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

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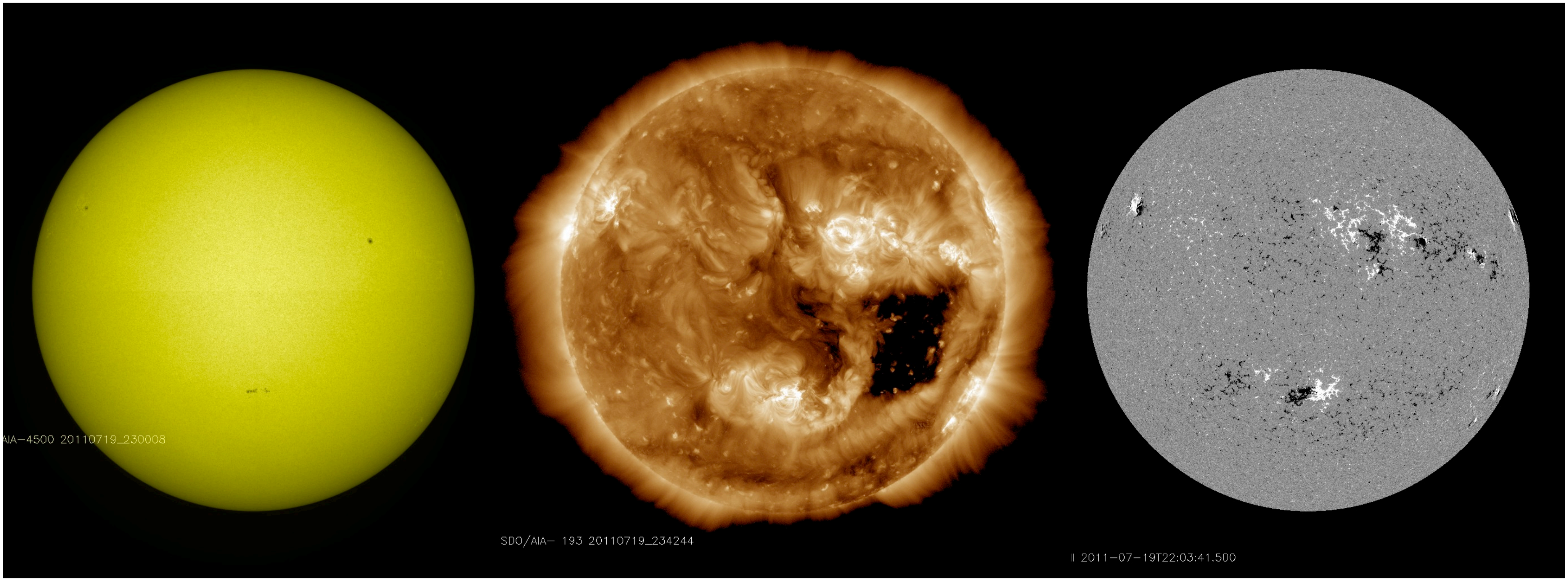
With liberal “borrowing” from Hansteen, Schrijver, Gosling, Jokipii, Giacalone, Lean, …

The corona – a dramatic view

July 2, 2019 – Cerro Tololo Inter-American Observatory, Chile

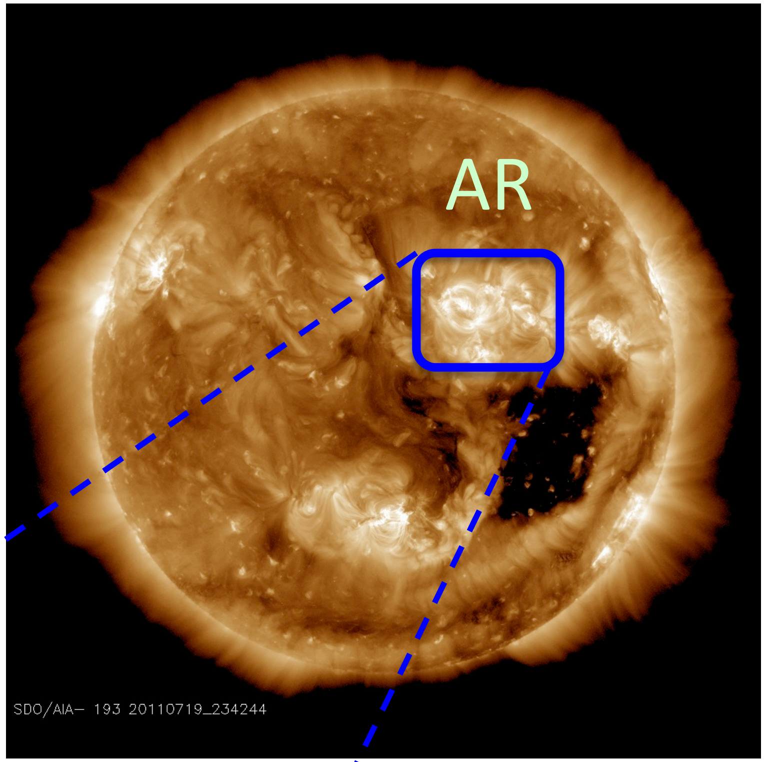


Coronal (EUV) imaging – the basics:

- what you see is all the same T (1.5 x 10^6 K)
- bright = dense plasma – n_e^2
- heating **can*** make plasma dense & thus bright
- heating is evidently magnetic

* if magnetic field lines are closed – magnetic bottle

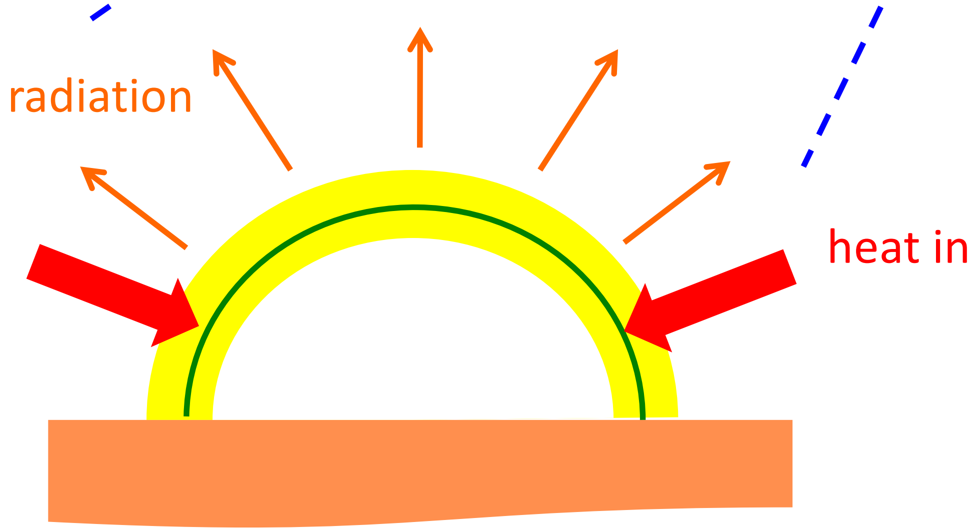
B large enough to restrict plasma motion: only along field lines

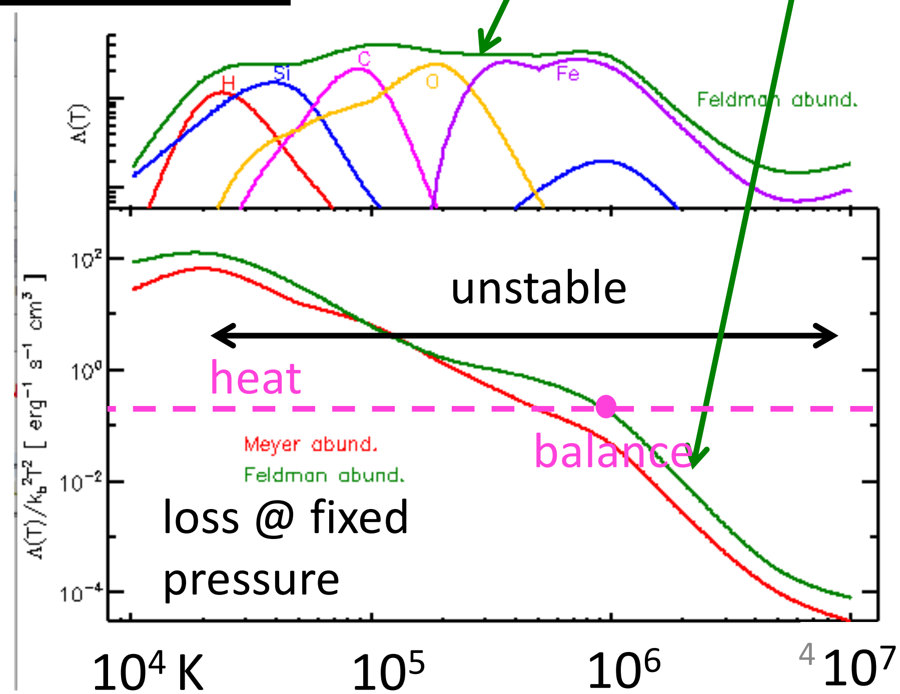


0d picture:
balance between
heat & radiation
@ fixed pressure

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

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



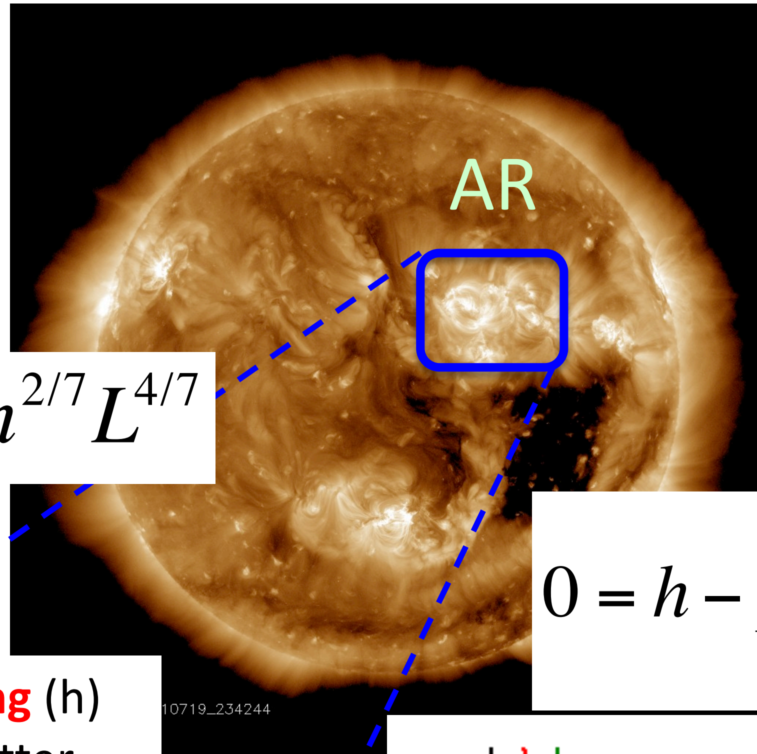


balance:
(RTV)

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

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

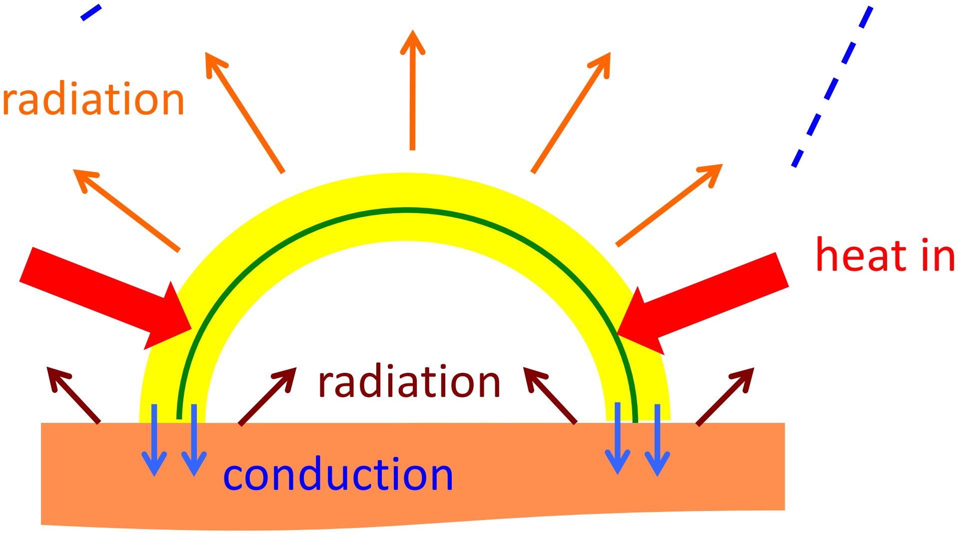
$$I \sim n_e^2 \sim h^{8/7} L^{2/7}$$

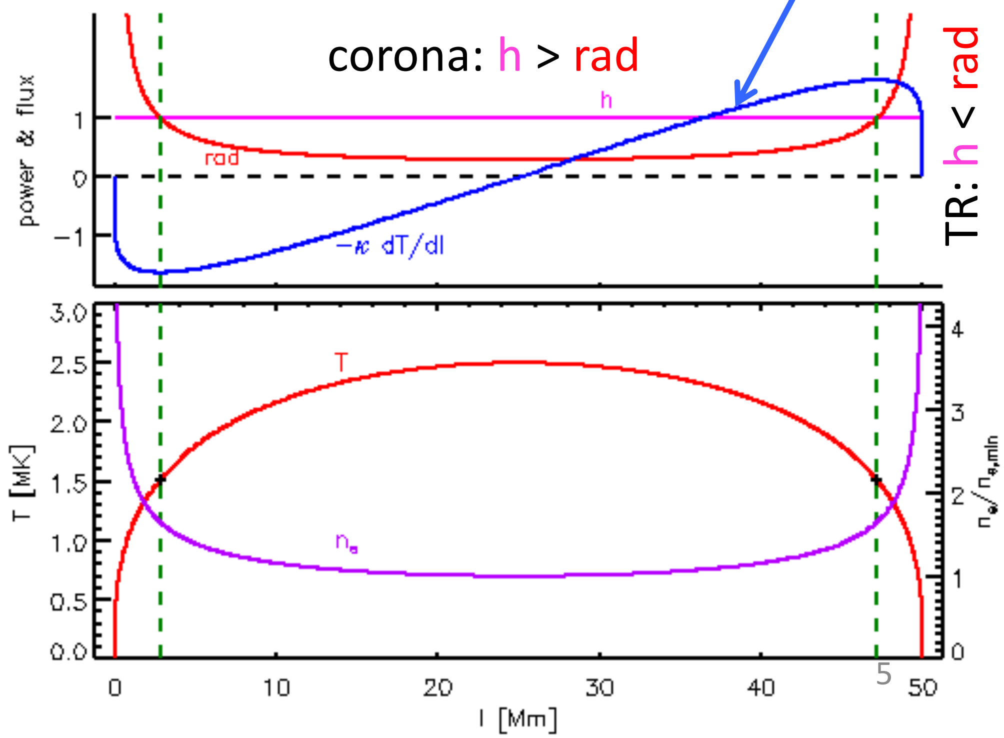


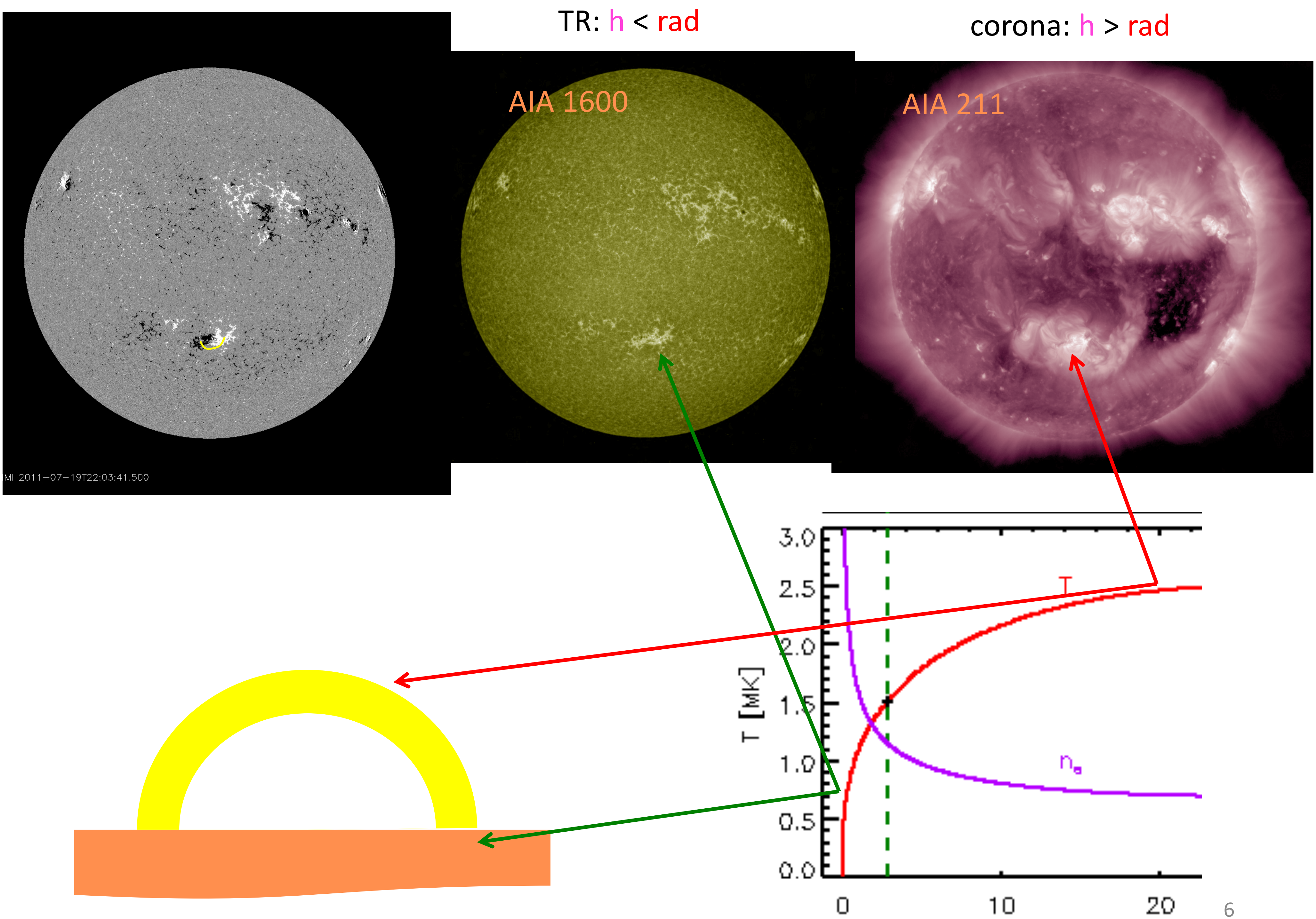
Need 1d:
include thermal
conduction to
move heat to
chromosphere

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

more heating (h)
➔ little hotter
much brighter

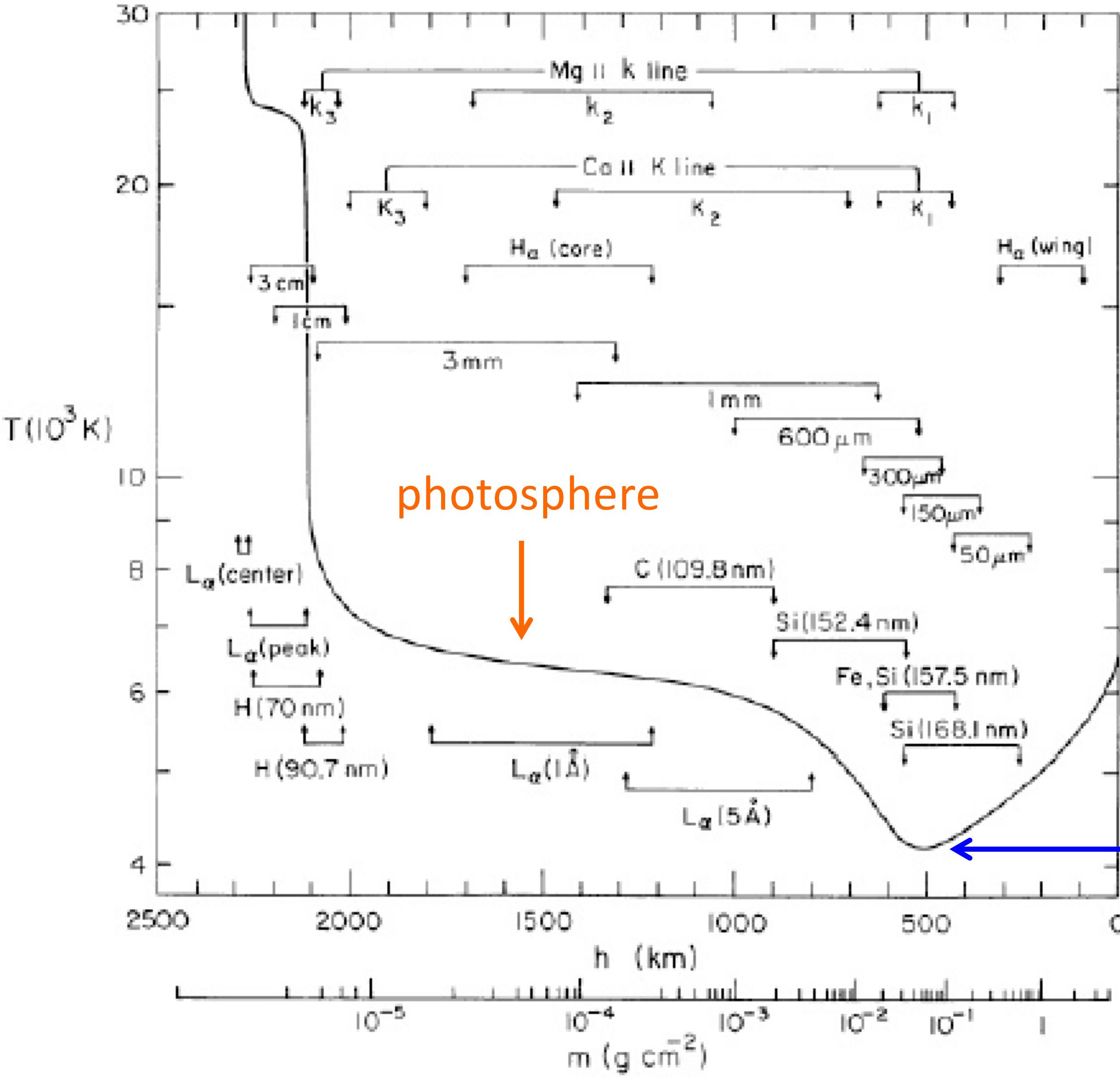





TR: h < rad
corona: h > rad
AIA 1600
AIA 211
HMI 2011-07-19T22:03:41.500
T [MK]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
T
n_e

Below the TR – hairy details

Vernazza *et al.* 1981

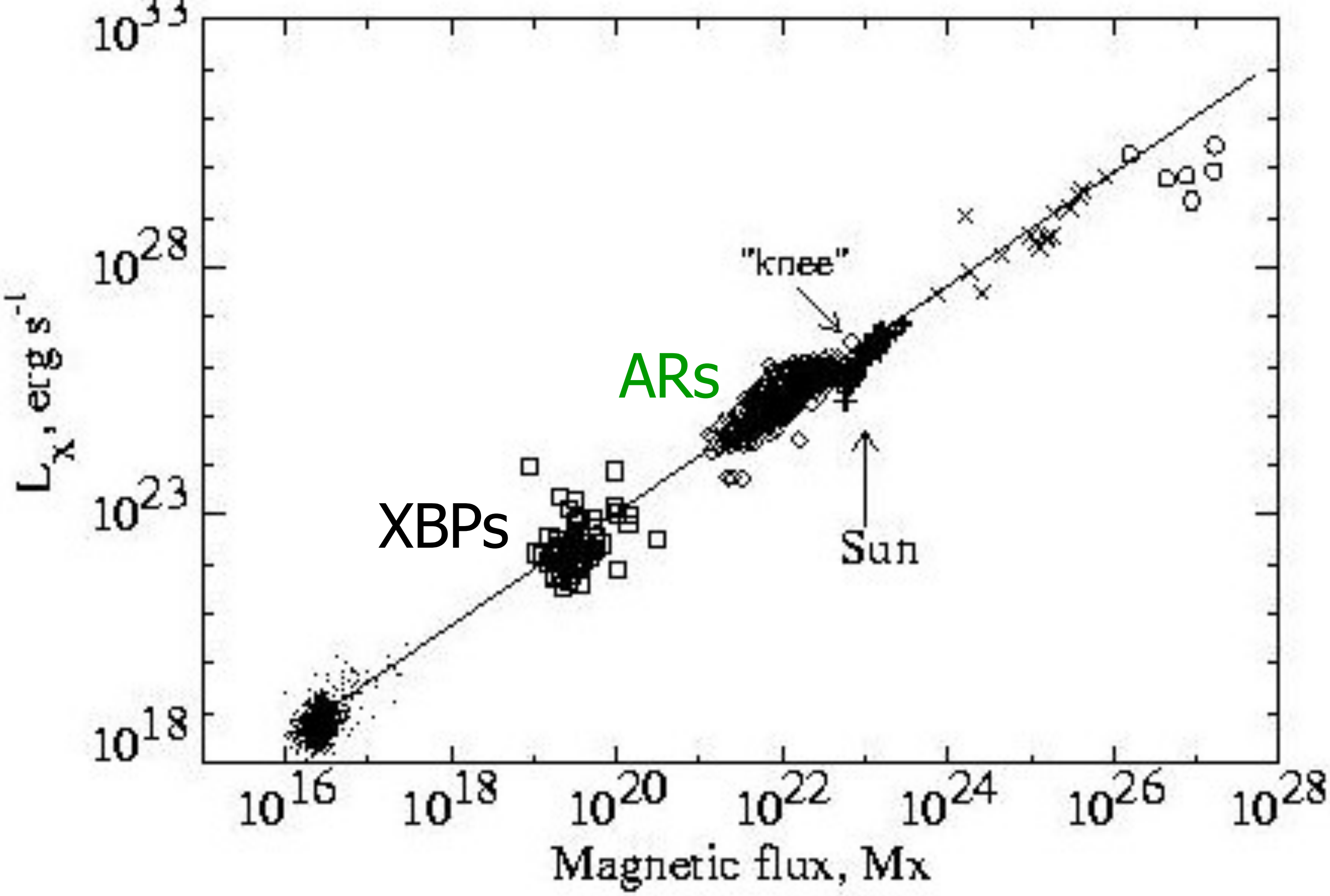


temperature minimum

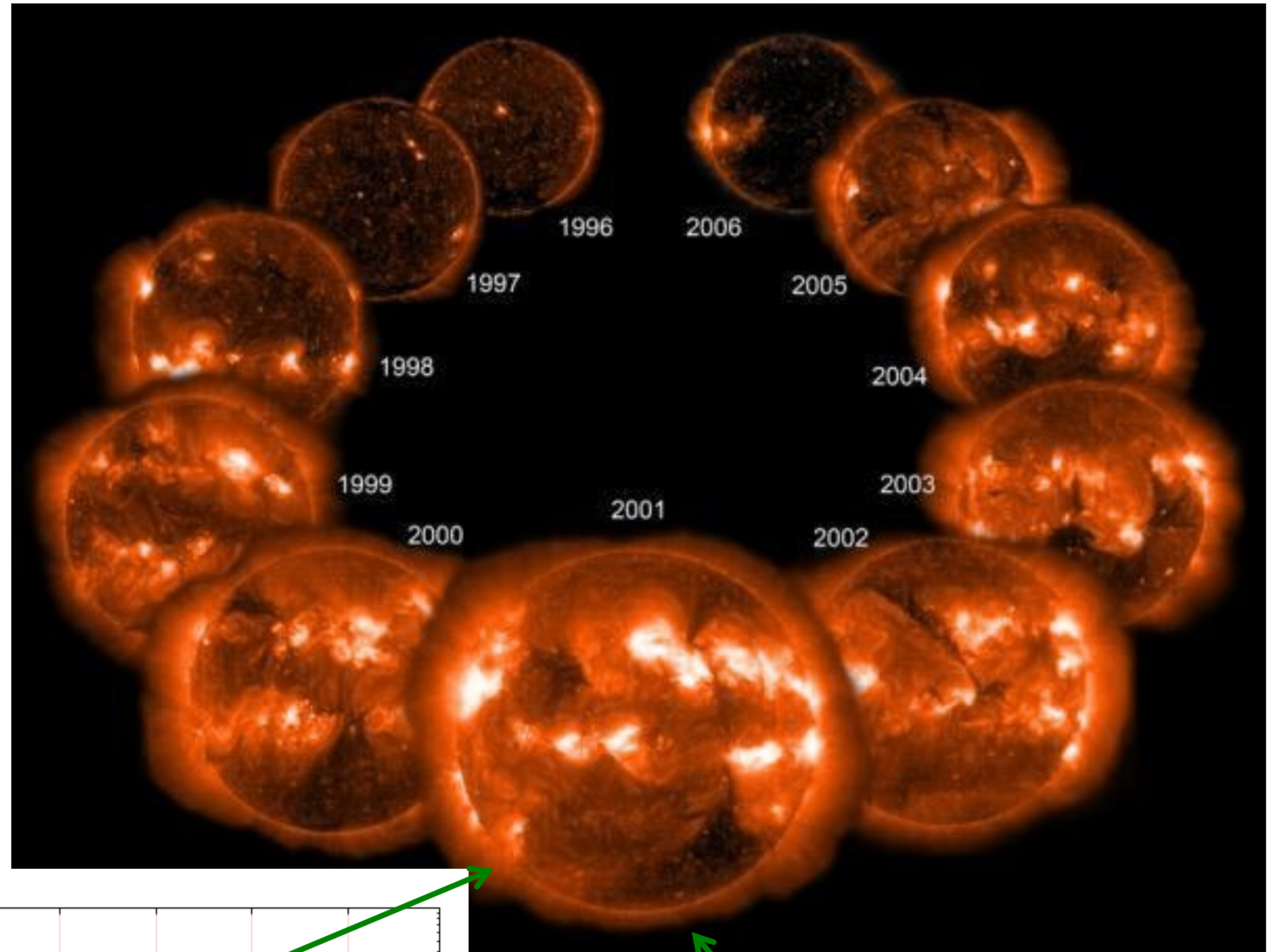
- Radiation: not optically thin
- Ionization level varies with T

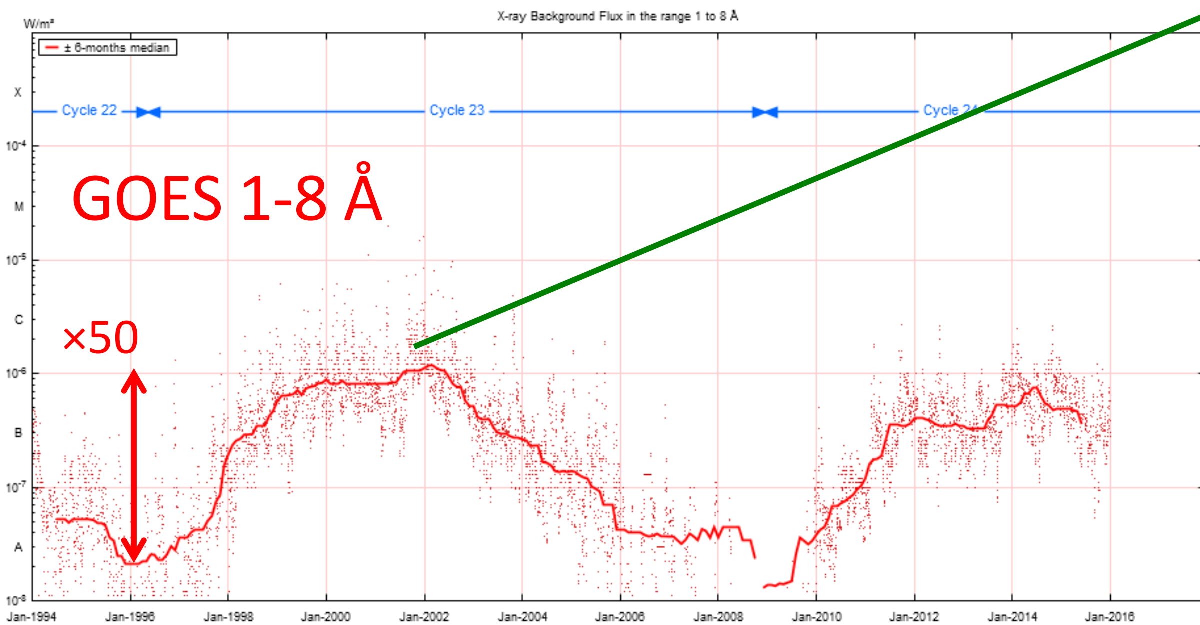
Heating is Magnetic

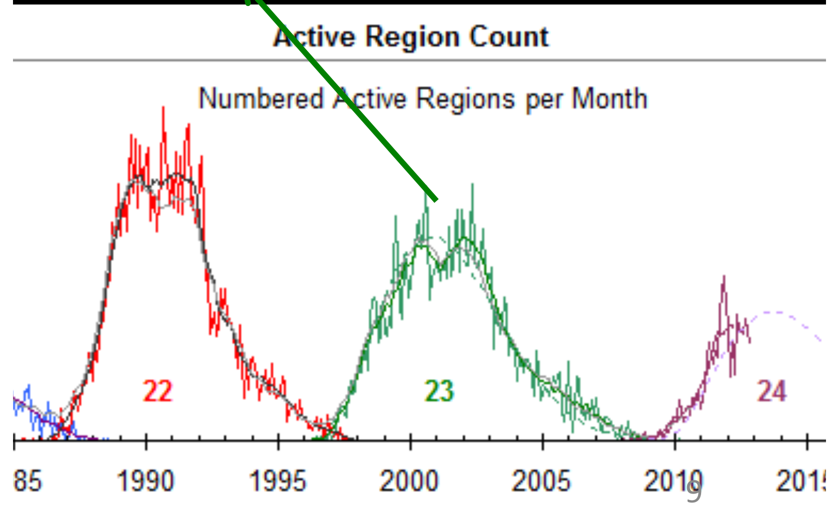
Pevtsov et al. 2003



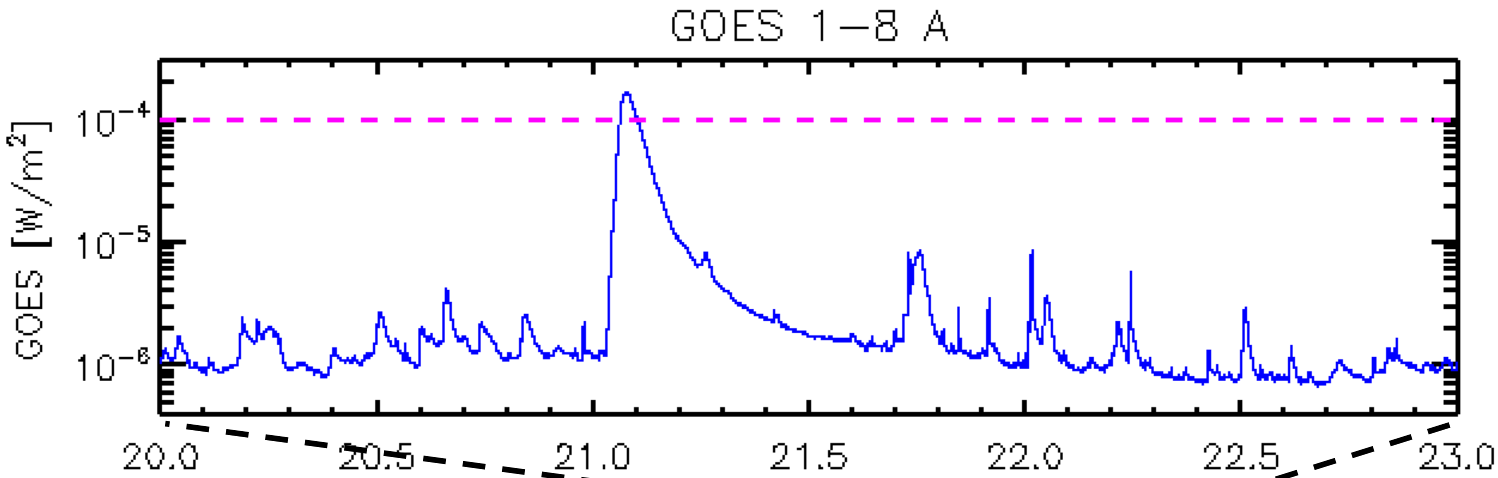
Field varies – corona varies

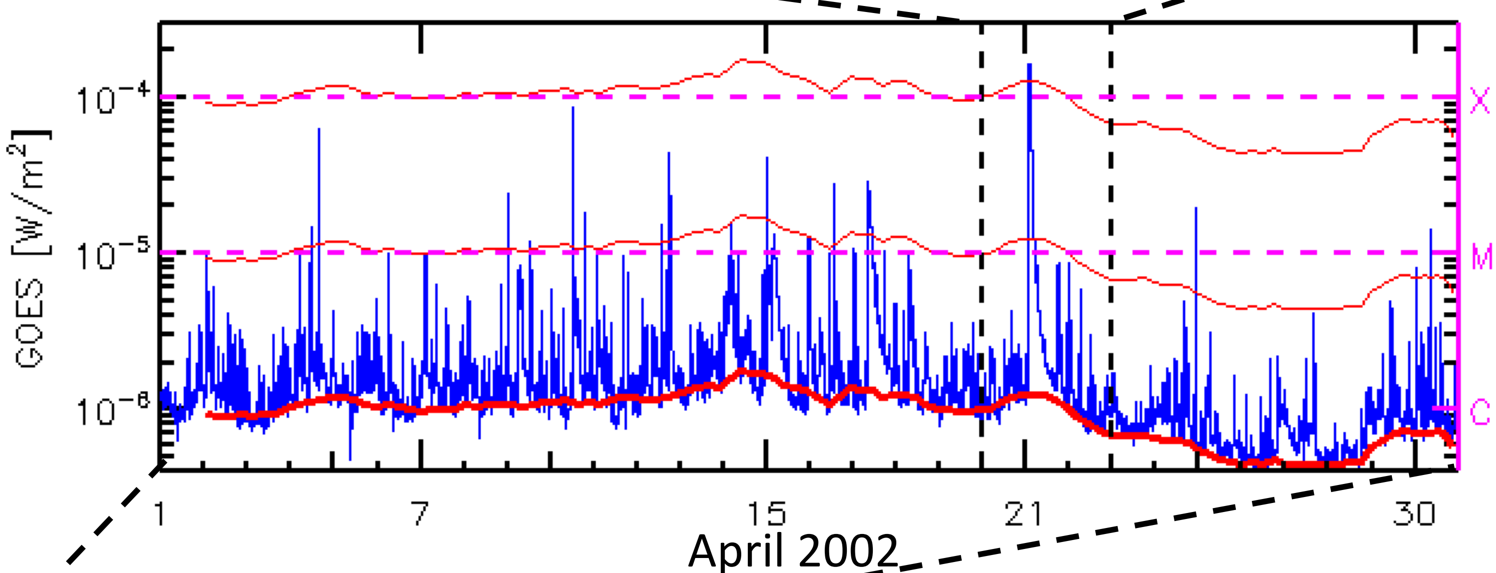


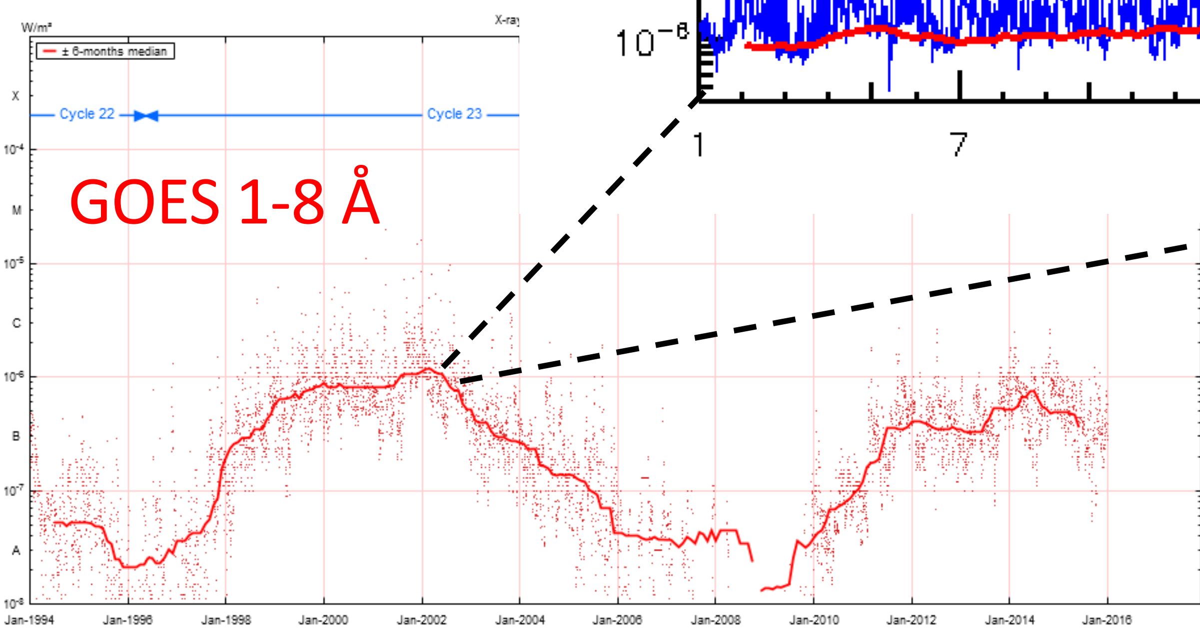




X-rays: highly variable – flares

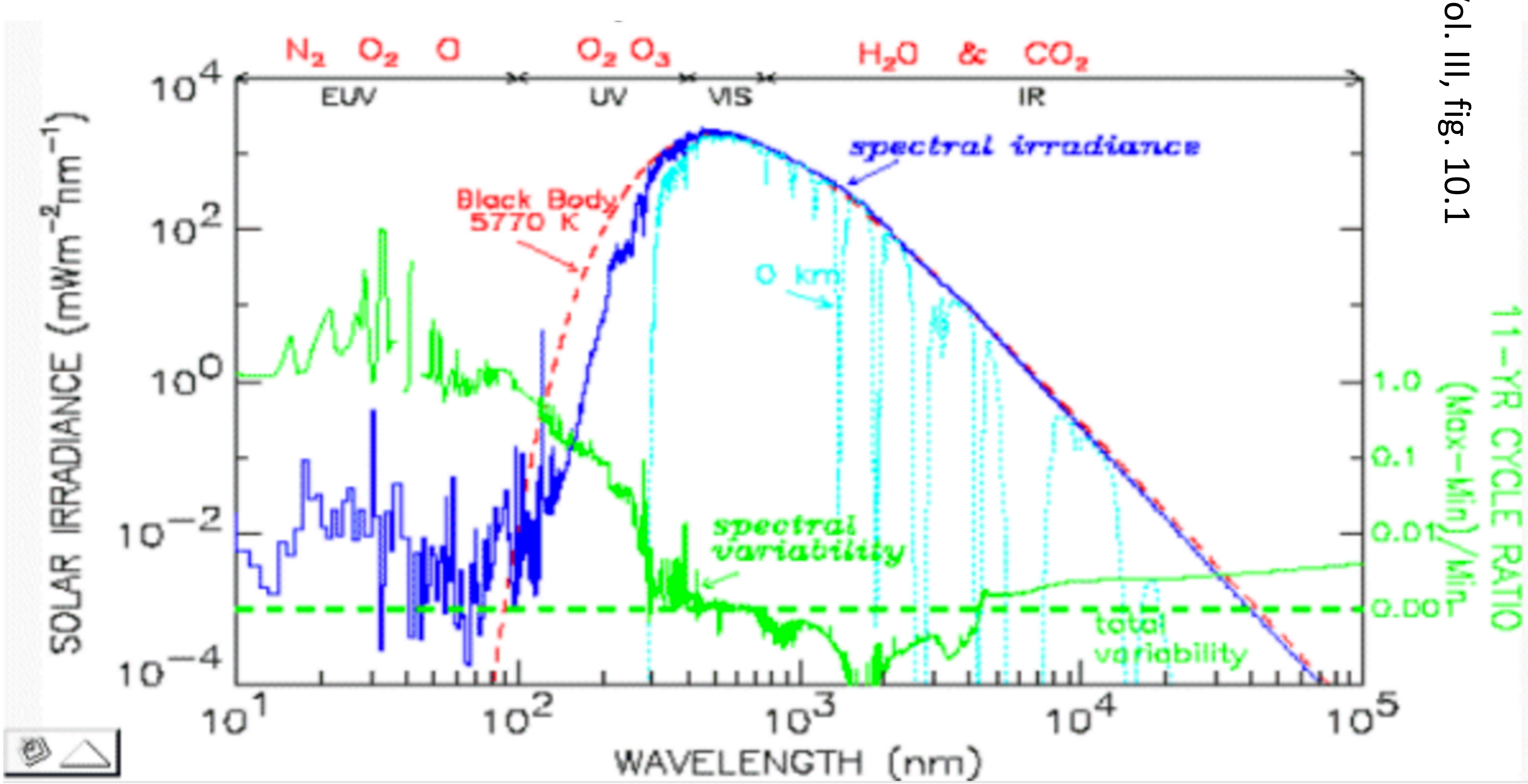






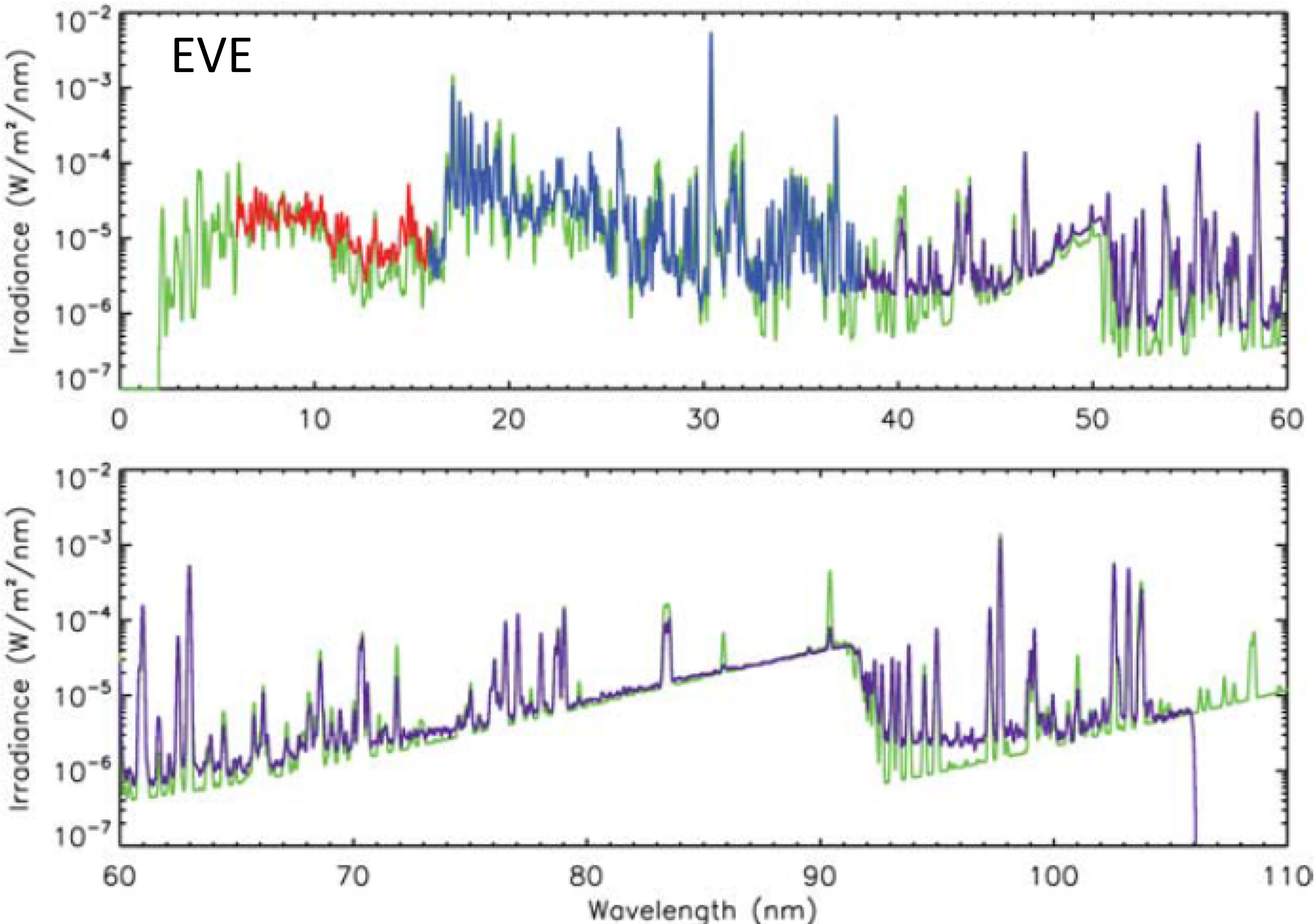
do smaller flares heat the corona?

Corona produces EUV & X-ray

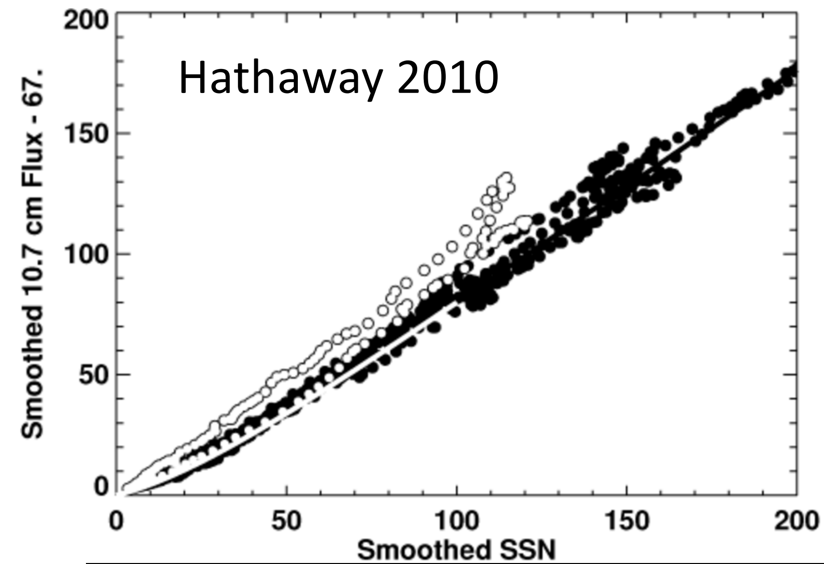


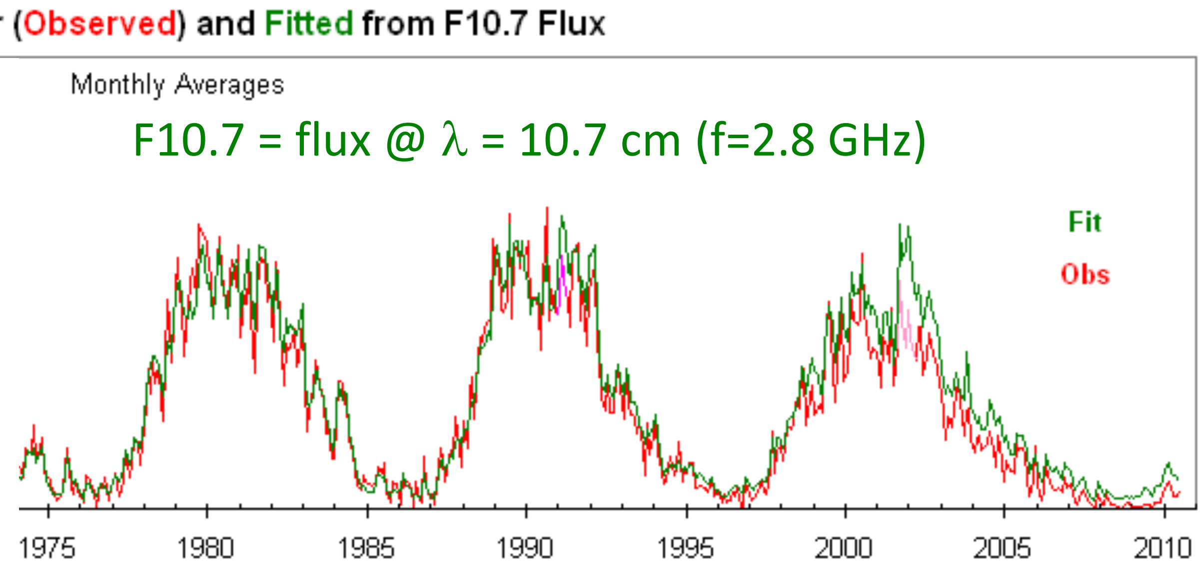
Vol. III, fig. 10.1

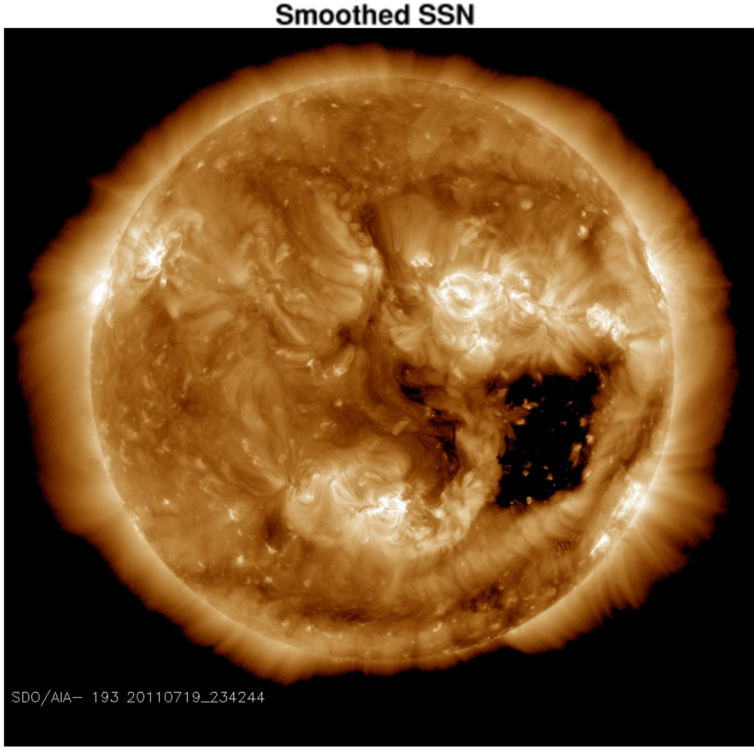
Chamberlin *et al.* 2009

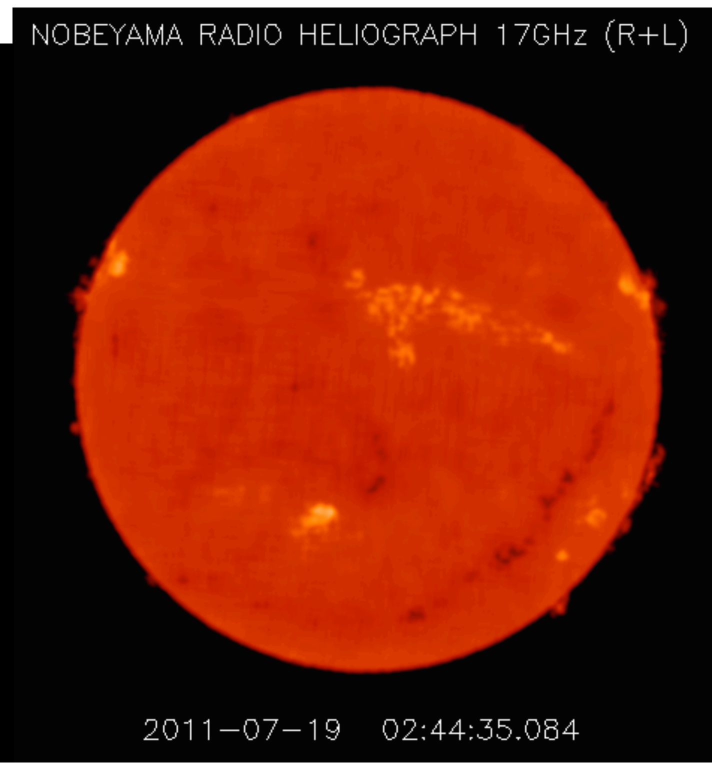


Corona produces μ-waves

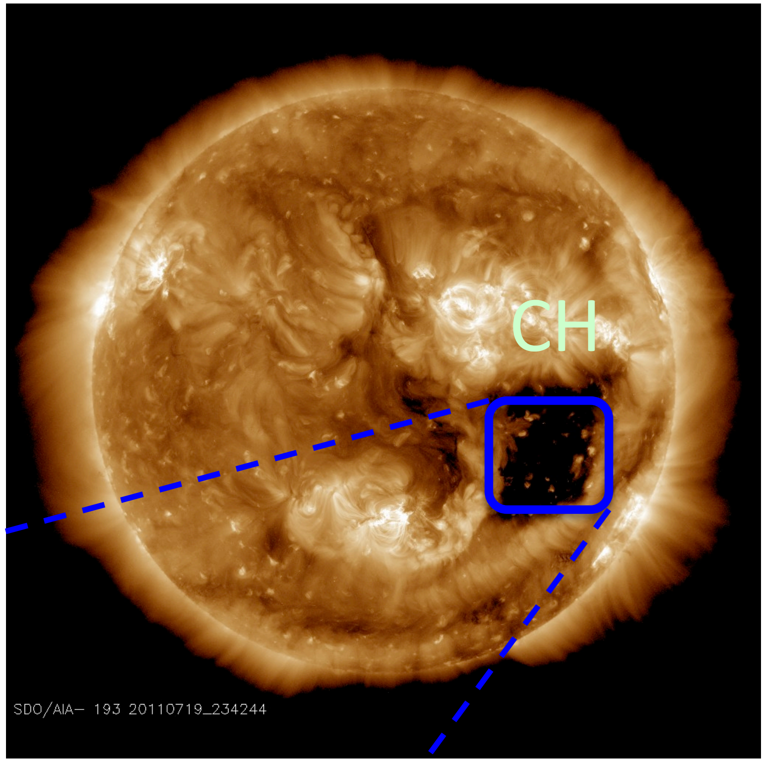




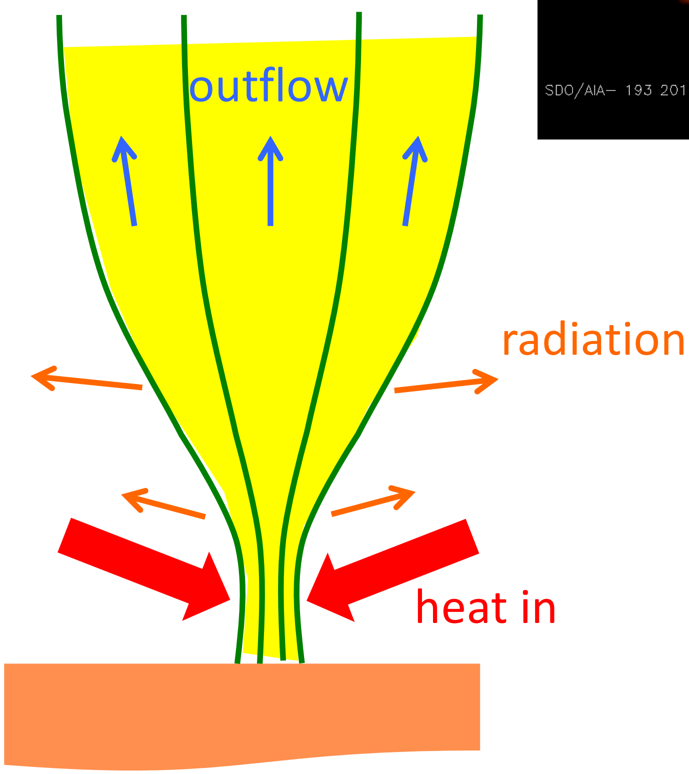




B large enough to restrict plasma motion: only along field lines



Wind: from open flux



specific enthalpy

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

Advective energy loss –

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

>> radiative loss

Bernoulli's law: $\frac{Q}{\dot{M}} = \text{const.}$

Energy loss = $A\rho v\left[\frac{1}{2}v^2 + w(\rho) + \Psi(s)\right]$ = Q = fixed & given

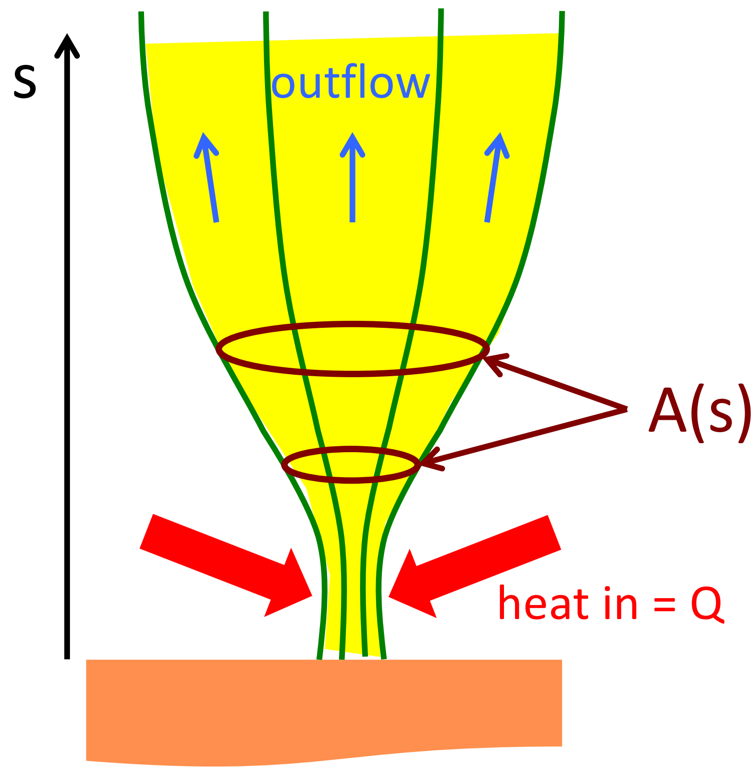
mass loss fixed & unknown

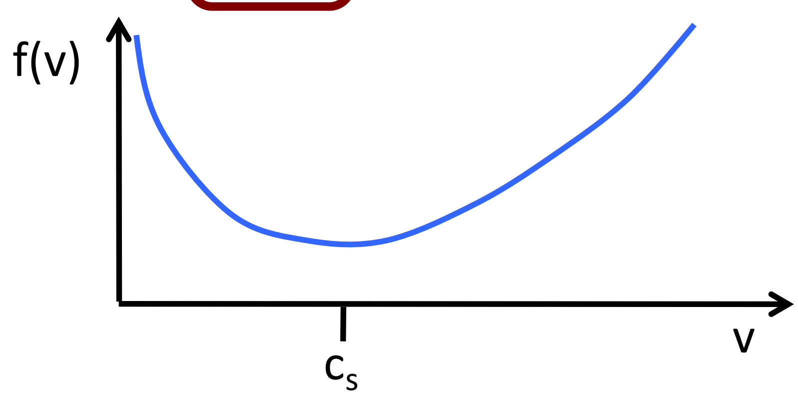
Simple case: Isothermal ... $\gamma \rightarrow 1$

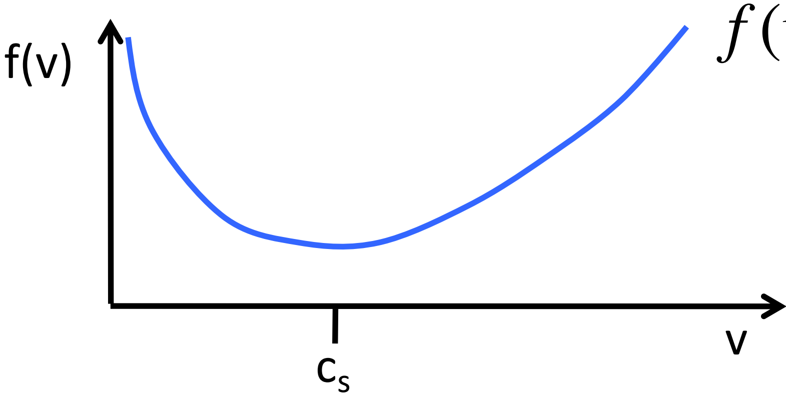
$$w(\rho) \propto \frac{\gamma}{\gamma - 1}\rho^{\gamma-1} \rightarrow c_s^2 \ln(\rho) + \text{const.}$$

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

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







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

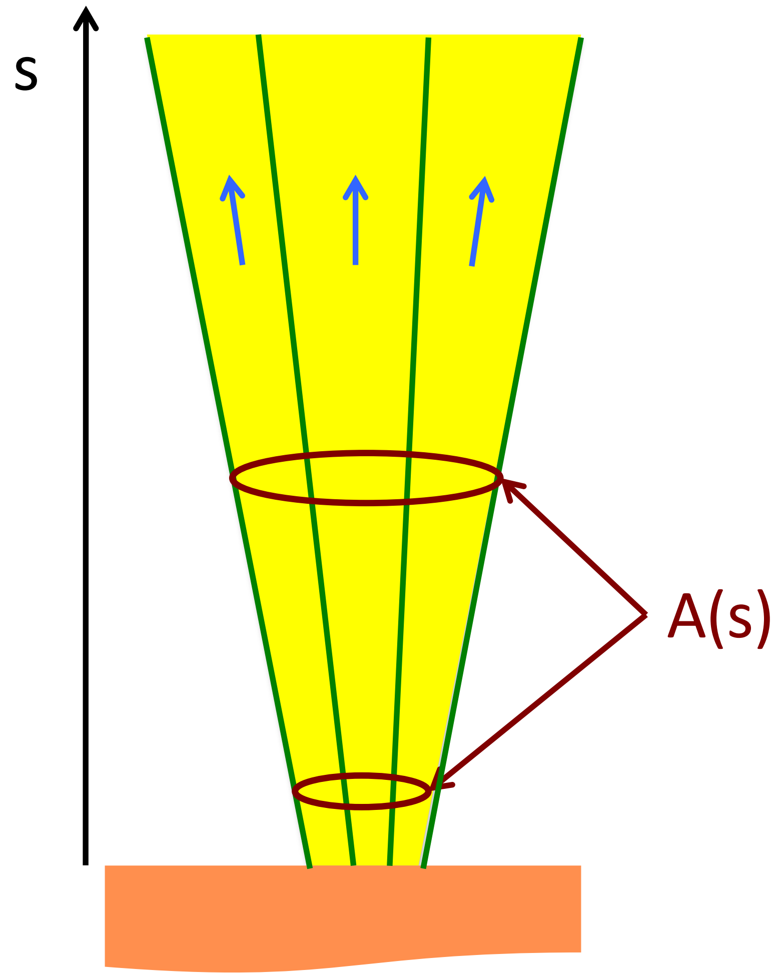
$$g(s) = -c_s^2 \ln[A(s)] - \frac{R_o v_{\mathrm{esc}}^2}{2r(s)}$$

tube:

cone w/ vertical axis

$A(s) \sim s^2$ $\quad$ $s = r$

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



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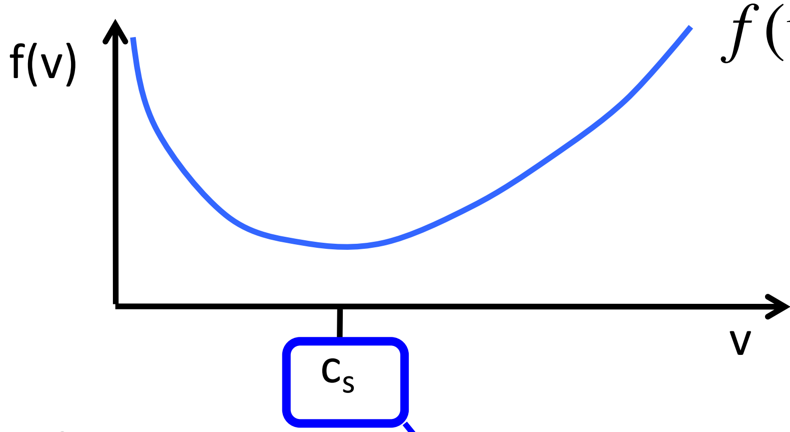


$$F(v,r) = f(v) + g(r) = \frac{Q}{\dot{M}} = \text{const.}$$

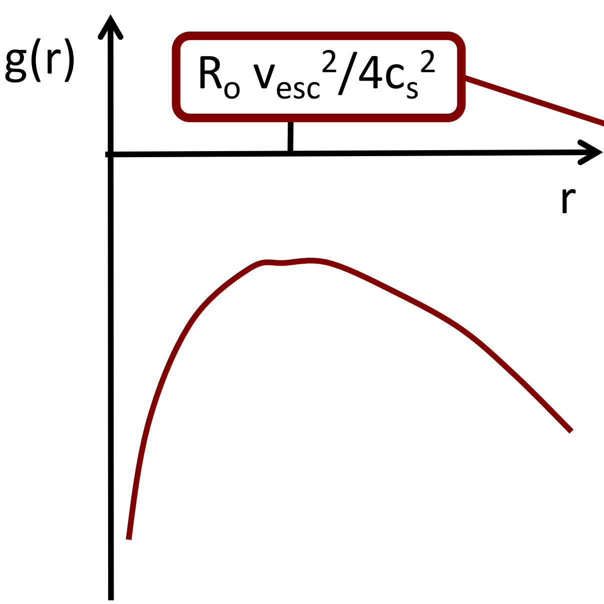
tube:

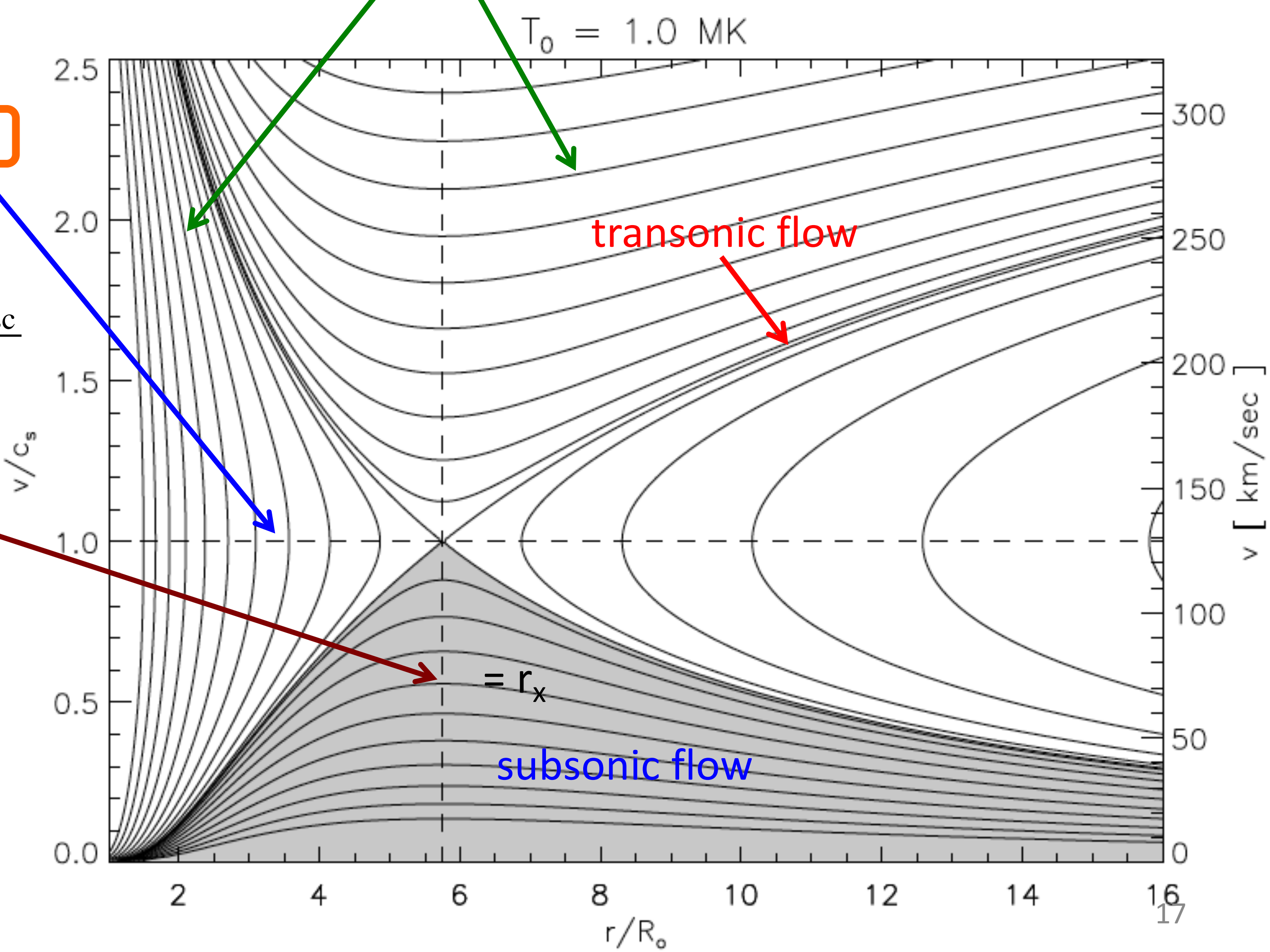
cone w/ vertical axis

$A(s) \sim s^2$

$s = r$

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





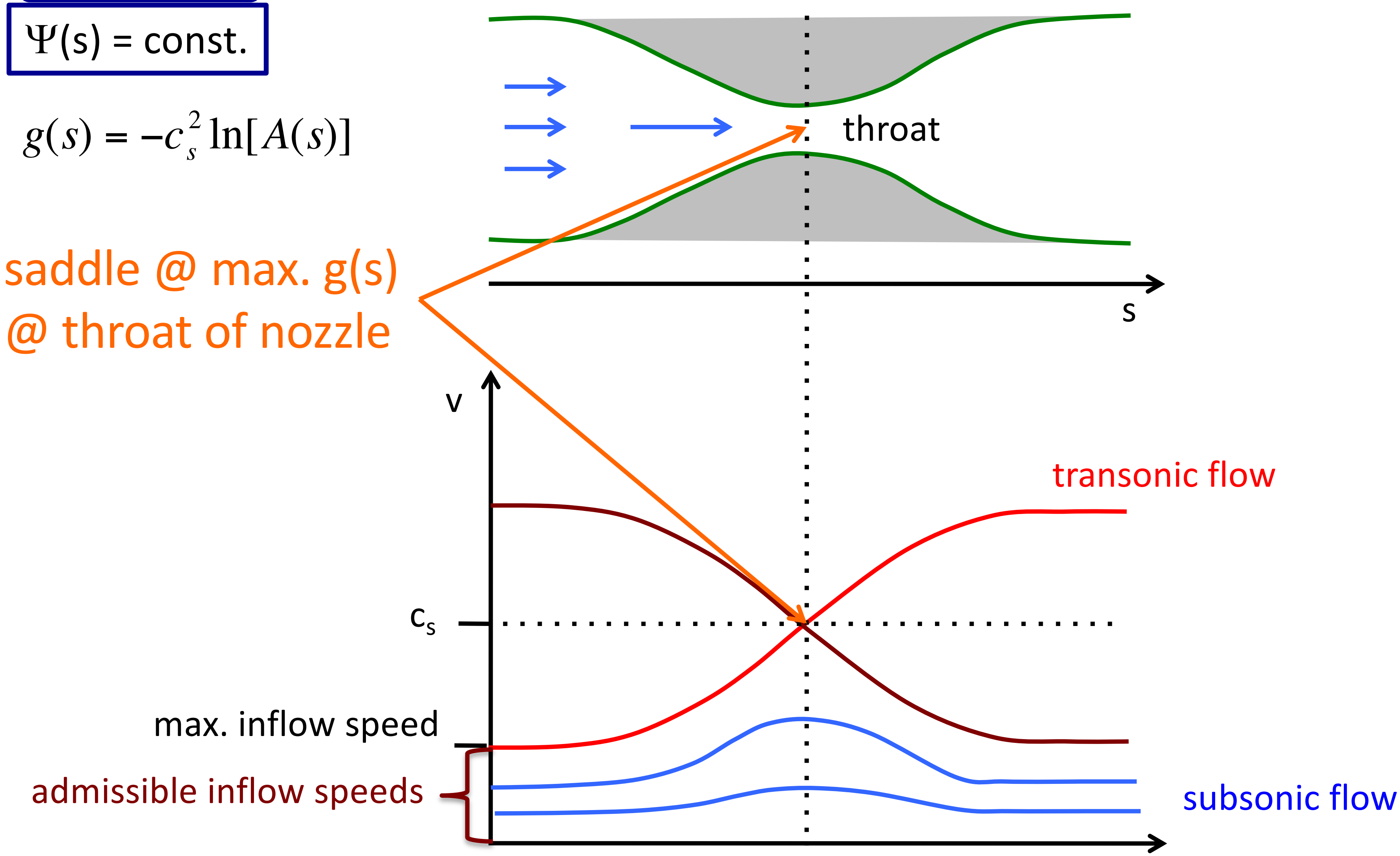
tube:

horizontal nozzle

$\Psi(s)$ = const.

$$g(s) = -c_s^2 \ln[A(s)]$$

$$g(s) = -c_s^2 \ln[A(s)] + \Psi(s)$$



tube:

horizontal nozzle

$\Psi(s) = \text{const.}$

$$g(s) = -c_s^2 \ln[A(s)] + \Psi(s)$$

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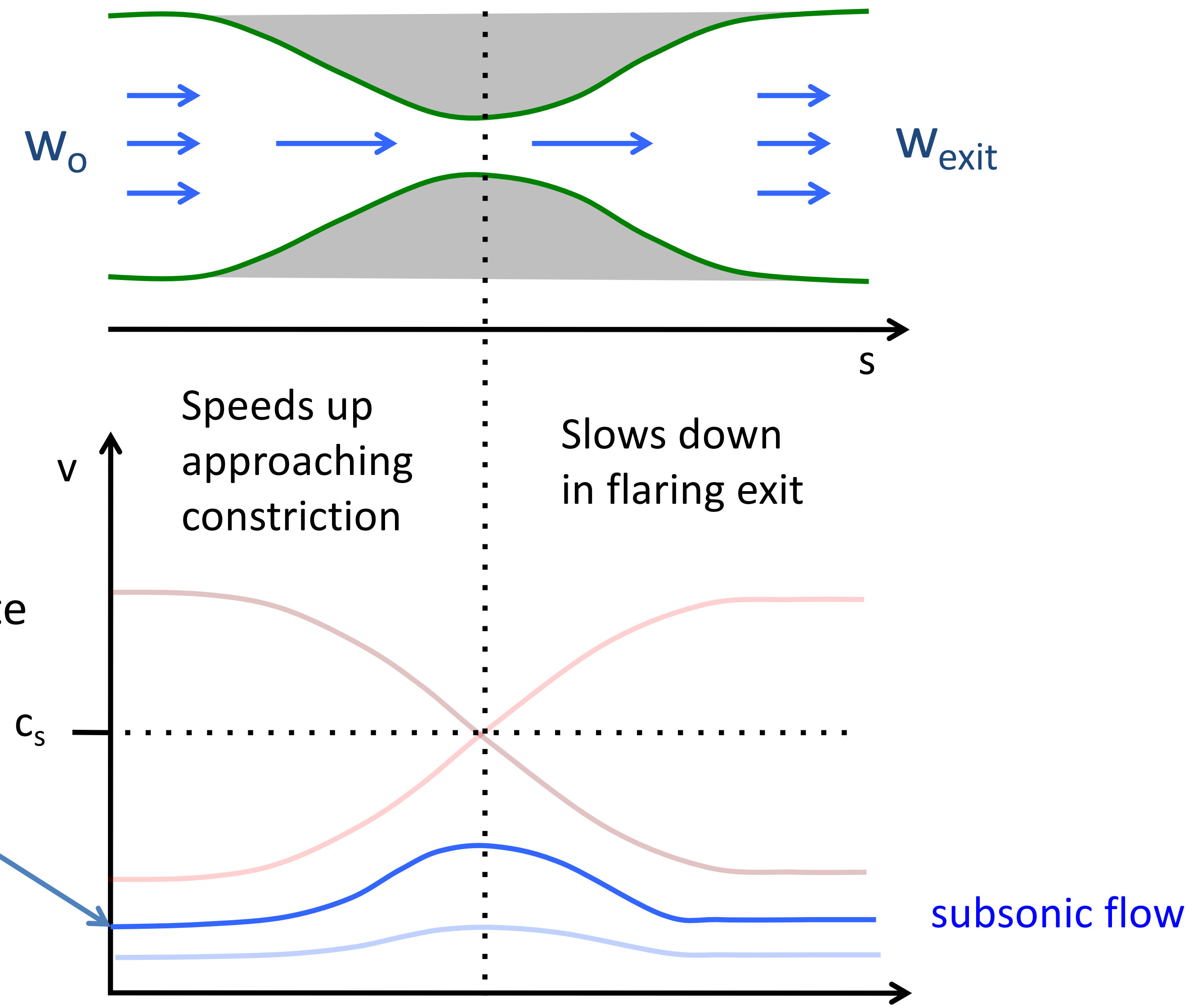


Inflow = mass loss rate

set by back-pressure

W_{exit}

tube:

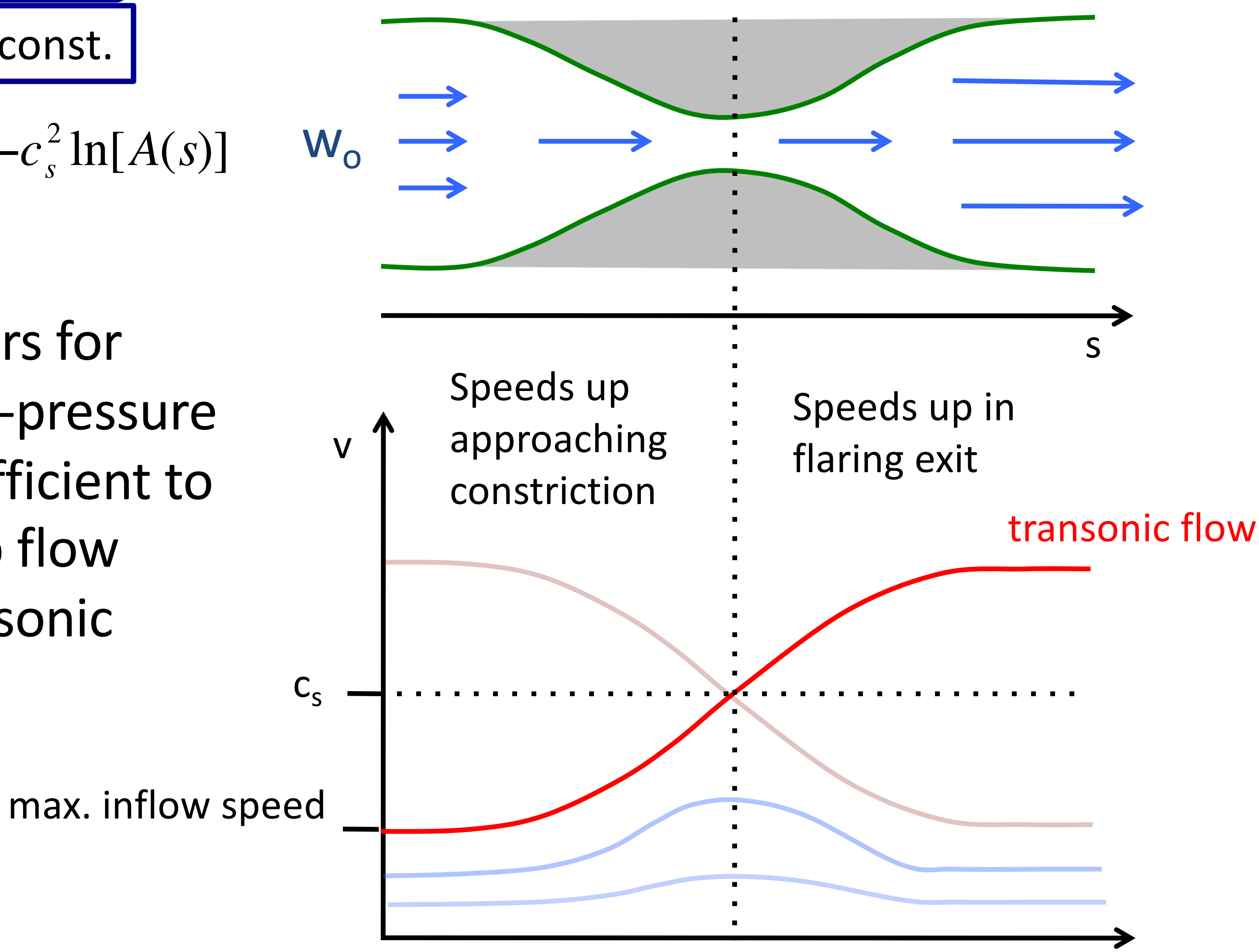
horizontal nozzle

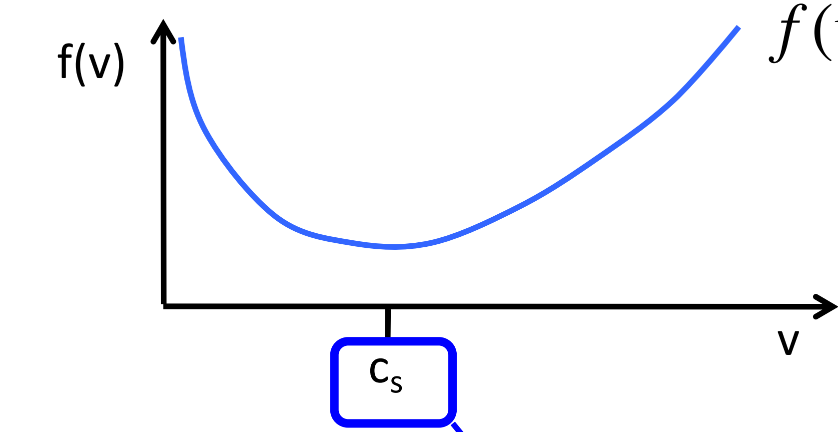
$\Psi(s)$ = const.

$$g(s) = -c_s^2 \ln[A(s)]$$

$$g(s) = -c_s^2 \ln[A(s)] + \Psi(s)$$

occurs for back-pressure insufficient to keep flow sub-sonic

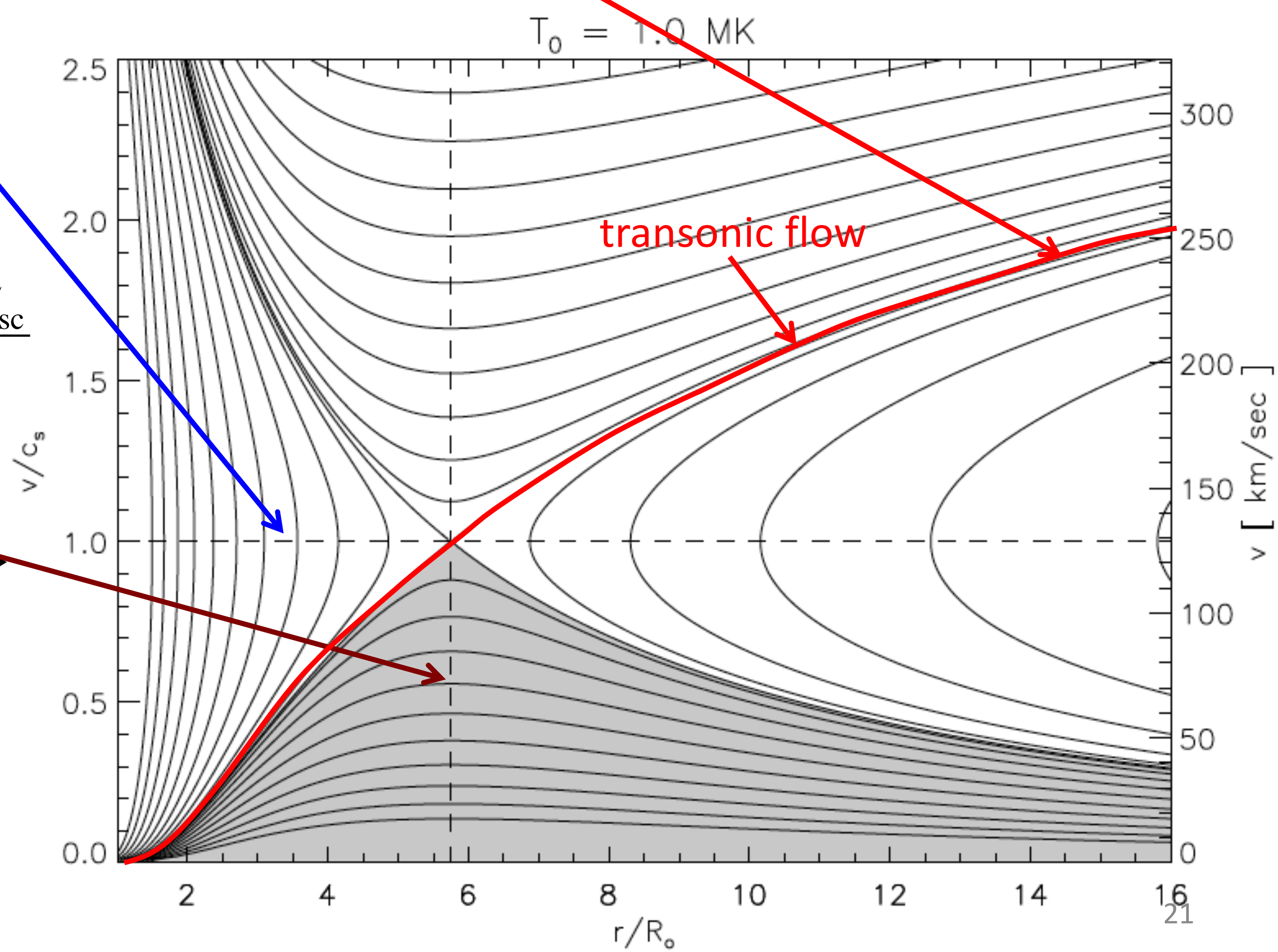




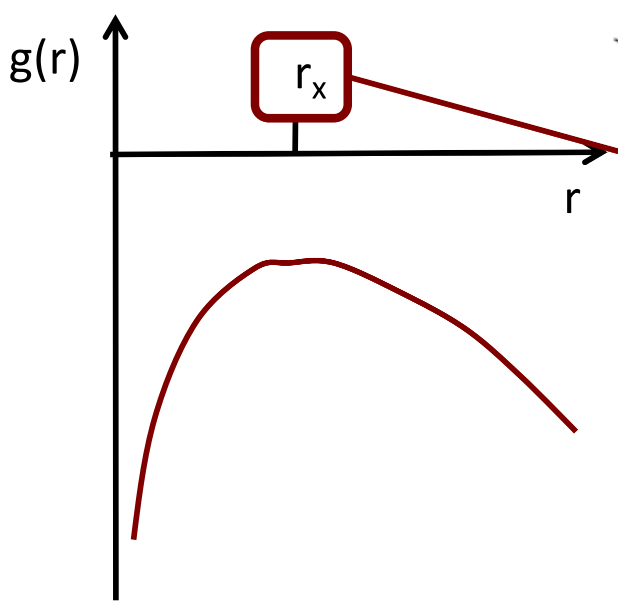
$$f(v) = \frac{1}{2}v^2 - c_s^2 \ln(v)$$

const. fixed by need to become transonic when external back-pressure is insufficient – i.e. vacuum around sun

$$F_x = f(c_s) + g(r_x) = \frac{Q}{\dot{M}}$$



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



➔ Mass loss rate is set by heating rate*

$$\dot{M} = \frac{Q}{F_x}$$

➔ density everywhere is set by mass loss rate

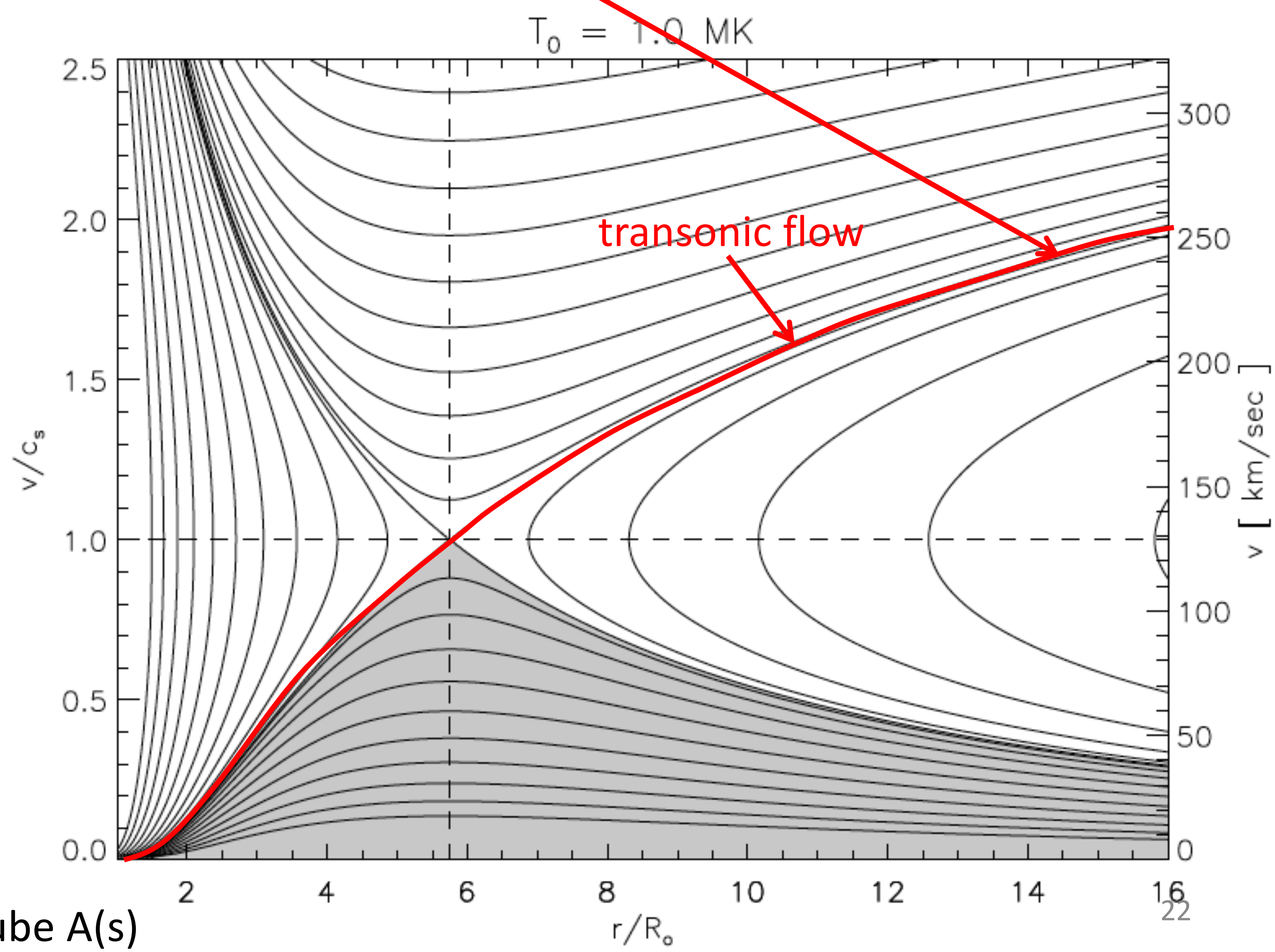
$$\rho(r_x) = \frac{\dot{M}}{A(r_x)c_s}$$

➔ density @ base is set by heating rate*…

… and it will be lower than density on closed loops w/ same heating (Why?)

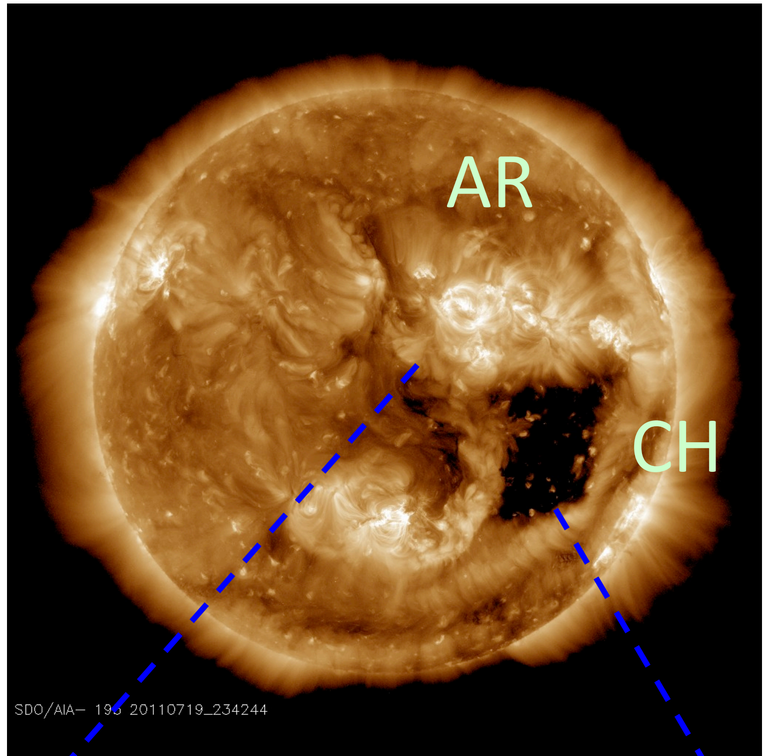
const. fixed by need to become transonic when external back-pressure is insufficient – i.e. vacuum around sun

$$F_x = f(c_s) + g(r_x) = \frac{Q}{\dot{M}}$$

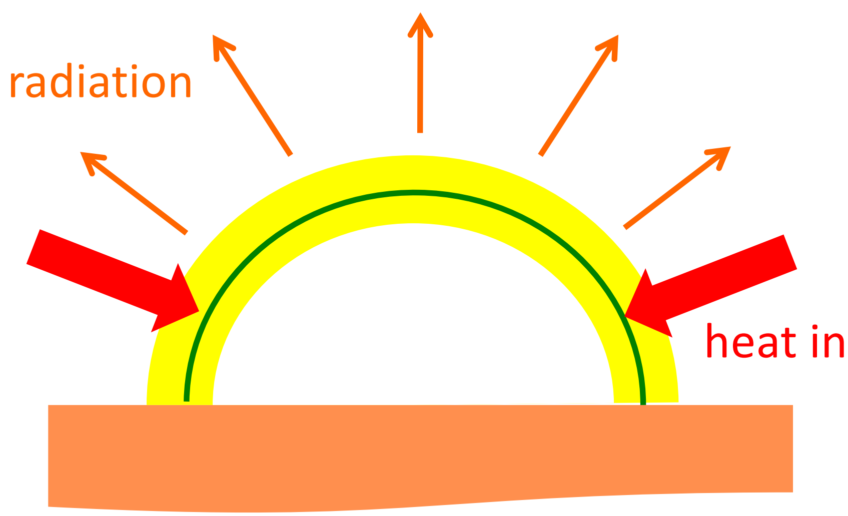


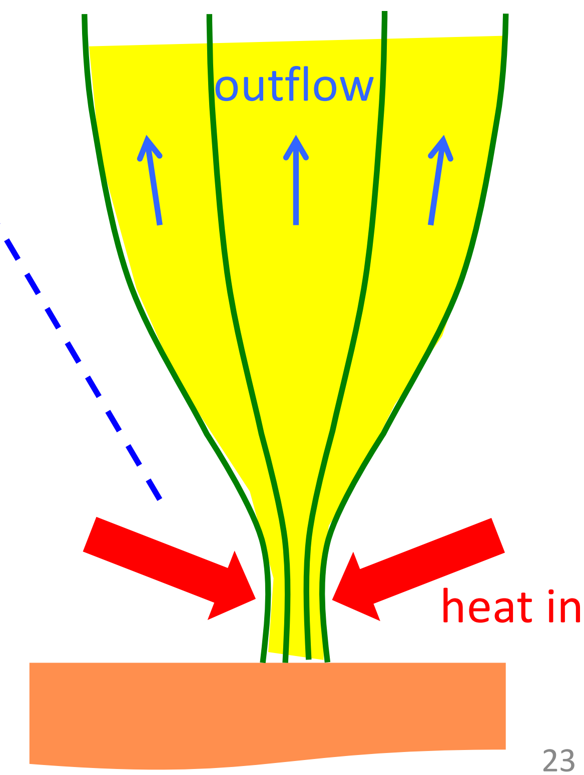
* … and geometry of flux tube A(s)

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)

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

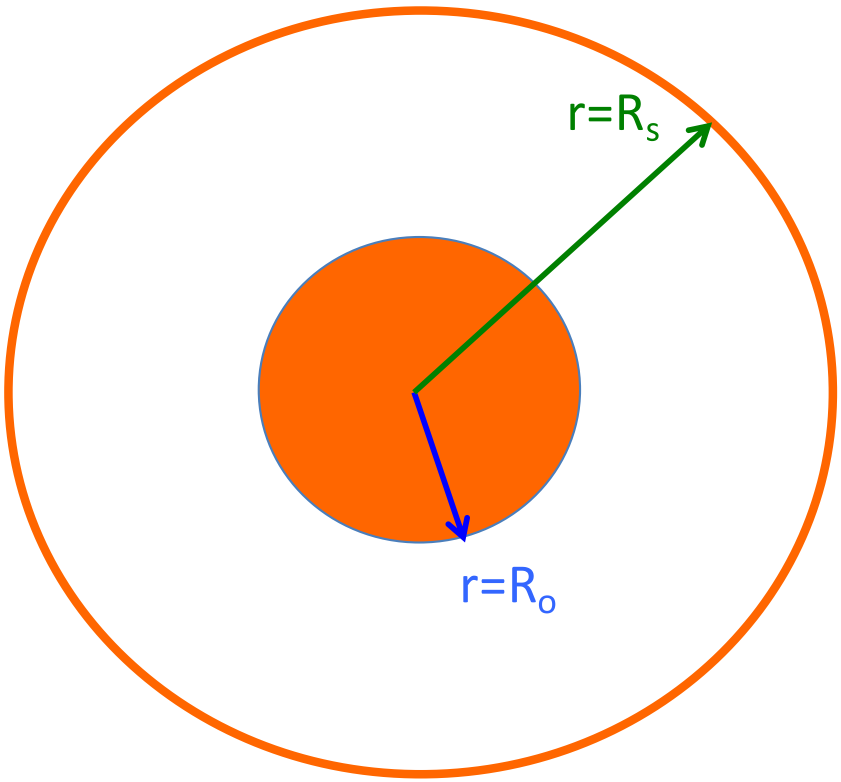
potential field
(cf. electrostatics)

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

harmonic potential
(cf. electrostatics in vacuum)

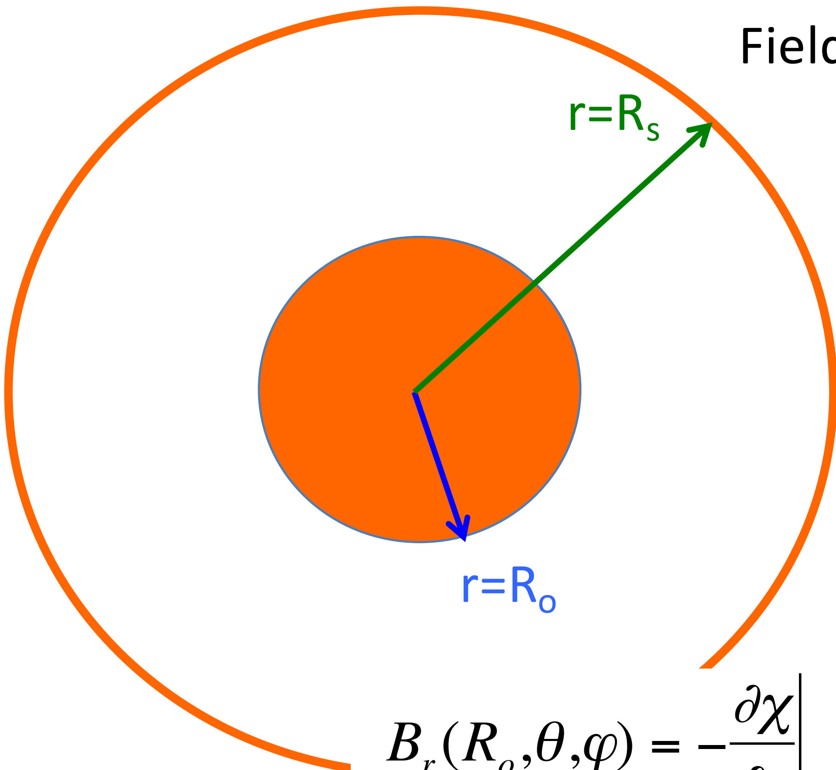
$$\mathbf{B} = -\nabla\chi \quad \& \quad \nabla^2\chi = 0$$

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

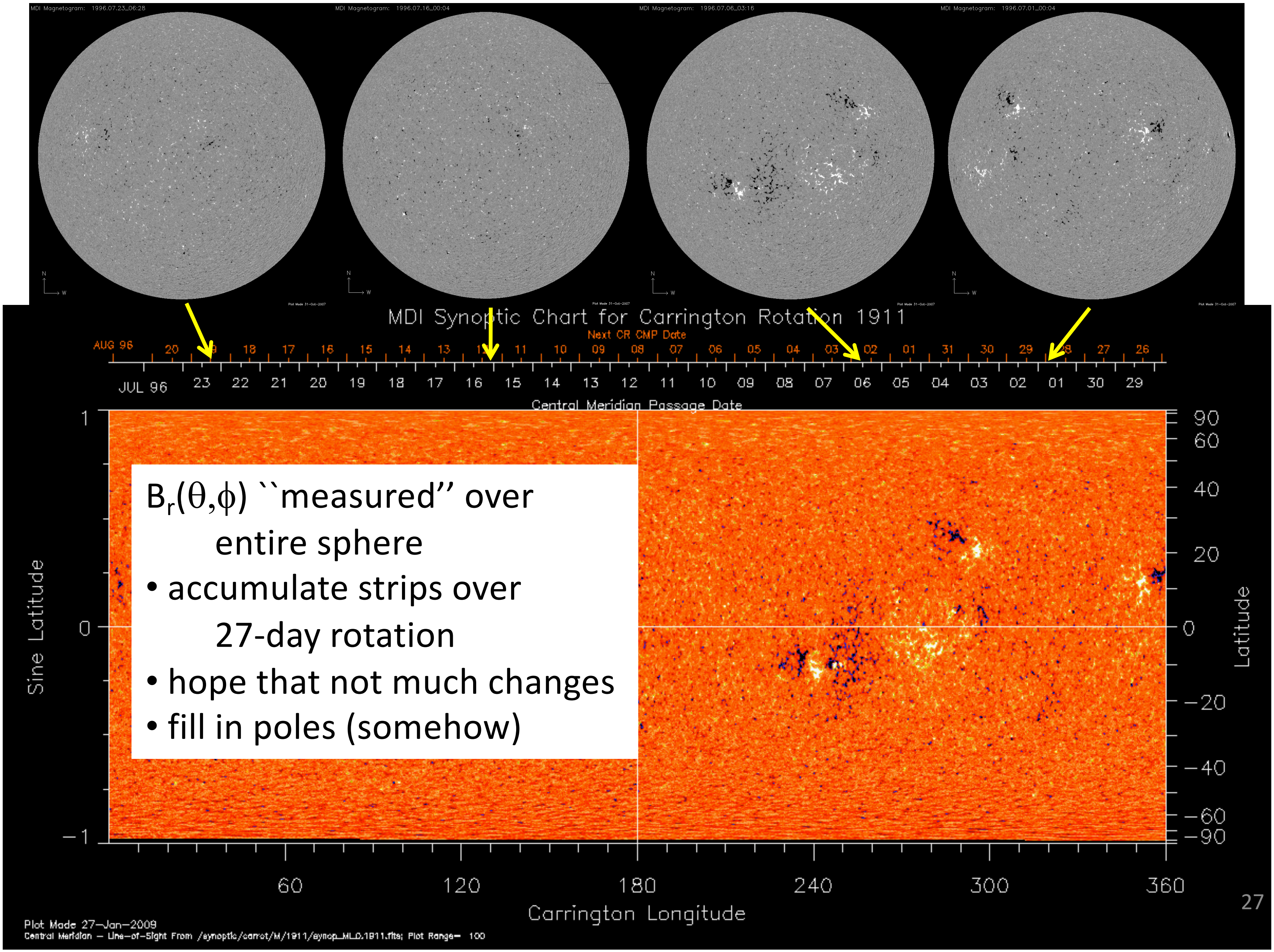
$$\chi(r,\theta,\varphi) = \sum_{\ell,m} A_{\ell,m}\left[\left(\frac{R_s}{r}\right)^{\ell+1} - \left(\frac{r}{R_s}\right)^{\ell}\right]Y_{\ell,m}(\theta,\varphi)$$

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

time



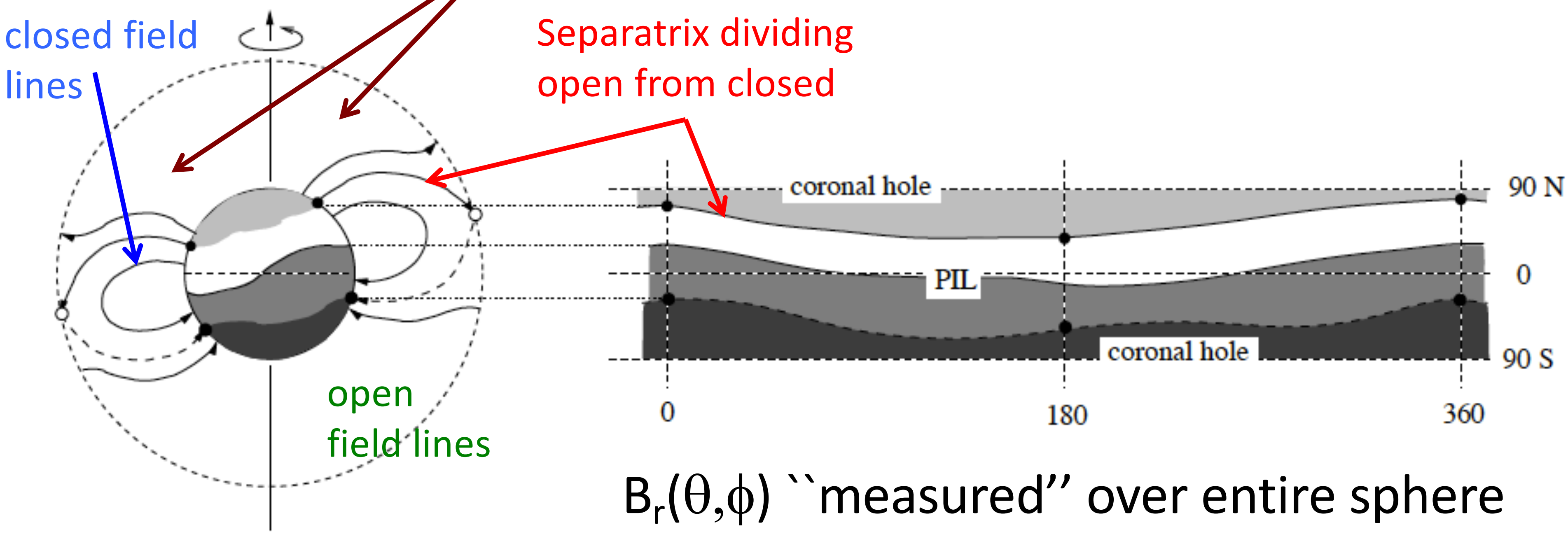
$B_r(\theta,\phi)$ ``measured'' over entire sphere

- accumulate strips over 27-day rotation
- hope that not much changes
- fill in poles (somehow)

PFSS model

(potential field source surface)

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



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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. ➔ $A_{l,m}$

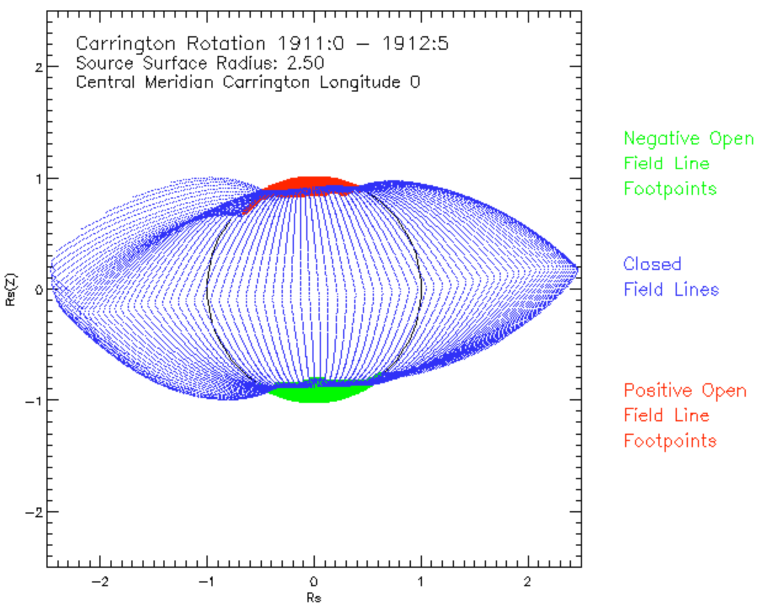
Assumptions of the PFSS

- No currents in coronal field (simplest equilibrium)

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

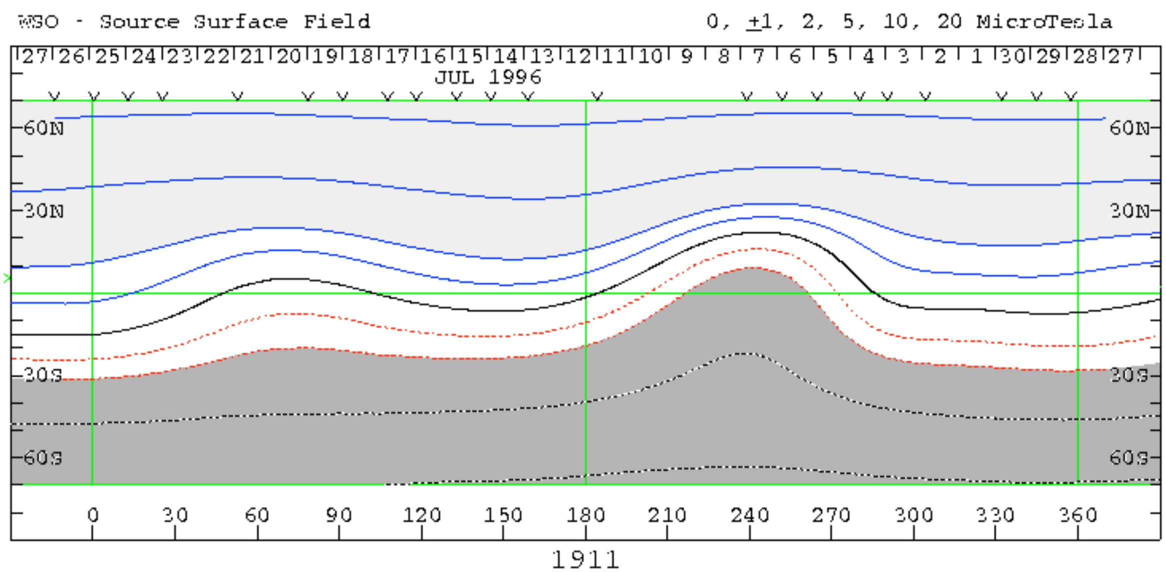
- Field becomes open (radial) @ fixed radius $r = R_s$

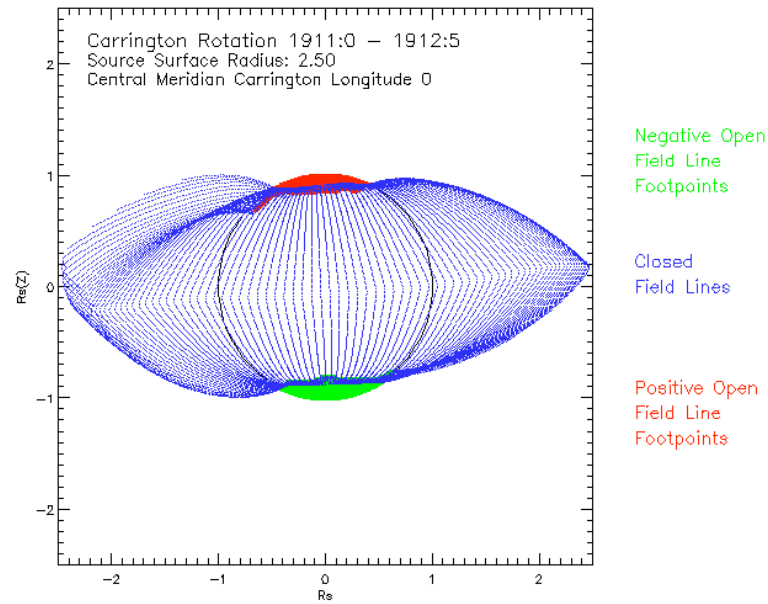
- Not much change during 27-day accumulation

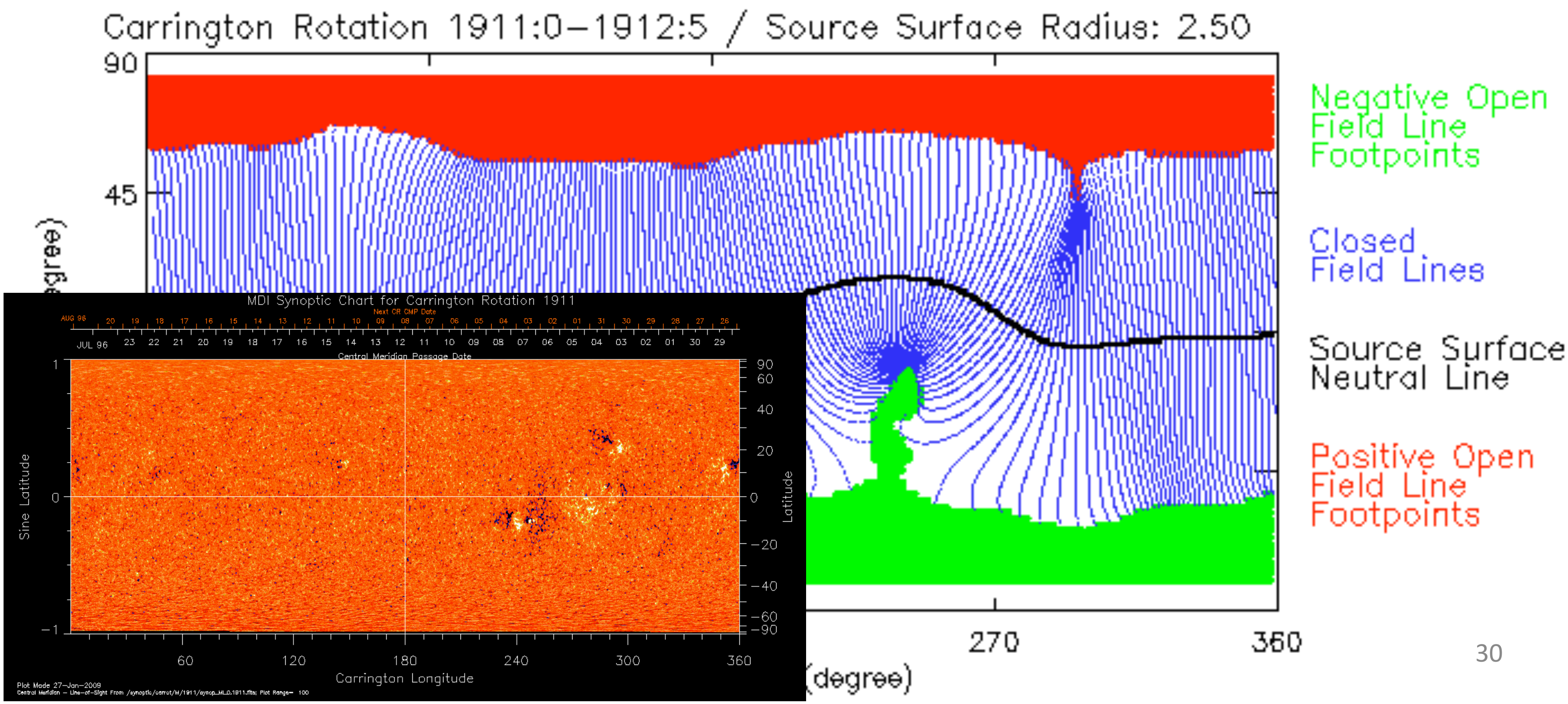


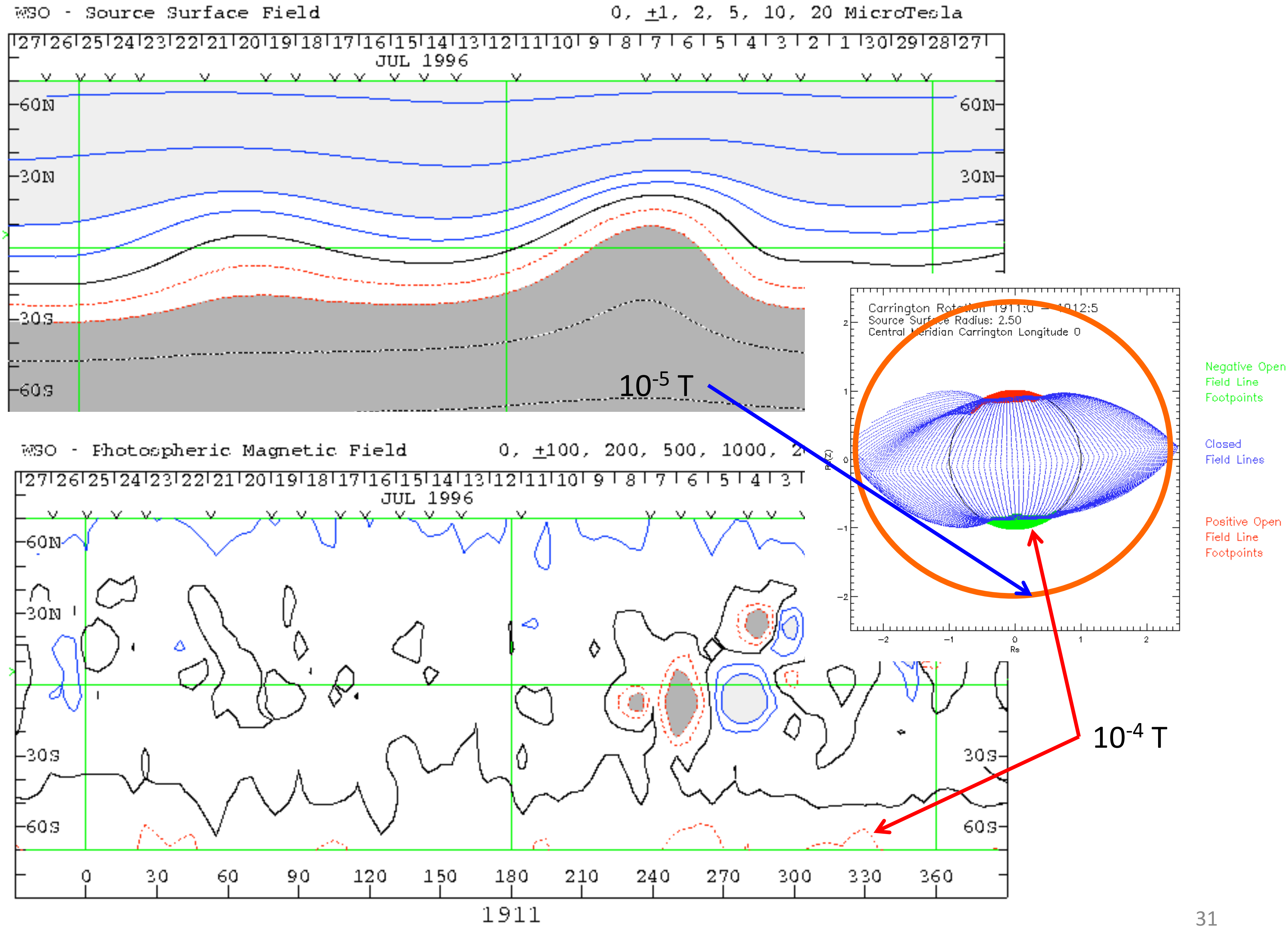
➔ **Model** distinguishing open/closed coronal field

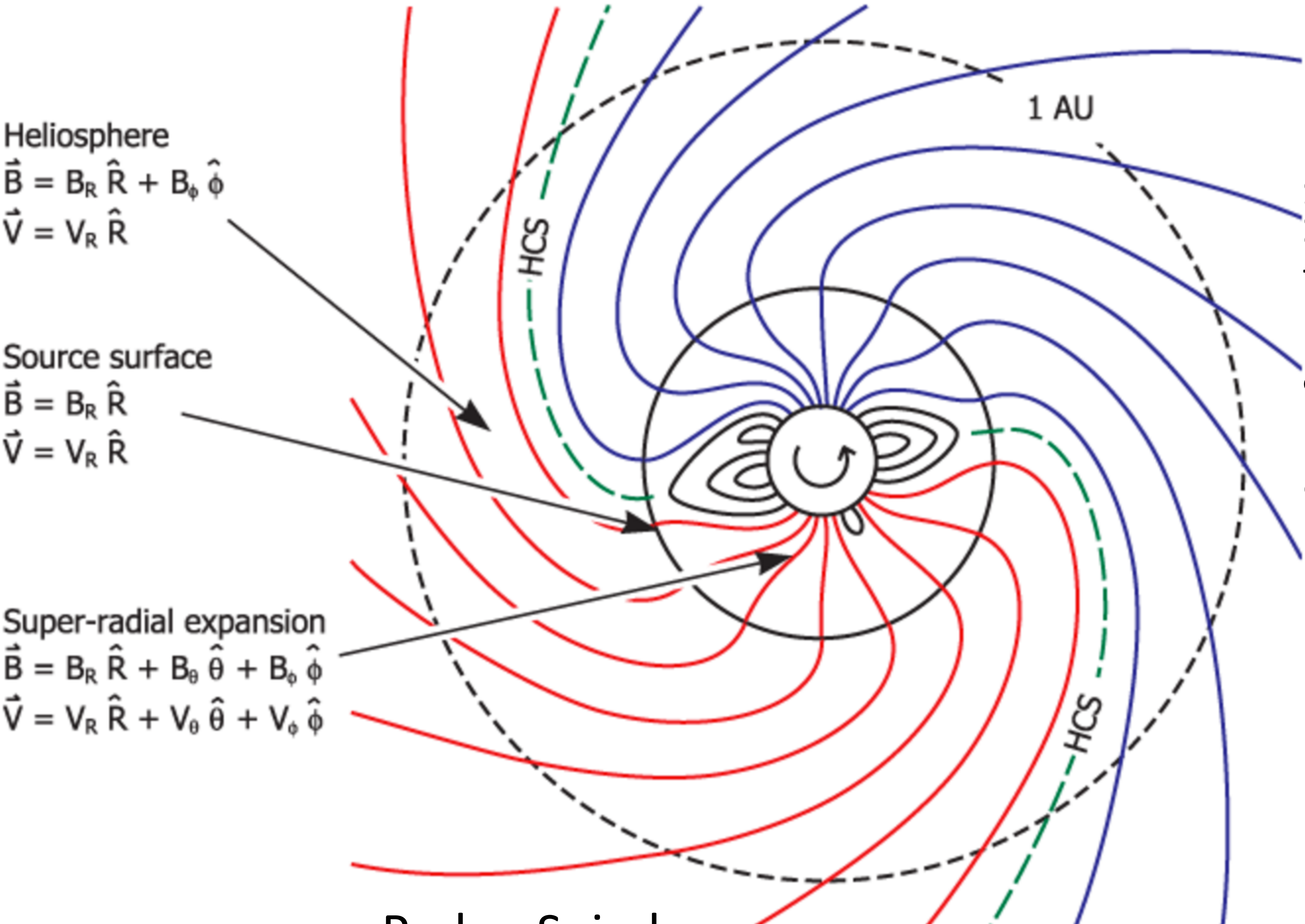
➔ Field **actually** open will be source of solar wind, less dense & dark in EUX & SXR


WSO - Source Surface Field
0, ±1, 2, 5, 10, 20 MicroTesla
JUL 1996
60N
30N
30S
60S
0 30 60 90 120 150 180 210 240 270 300 330 360
1911


Carrington Rotation 1911:0 – 1912:5
Source Surface Radius: 2.50
Central Meridian Carrington Longitude 0
Rs(Z)
Rs
Negative Open Field Line Footpoints
Closed Field Lines
Positive Open Field Line Footpoints

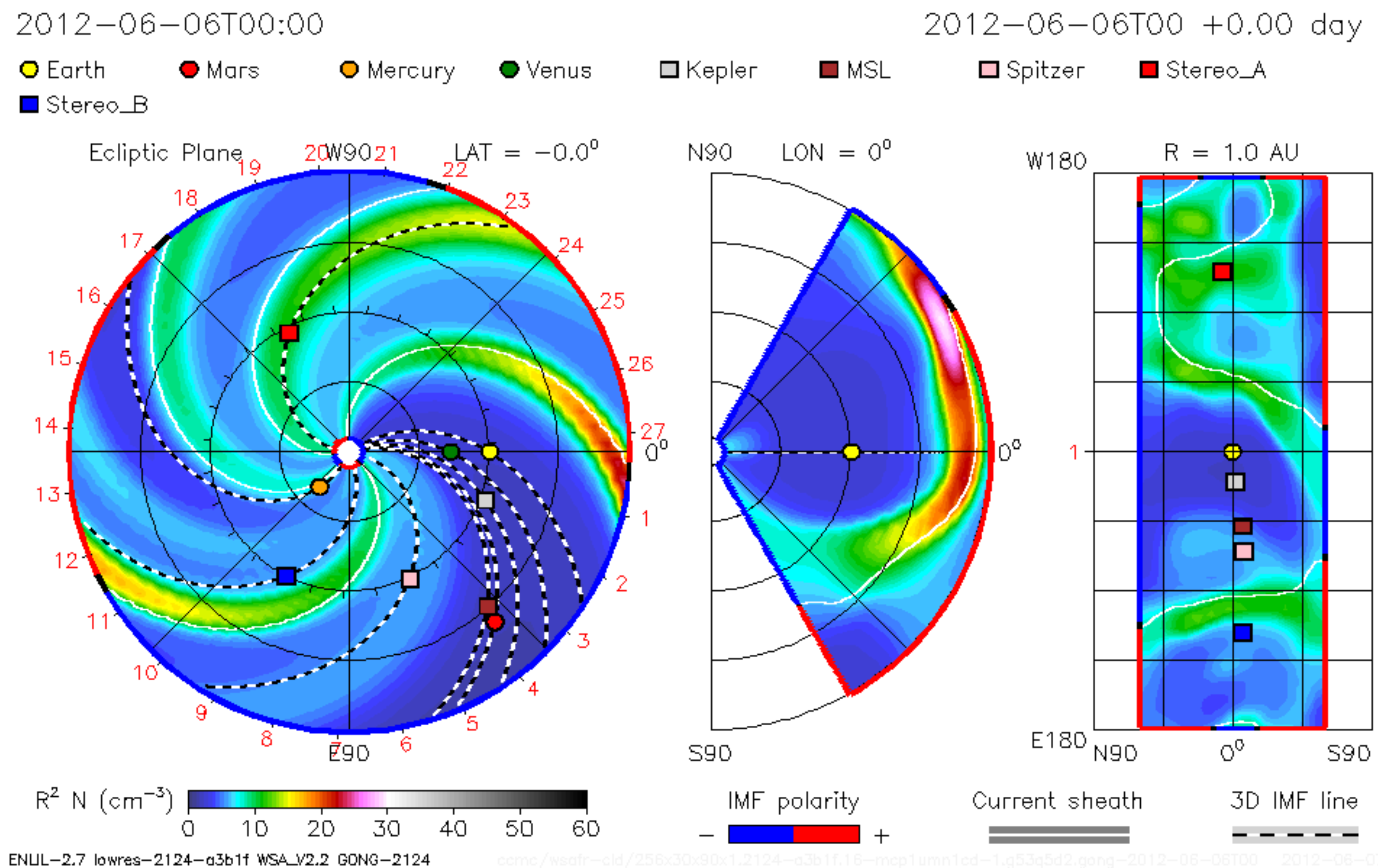

Carrington Rotation 1911:0–1912:5 / Source Surface Radius: 2.50
90
45
270
360
(degree)
Negative Open Field Line Footpoints
Closed Field Lines
Source Surface Neutral Line
Positive Open Field Line Footpoints
MDI Synoptic Chart for Carrington Rotation 1911
Central Meridian Passage Date
Sine Latitude
Latitude
60 120 180 240 300 360
Carrington Longitude

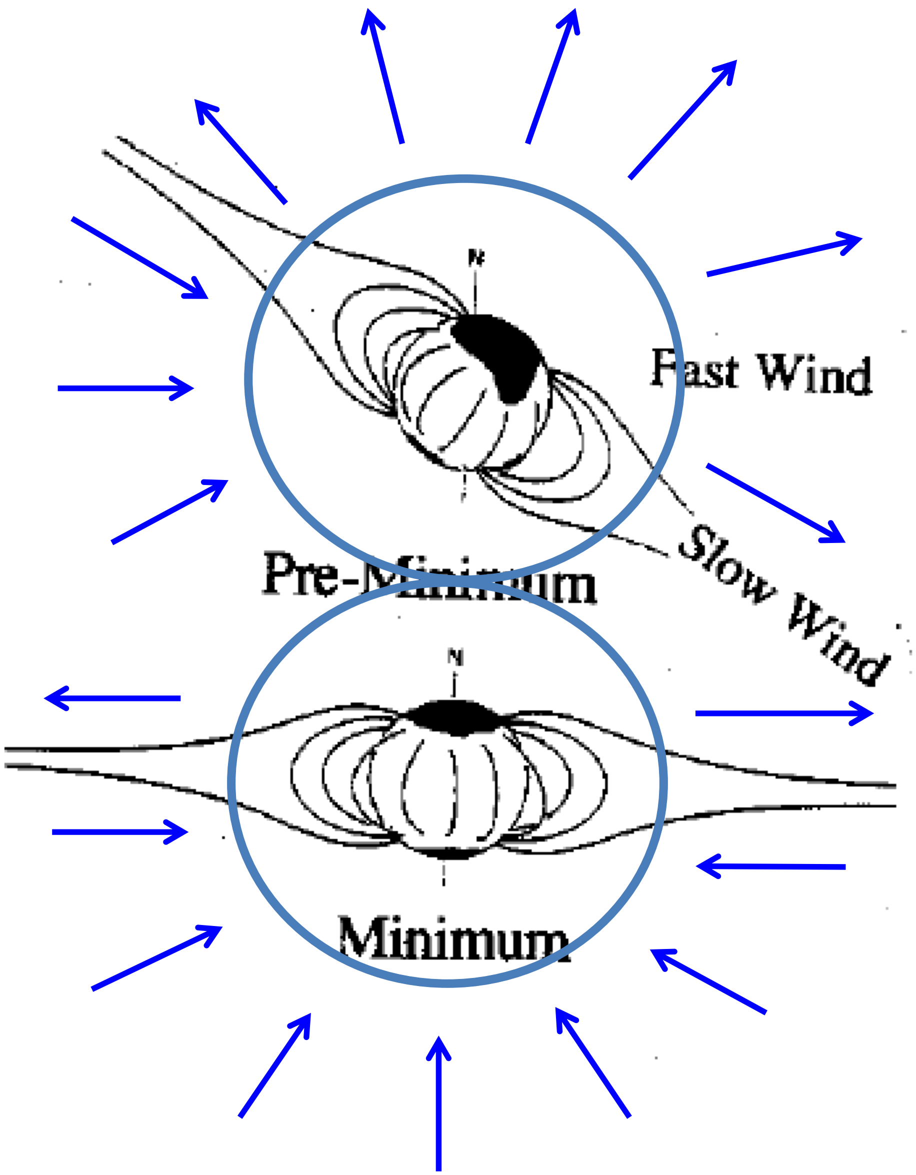

WSO - Source Surface Field
0, ±1, 2, 5, 10, 20 MicroTesla
JUL 1996
60N
30N
30S
60S
10-5 T
Carrington Rotation 1911:0 — 1912:5
Source Surface Radius: 2.50
Central Meridian Carrington Longitude 0
Negative Open Field Line Footpoints
Closed Field Lines
Positive Open Field Line Footpoints
Rs
WSO - Photospheric Magnetic Field
0, ±100, 200, 500, 1000, 2
10-4 T
0
30
60
90
120
150
180
210
240
270
300
330
360
1911

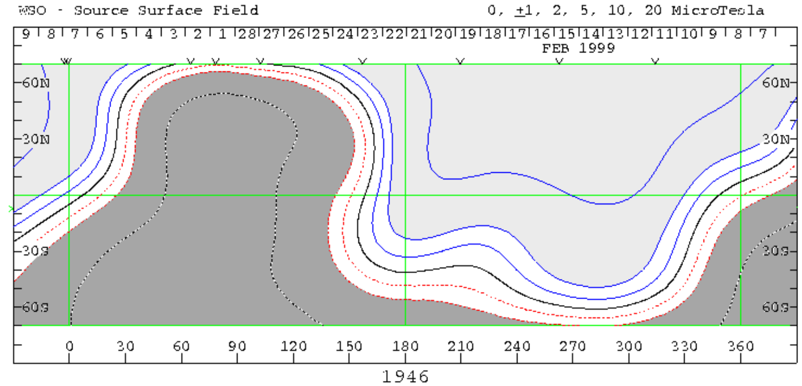


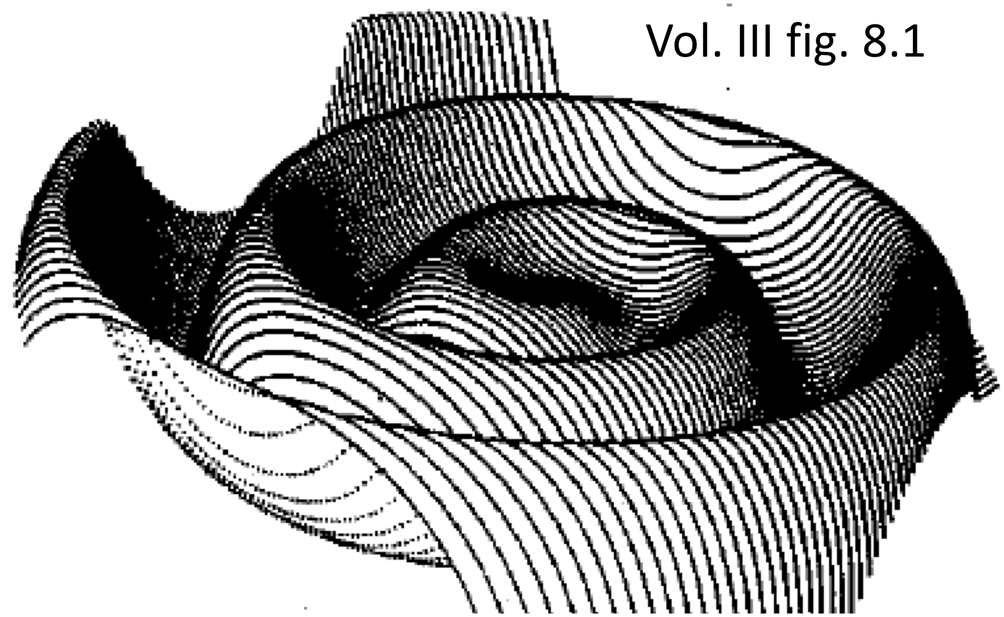
Parker Spiral

Owens & Forsyth 2013

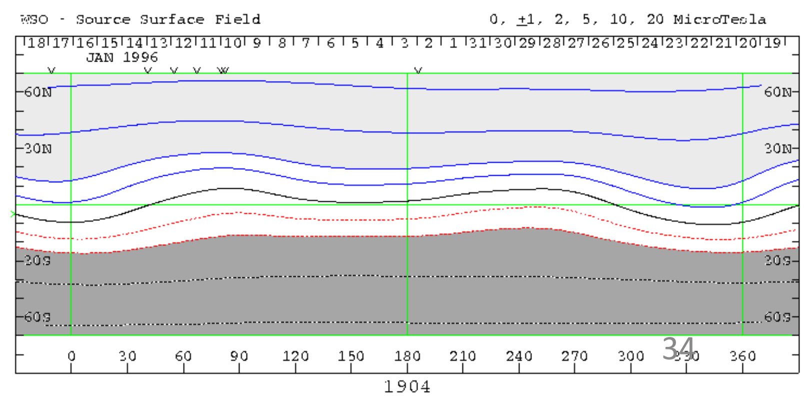

2012-06-06T00:00
2012-06-06T00 +0.00 day
Earth
Mars
Mercury
Venus
Kepler
MSL
Spitzer
Stereo_A
Stereo_B
Ecliptic Plane
W90
E90
LAT = -0.0°
N90
LON = 0°
S90
W180
R = 1.0 AU
E180
N90
0°
S90
R² N (cm⁻³)
0 10 20 30 40 50 60
IMF polarity
- +
Current sheath
3D IMF line
ENLIL-2.7 lowres-2124-a3b1f WSA_V2.2 GONG-2124

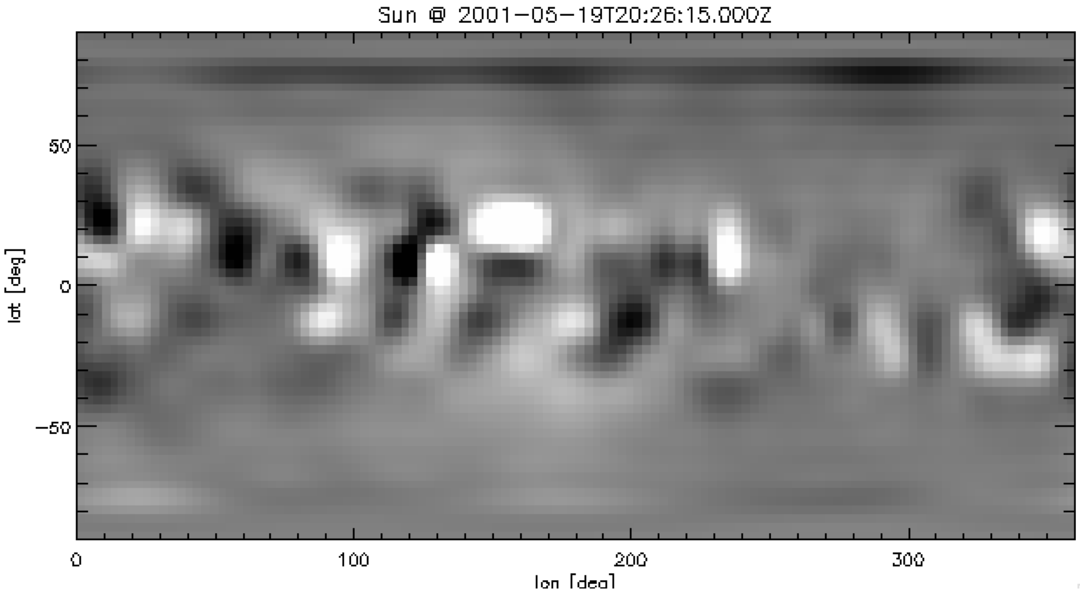






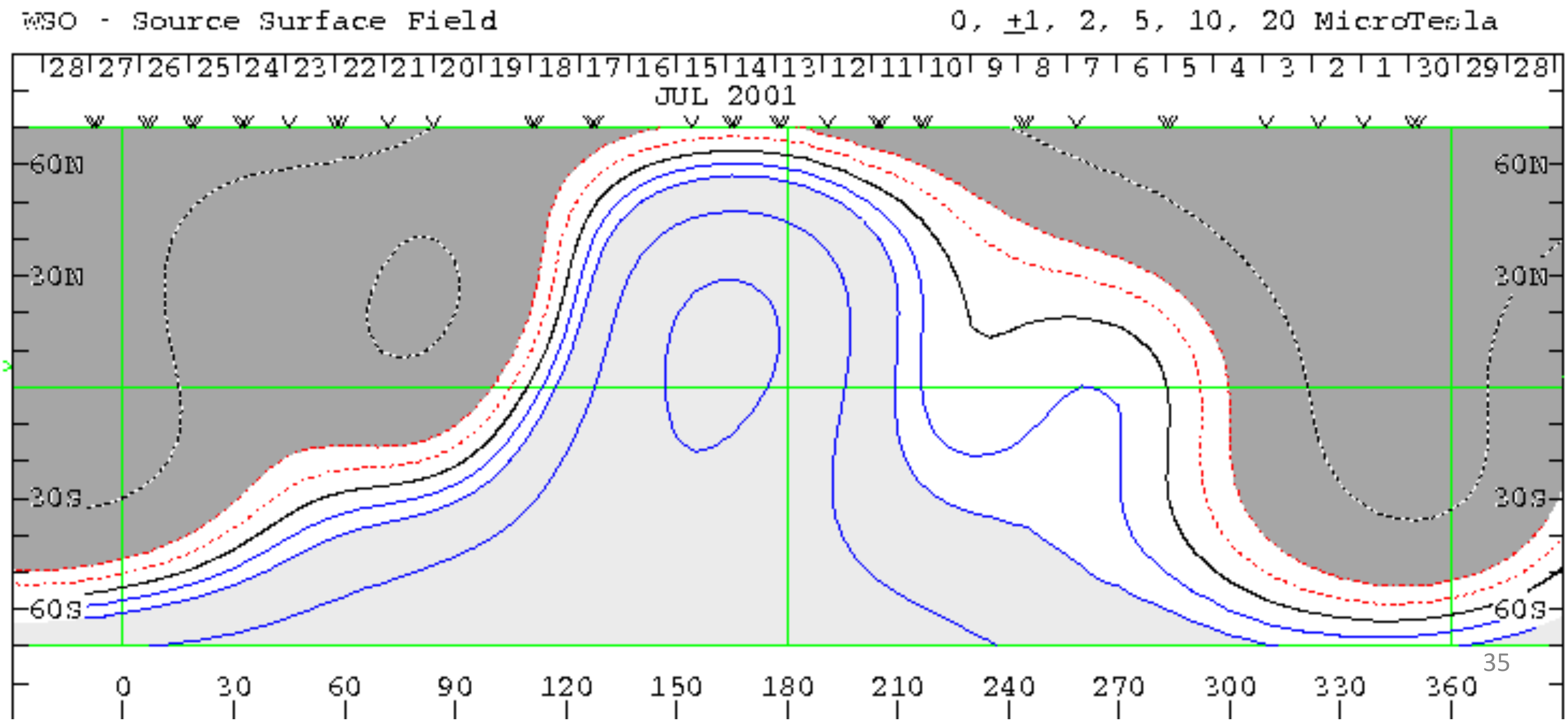
Vol. III fig. 8.1

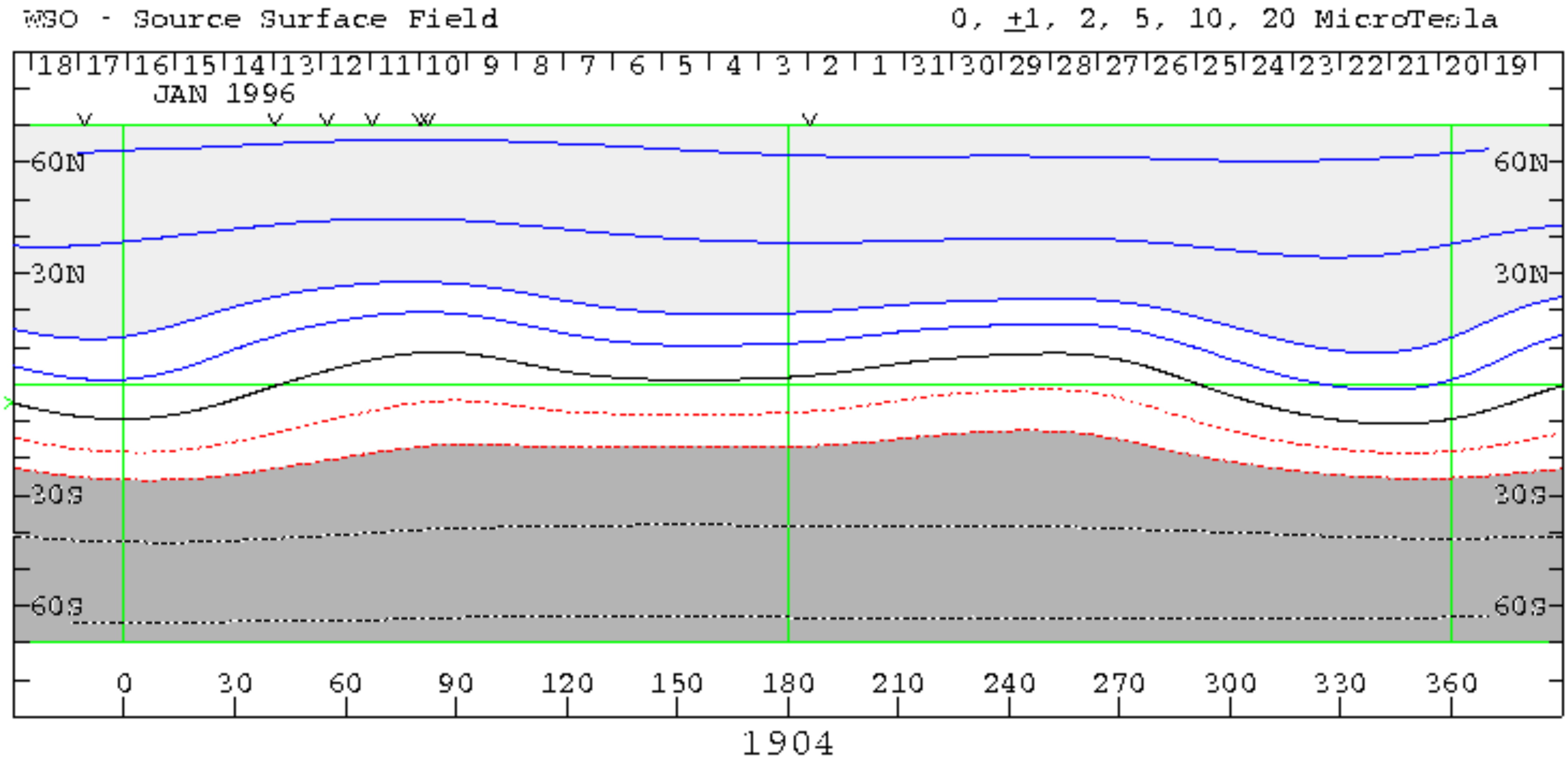


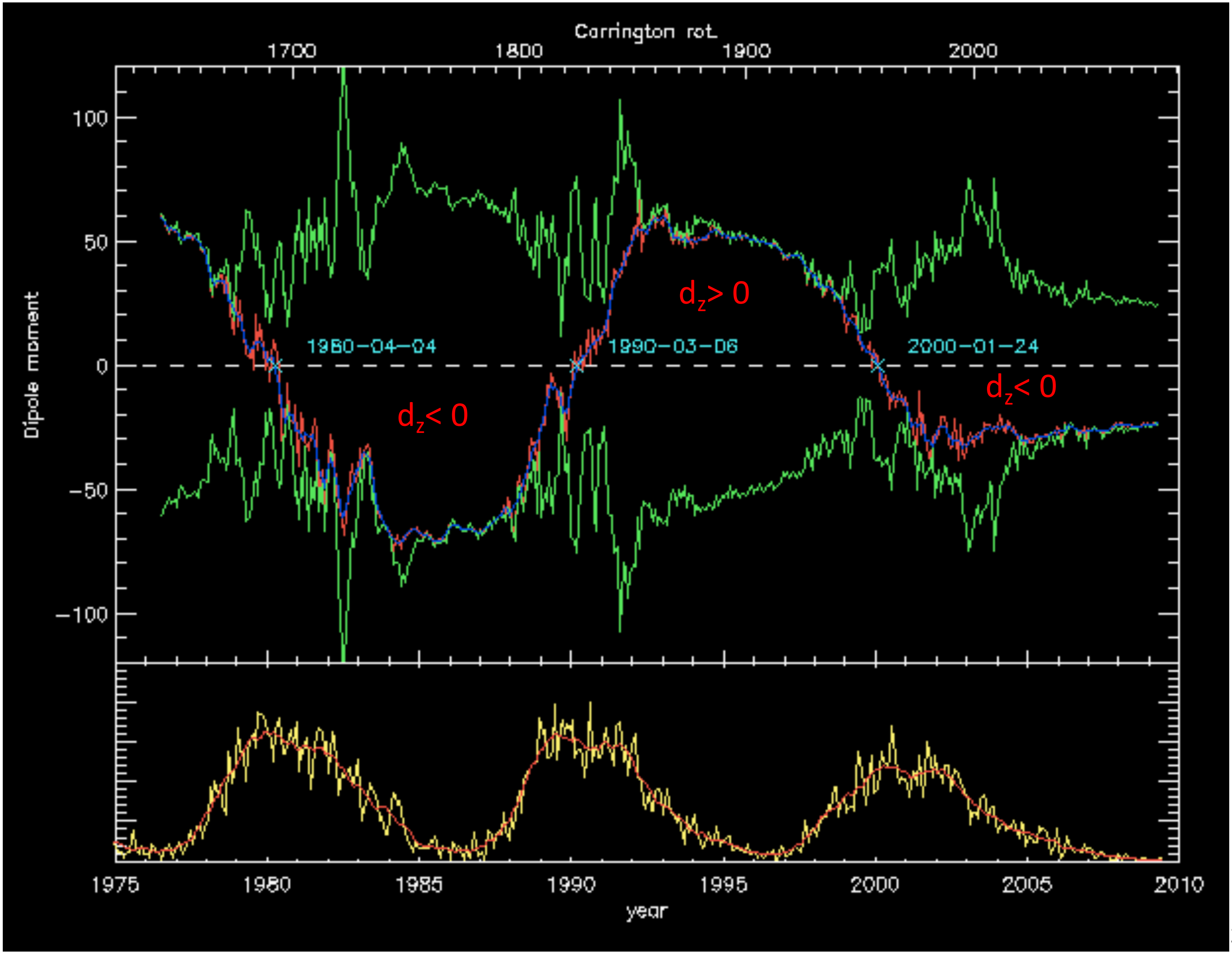


r = $R_\odot$

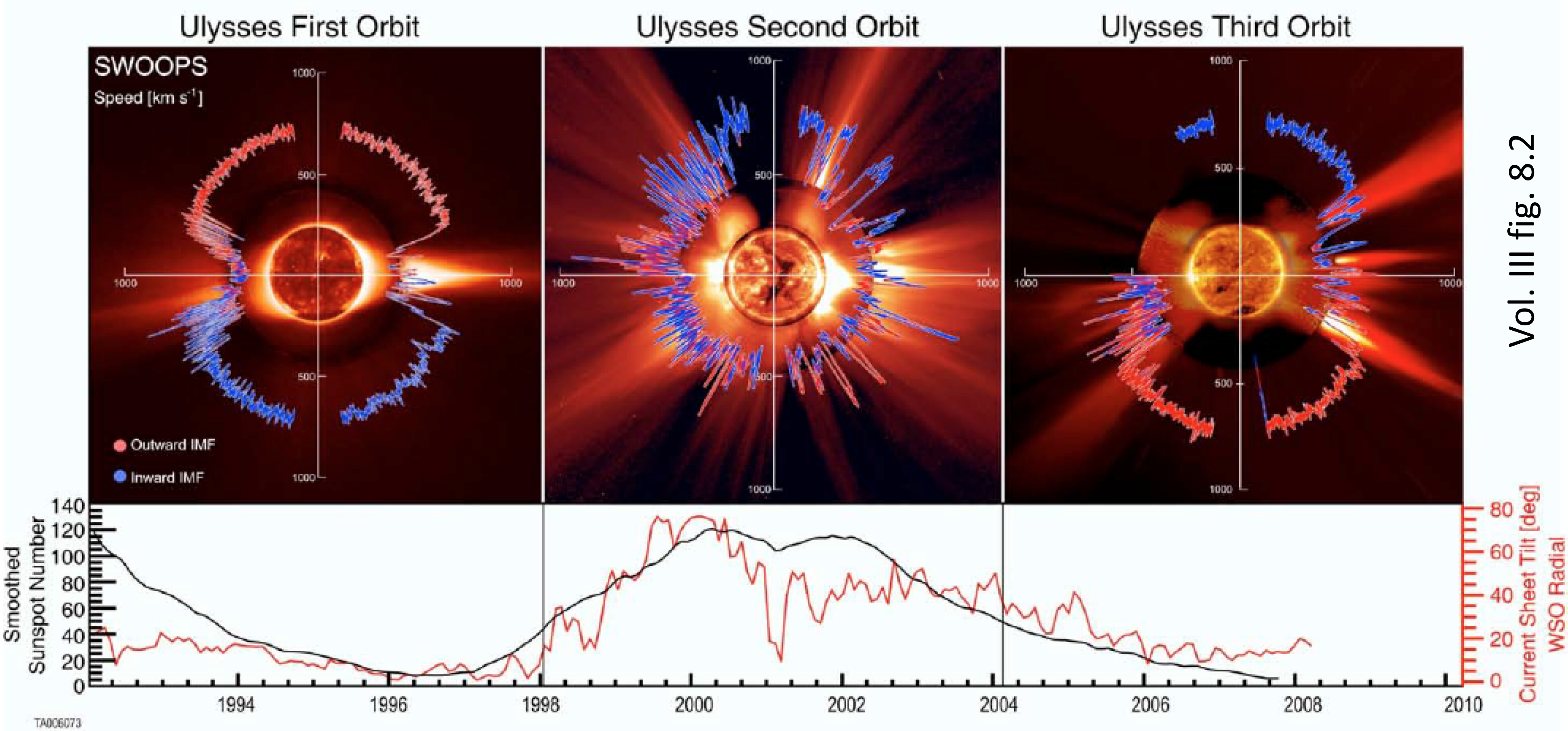
r = 2.5 $R_\odot$




WSO - Source Surface Field
0, ±1, 2, 5, 10, 20 MicroTesla
18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 31 30 29 28 27 26 25 24 23 22 21 20 19
JAN 1996
60N
30N
30S
60S
0 30 60 90 120 150 180 210 240 270 300 330 360
1904

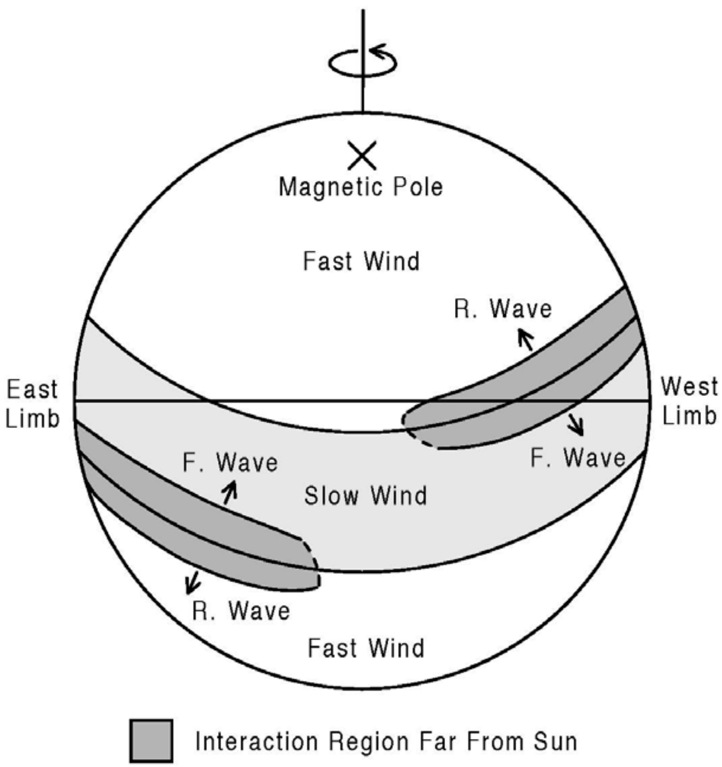

Carrington rot.
1700
1800
1900
2000
100
50
0
-50
-100
Dipole moment
1980-04-04
1990-03-06
2000-01-24
$d_z > 0$
$d_z < 0$
$d_z < 0$
1975
1980
1985
1990
1995
2000
2005
2010
year

The wind through the cycle

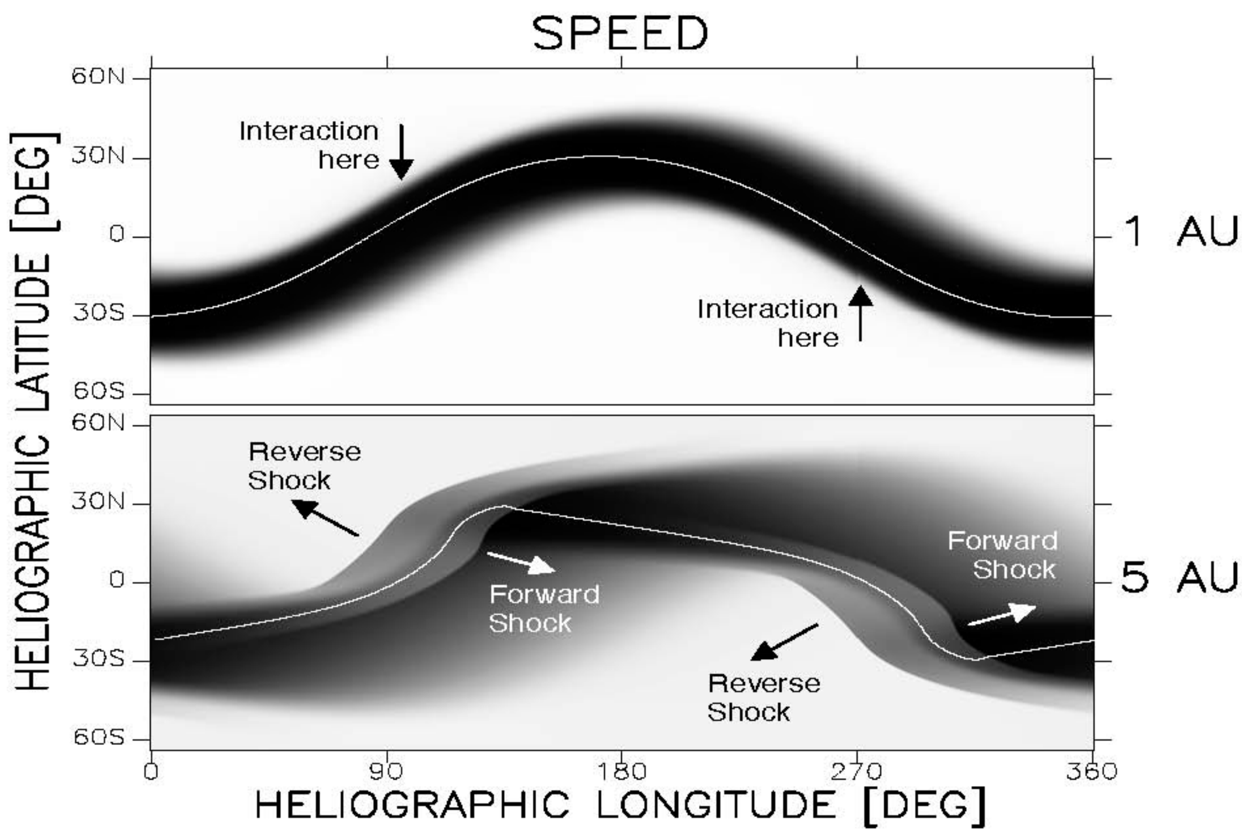


Vol. III fig. 8.2

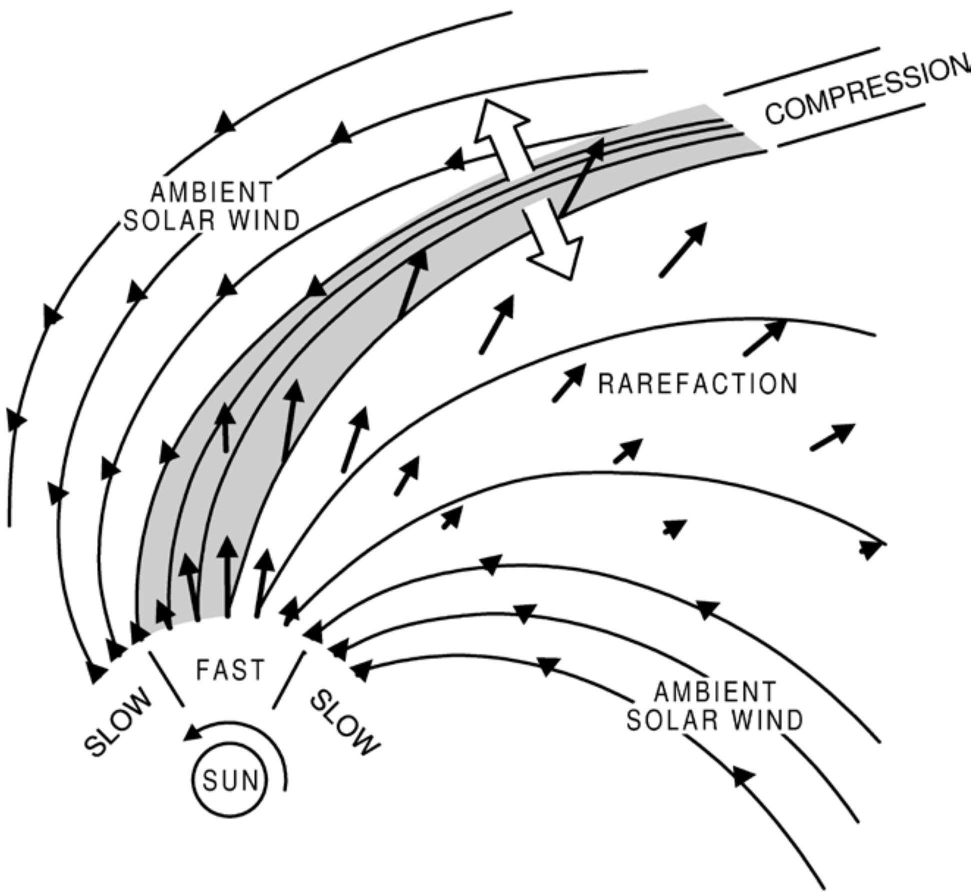
Effect of a ``warped” HCS

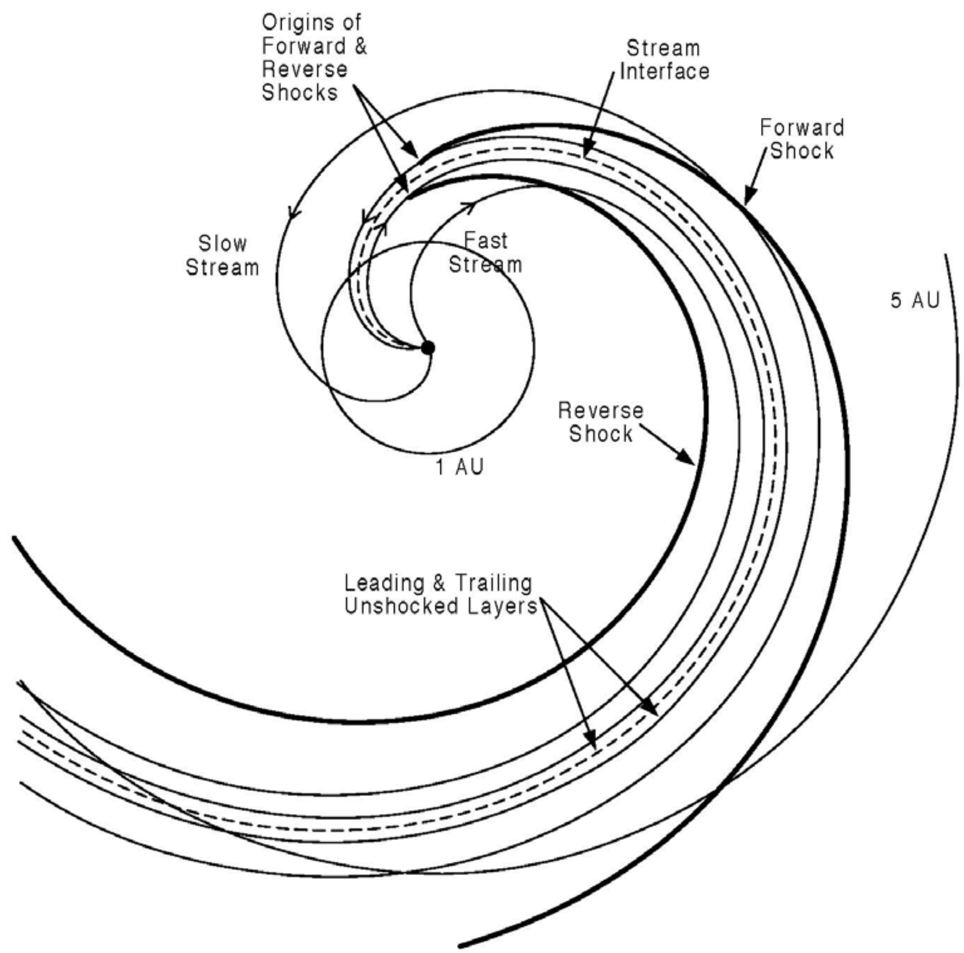


Vol. III fig. 8.6

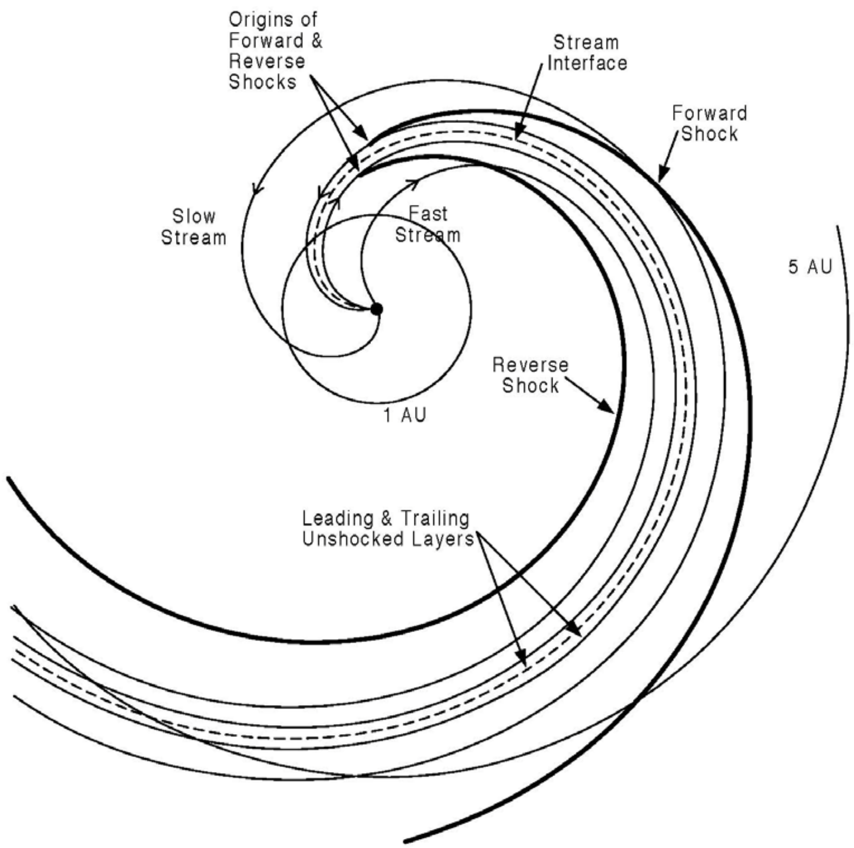


Vol. III fig. 8.7

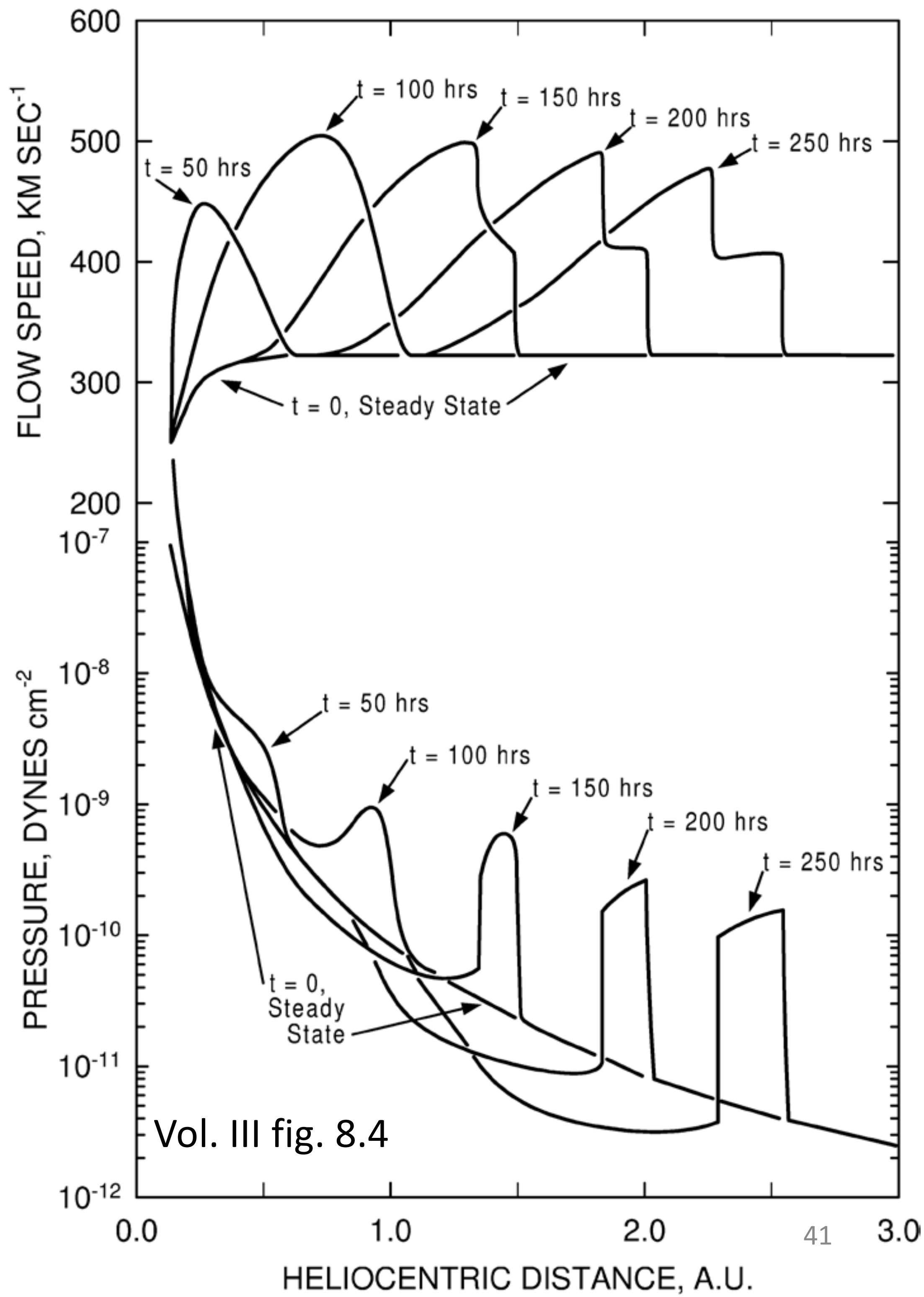




Vol. III fig. 8.5

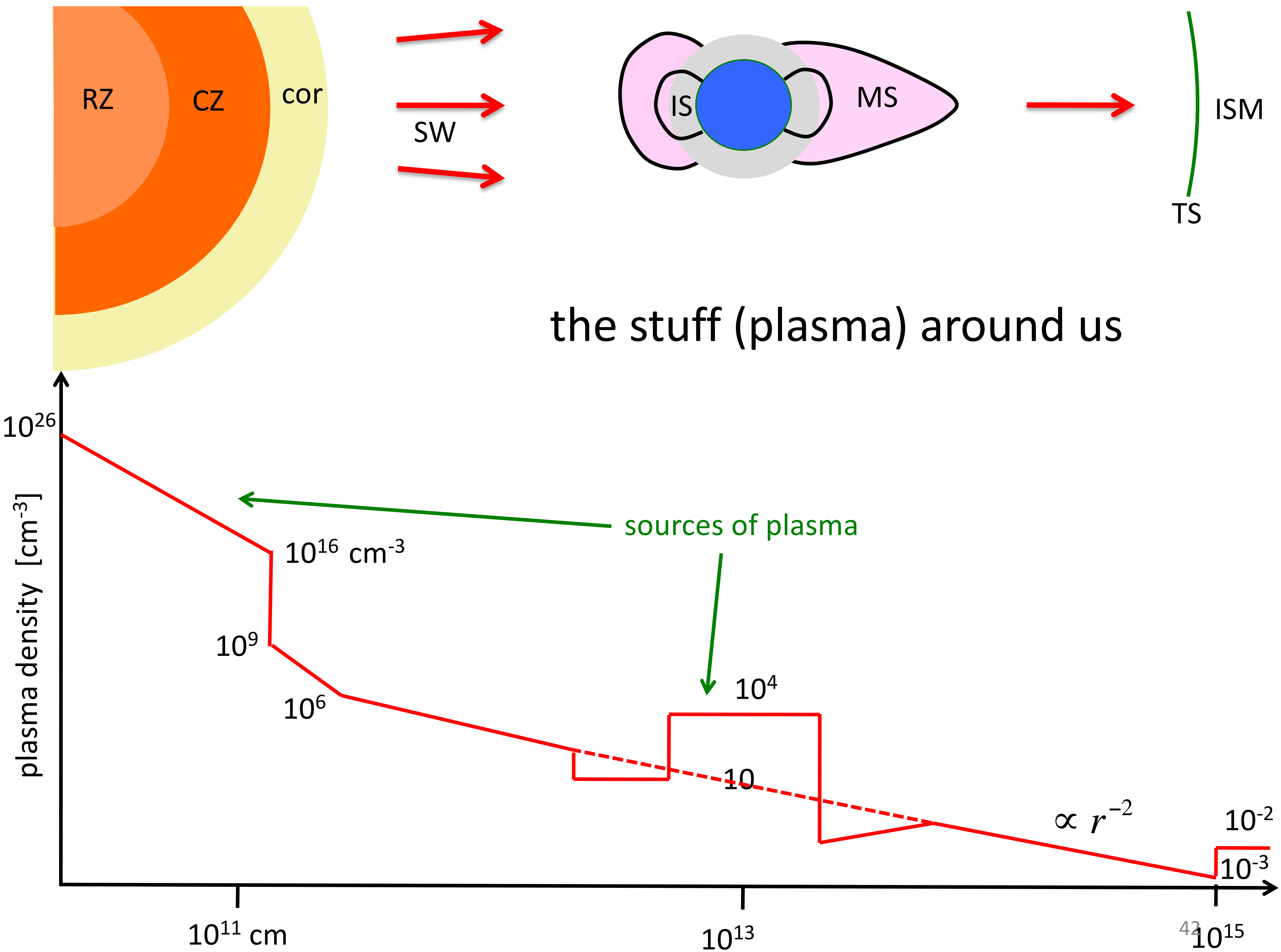


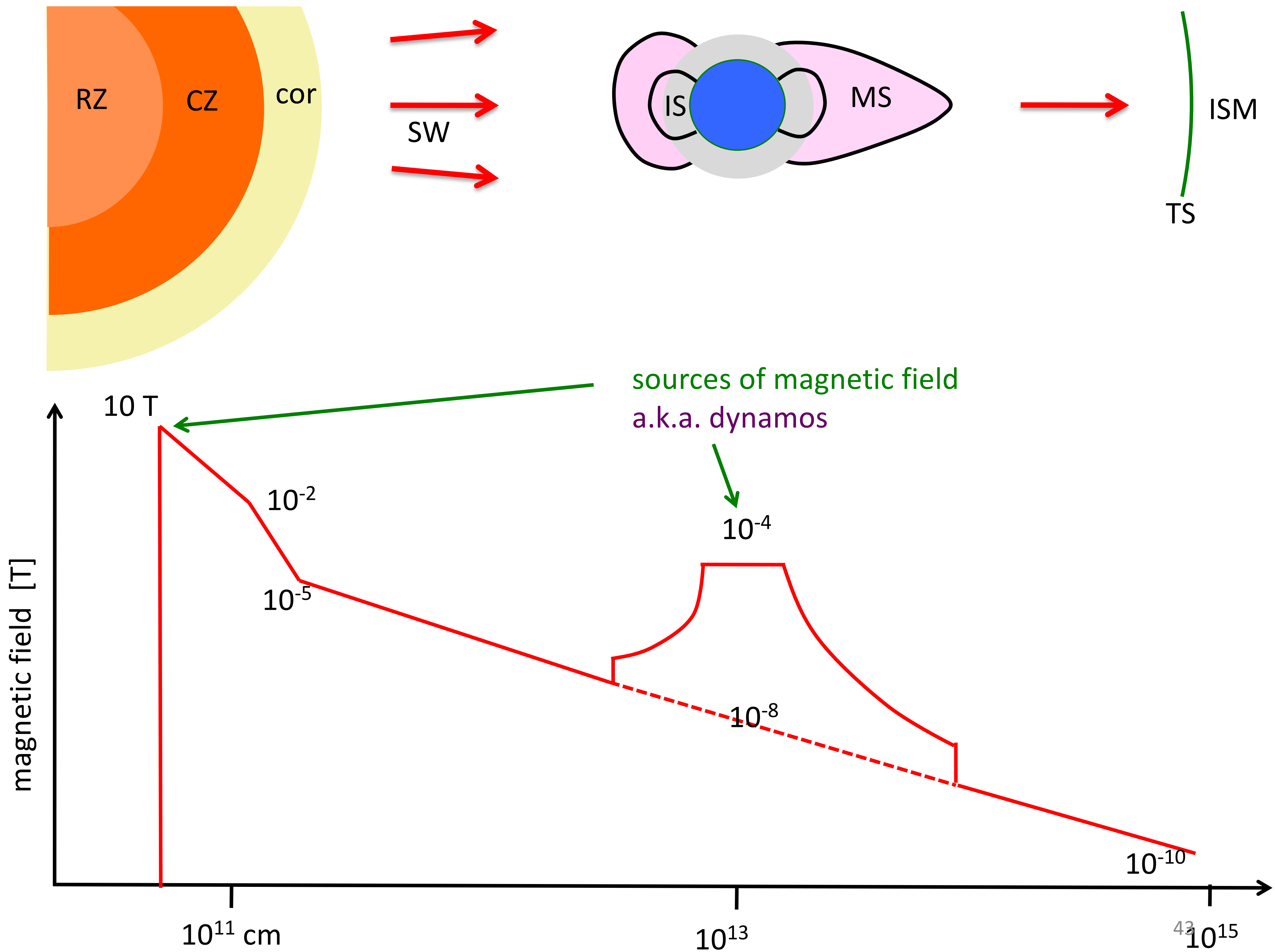
Vol. III fig. 8.5

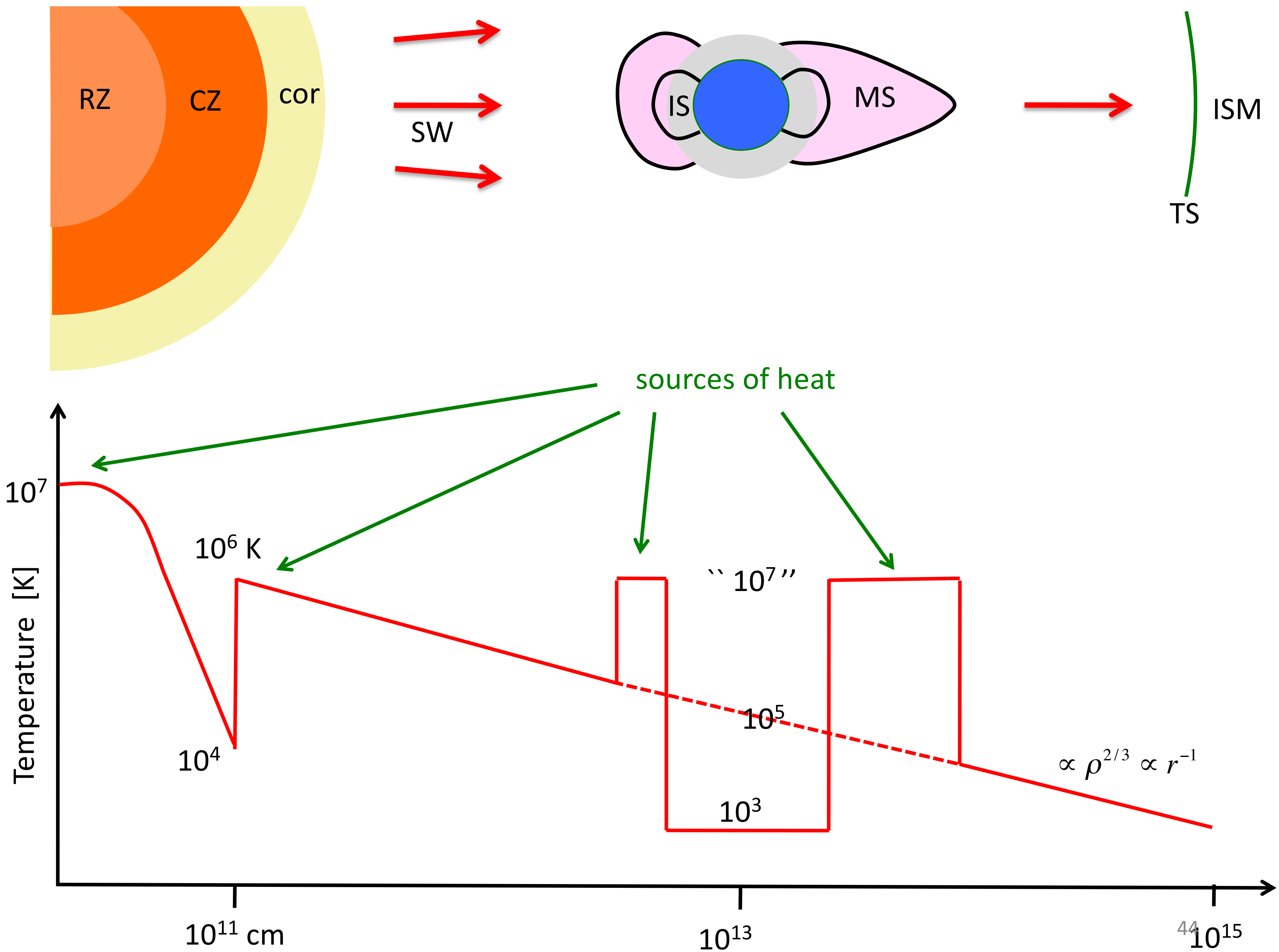


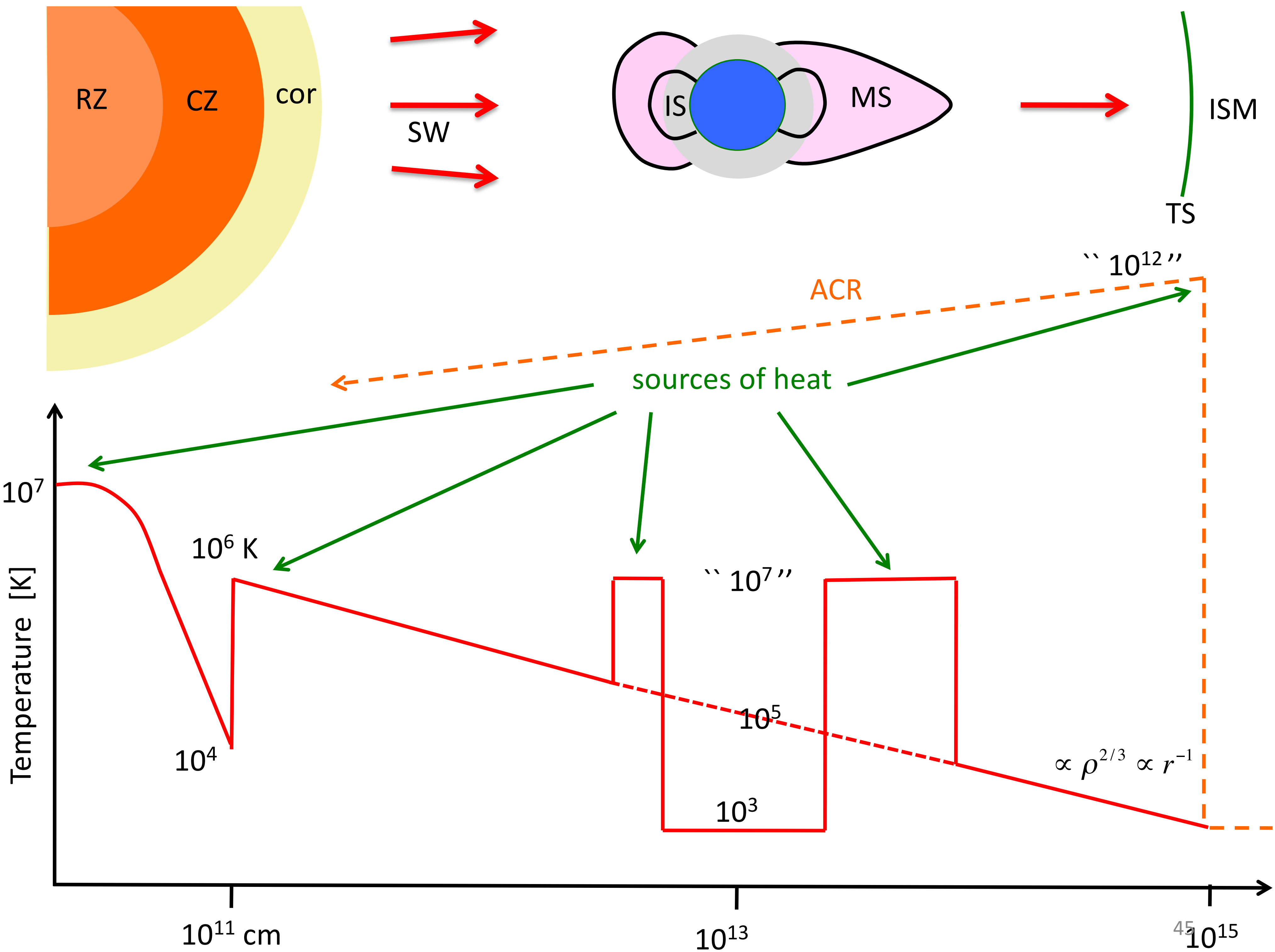
Vol. III fig. 8.4

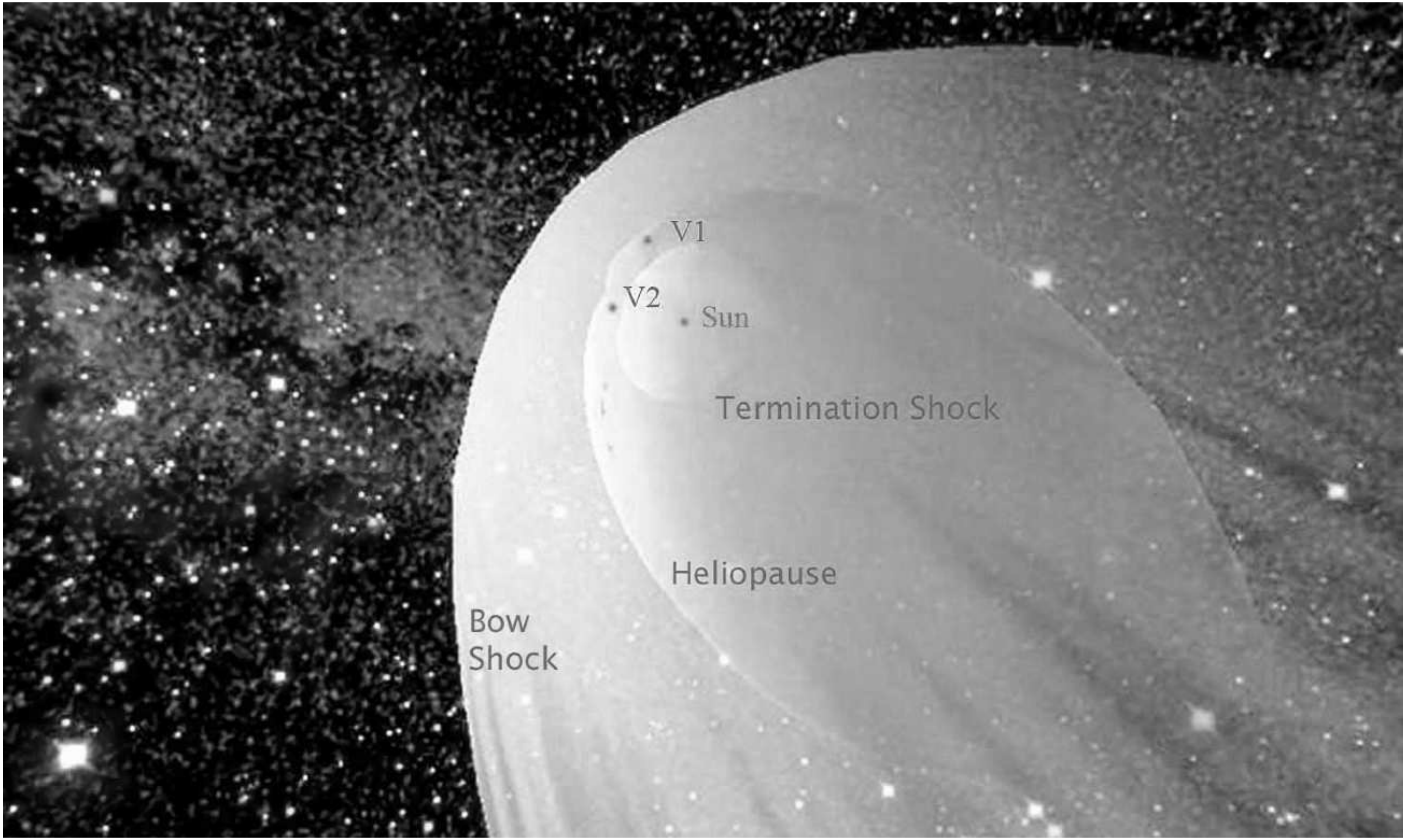
the stuff (plasma) around us




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}


RZ
CZ
cor
SW
IS
MS
TS
ISM
sources of heat
Temperature [K]
10^7
10^6 K
10^4
“ 10^7 ”
10^5
10^3
$\propto \rho^{2/3} \propto r^{-1}$
10^{11} cm
10^{13}
10^{15}


RZ
CZ
cor
SW
IS
MS
ISM
TS
`` 10¹² ''
ACR
sources of heat
Temperature [K]
10⁷
10⁶ K
10⁴
`` 10⁷ ''
10⁵
10³
$\propto \rho^{2/3} \propto r^{-1}$
10¹¹ cm
10¹³
10¹⁵



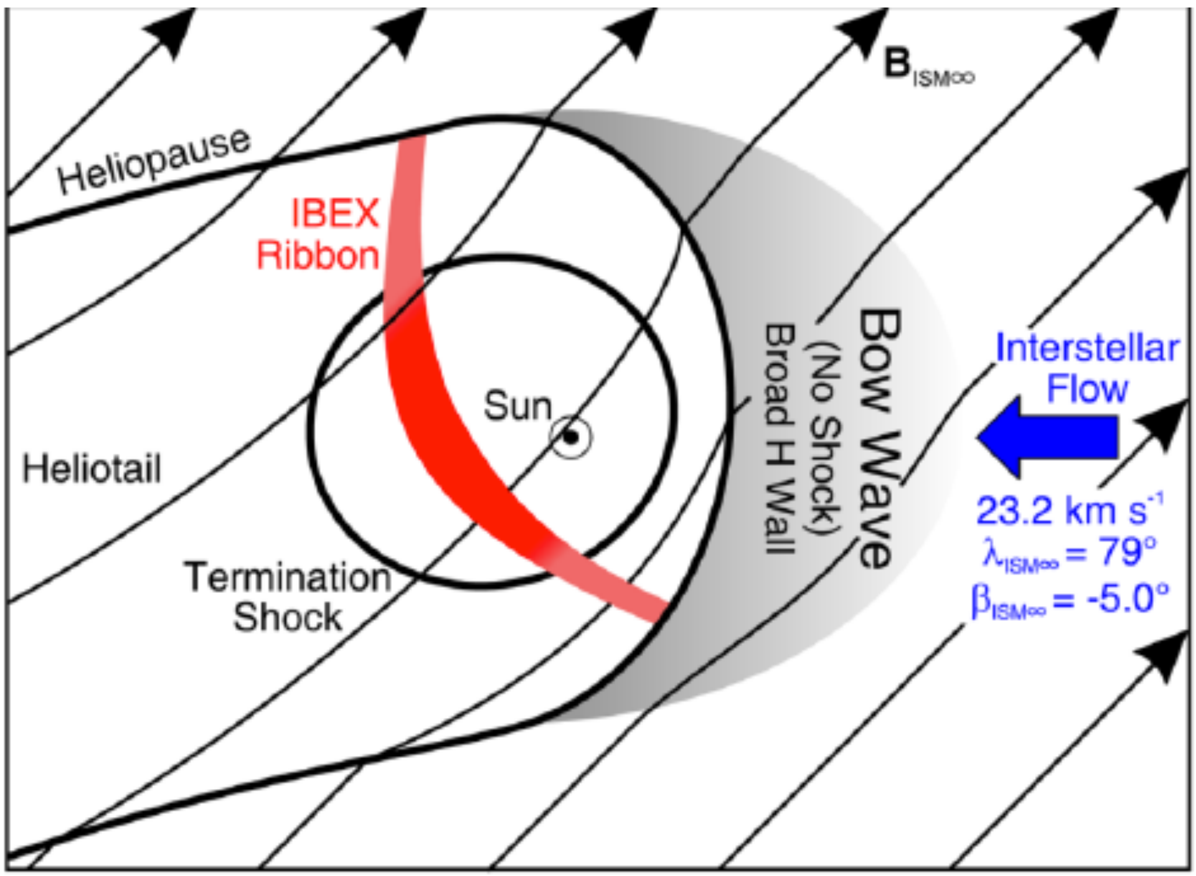
Vol. III fig. 9.1

The Heliosphere's Interstellar Interaction: No Bow Shock

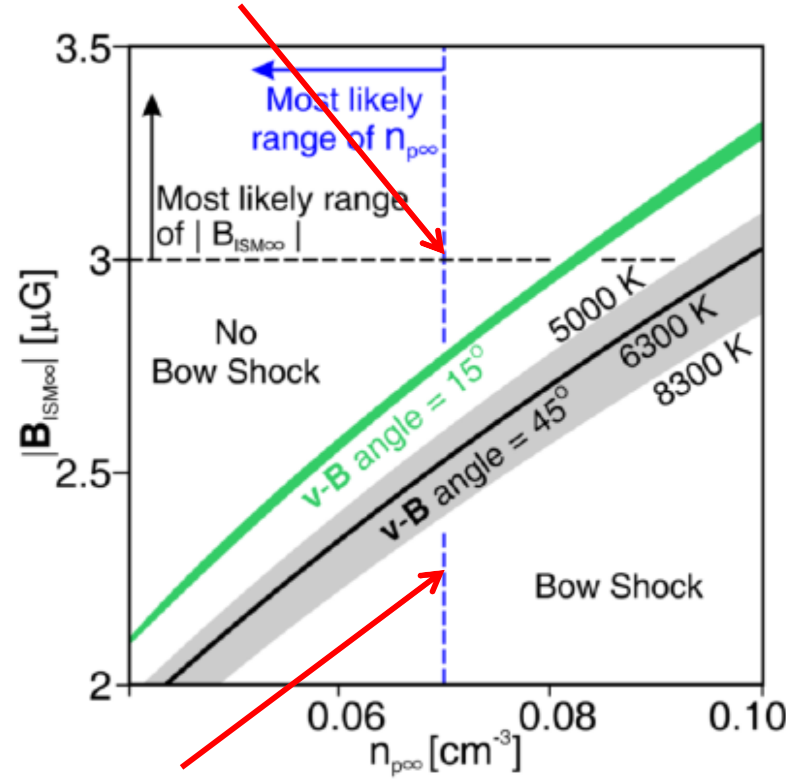
Science May 10, 2012

D. J. McComas,[1,2*] D. Alexashov,[3] M. Bzowski,[4] H. Fahr,[5] J. Heerikhuisen,[6] V. Izmodenov,[3] M. A. Lee,[7] E. Möbius,[7,8] N. Pogorelov,[6] N. A. Schwadron,[7] G. P. Zank[6]

Result from IBEX



v_{fms} = 26.8 km/s



v_{fms} = 21.4 km/s

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