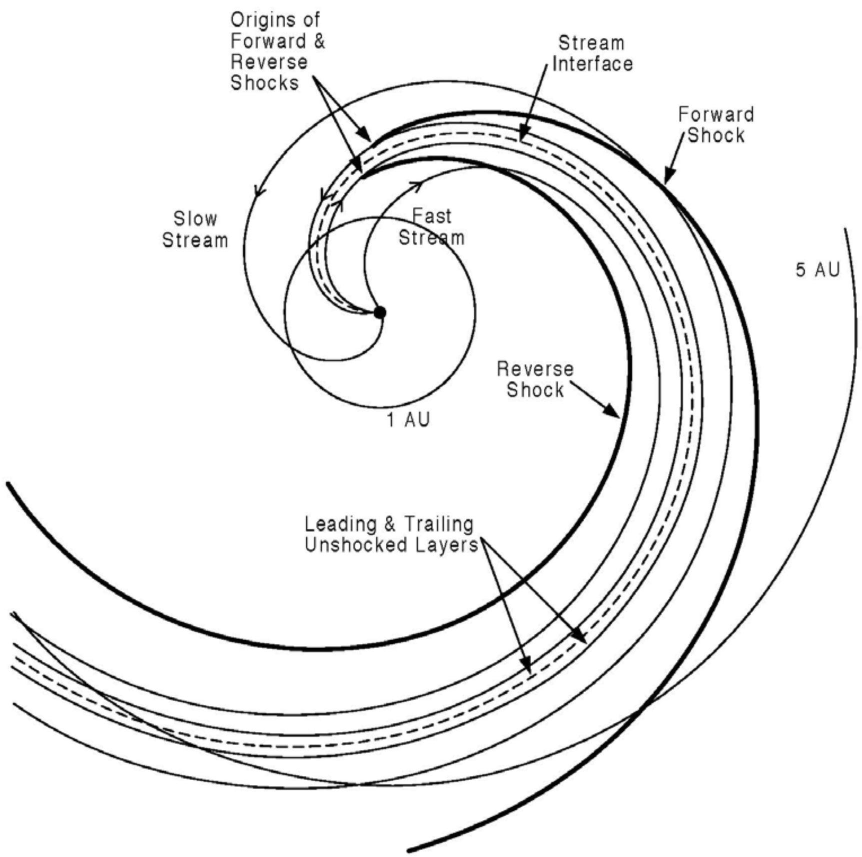
Vol. III fig. 8.6



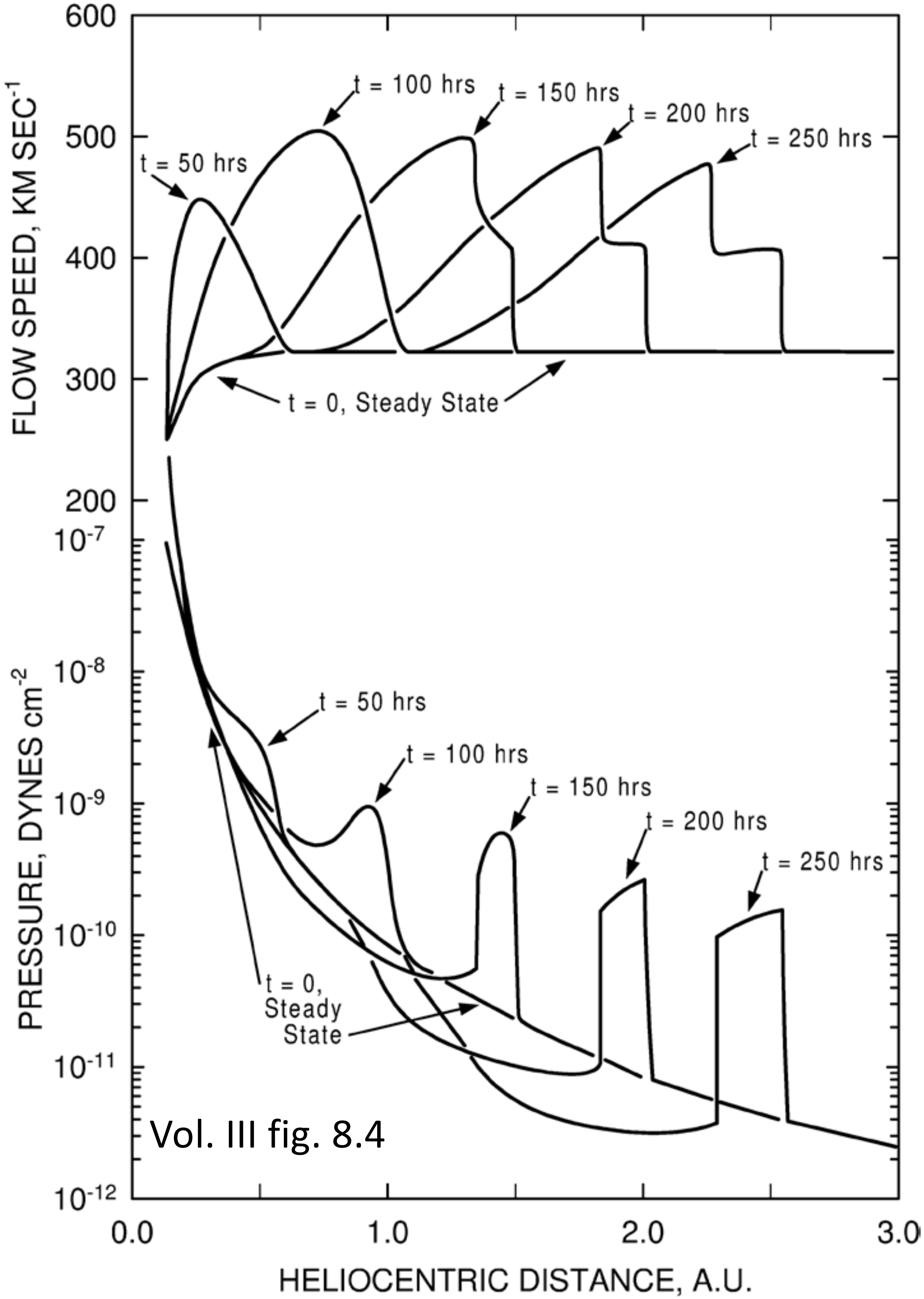
Vol. III fig. 8.7



Vol. III fig. 8.5



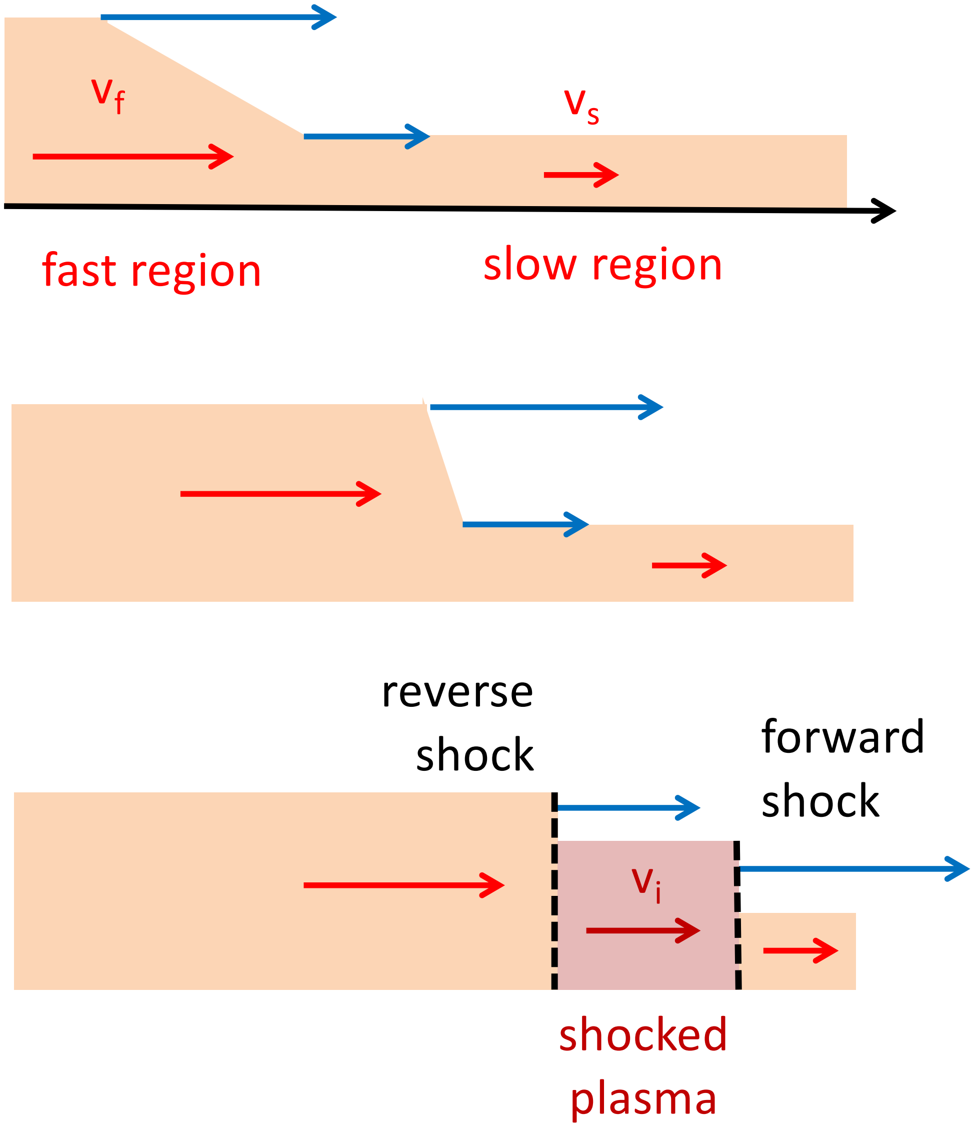
Vol. III fig. 8.5



Vol. III fig. 8.4

Why does the ``reverse shock'' propagate forward (i.e. outward)?

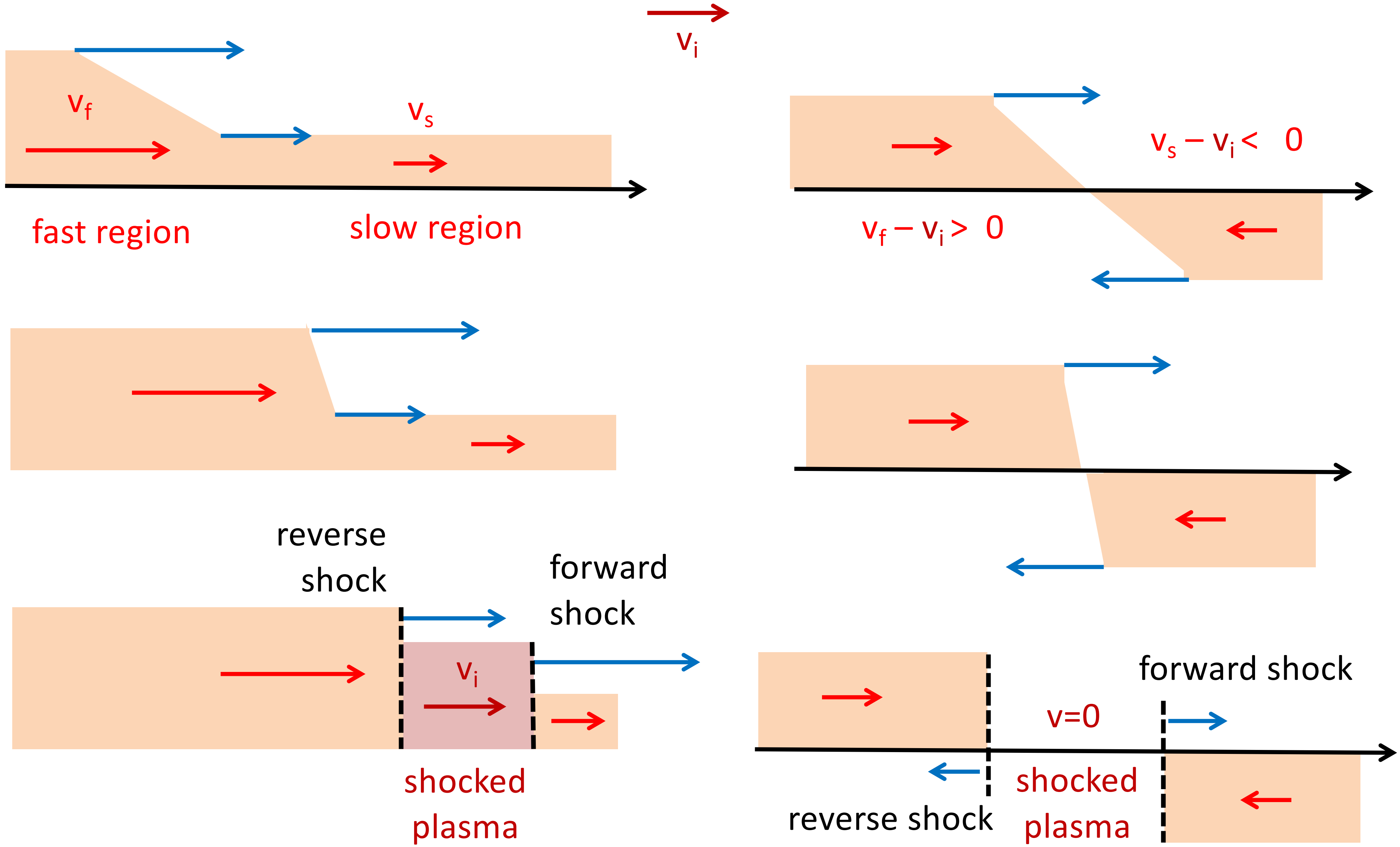
Ignore spherical geometry:
1d picture of fast behind slow:

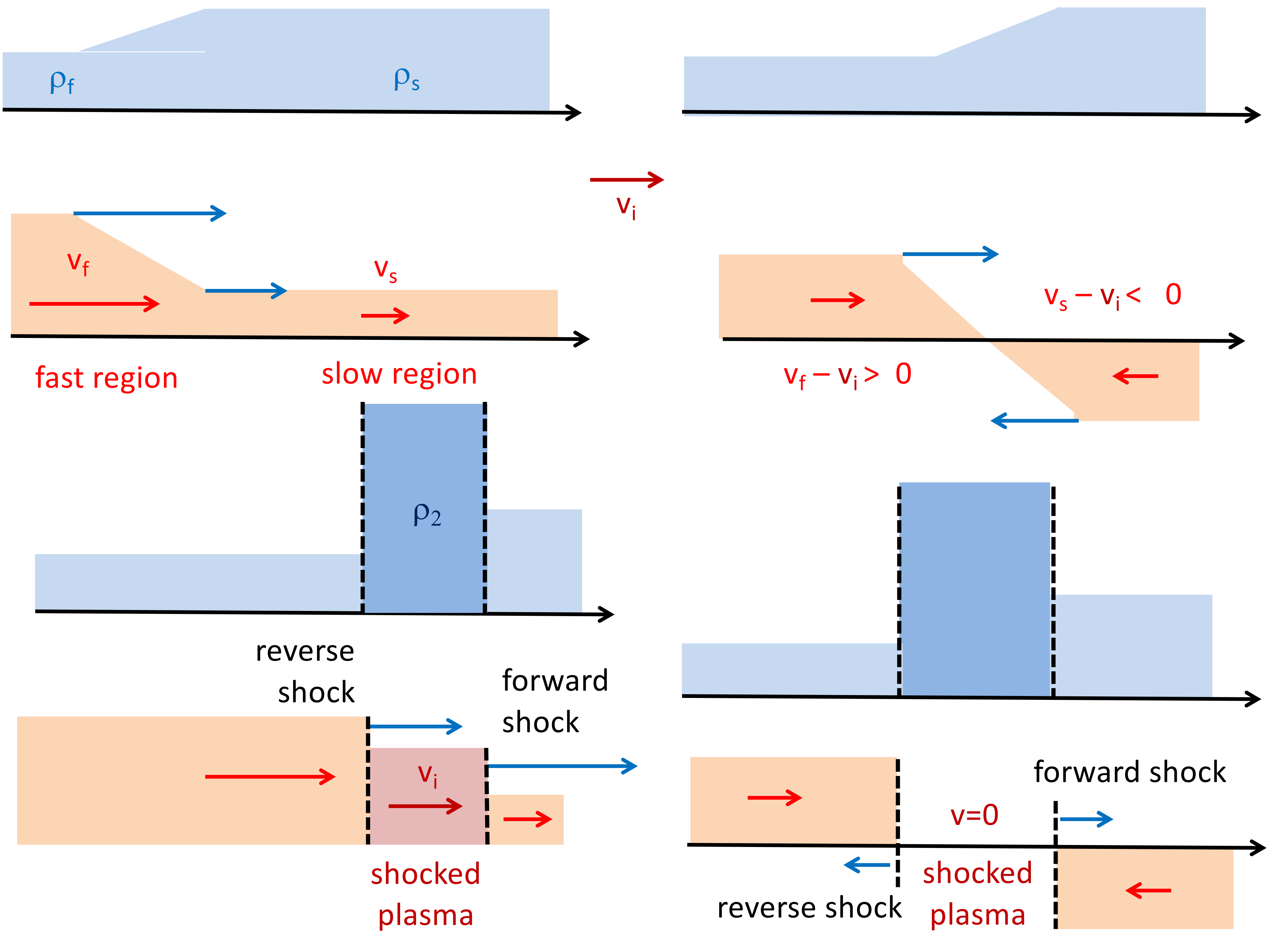


Why does the ``reverse shock'' propagate forward (i.e. outward)?

Ignore spherical geometry:
1d picture of fast behind slow:

transform to frame @ intermediate velocity v_i




ρf
ρs
vi
vf
vs
fast region
slow region
vs − vi < 0
vf − vi > 0
ρ2
reverse shock
forward shock
vi
shocked plasma
forward shock
v=0
reverse shock
shocked plasma

Summary

- Corona: because there is heating – reaches high T because radiation cannot balance heating so conduction is needed
- More heat ➔ higher density
- Wind: because there is heating – advective energy flux balances heating
- Creates heliosphere