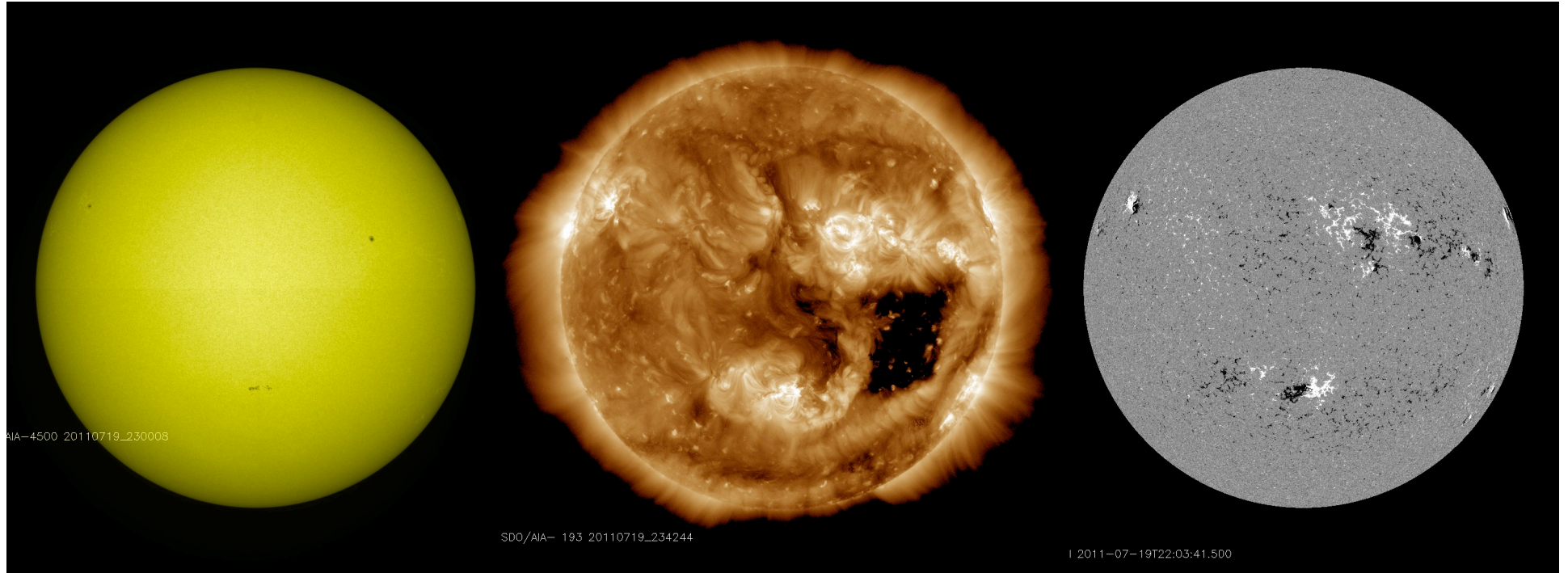


Q: Why does the Sun have a  
Corona? A Wind?

Dana Longcope

Montana State University

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

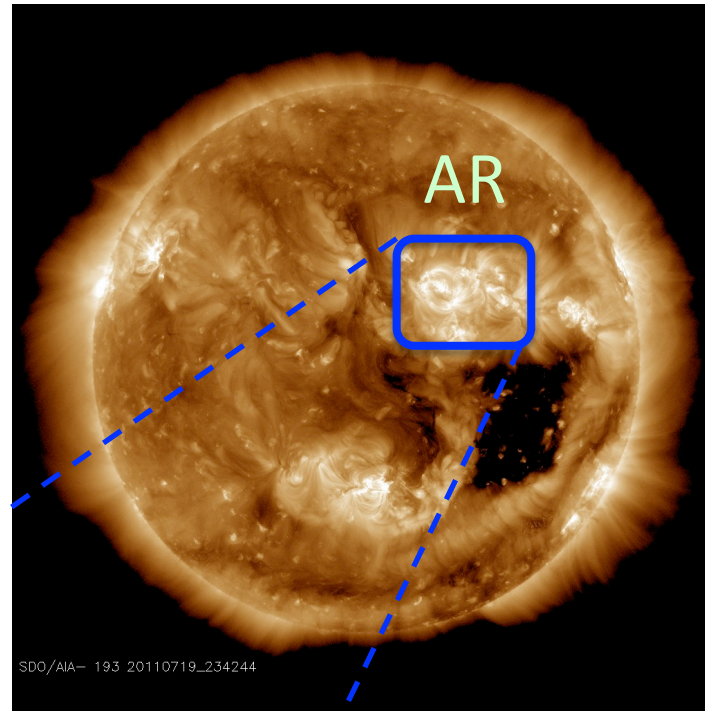


## Coronal (EUV) imaging – the basics:

- what you see is all the same T ( $1.5 \times 10^6$  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

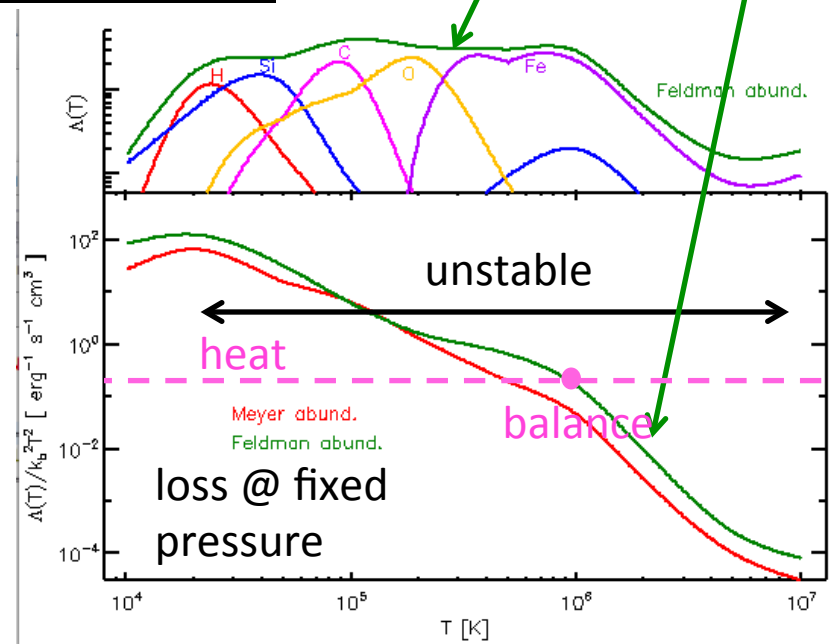
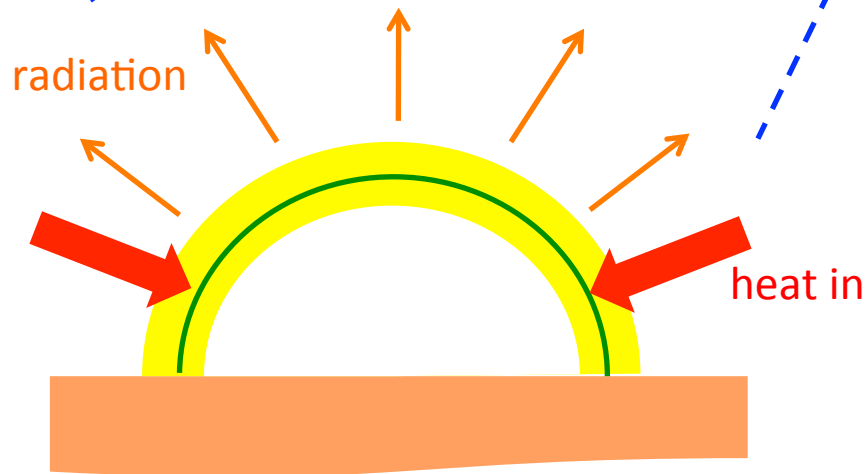
**B** large enough to restrict plasma motion: only along field lines



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

Radiative losses per volume:  
Eq. (8.6)

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

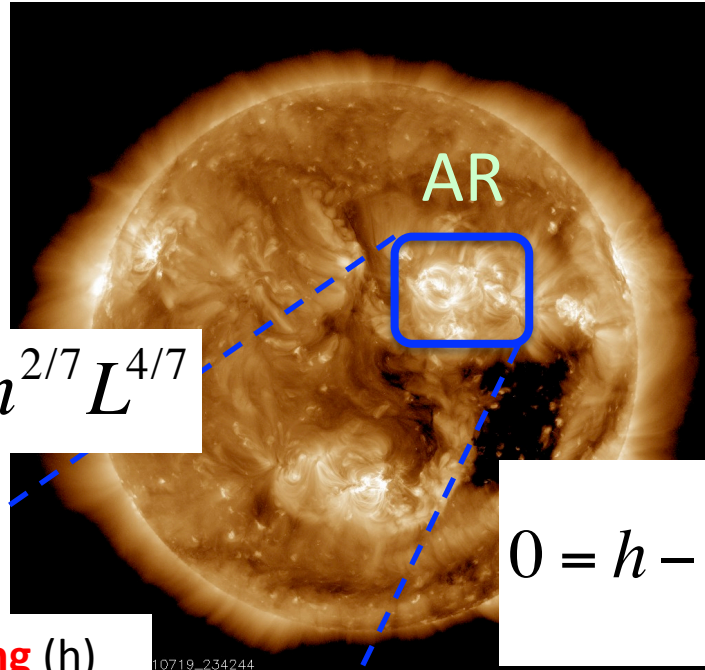


balance:  
(RTV)

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

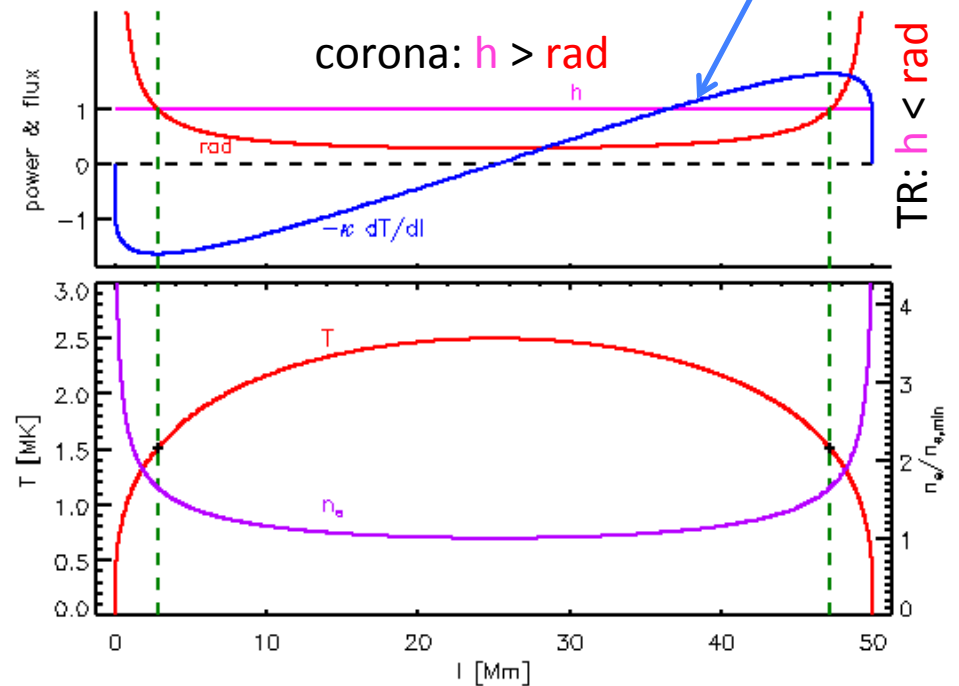
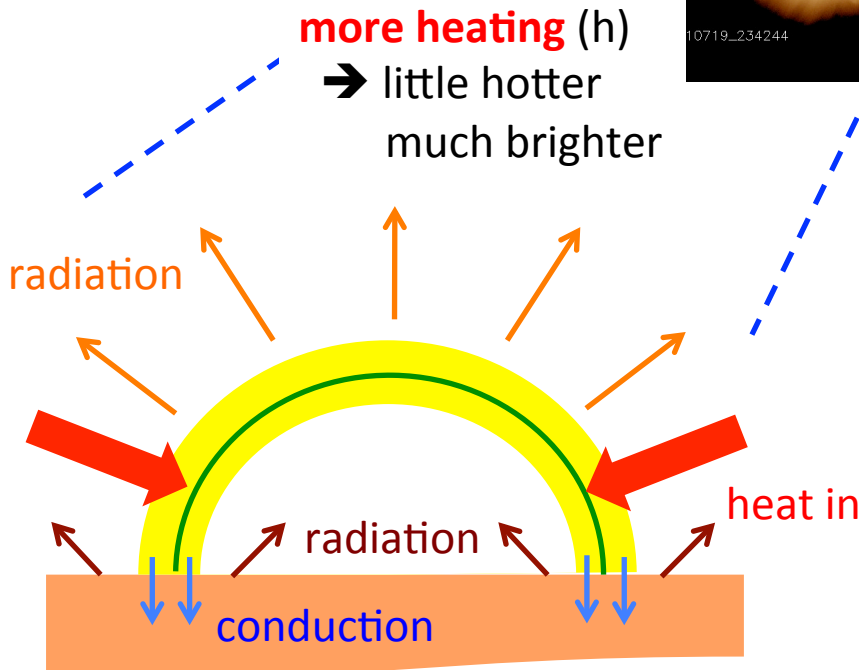
$$T_{\max} \sim (pL)^{1/3} \sim h^{2/7} L^{4/7}$$

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



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

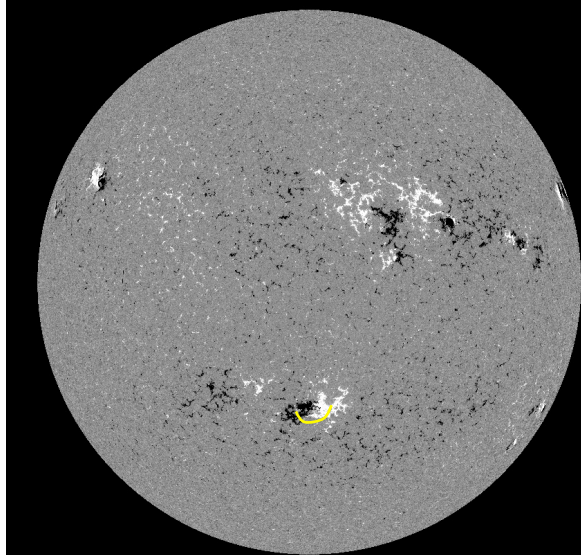
$$0 = h - p^2 \frac{\Lambda(T)}{k_B^2 T^2} + \frac{\partial}{\partial \ell} \left( \kappa \frac{\partial T}{\partial \ell} \right)$$



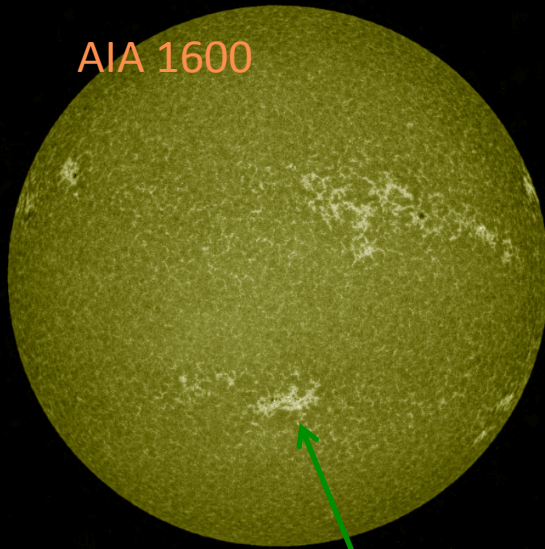


TR:  $h < \text{rad}$

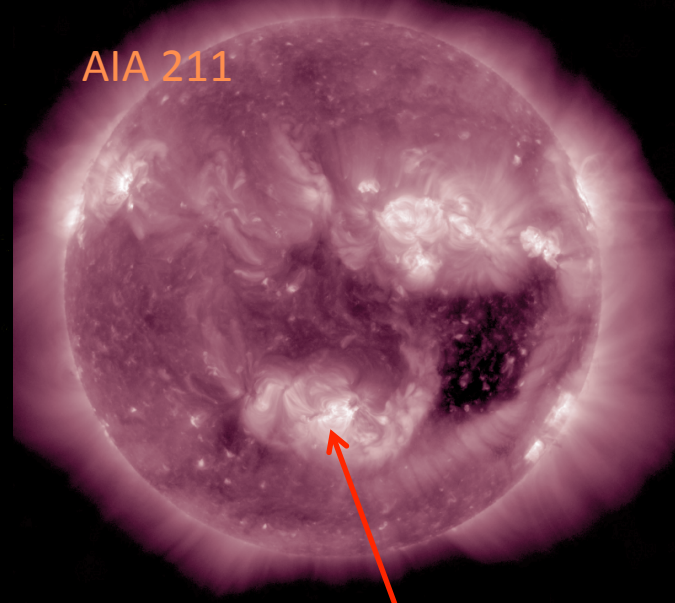
corona:  $h > \text{rad}$



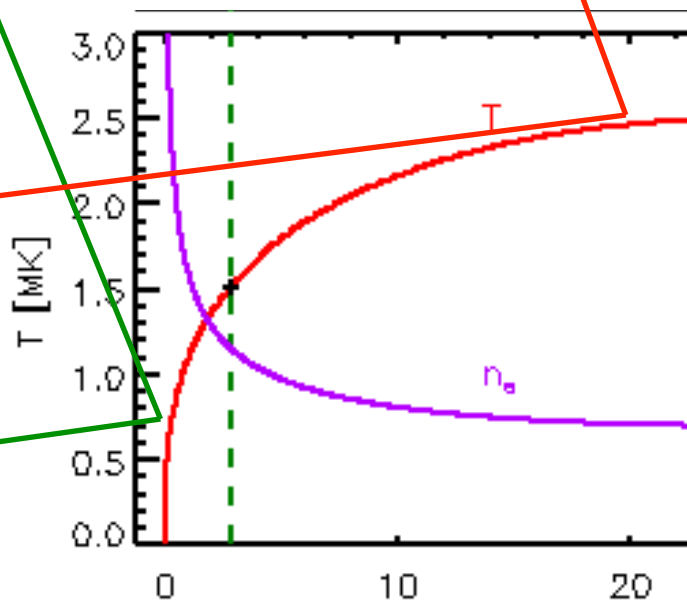
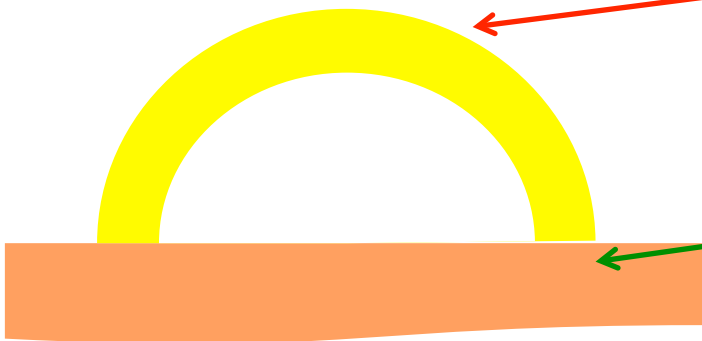
AIA 1600



AIA 211

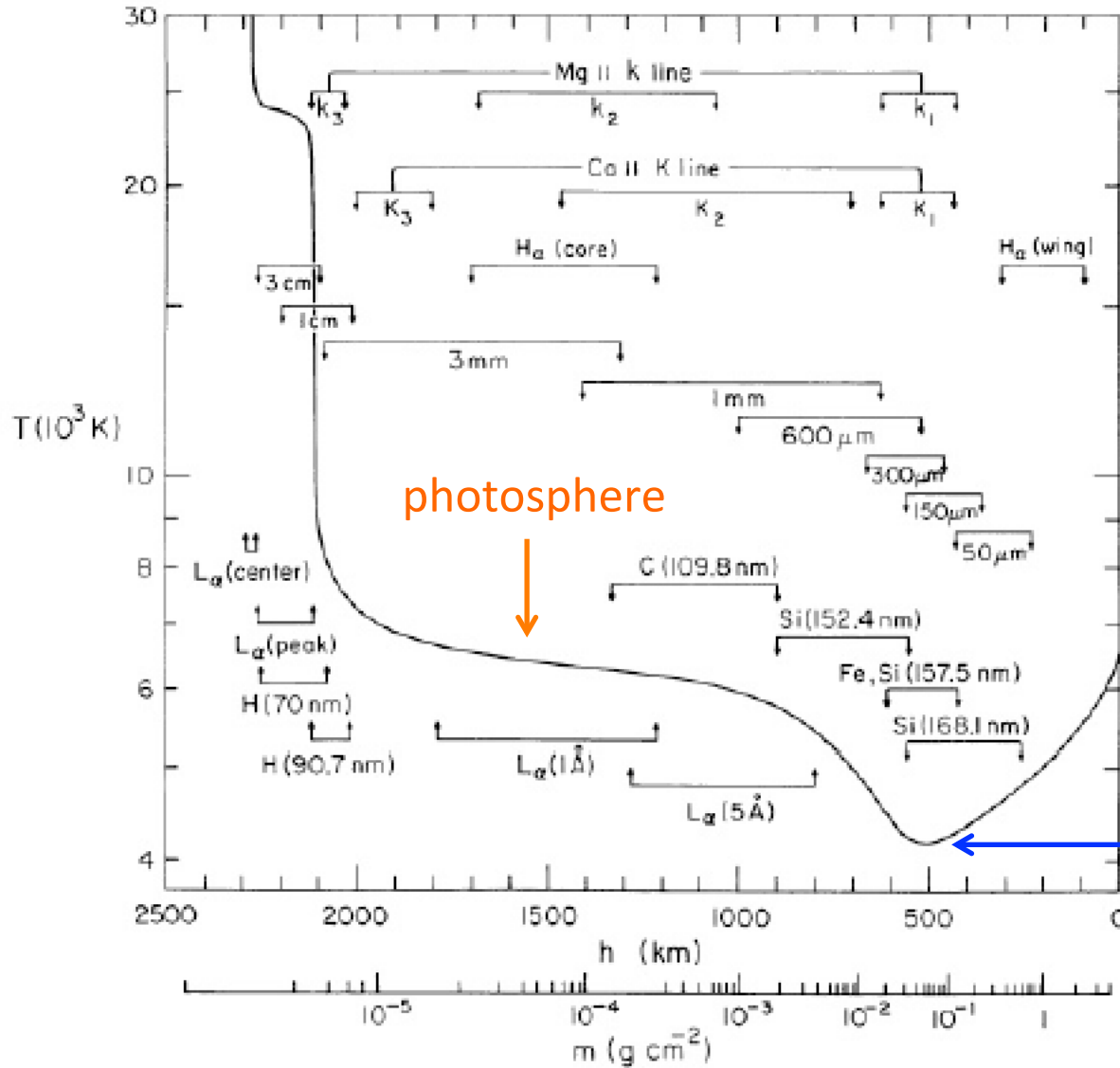


MI 2011-07-19T22:03:41.500



# Below the TR – hairy details

Vernazza *et al.* 1981

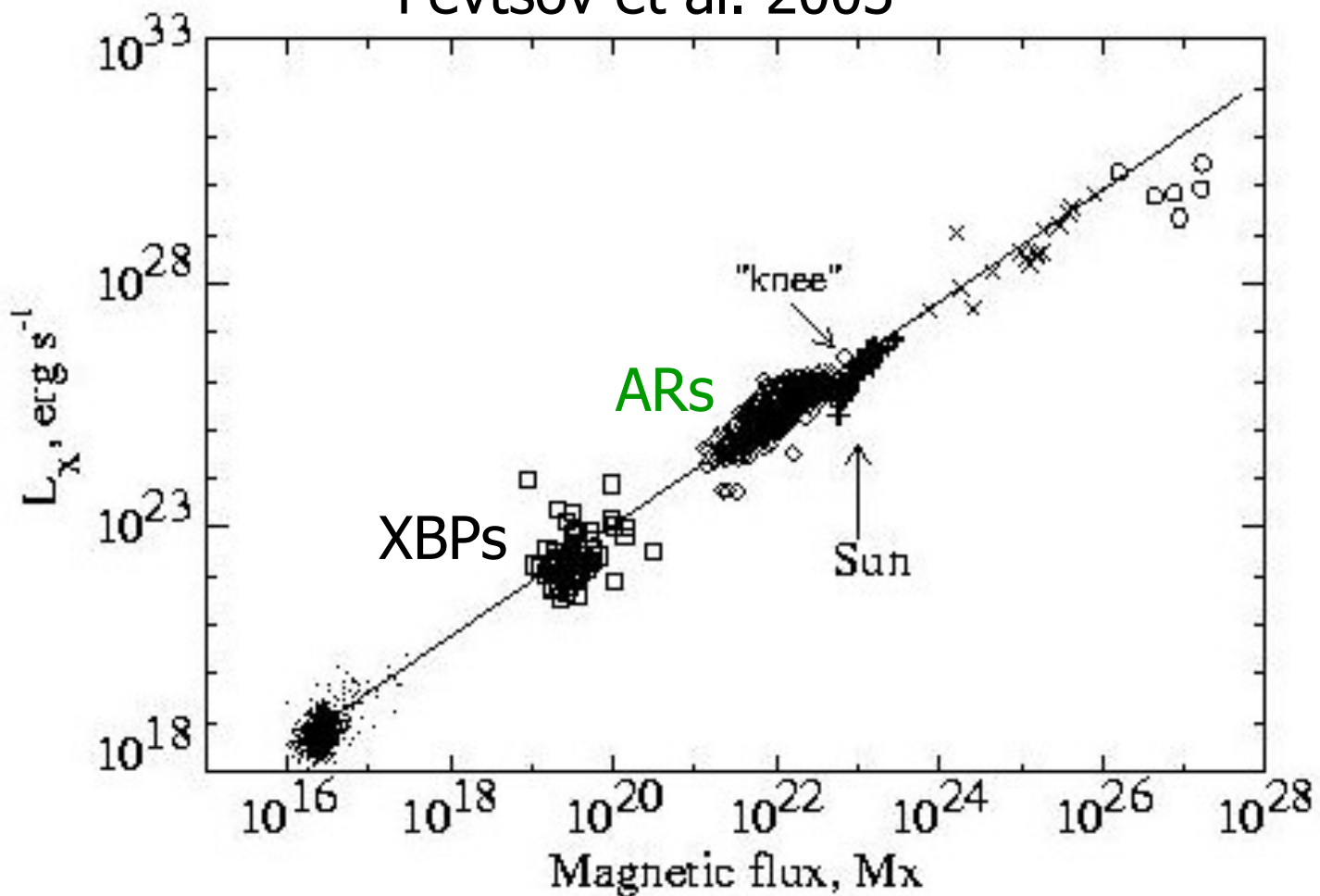


- Radiation: not optically thin
- Ionization level varies with T

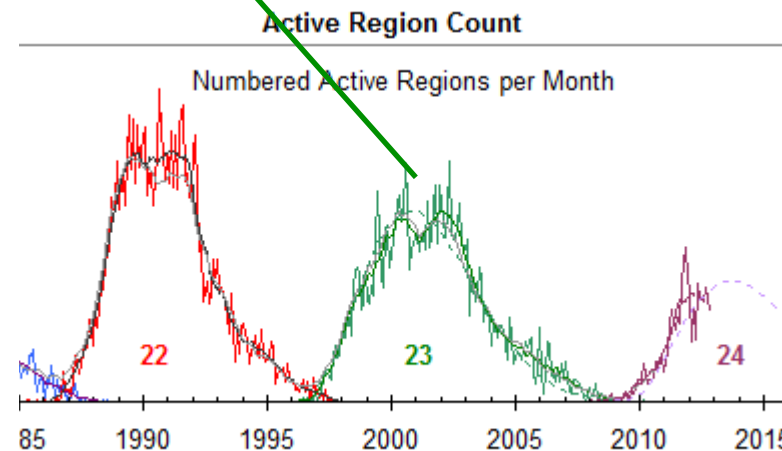
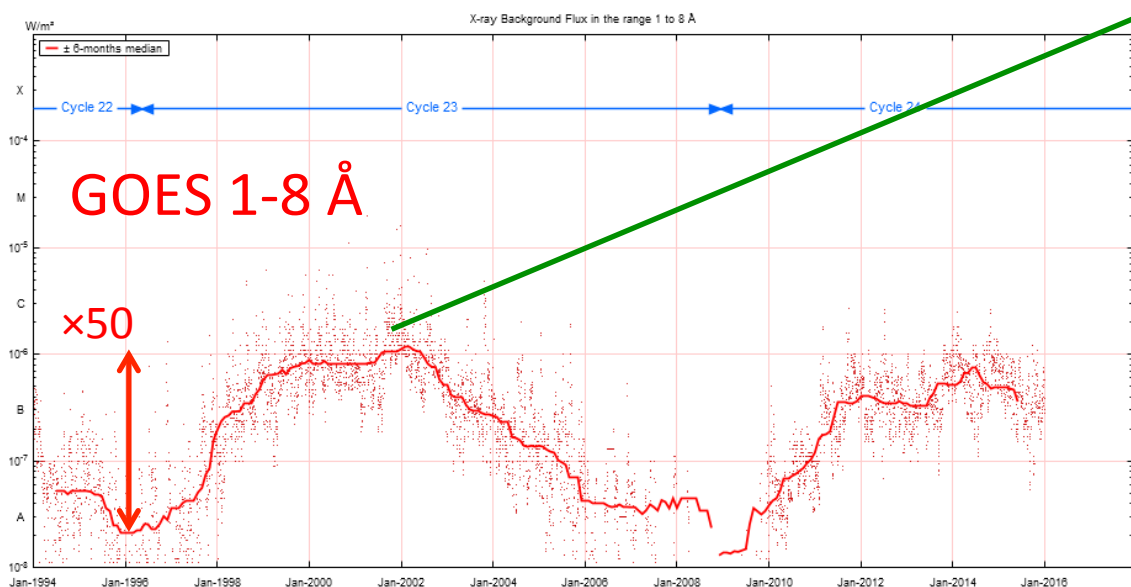
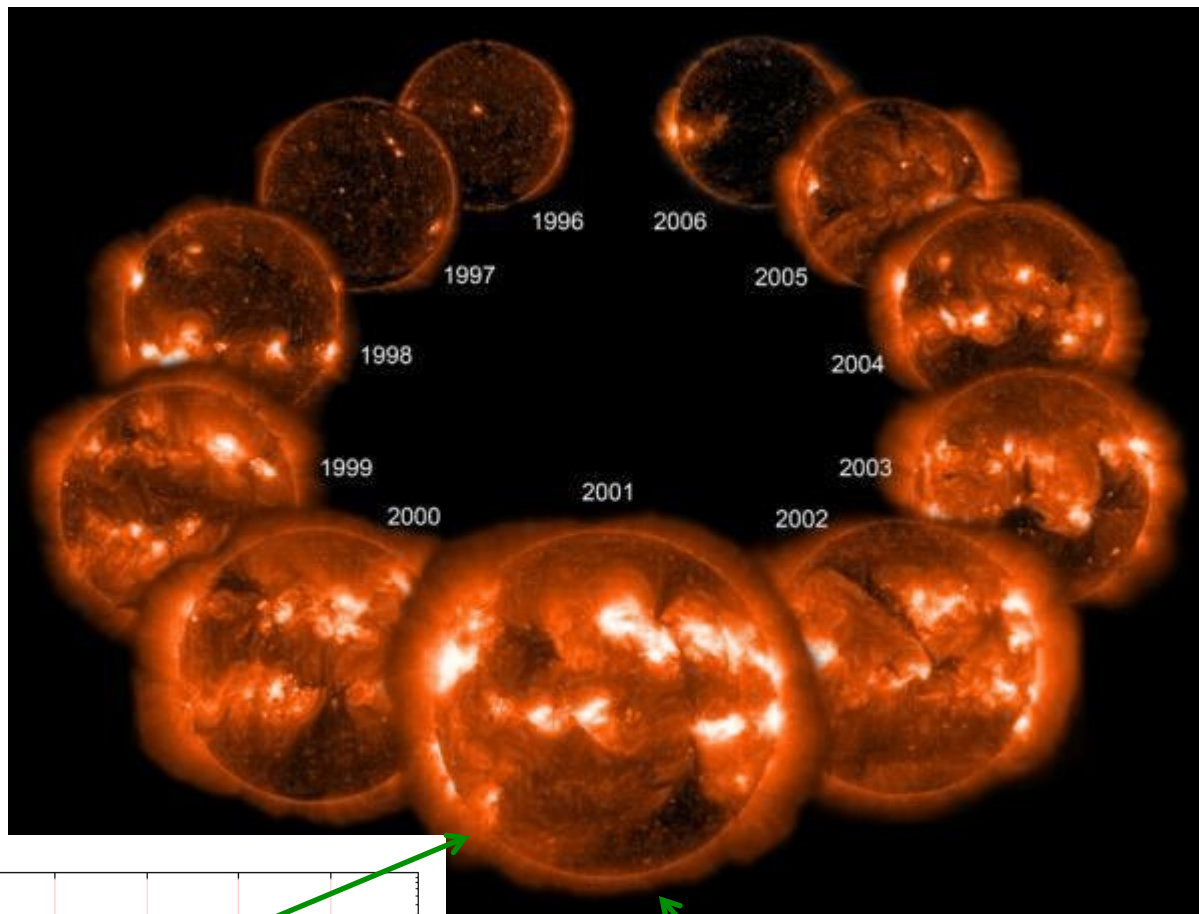
temperature minimum

# Heating is Magnetic

Pevtsov et al. 2003

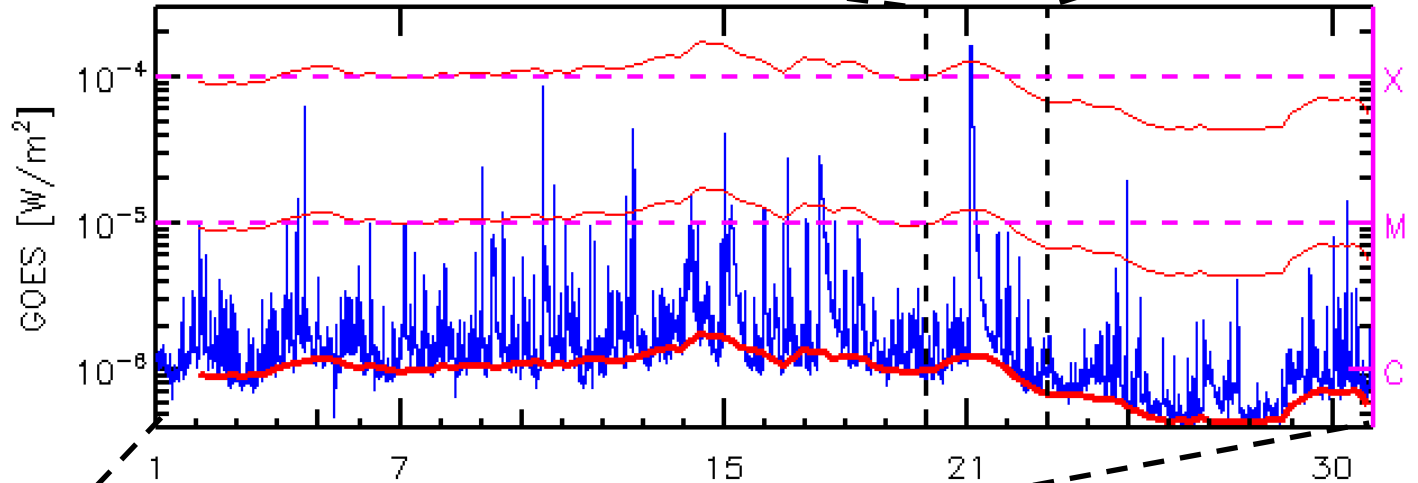
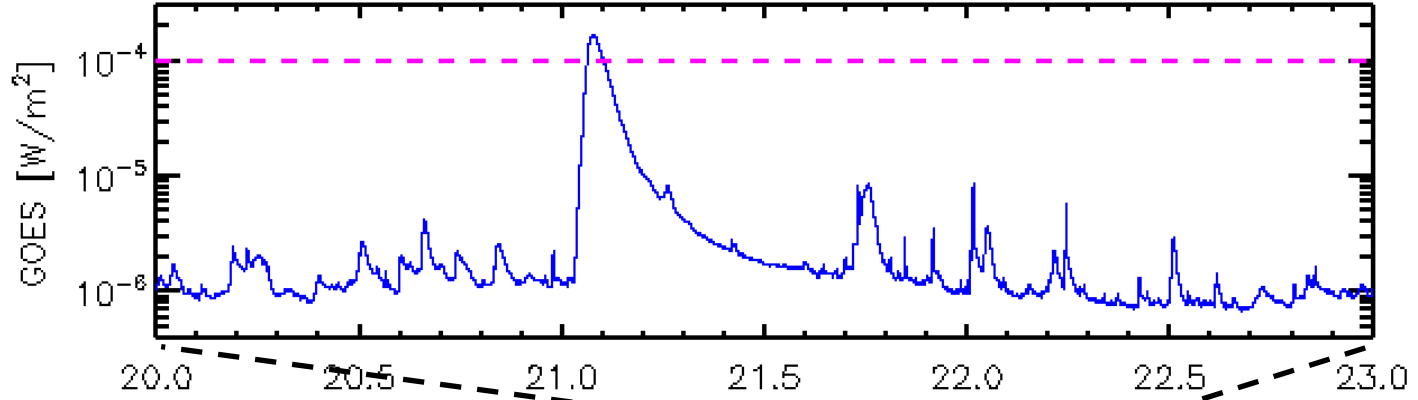


Field  
varies –  
corona  
varies

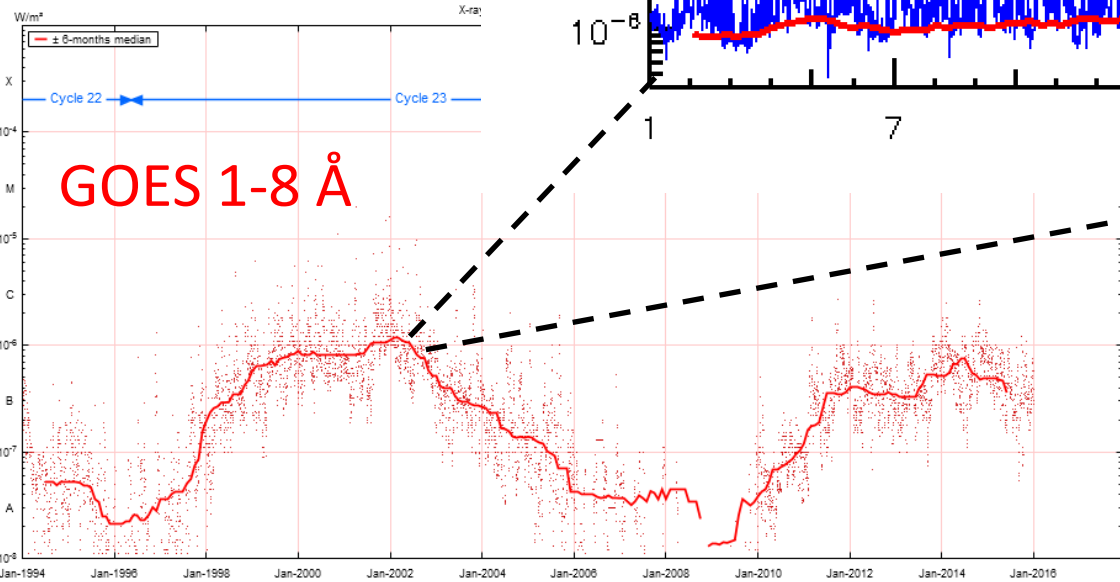


X-rays:  
highly  
variable –  
flares

GOES 1–8 A



April 2002

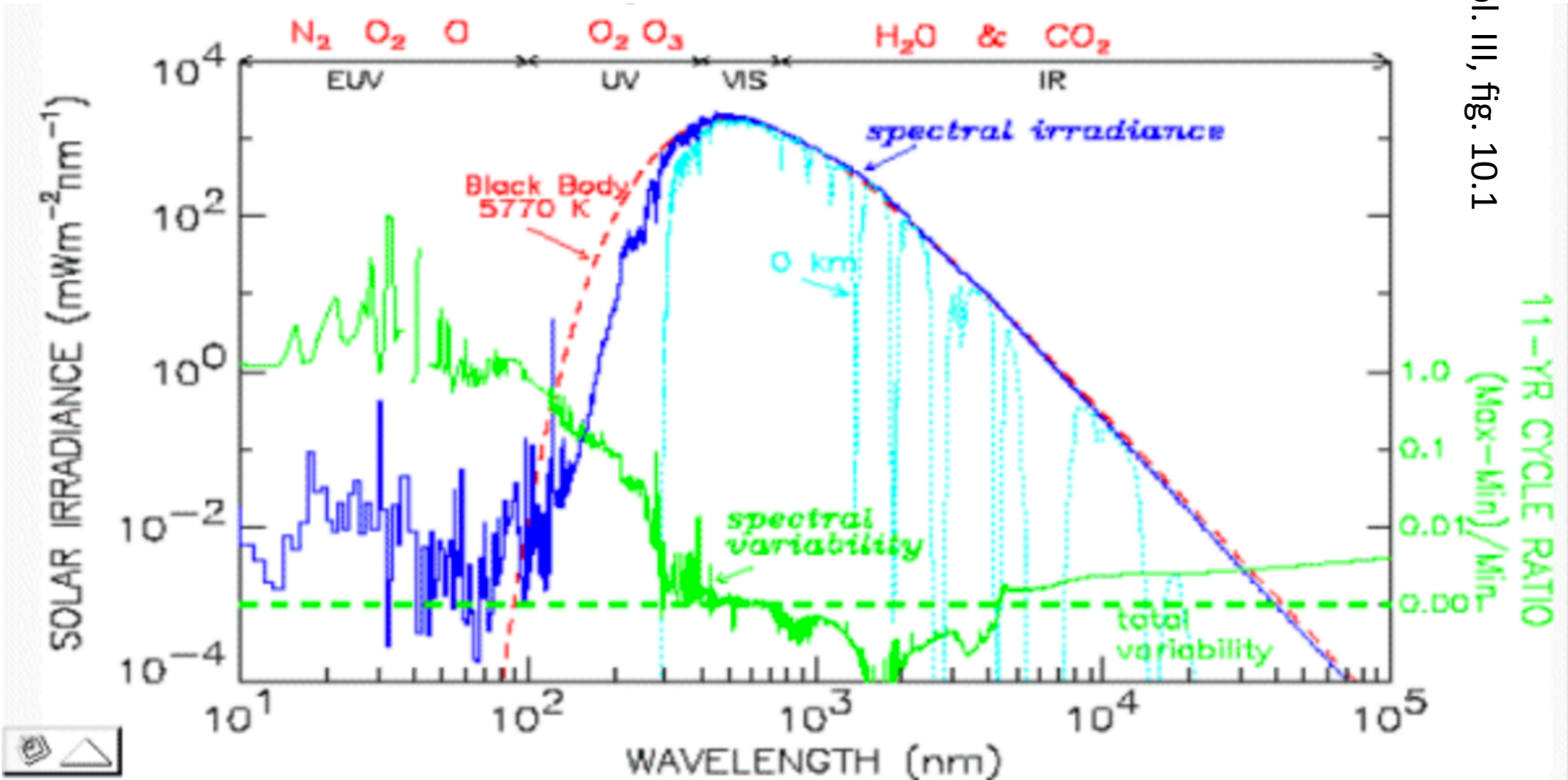


GOES 1-8 Å

do smaller  
flares heat  
the corona?

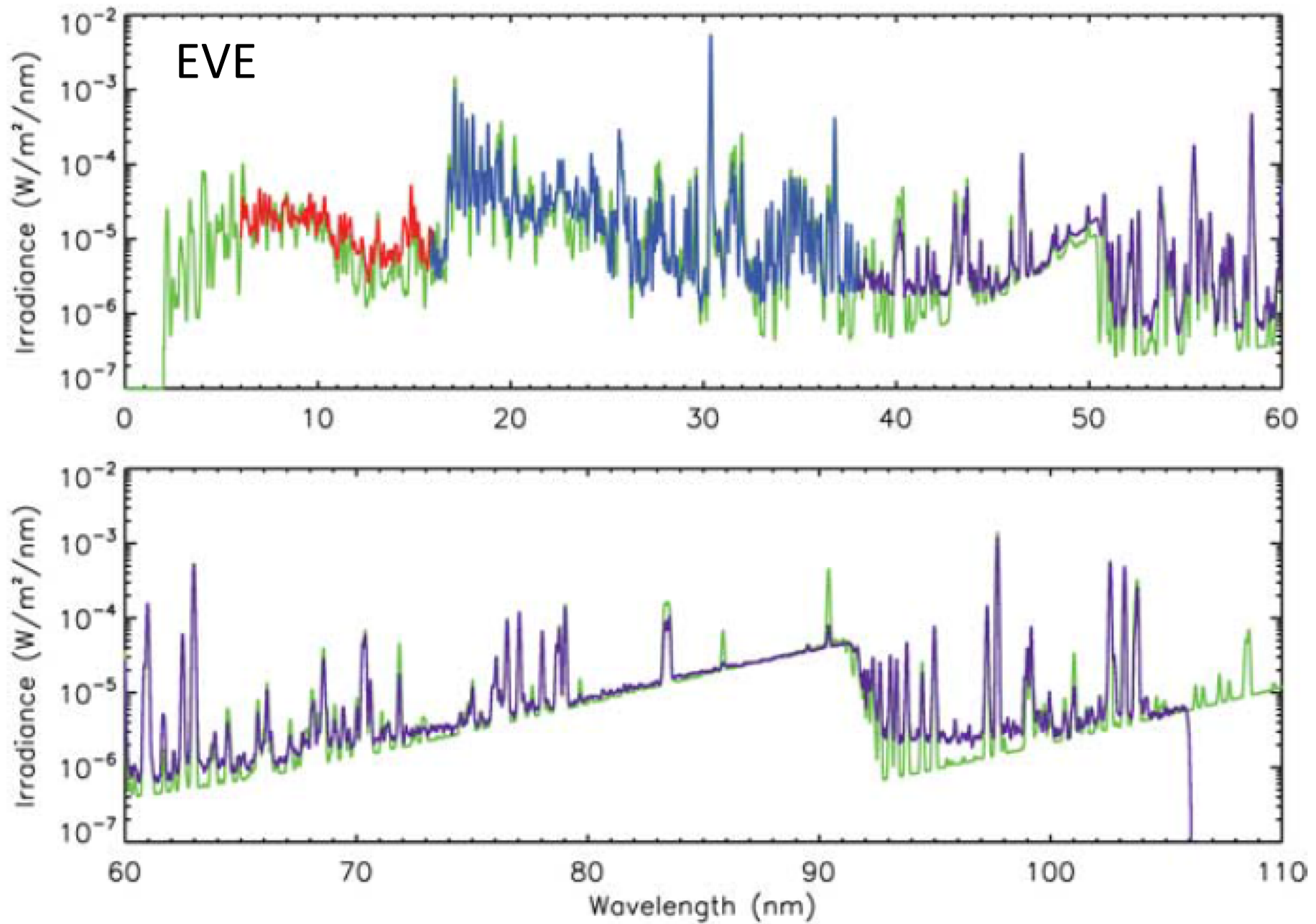


# Corona produces EUV & X-ray



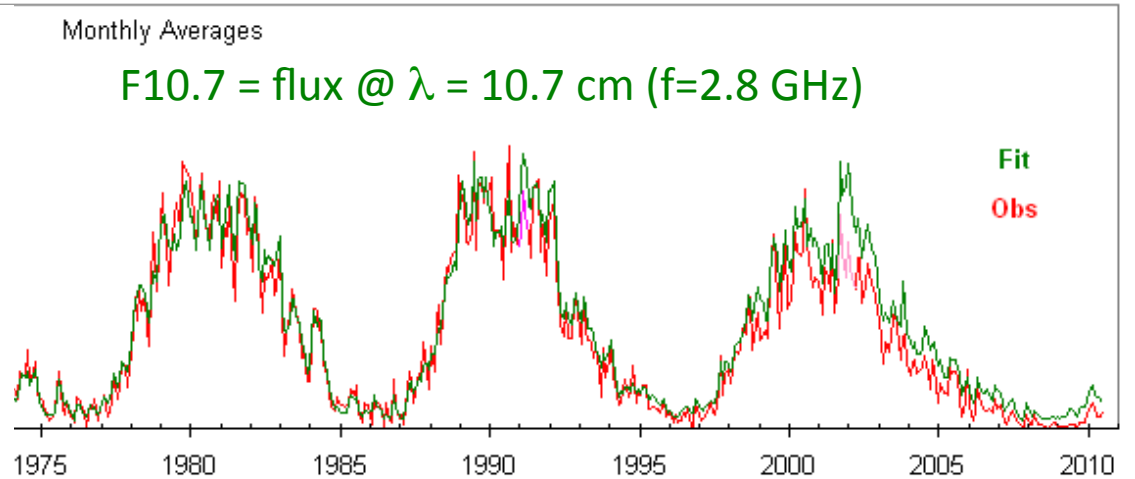
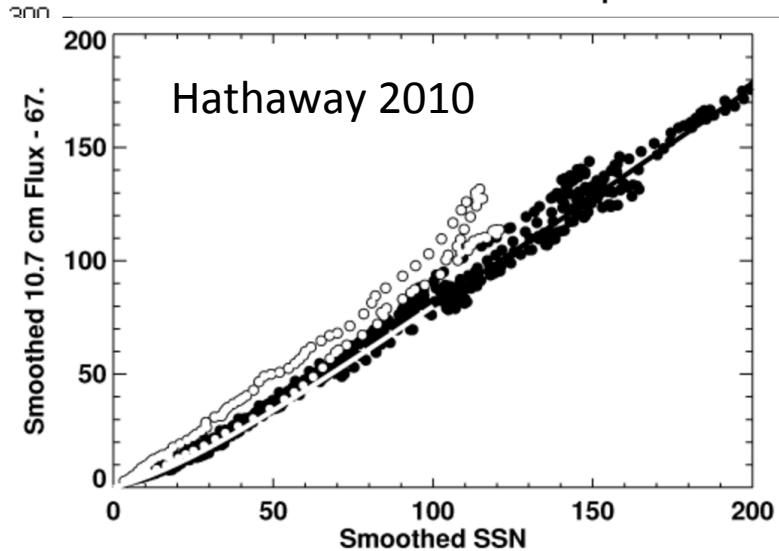
Vol. III, fig. 10.1

11-YR CYCLE RATIO (Max-Min)/Min

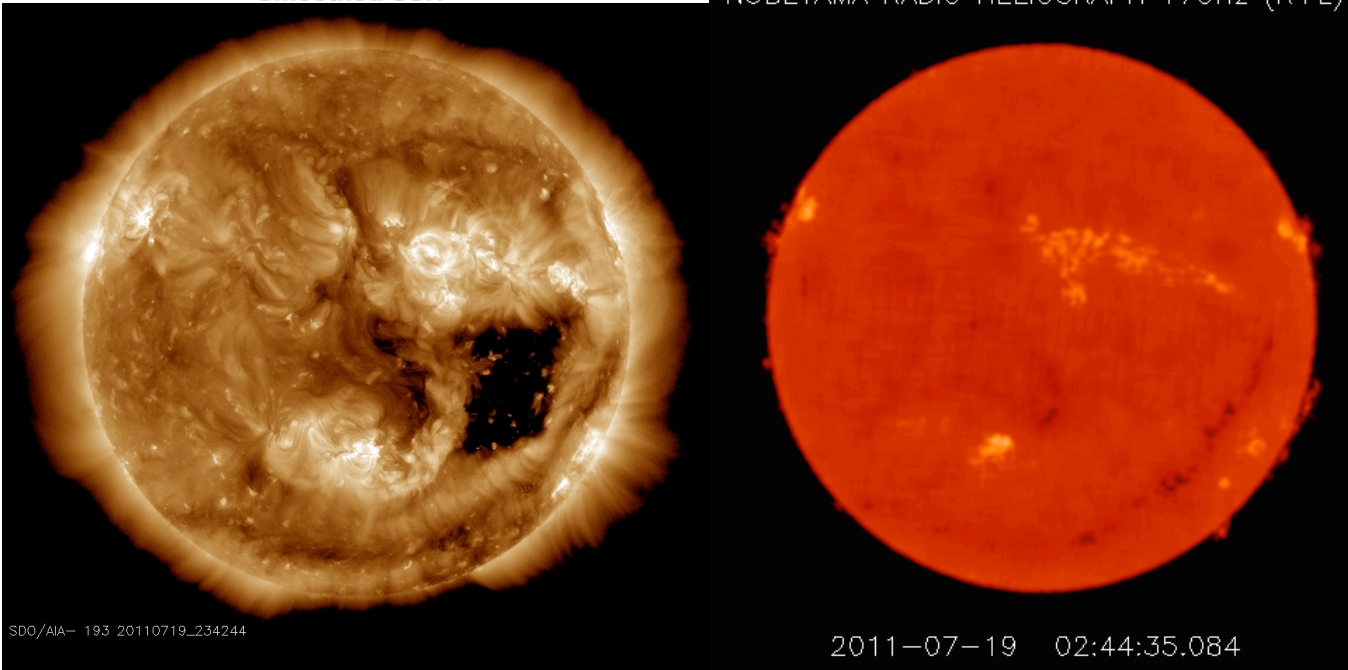


# Corona produces $\mu$ -waves

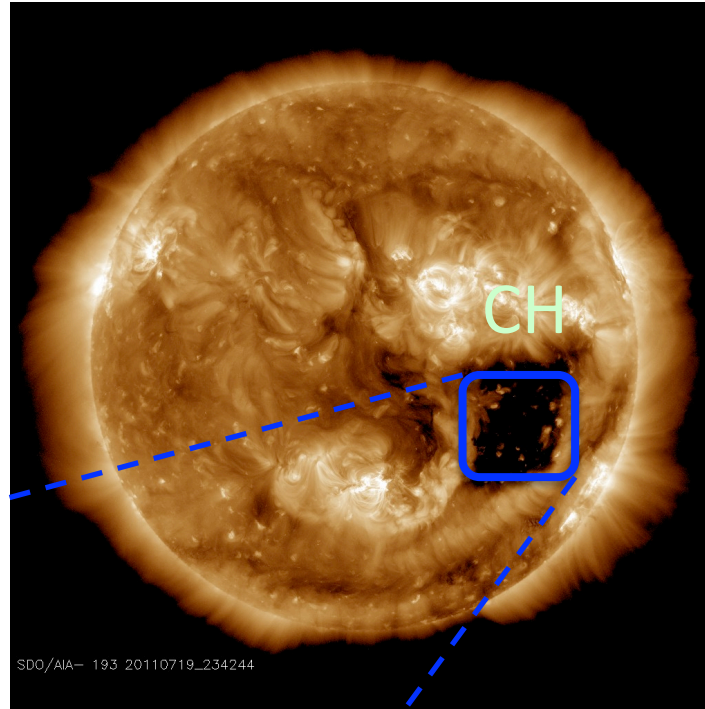
Sunspot Number (Observed) and Fitted from F10.7 Flux



NOBEYAMA RADIO HELIOGRAPH 17GHz (R+L)



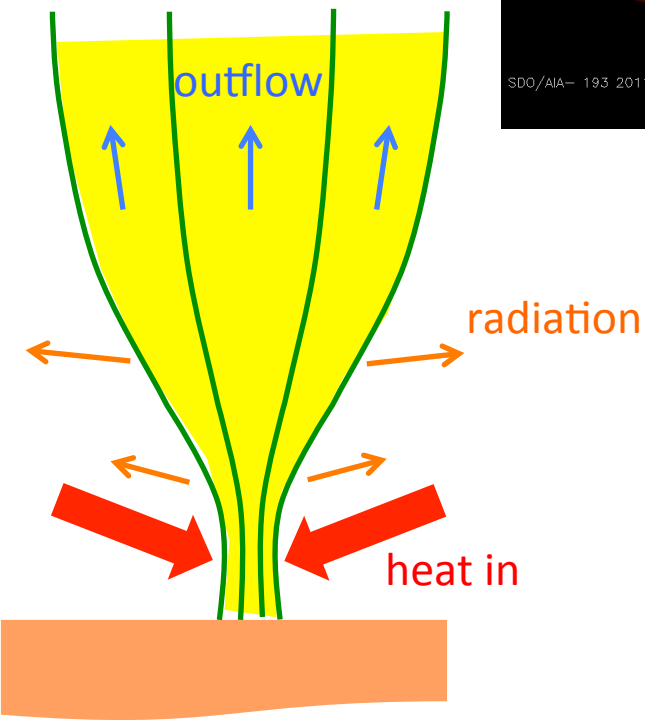
**B** large enough to restrict plasma motion: only along field lines



Wind: from open flux

specific enthalpy

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



Advective energy loss –

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

>> radiative loss

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

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

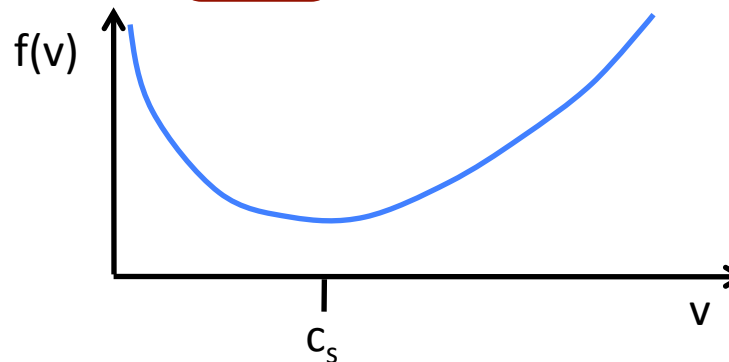
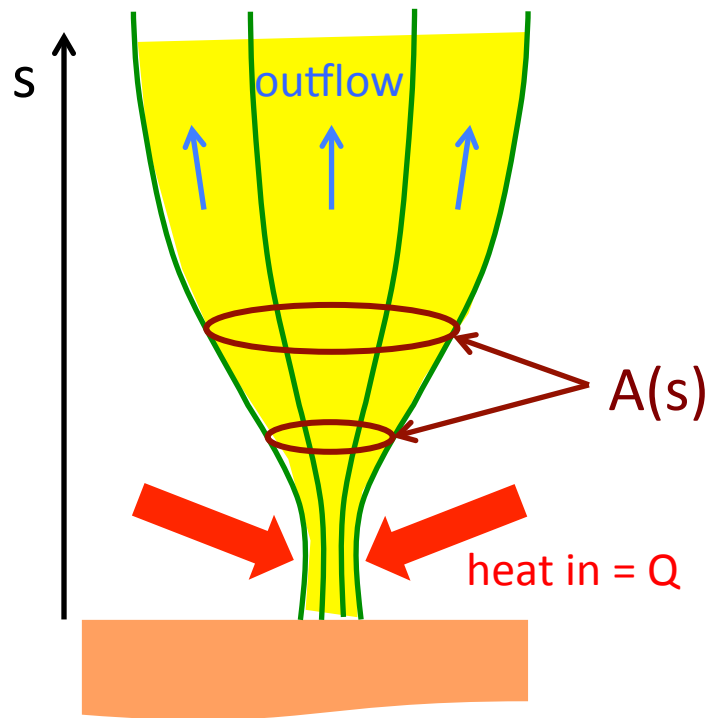
mass loss fixed & unknown

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

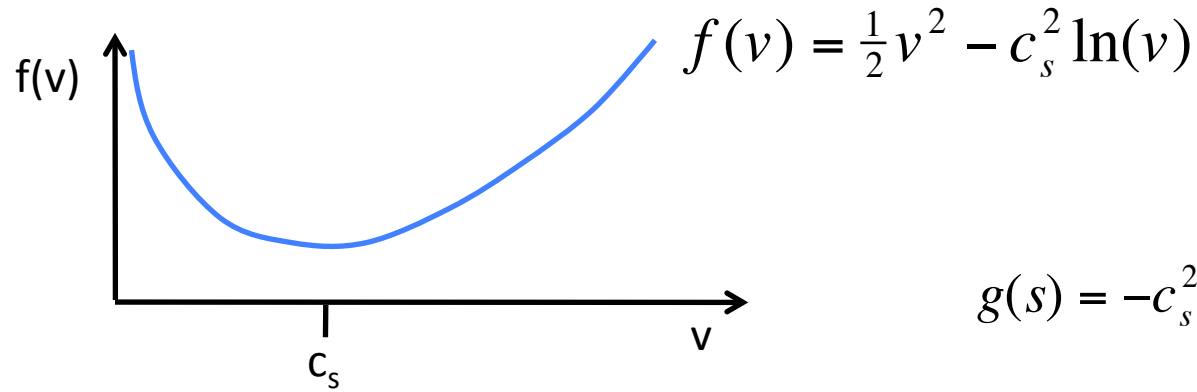
$$w(\rho) \propto \frac{\gamma}{\gamma - 1} \rho^{\gamma - 1} \rightarrow c_s^2 \ln(\rho) + \text{const.}$$

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

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







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

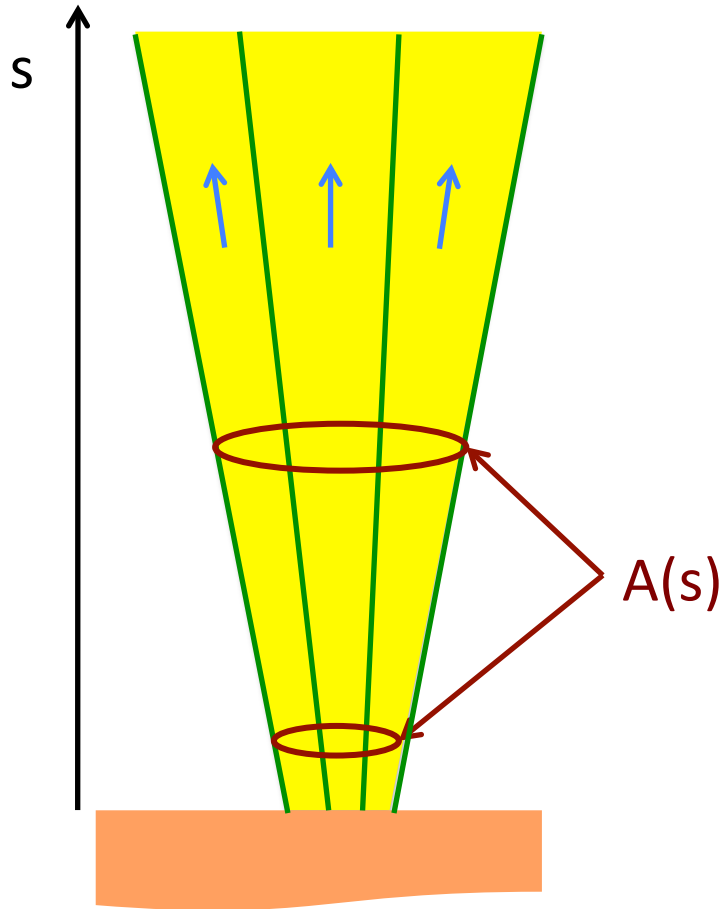
tube:

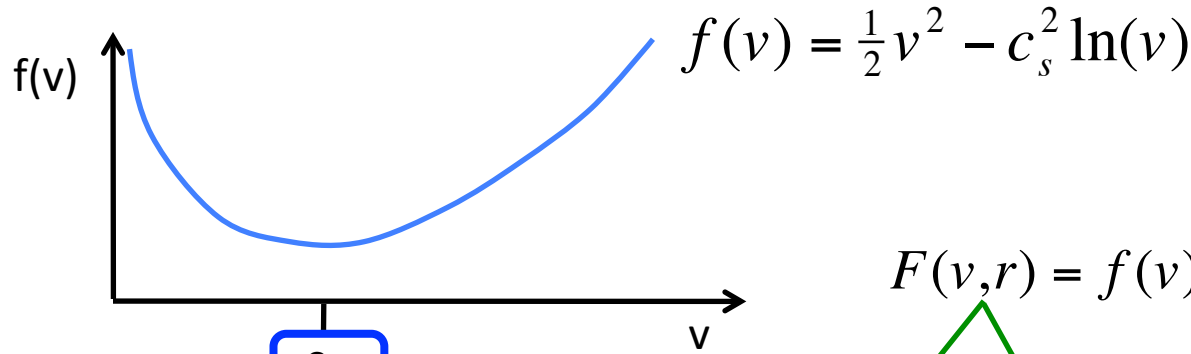
cone w/ vertical axis

$$A(s) \sim s^2$$

$$s = r$$

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





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

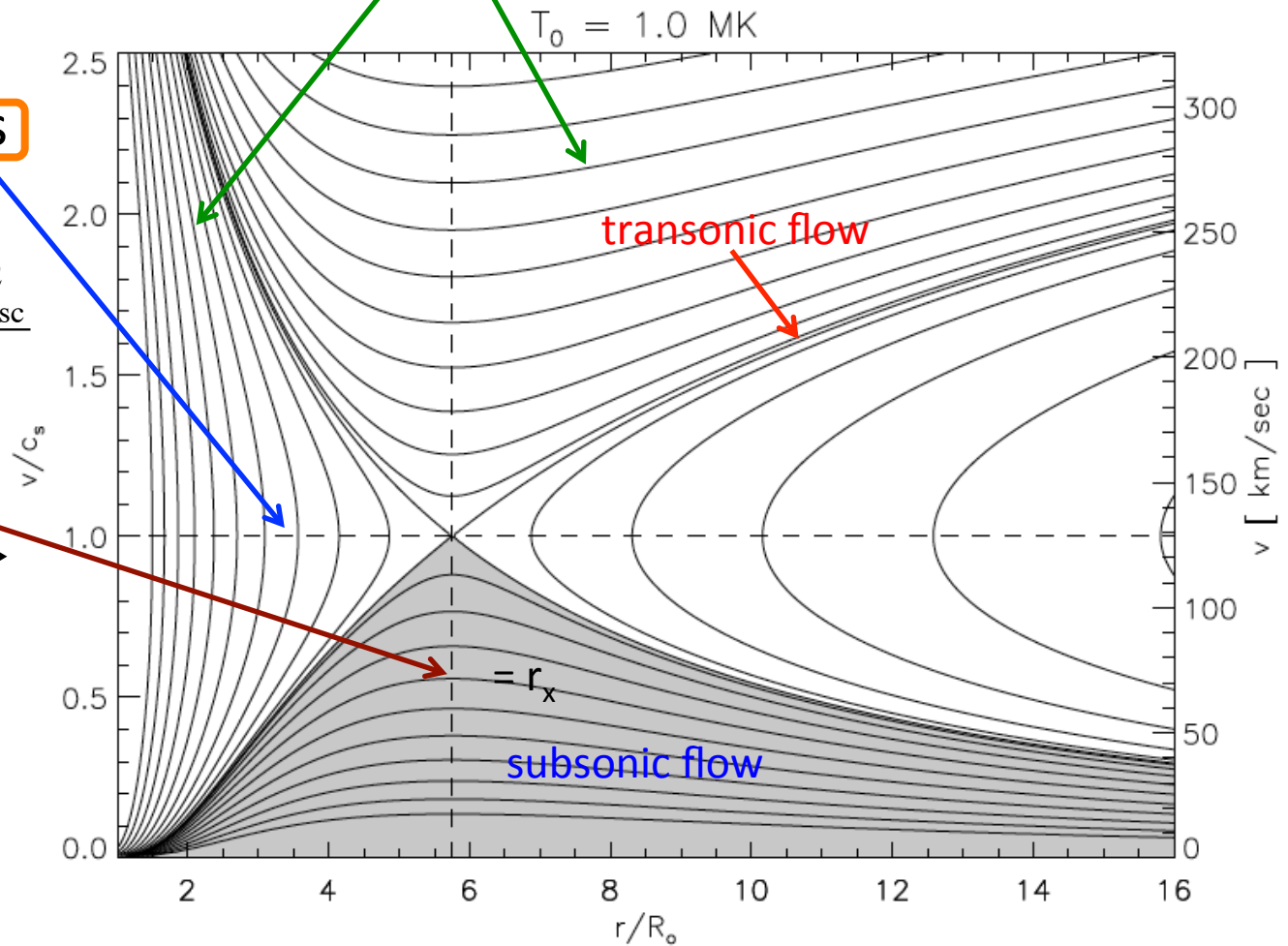
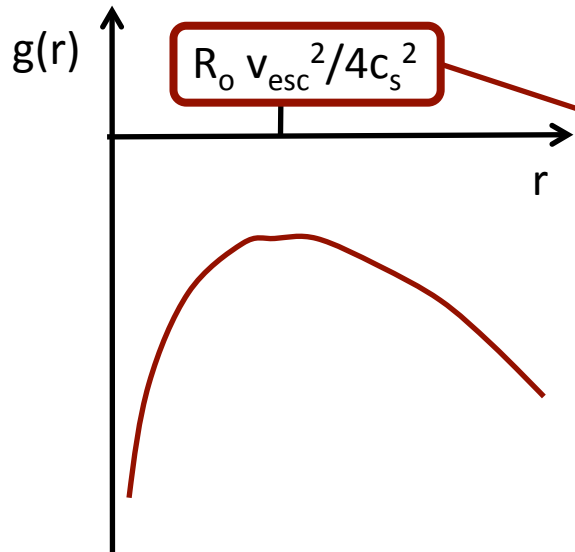
tube:

cone w/ vertical axis

$$A(s) \sim s^2$$

$$s = r$$

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



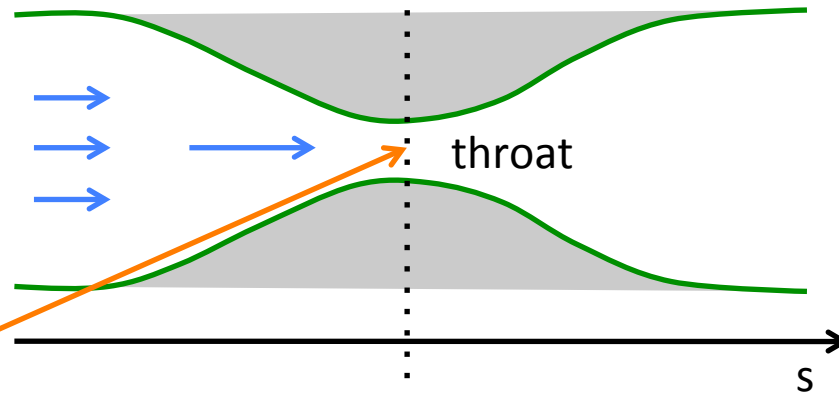
tube:

horizontal nozzle

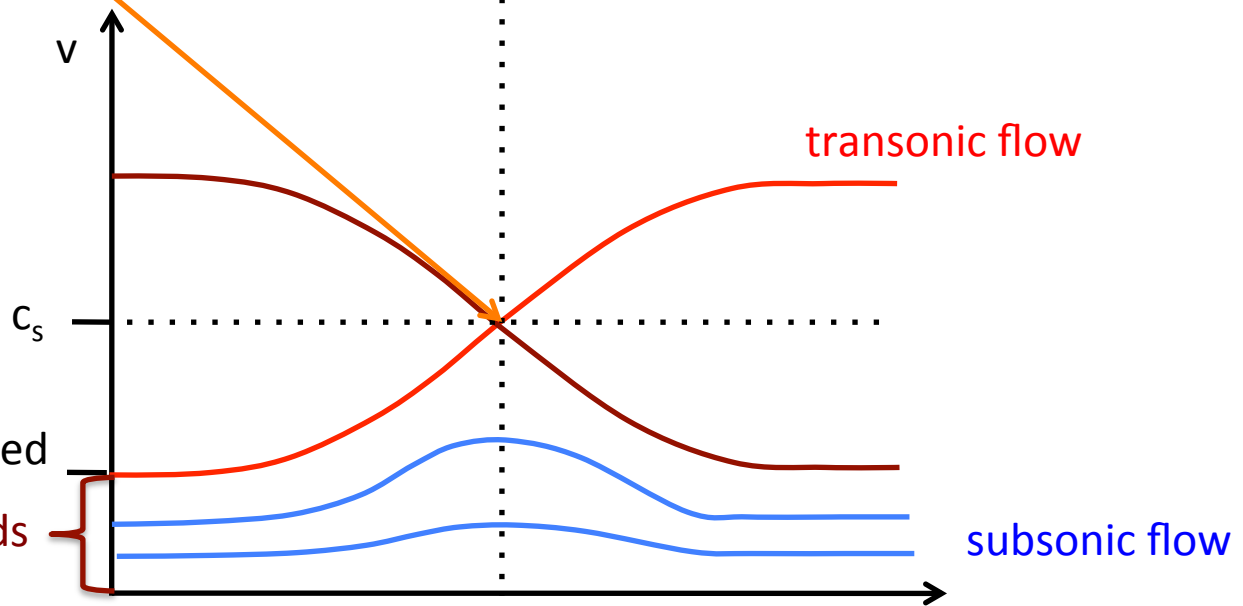
$$\Psi(s) = \text{const.}$$

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

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



saddle @ max.  $g(s)$   
@ throat of nozzle



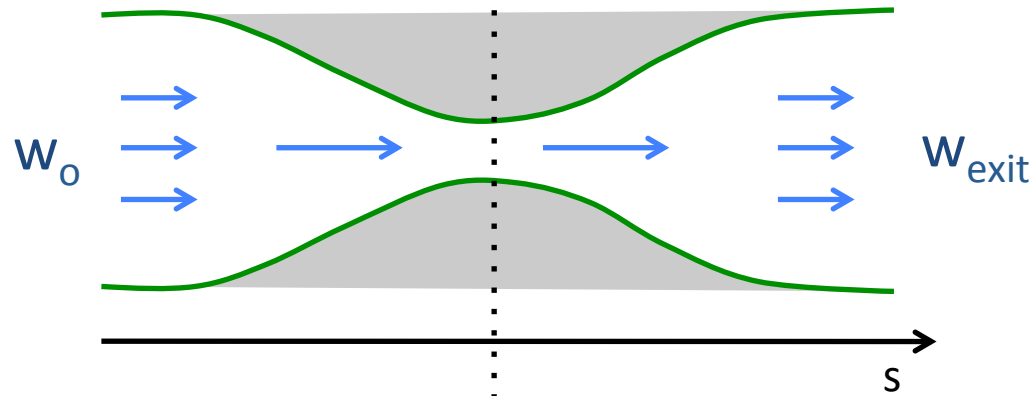
tube:

horizontal nozzle

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

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

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



Speeds up approaching constriction      Slows down in flaring exit

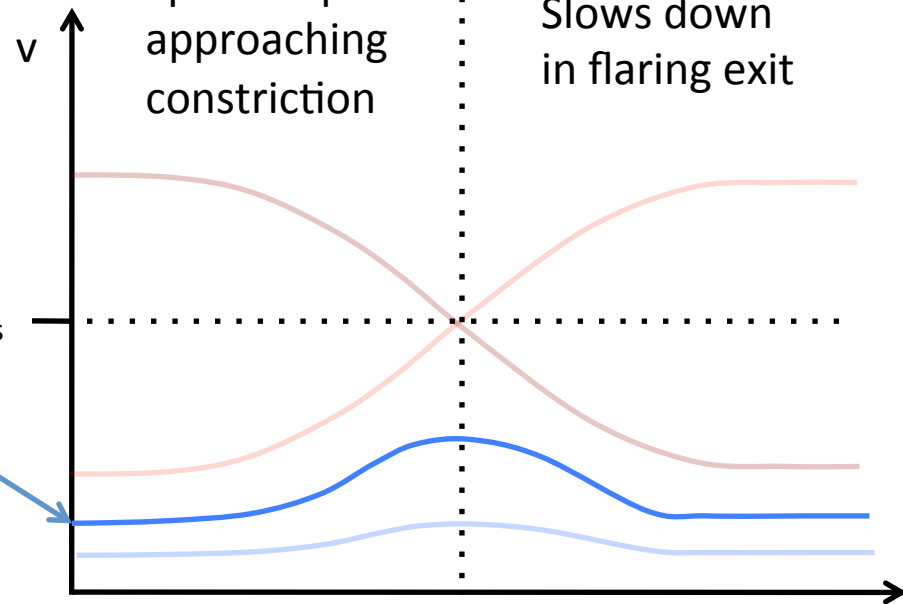
Inflow = mass loss rate

set by  
back-pressure

$W_{\text{exit}}$

$c_s$

subsonic flow



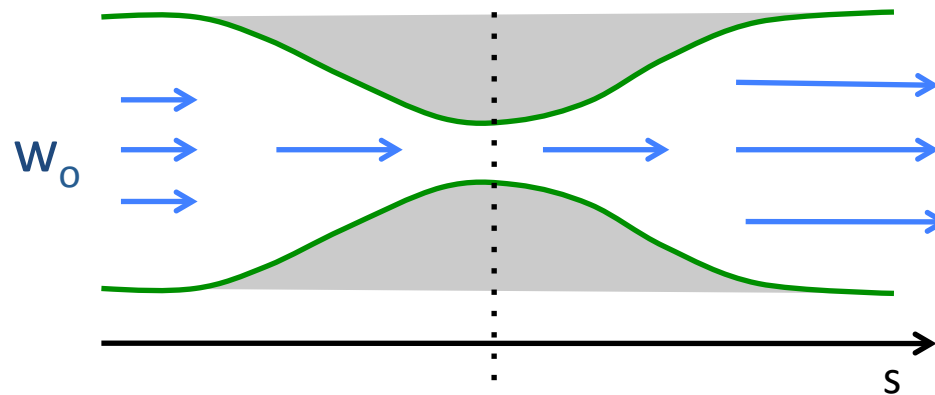
tube:

**horizontal** nozzle

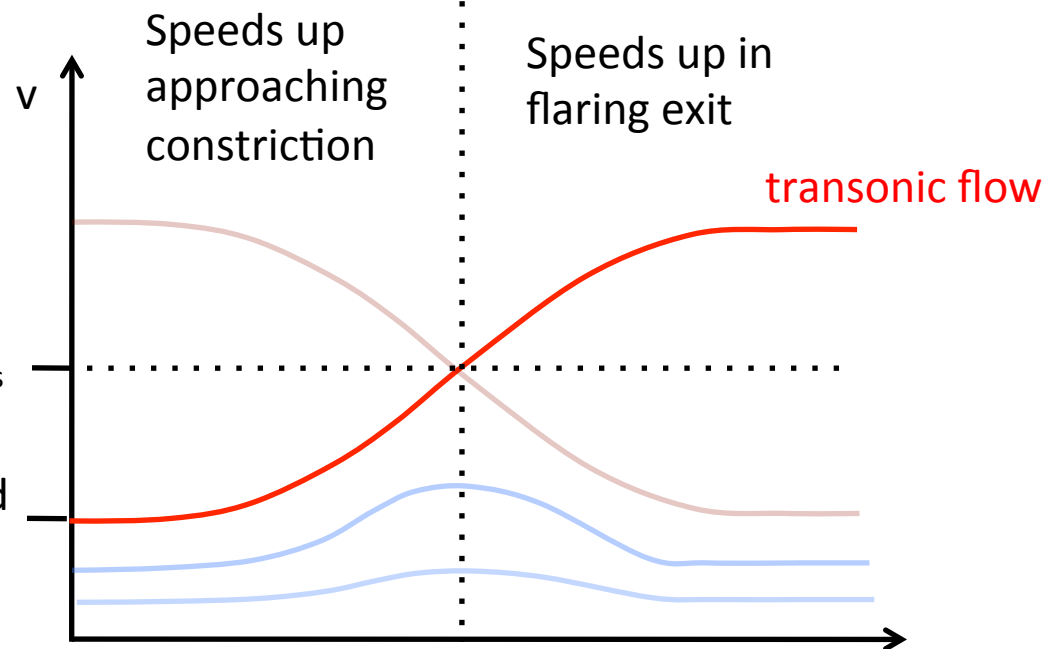
$\Psi(s) = \text{const.}$

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

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



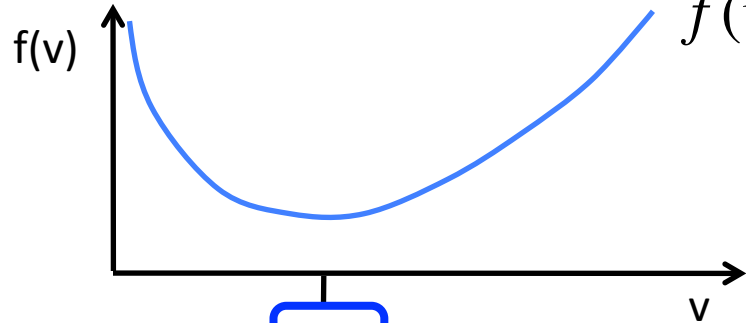
occurs for  
back-pressure  
insufficient to  
keep flow  
sub-sonic





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

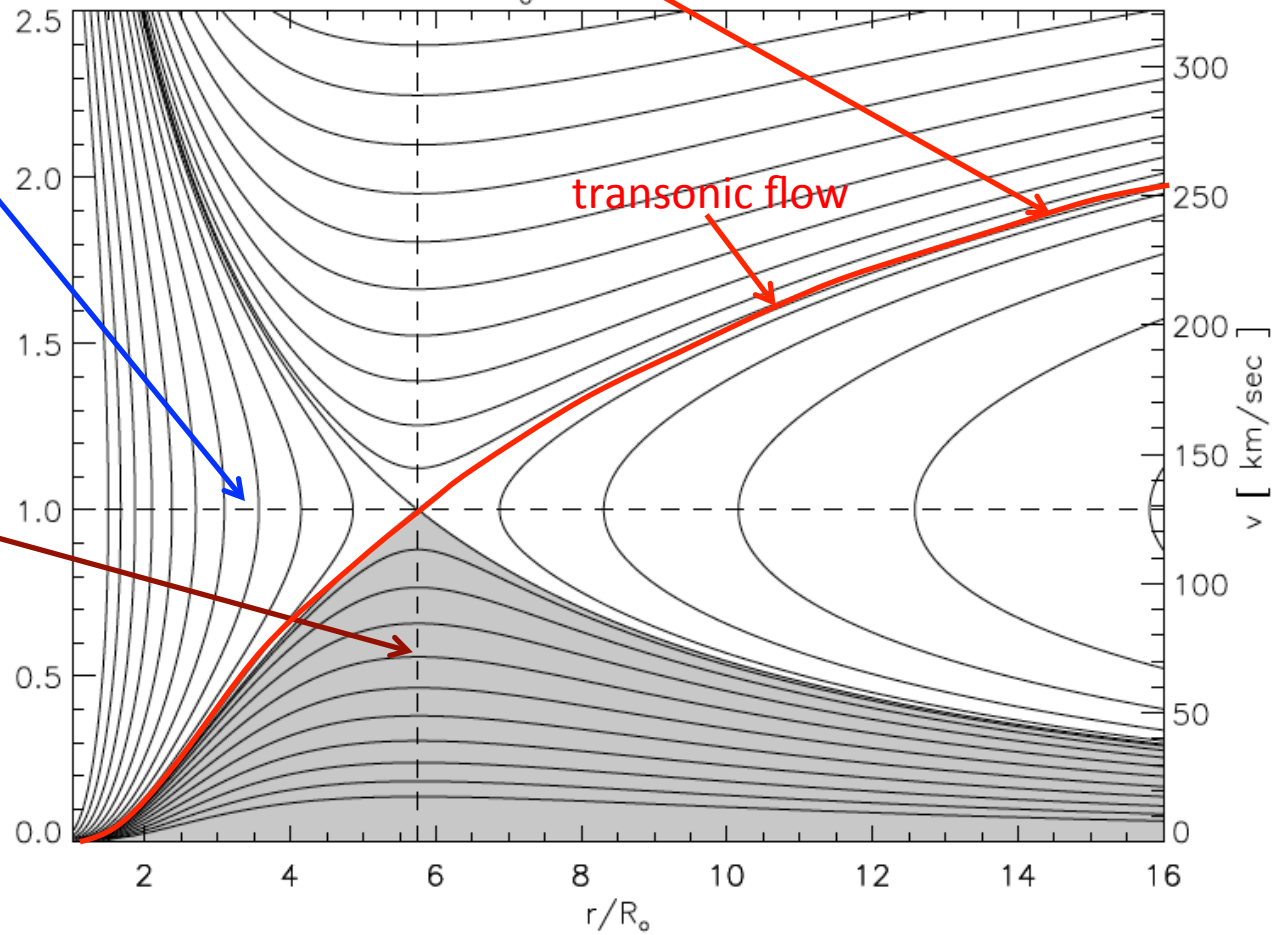
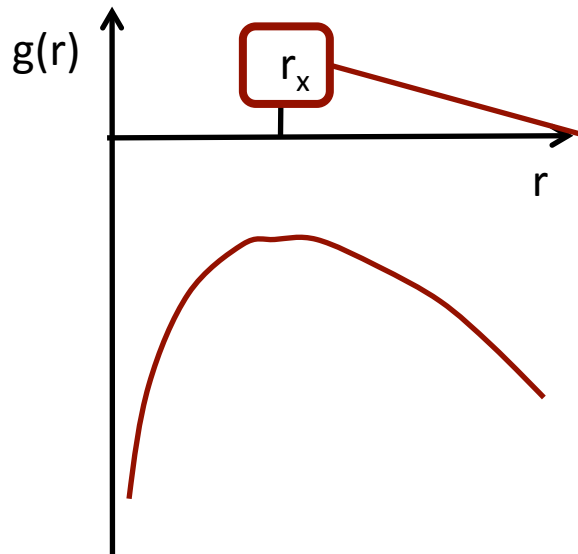
const. fixed by need to become transonic when external back-pressure is insufficient – i.e. vacuum around sun



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

$T_0 = 1.0 \text{ MK}$

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



→ 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\*...

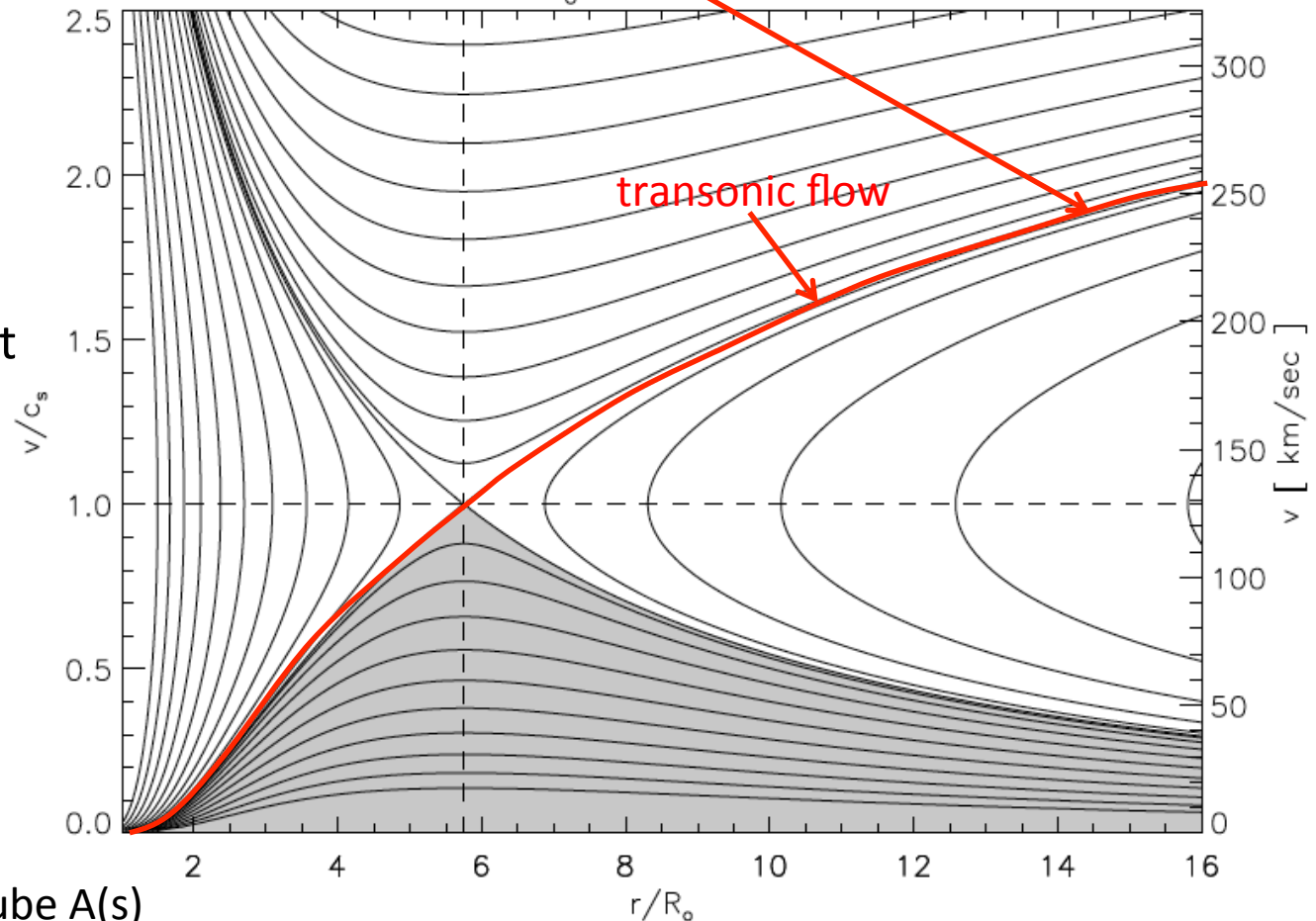
... and it will be lower than density on closed loops w/ same heating (Why?)

\* ... and geometry of flux tube A(s)

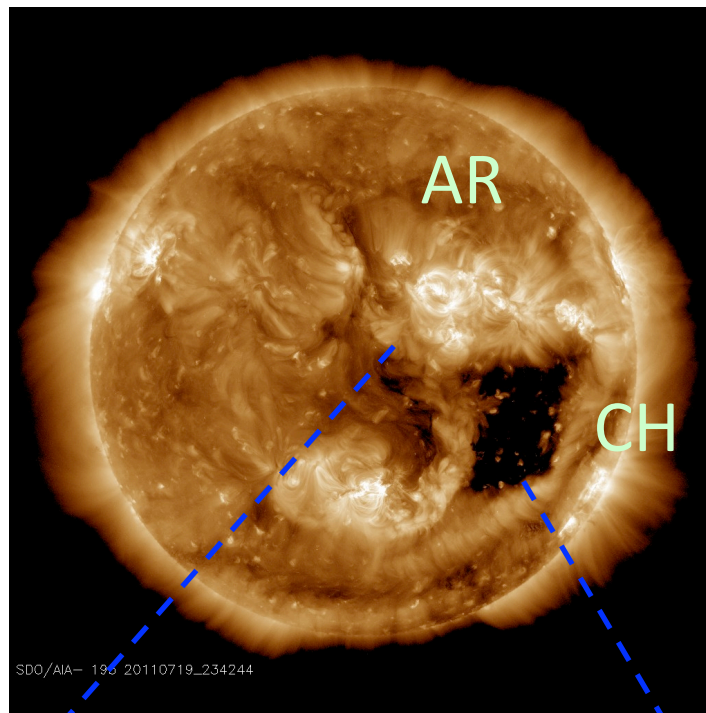
const. fixed by need to become transonic when external back-pressure is insufficient – i.e. vacuum around sun

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

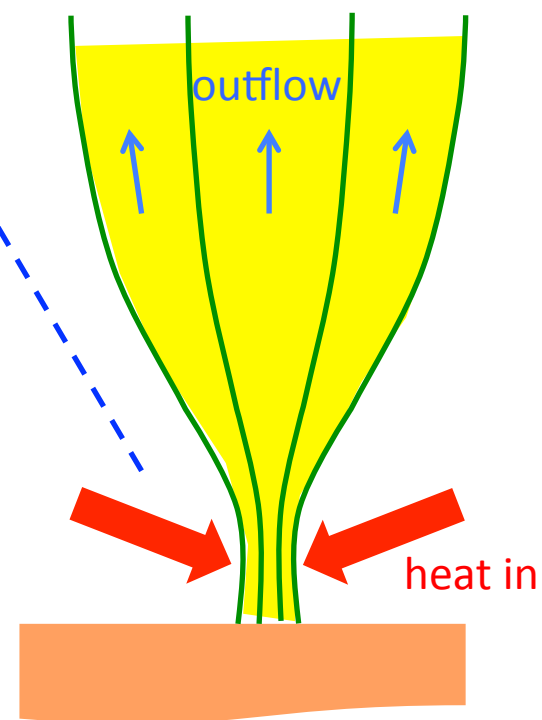
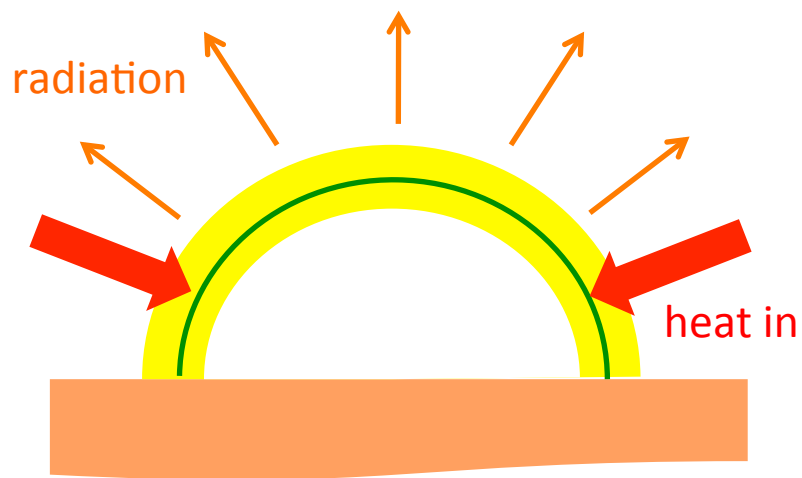
$T_0 = 1.0 \text{ MK}$



**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...

$$(\nabla \times \mathbf{B}) \times \mathbf{B} = 0$$
$$\Rightarrow \nabla \times \mathbf{B} = \alpha \mathbf{B} \quad (\text{i.e. } \parallel \mathbf{B})$$

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

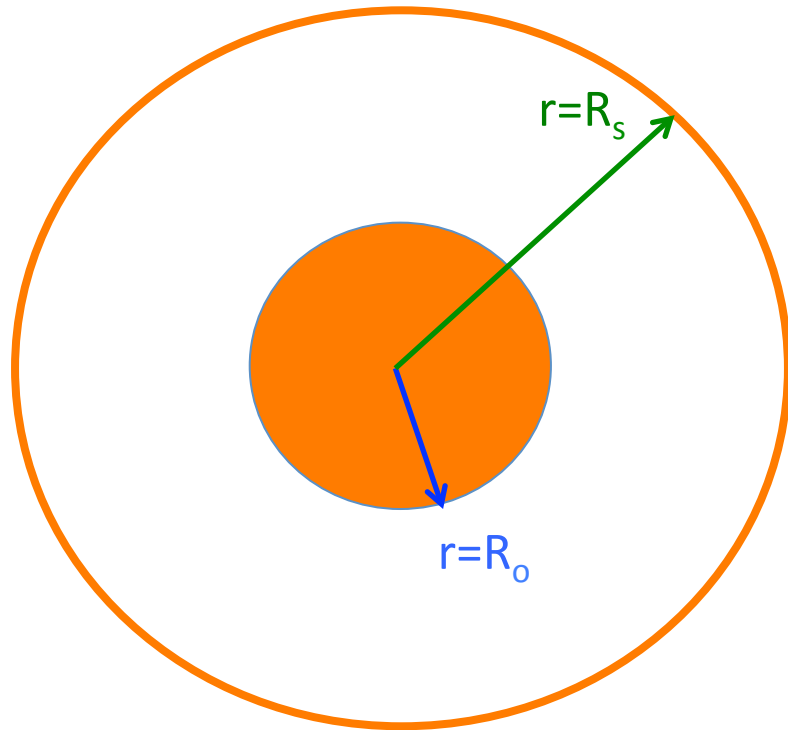
$$\Rightarrow \nabla \times \mathbf{B} = 0 \quad \Rightarrow \quad \mathbf{B} = -\nabla \chi$$

potential field  
(cf. electrostatics)

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

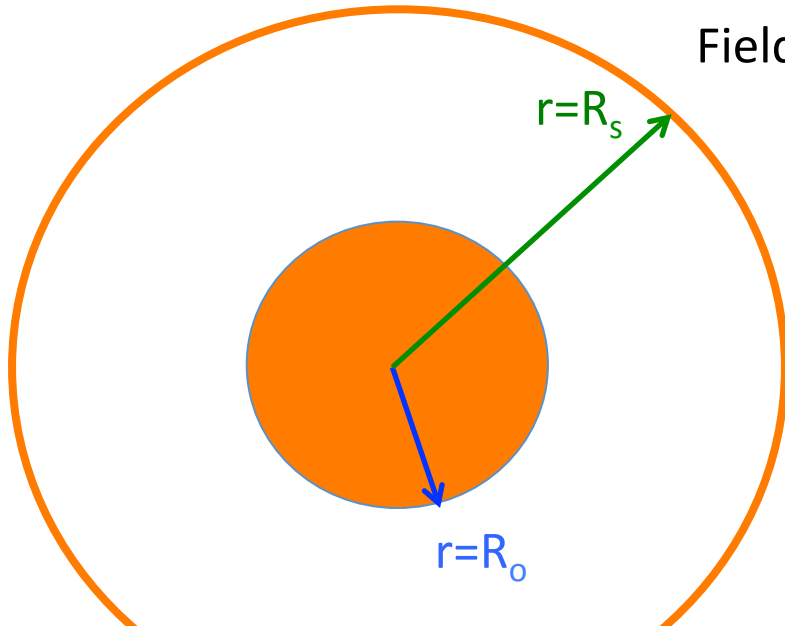
harmonic potential  
(cf. electrostatics in vacuum)

$$\mathbf{B} = -\nabla\chi \quad \& \quad \nabla^2\chi = 0 \quad \text{potential field outside sphere } r=R_0$$





$$\mathbf{B} = -\nabla\chi \quad \& \quad \nabla^2\chi = 0 \quad \text{potential field outside sphere } r=R_o$$



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

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

$$\Rightarrow \chi(R_s, \theta, \varphi) = 0 \quad \text{Dirichlet}$$

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

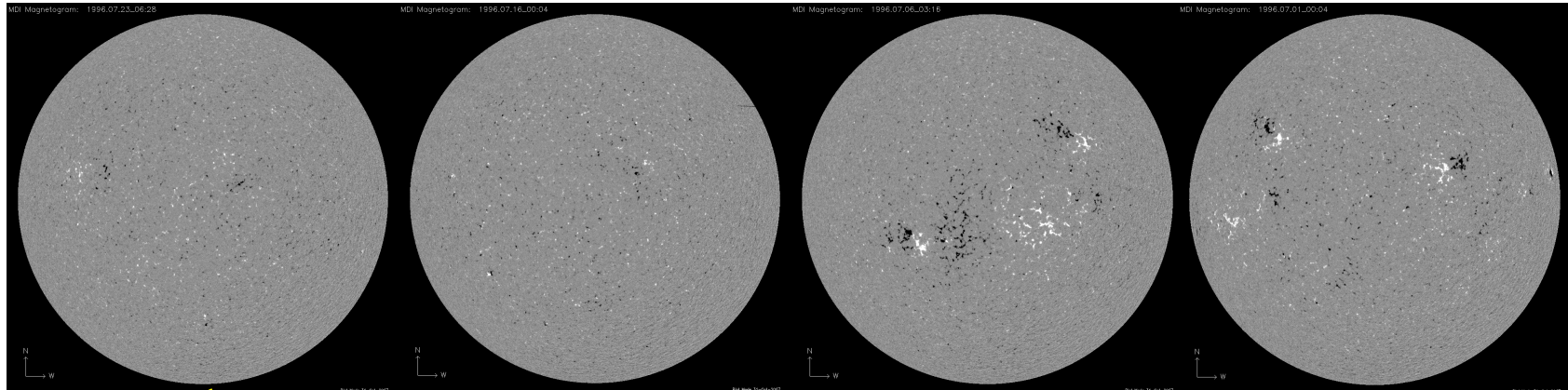
$$B_r(R_o, \theta, \varphi) = -\frac{\partial\chi}{\partial r} \Big|_{r=R_o}$$

Observed (Neumann)

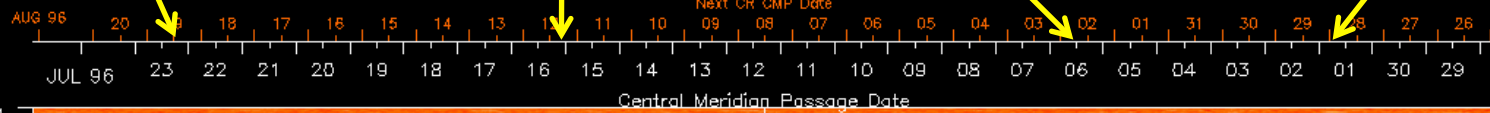
$$B_r(R_o, \theta, \varphi) = \sum_{\ell, m} \frac{A_{\ell, m}}{R_s} \left[ (\ell+1) \left( \frac{R_s}{R_o} \right)^{\ell+2} + \ell \left( \frac{R_o}{R_s} \right)^{\ell-1} \right] Y_{\ell, m}(\theta, \varphi)$$

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

← time

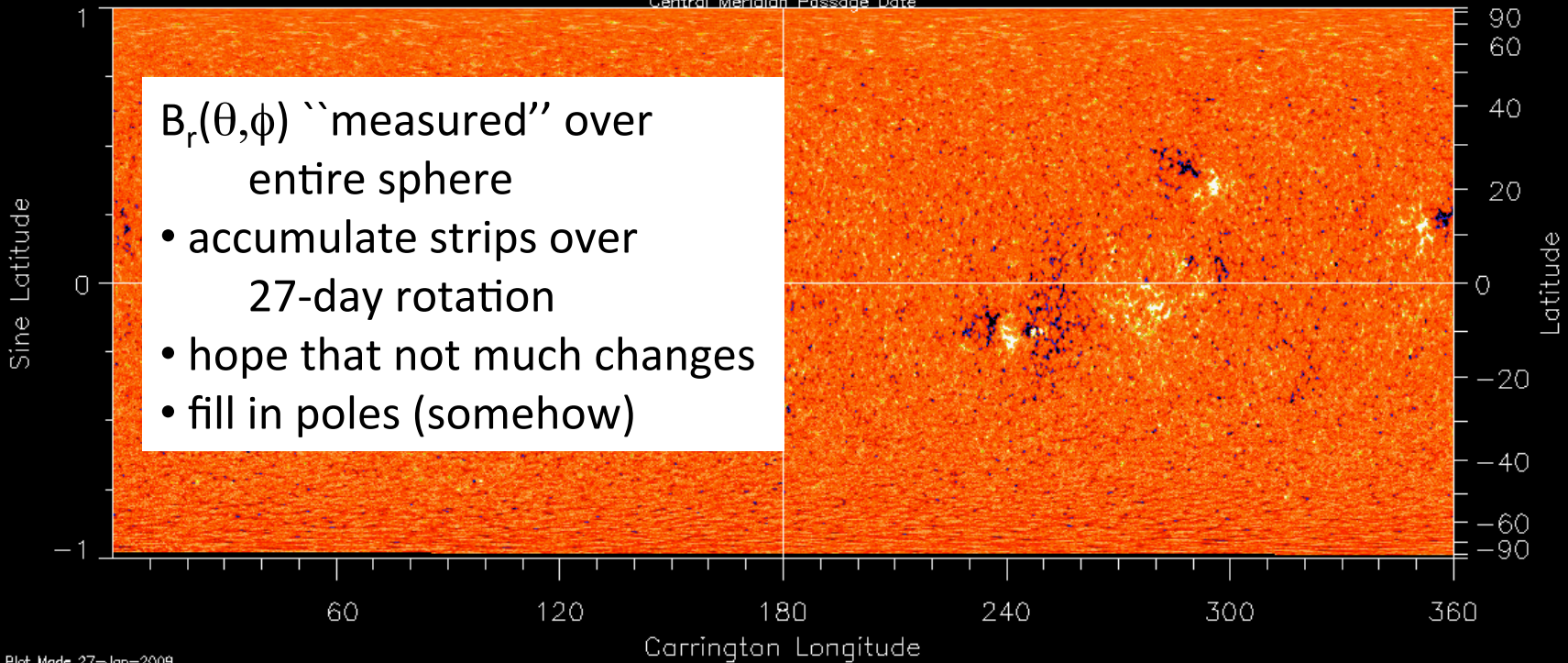


MDI Synoptic Chart for Carrington Rotation 1911



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

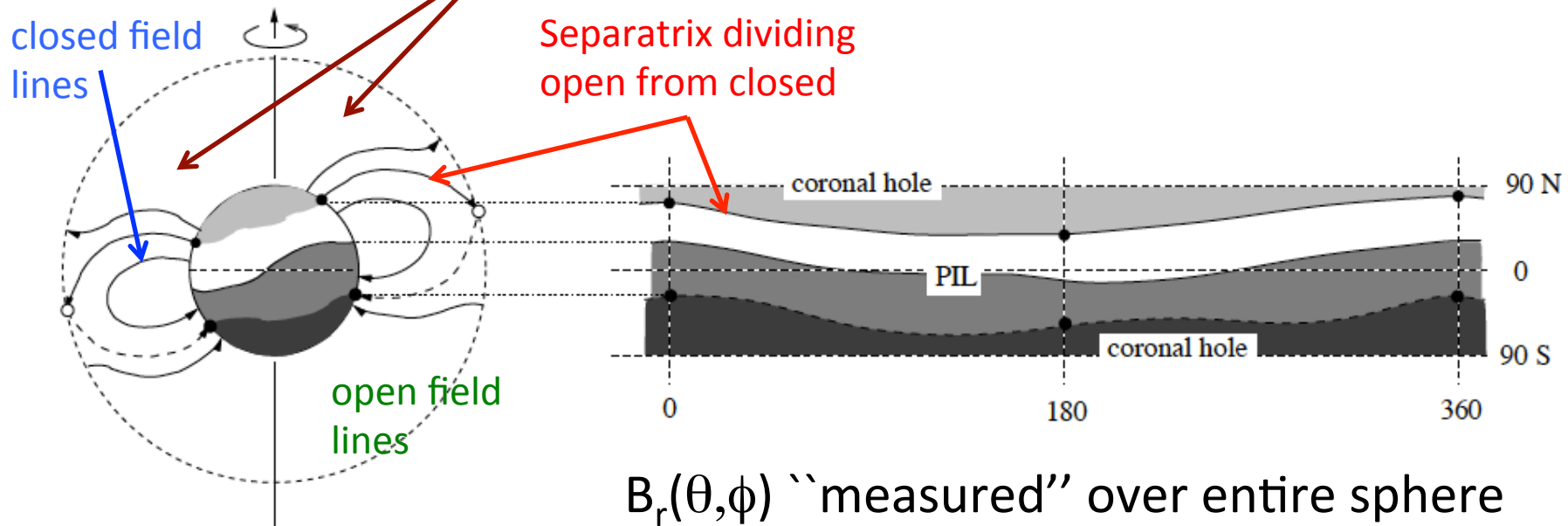
- accumulate strips over 27-day rotation
- hope that not much changes
- fill in poles (somehow)



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

# PFSS model

(potential field source surface)



Solar wind flows from open field crossing  $r=R_s$  ... the 'source' of the wind → the 'source surface'

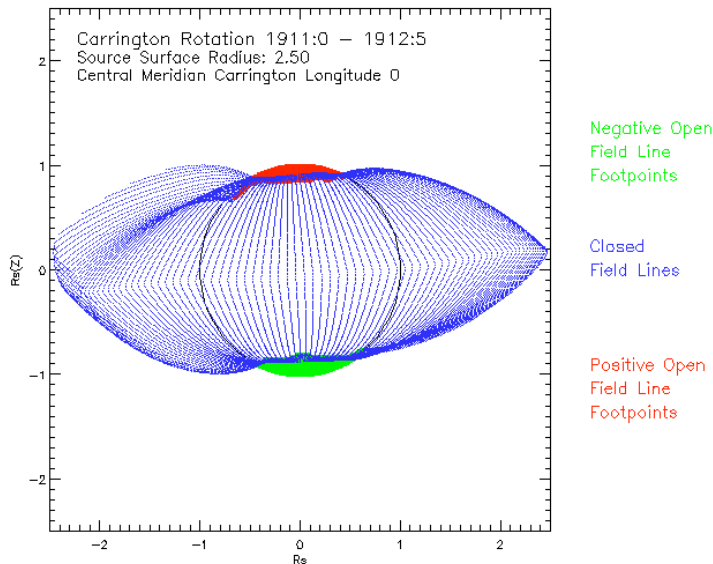
- $B_r(\theta, \phi)$  "measured" over entire sphere
- accumulate strips over 27-day rotation
  - hope that not much changes
  - fill in poles (somehow)
  - decompose w/ spherical harmonics
  - coeffs. →  $A_{l,m}$

# Assumptions of the PFSS

- No currents in coronal field (simplest equilibrium)

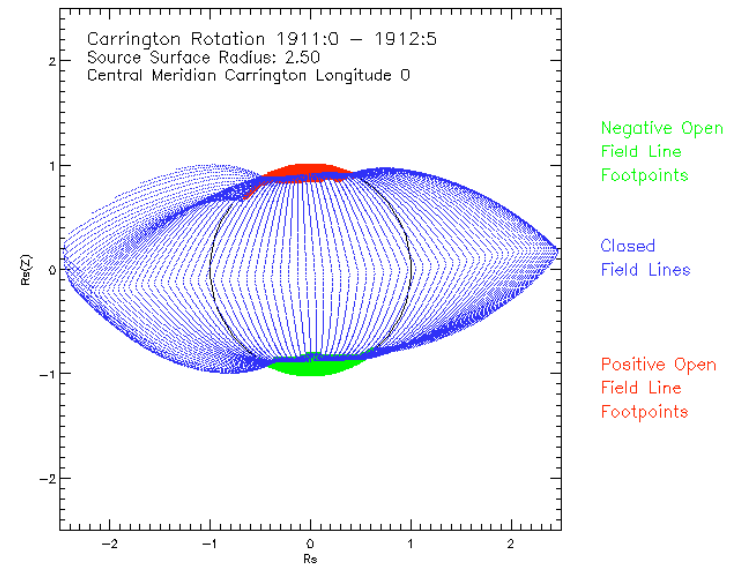
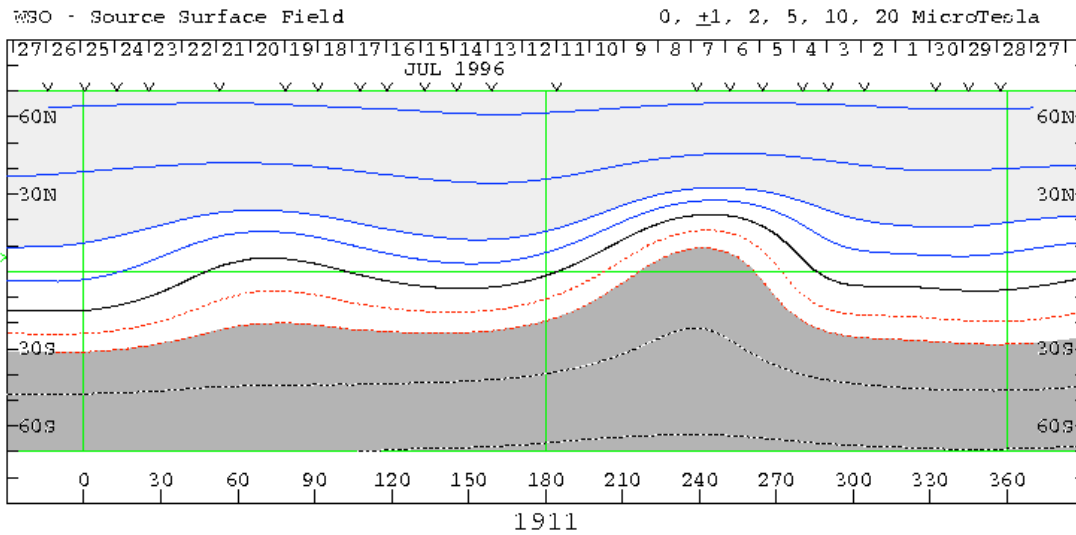
$$\nabla \times \mathbf{B} = 0 \quad R_o < r < R_s$$

- Field becomes open (radial) @ fixed radius  $r=R_s$
- Not much change during 27-day accumulation

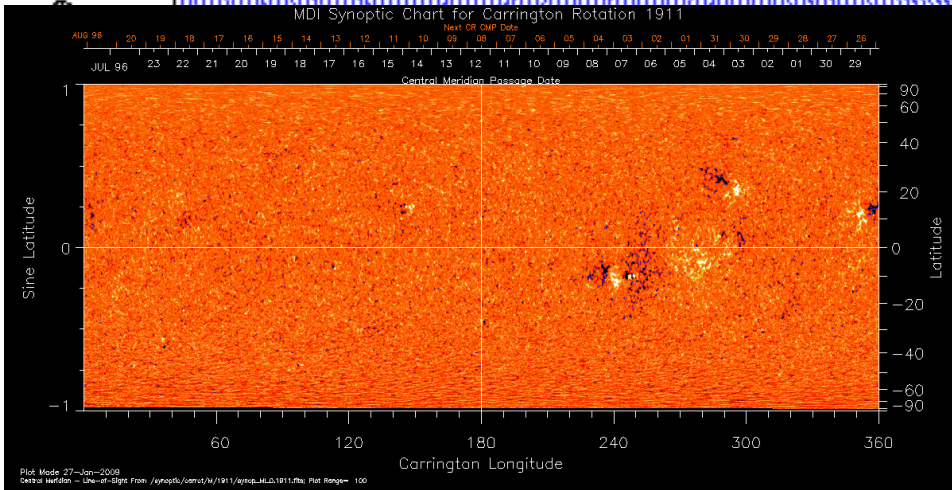
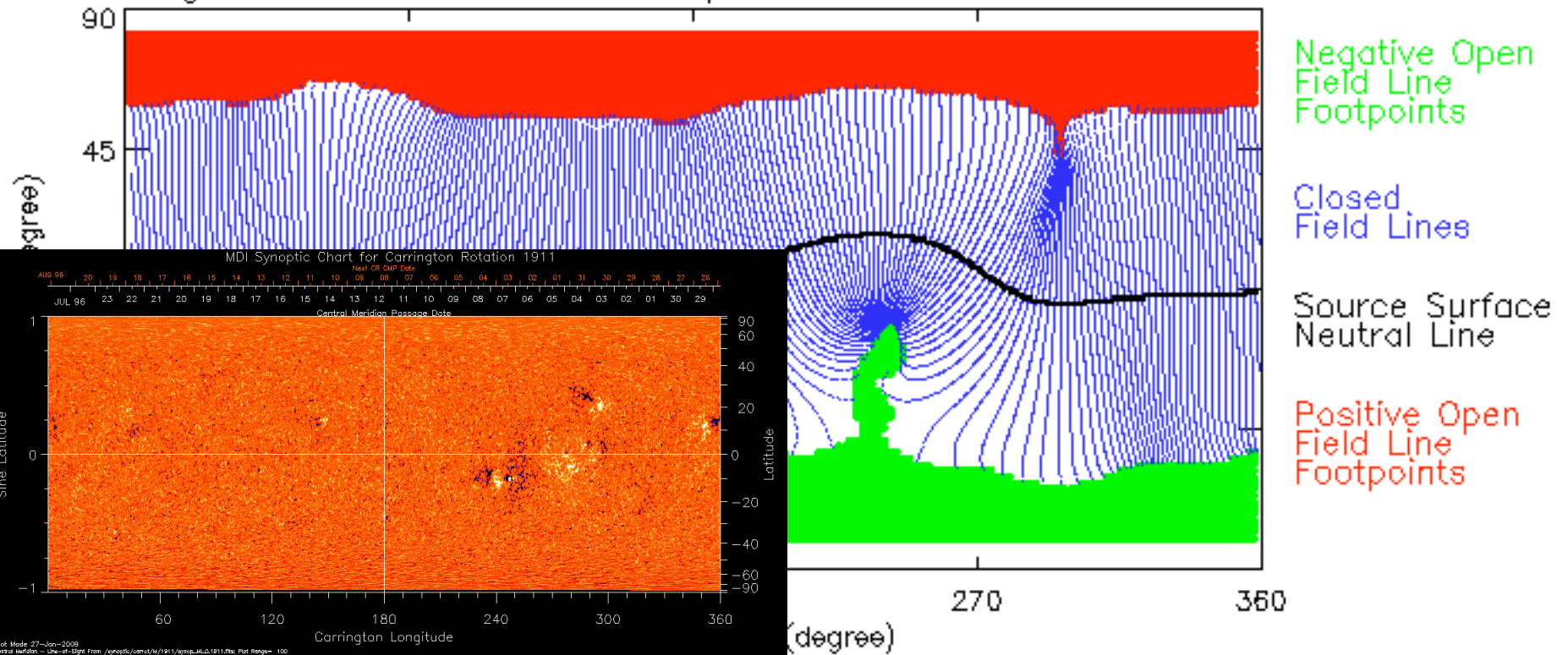


→ **Model** distinguishing open/closed coronal field

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



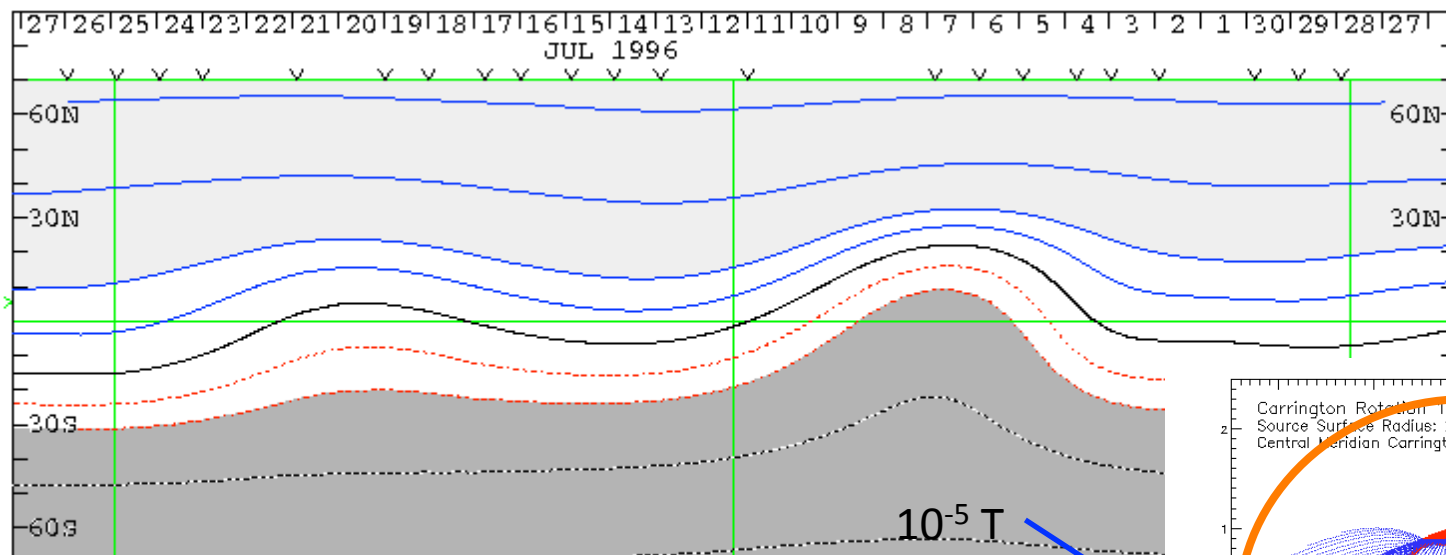
Carrington Rotation 1911:0-1912:5 / Source Surface Radius: 2.50





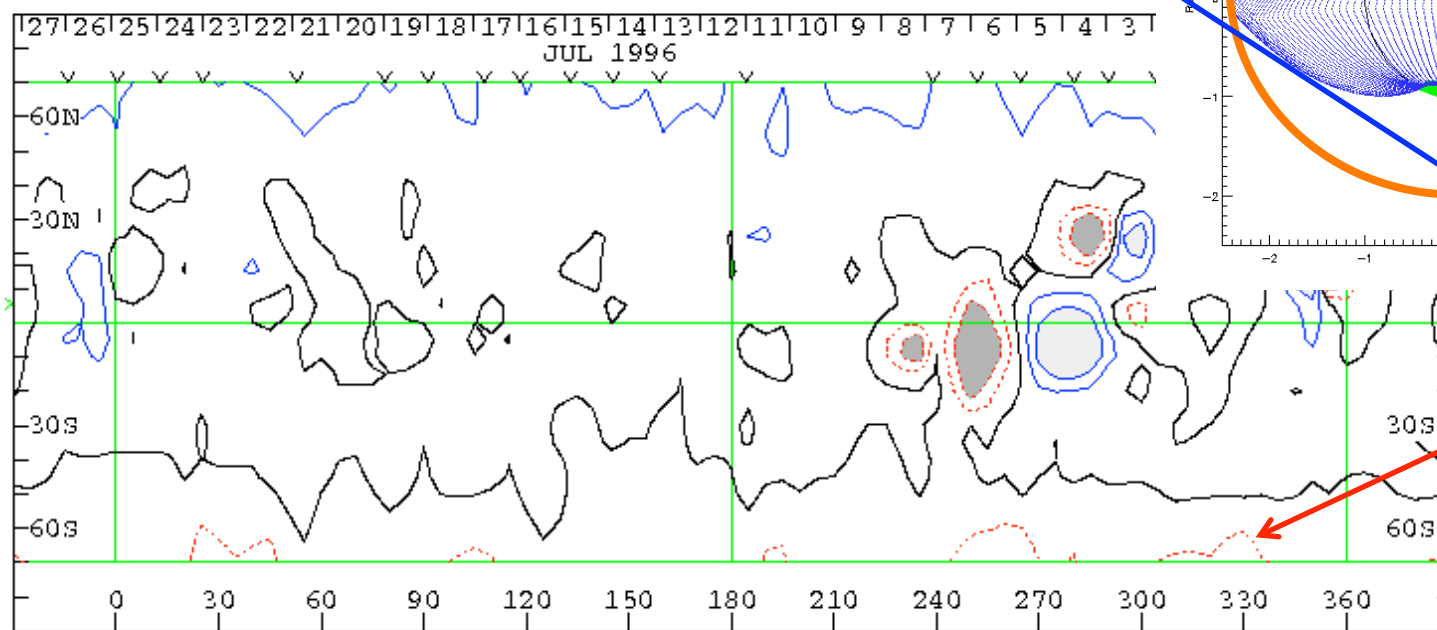
WSO - Source Surface Field

0, +1, 2, 5, 10, 20 MicroTesla

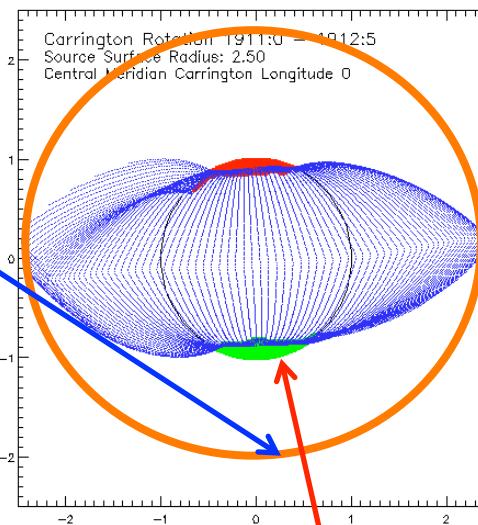


WSO - Photospheric Magnetic Field

0, +100, 200, 500, 1000, 2000



1911



Negative Open Field Line Footprints

Closed Field Lines

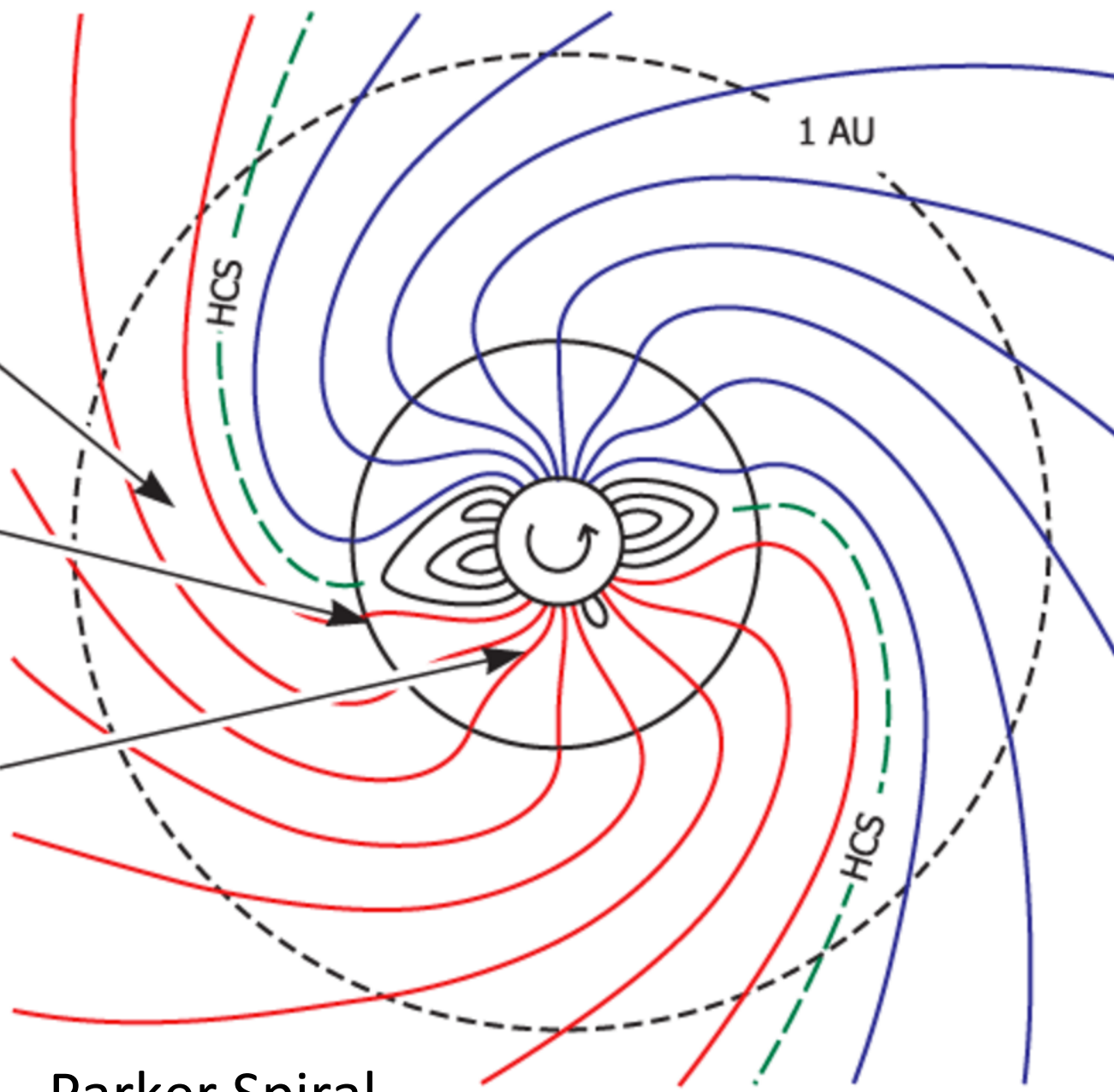
Positive Open Field Line Footprints



Heliosphere  
 $\vec{B} = B_R \hat{R} + B_\phi \hat{\phi}$   
 $\vec{V} = V_R \hat{R}$

Source surface  
 $\vec{B} = B_R \hat{R}$   
 $\vec{V} = V_R \hat{R}$

Super-radial expansion  
 $\vec{B} = B_R \hat{R} + B_\theta \hat{\theta} + B_\phi \hat{\phi}$   
 $\vec{V} = V_R \hat{R} + V_\theta \hat{\theta} + V_\phi \hat{\phi}$



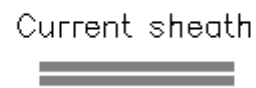
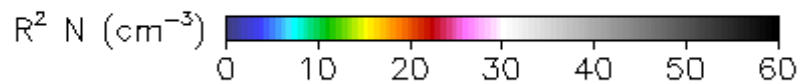
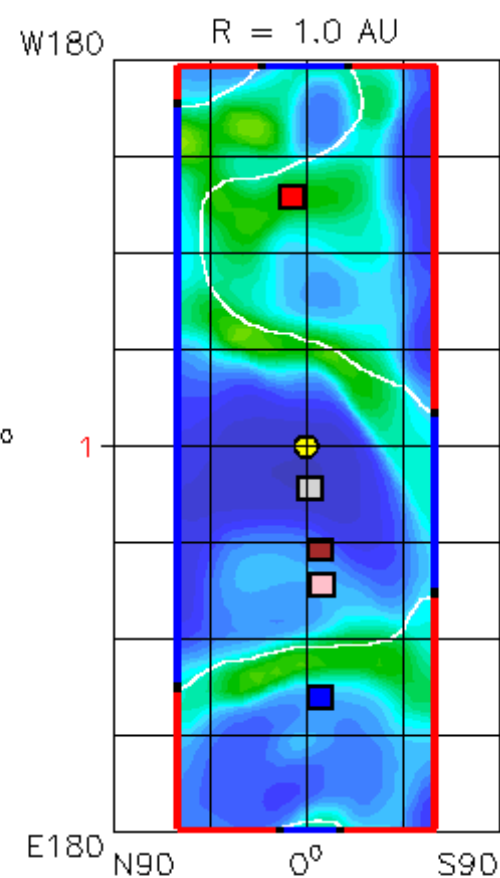
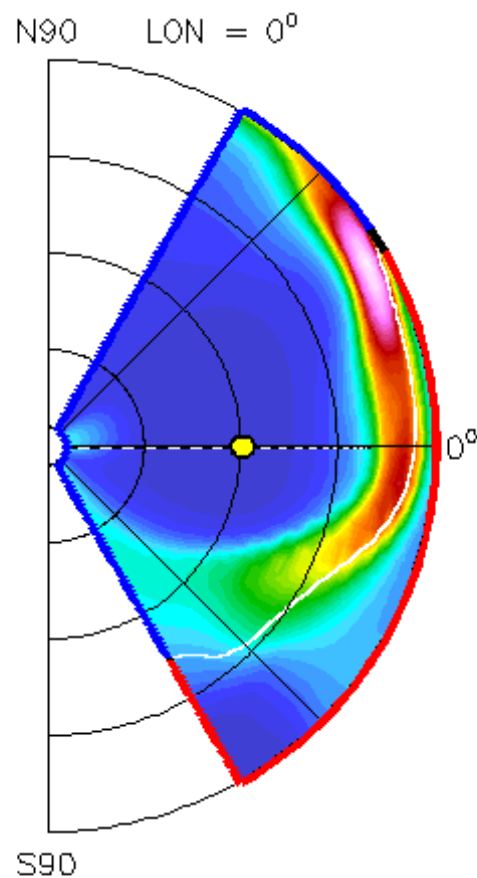
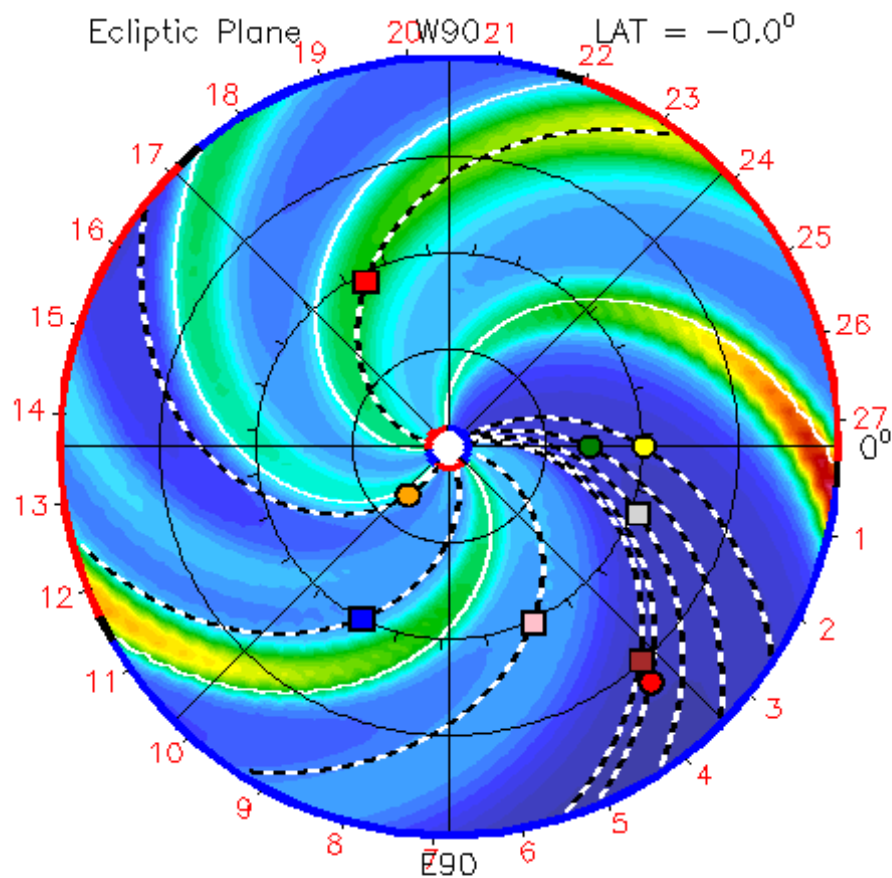
Owens & Forsyth 2013

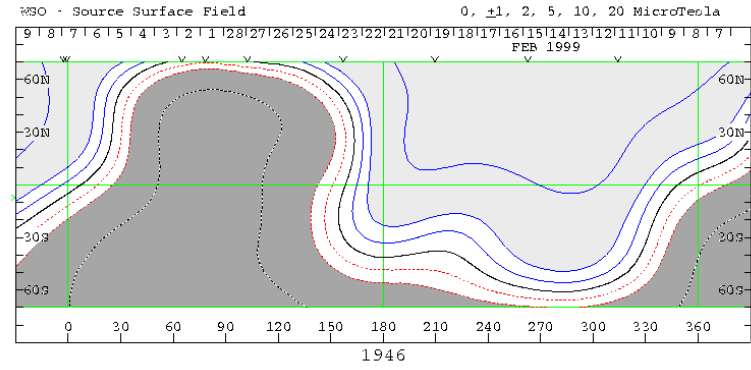
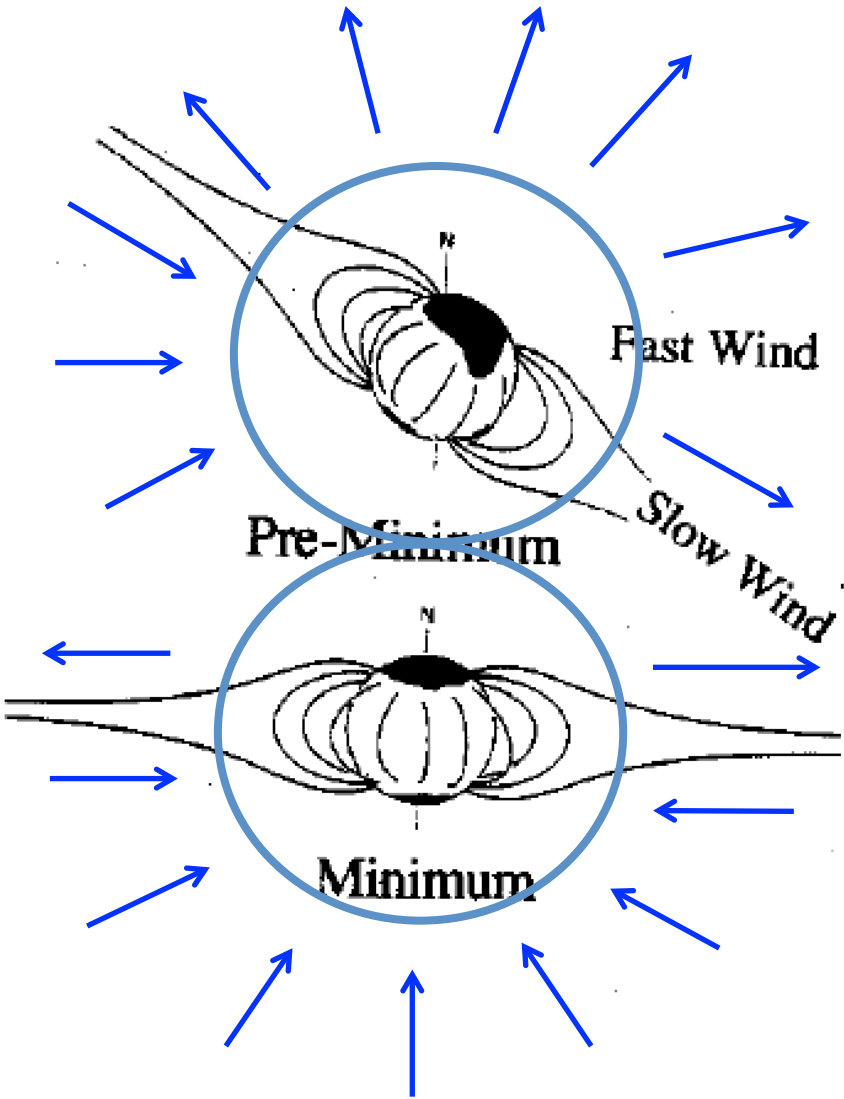
Parker Spiral

2012-06-06T00:00

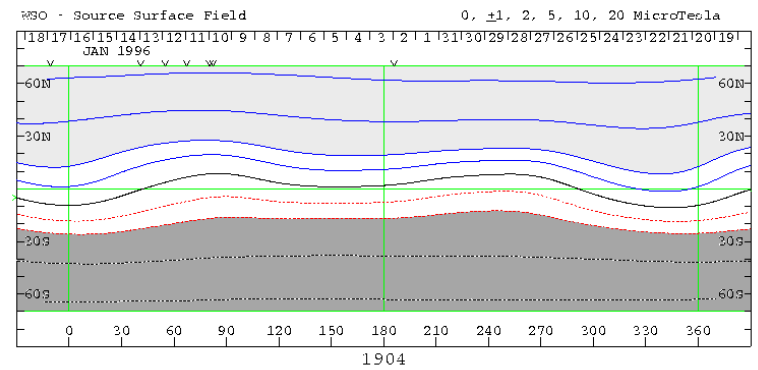
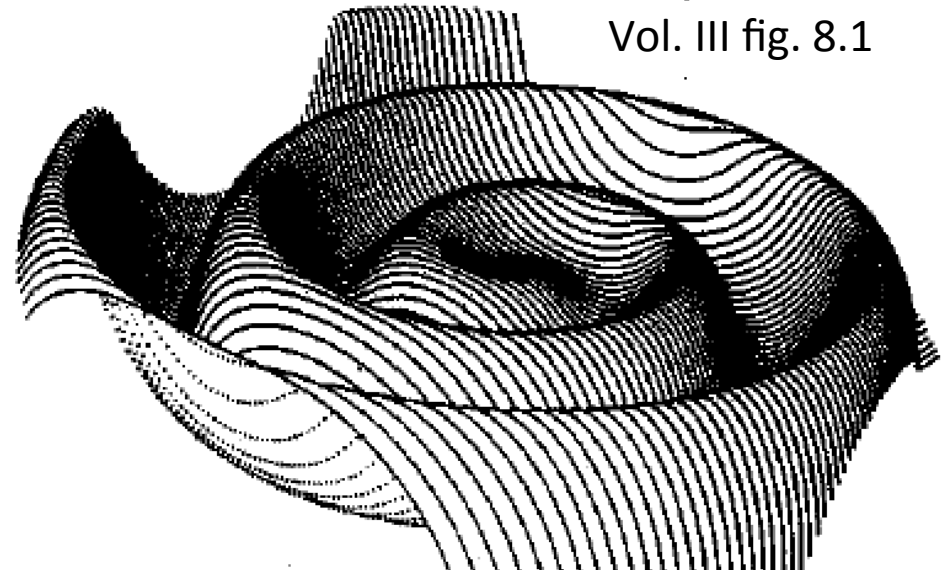
2012-06-06T00 +0.00 day

- Earth
- Mars
- Mercury
- Venus
- Stereo\_B
- Kepler
- MSL
- Spitzer
- Stereo\_A

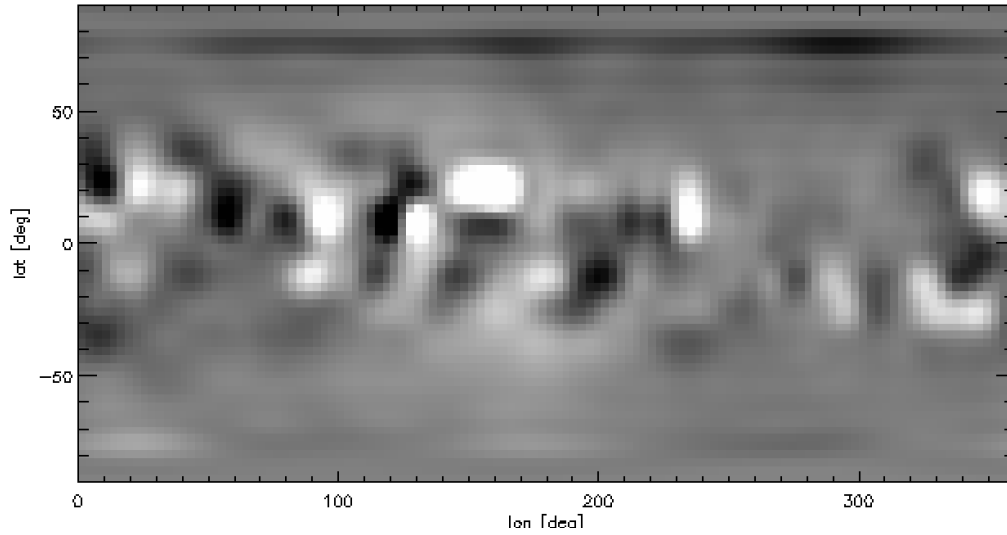




Vol. III fig. 8.1



Sun @ 2001-05-19T20:26:15.000Z

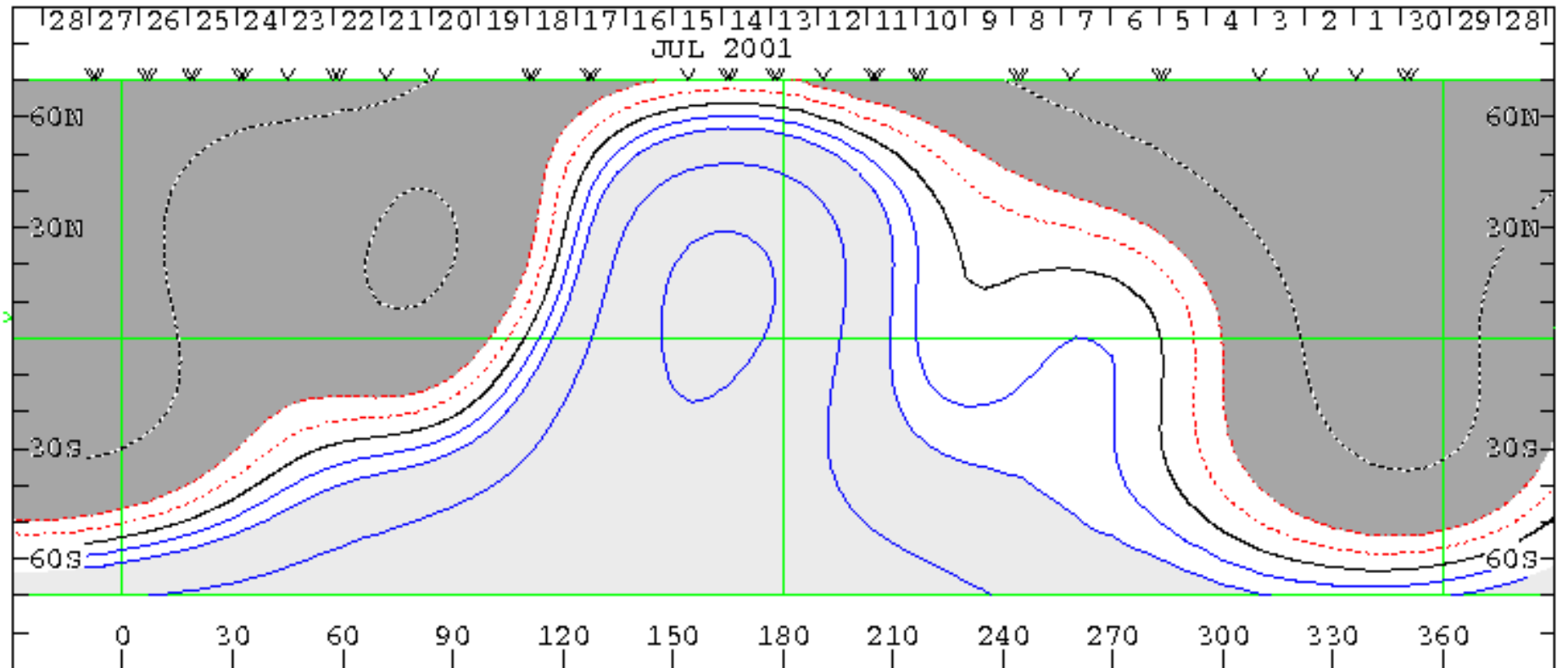


$r = R_{\odot}$

$r = 2.5 R_{\odot}$

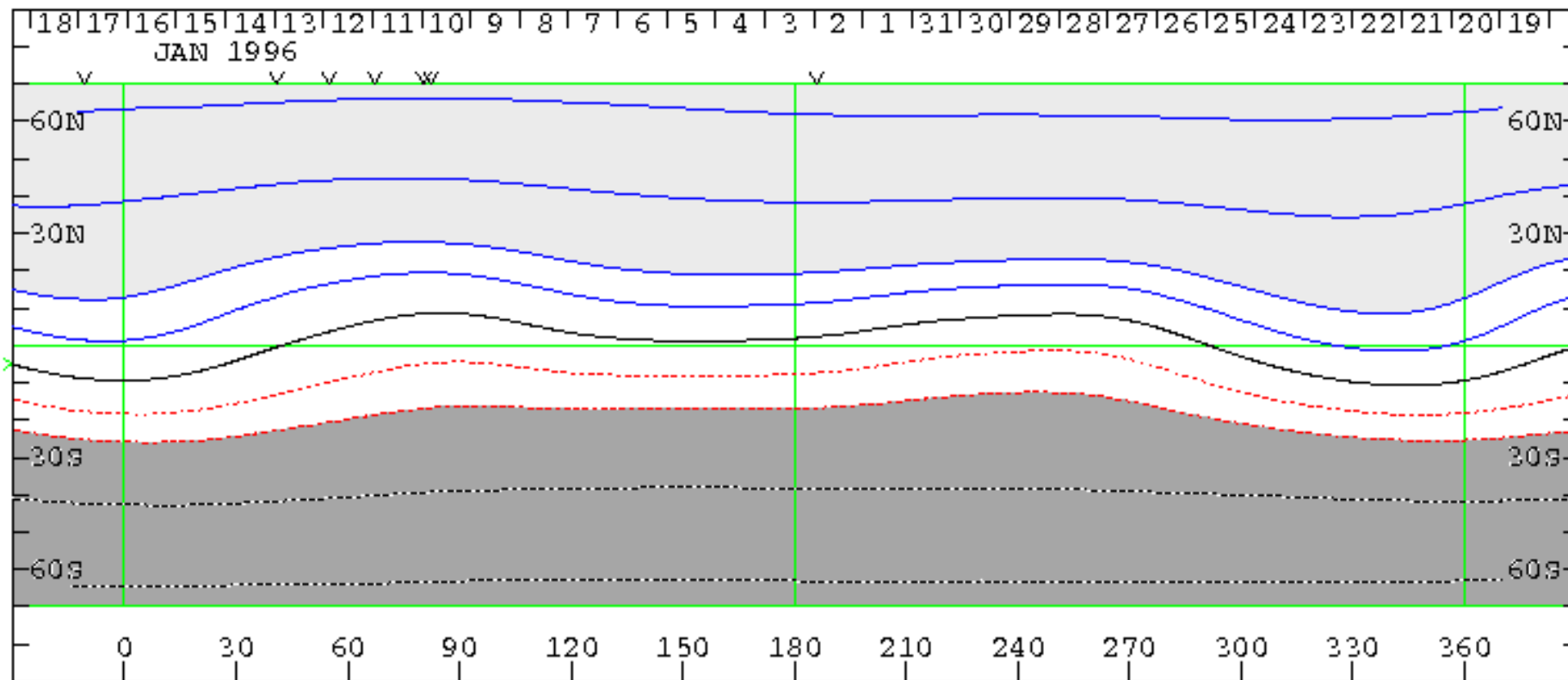
WSO - Source Surface Field

0, ±1, 2, 5, 10, 20 MicroTesla

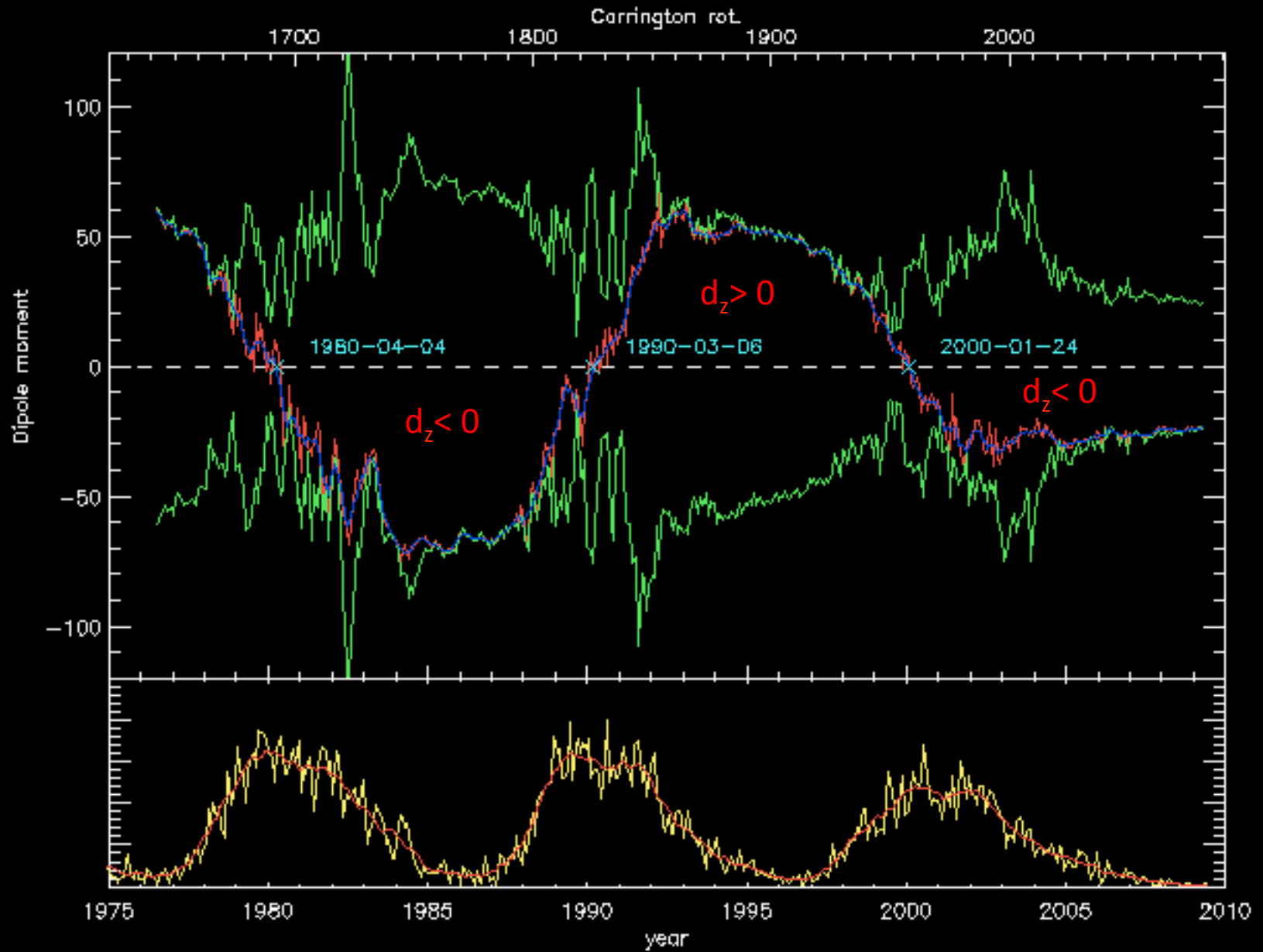


W30 - Source Surface Field

0,  $\pm 1$ , 2, 5, 10, 20 MicroTesla



1904



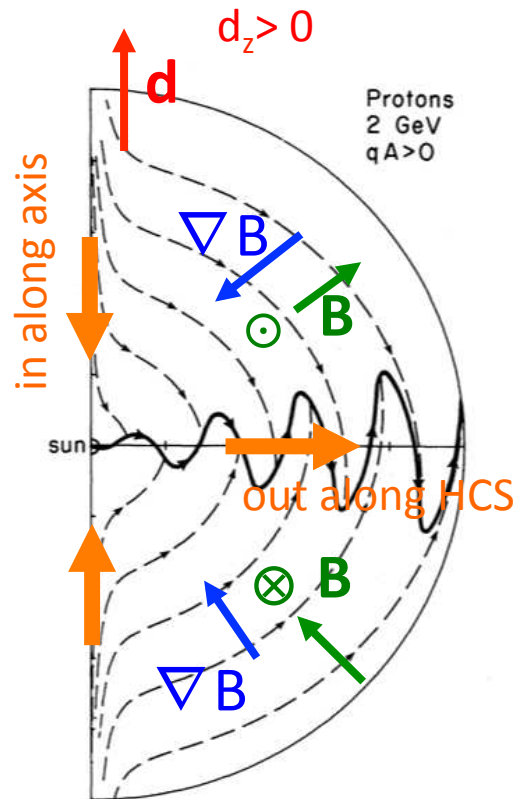
# cosmic rays

- Originate far away in galaxy – in supernova remnant shocks
- Enter solar system isotropically
- No collisions with SW particles
- Deflected by SW  $\mathbf{B}$

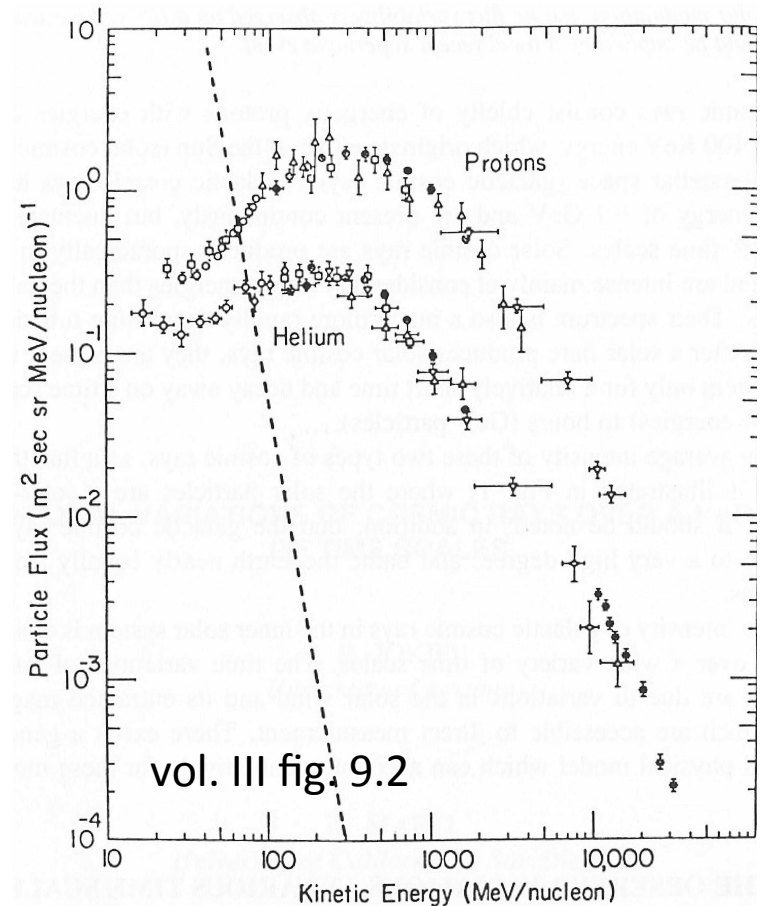
- Advected outward
- Diffused by  $\mathbf{B}$  fluctuations
- Drift:

$$\mathbf{v}_d = \frac{pcw}{3q} \nabla \times \left( \frac{\mathbf{B}}{B^2} \right)$$

$$\approx \frac{2pcw}{3q} \frac{\mathbf{B}}{B^3} \times \nabla B$$

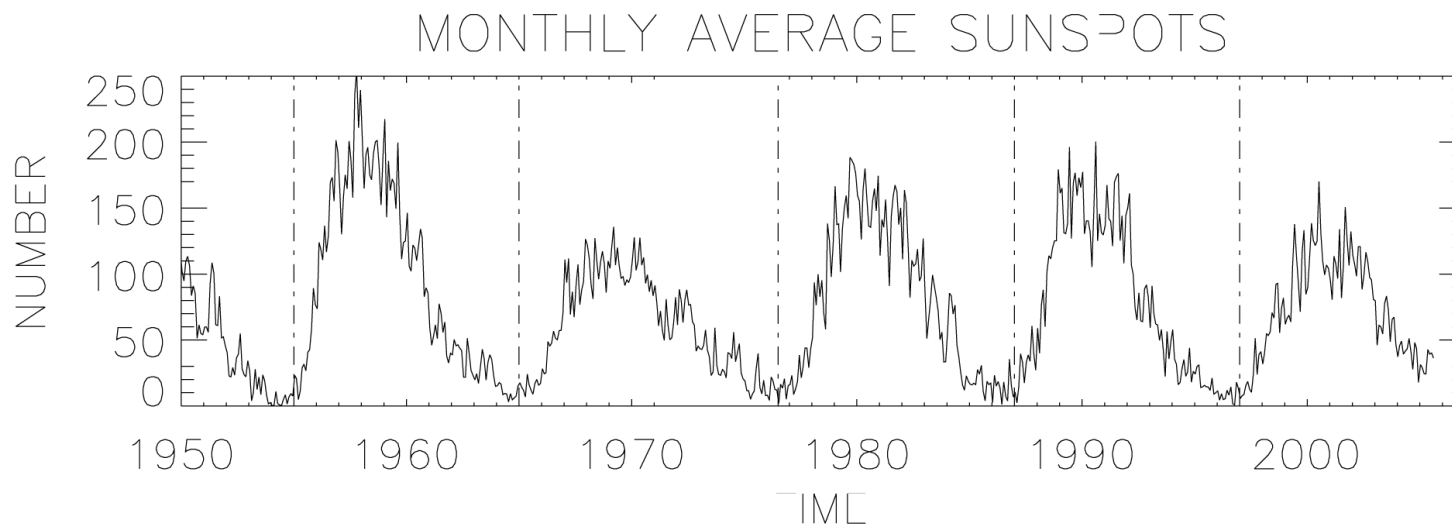
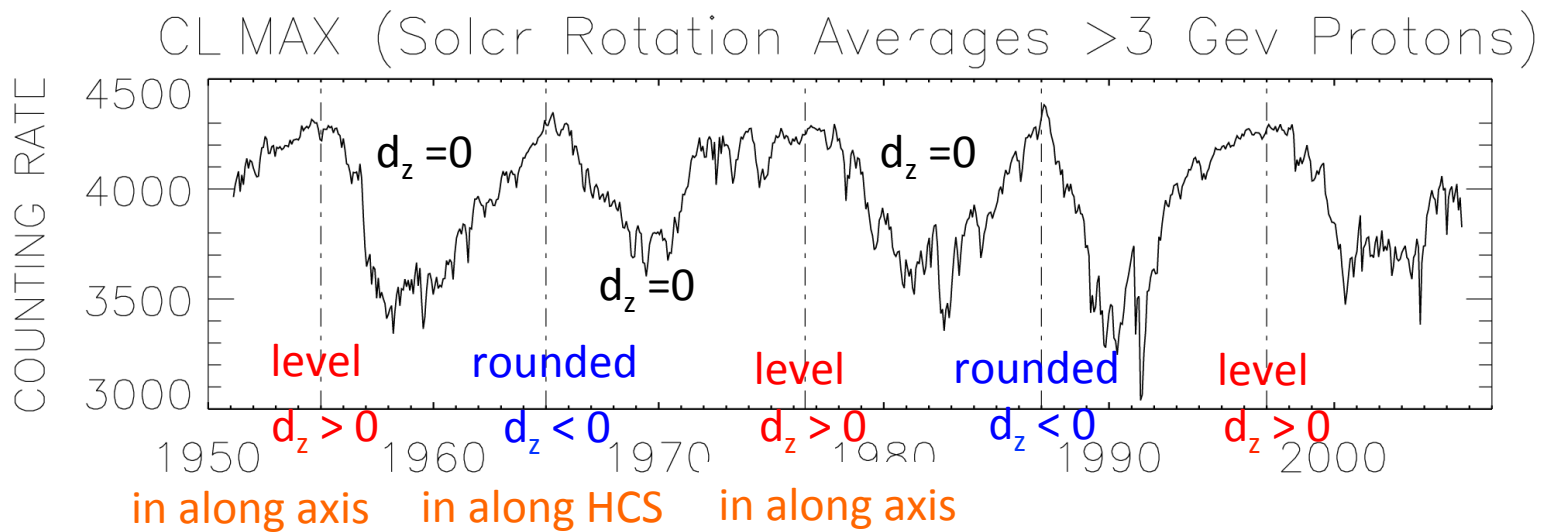


vol. III fig. 9.8

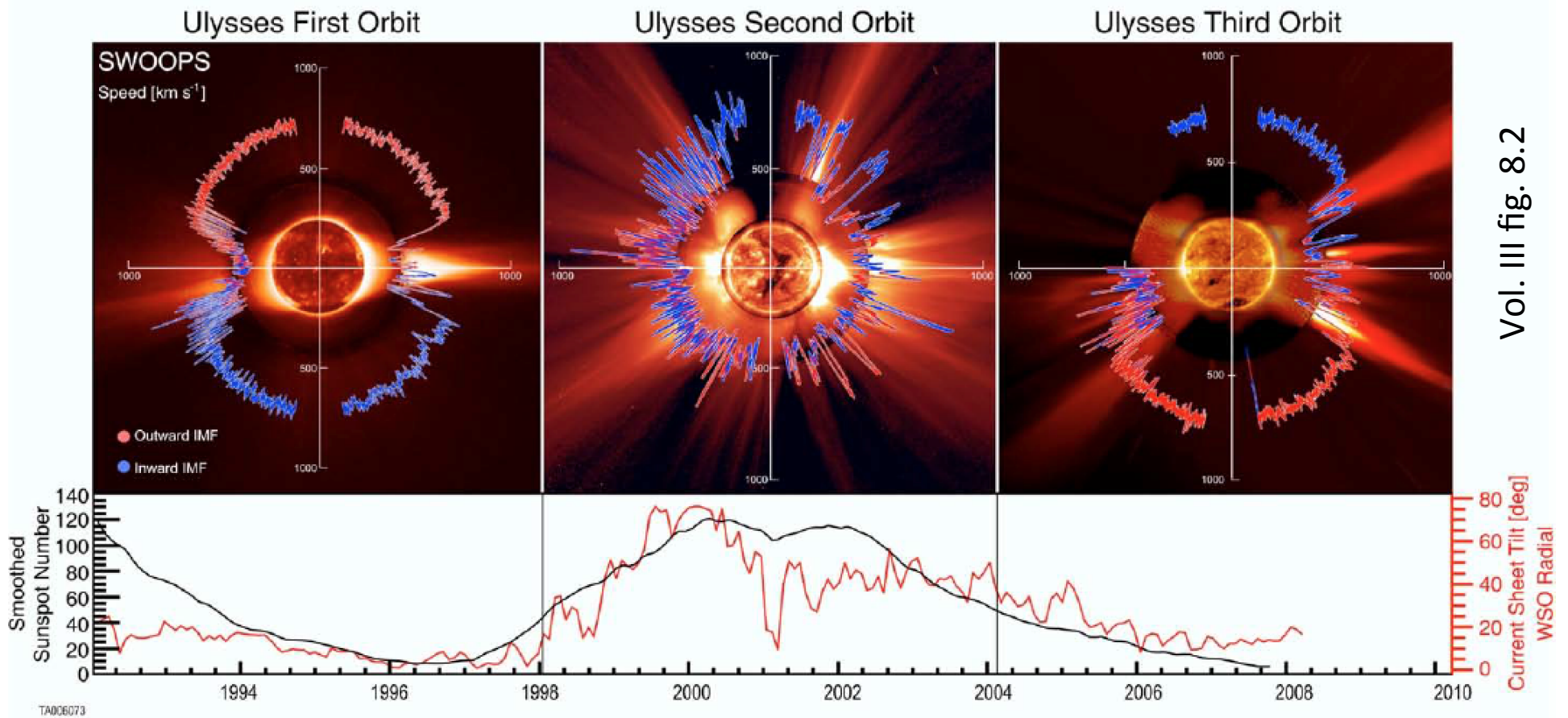




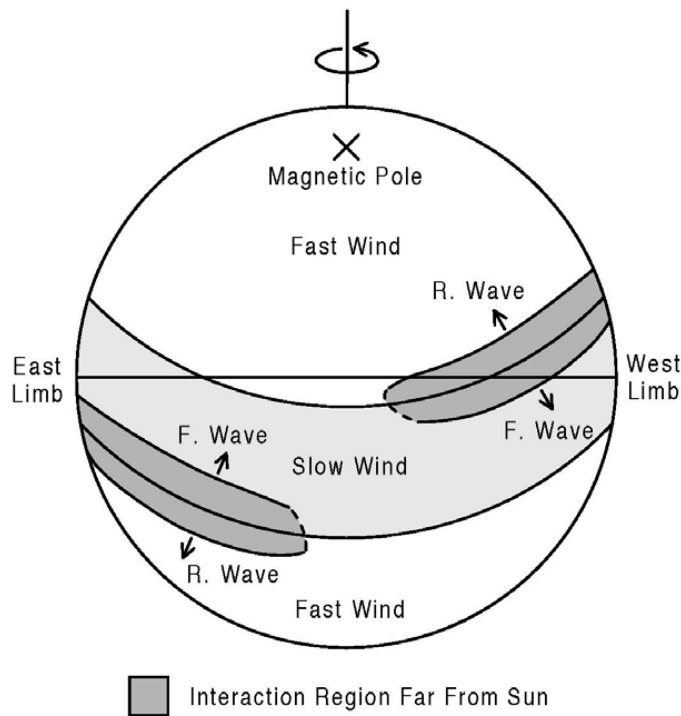
# Effect on cosmic rays



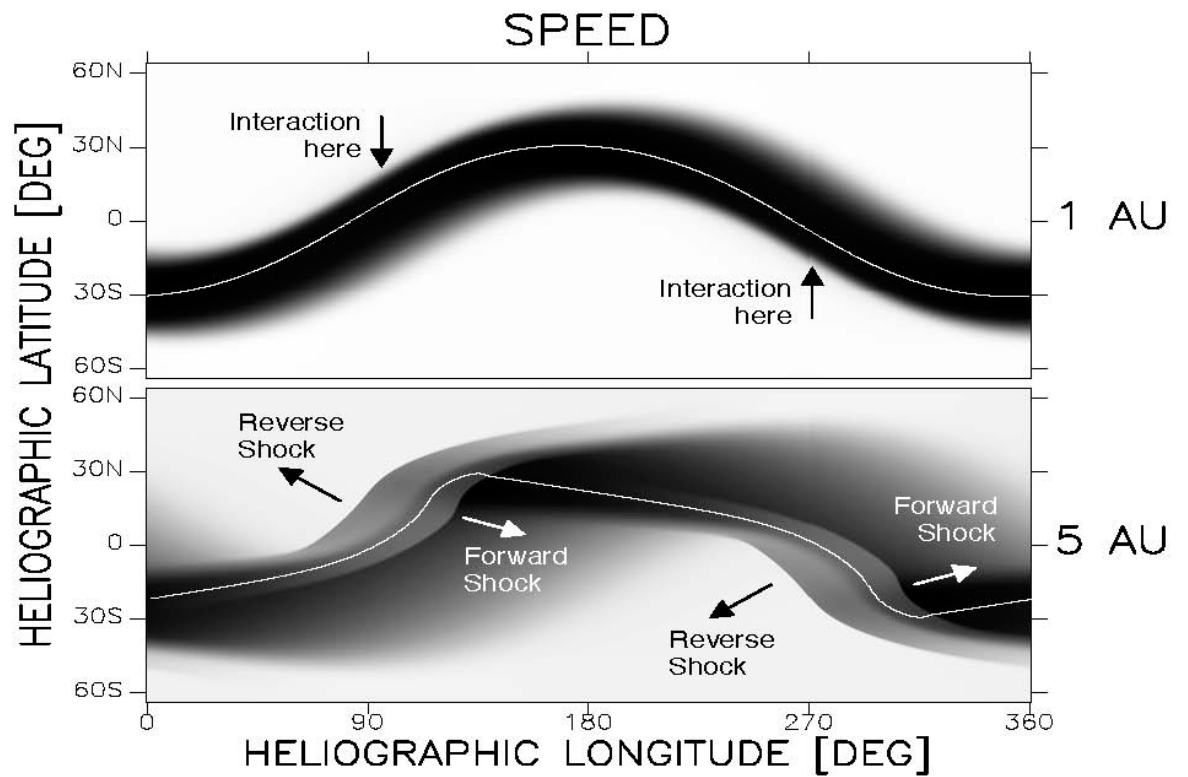
# The wind through the cycle



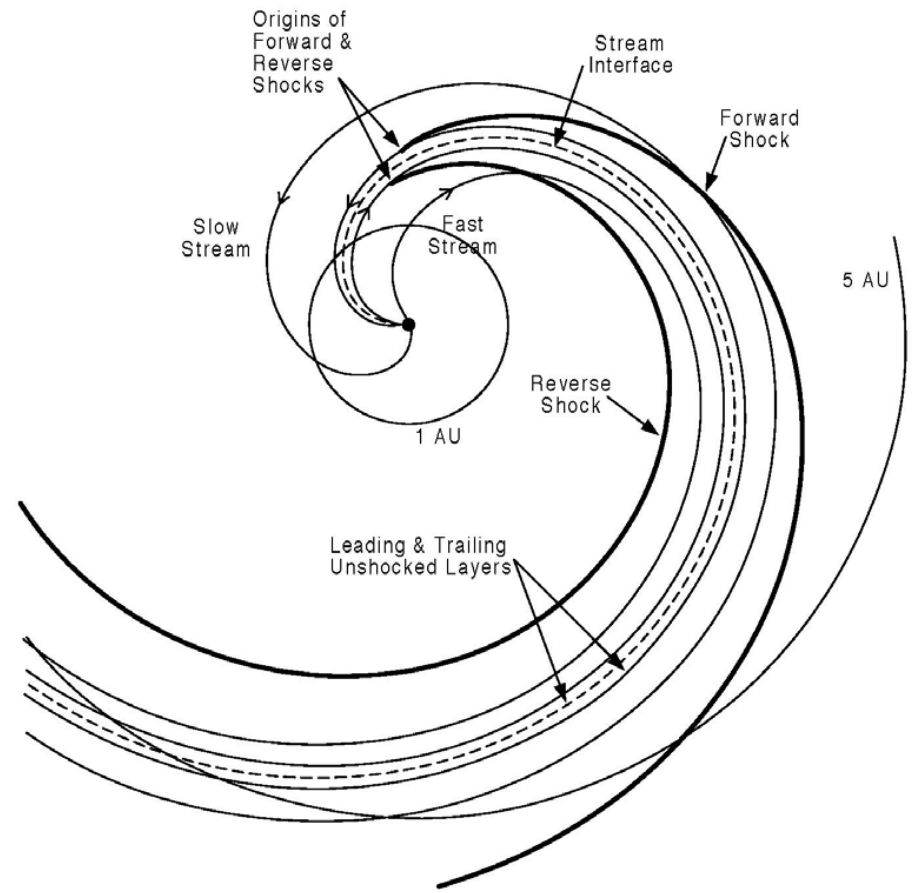
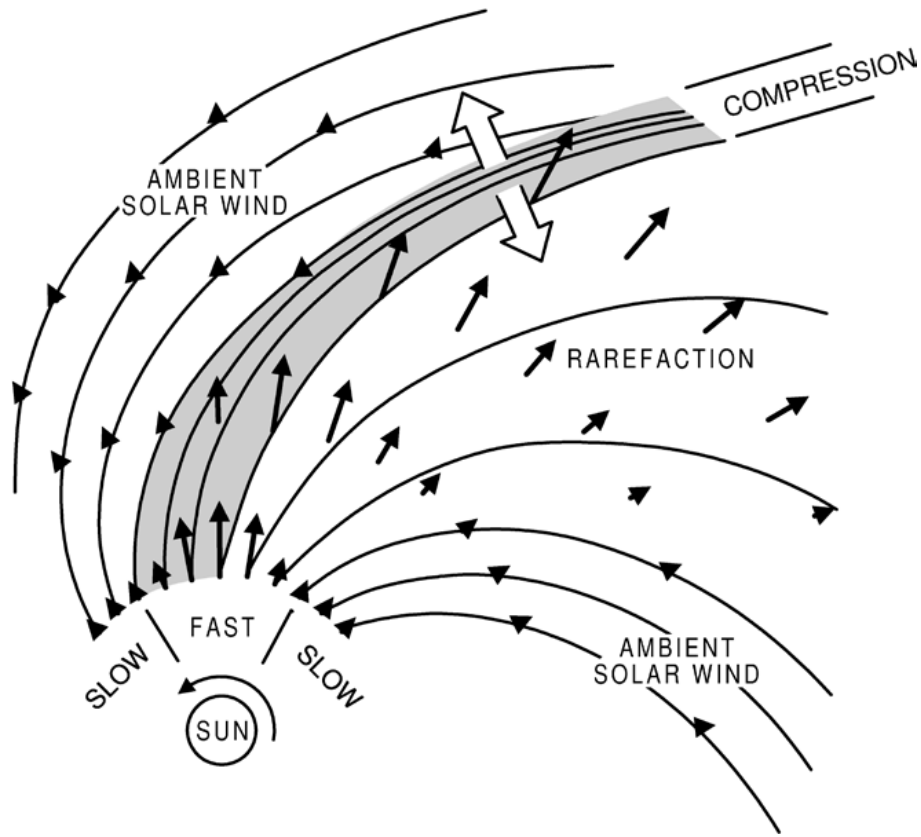
# Effect of a "warped" HCS



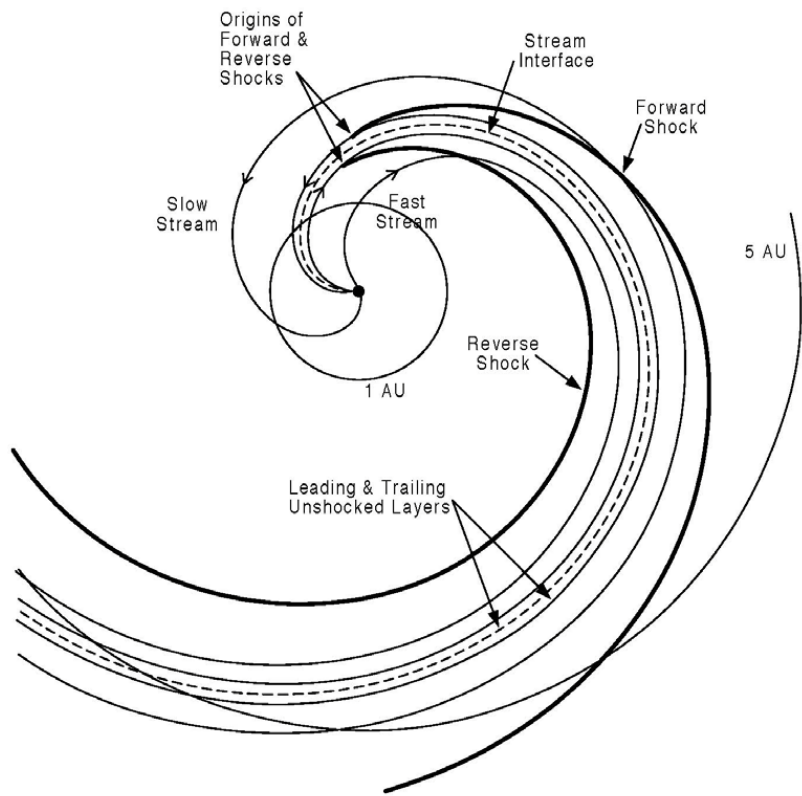
Vol. III fig. 8.6



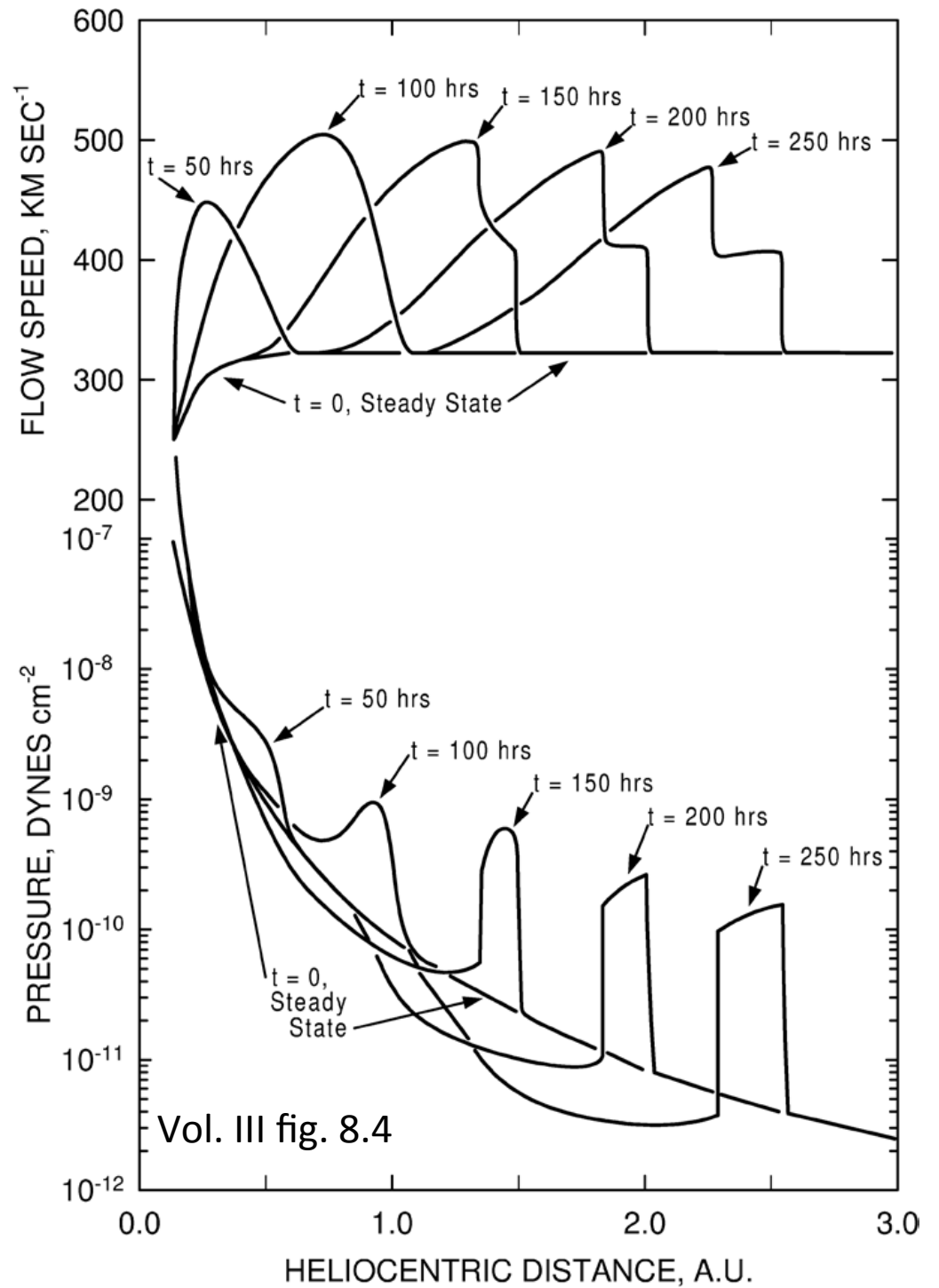
Vol. III fig. 8.7



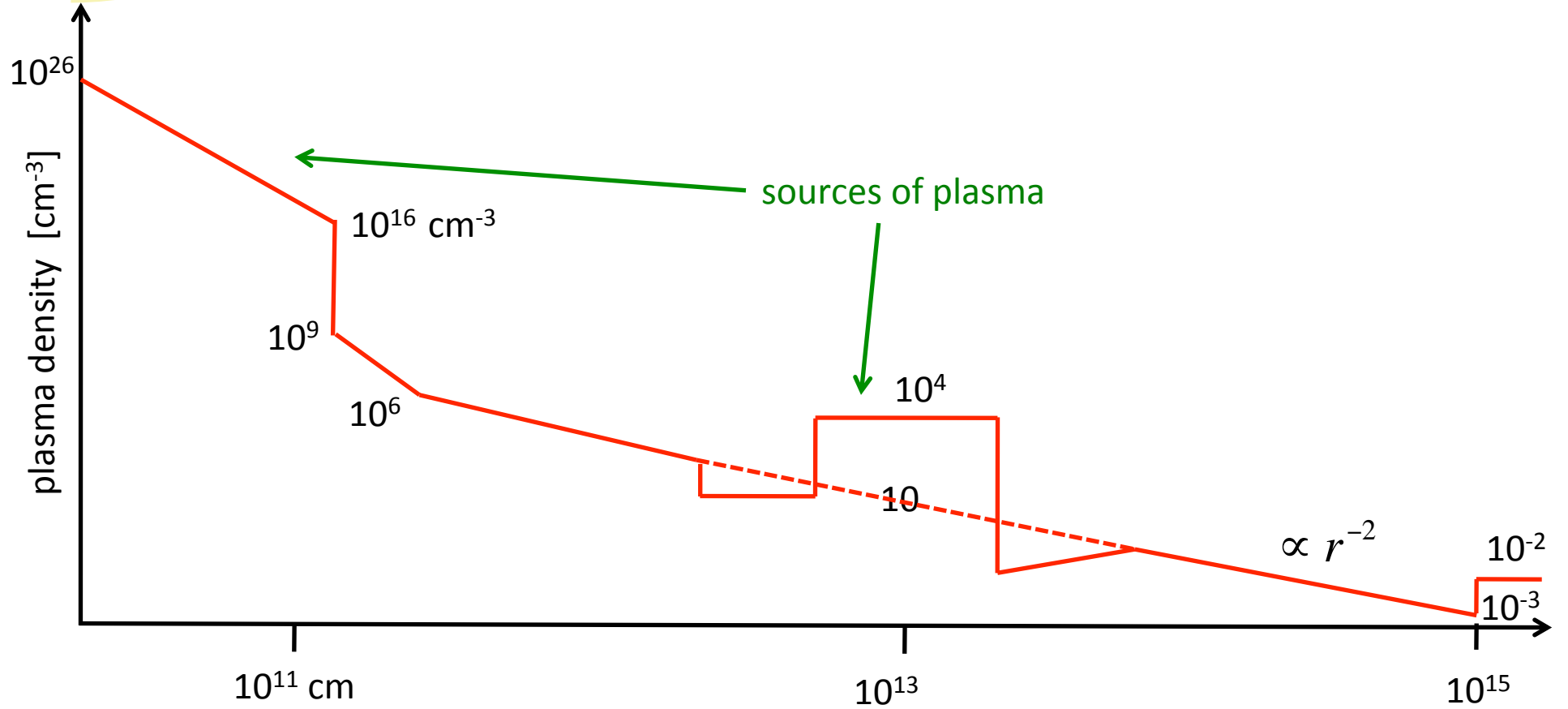
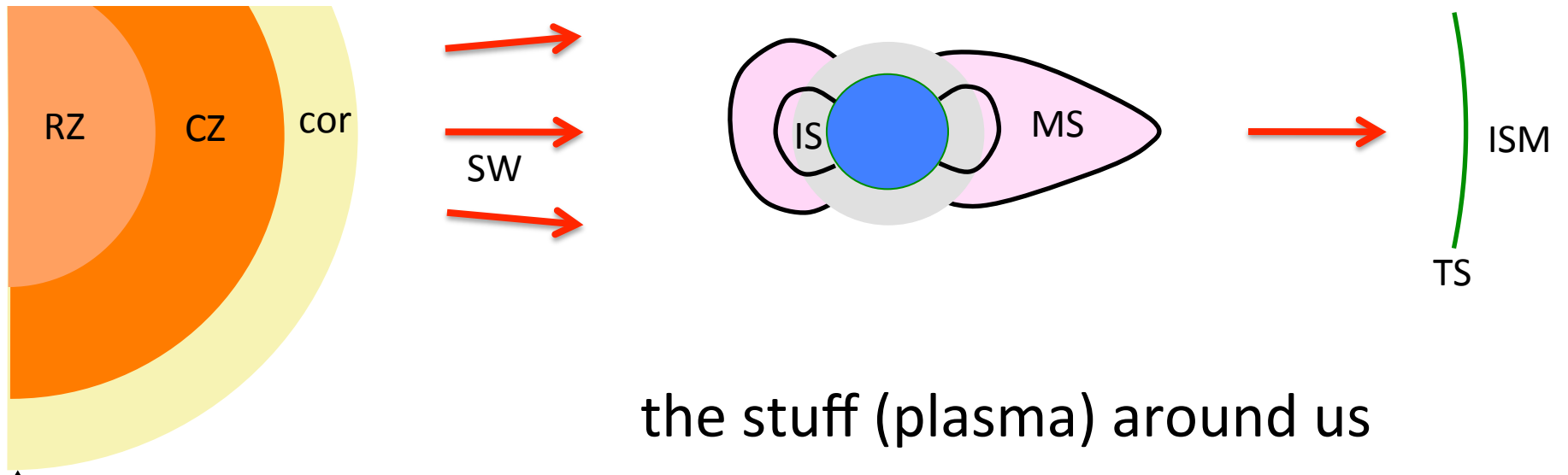
Vol. III fig. 8.5

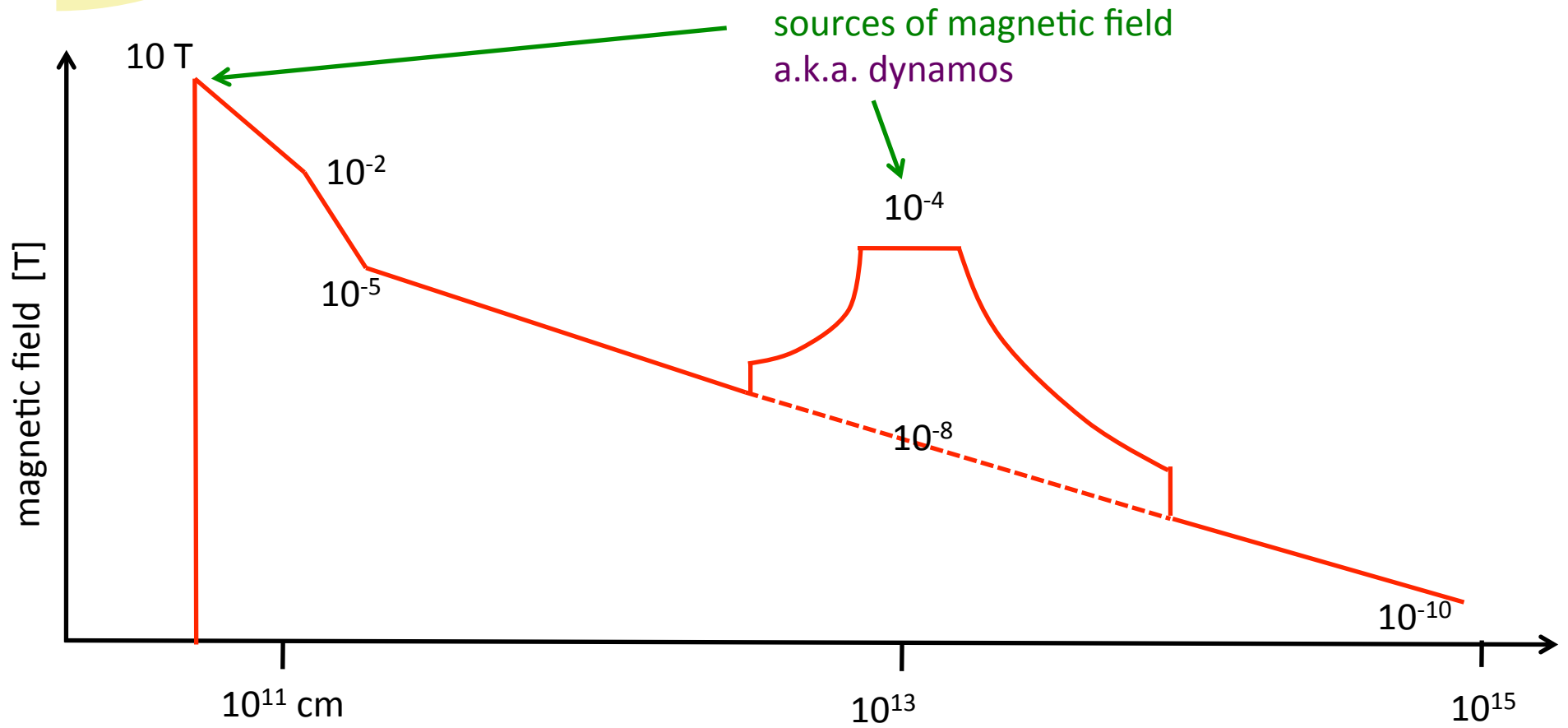
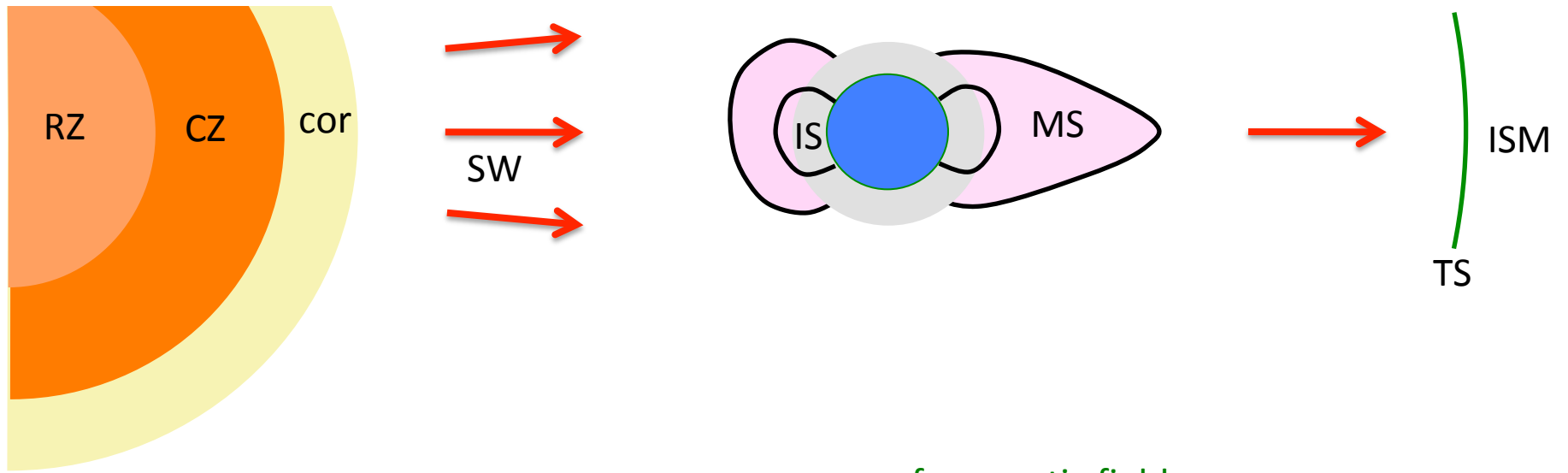


Vol. III fig. 8.5

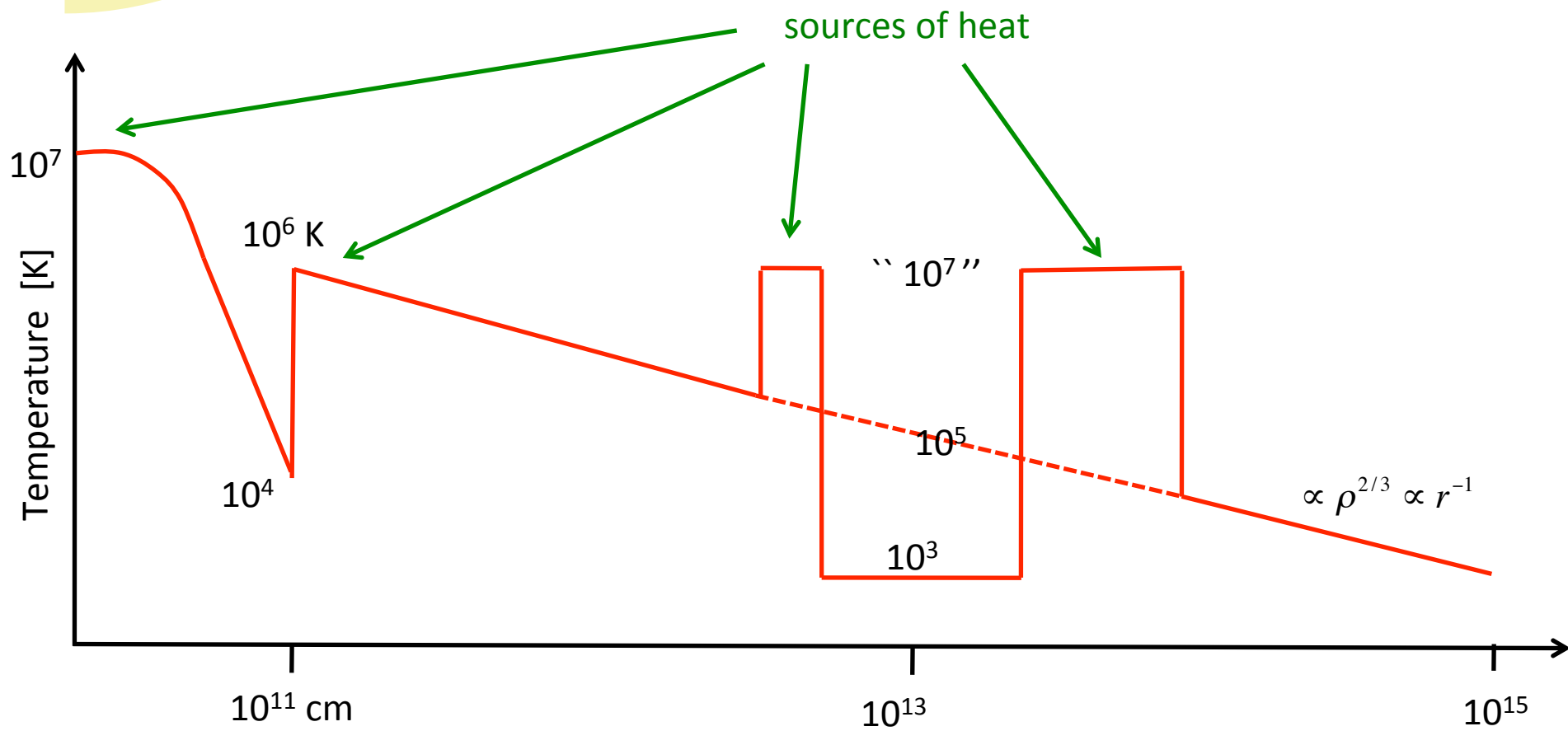
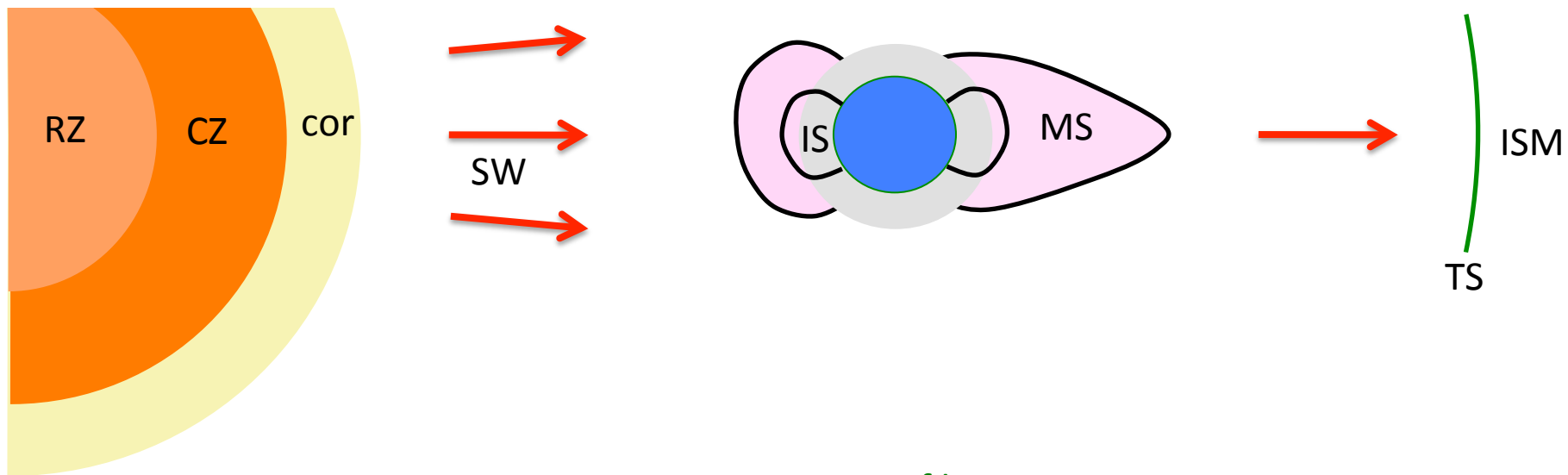


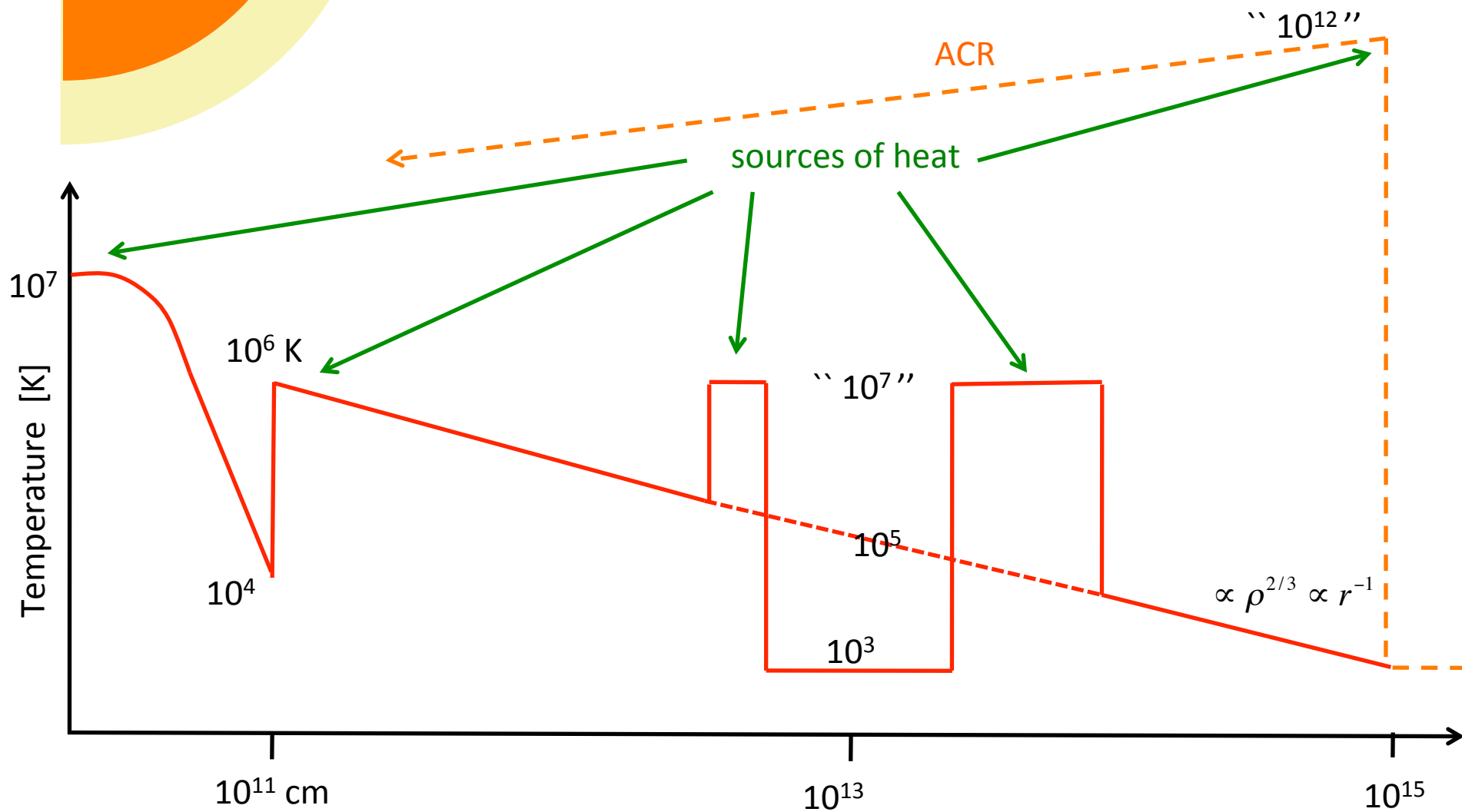
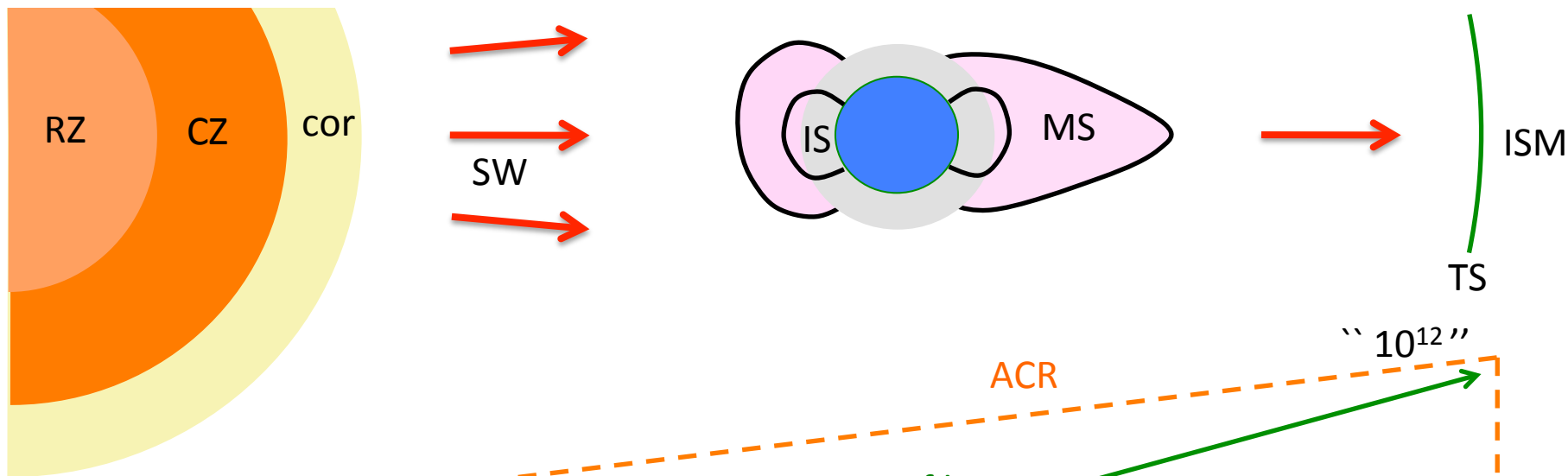
Vol. III fig. 8.4

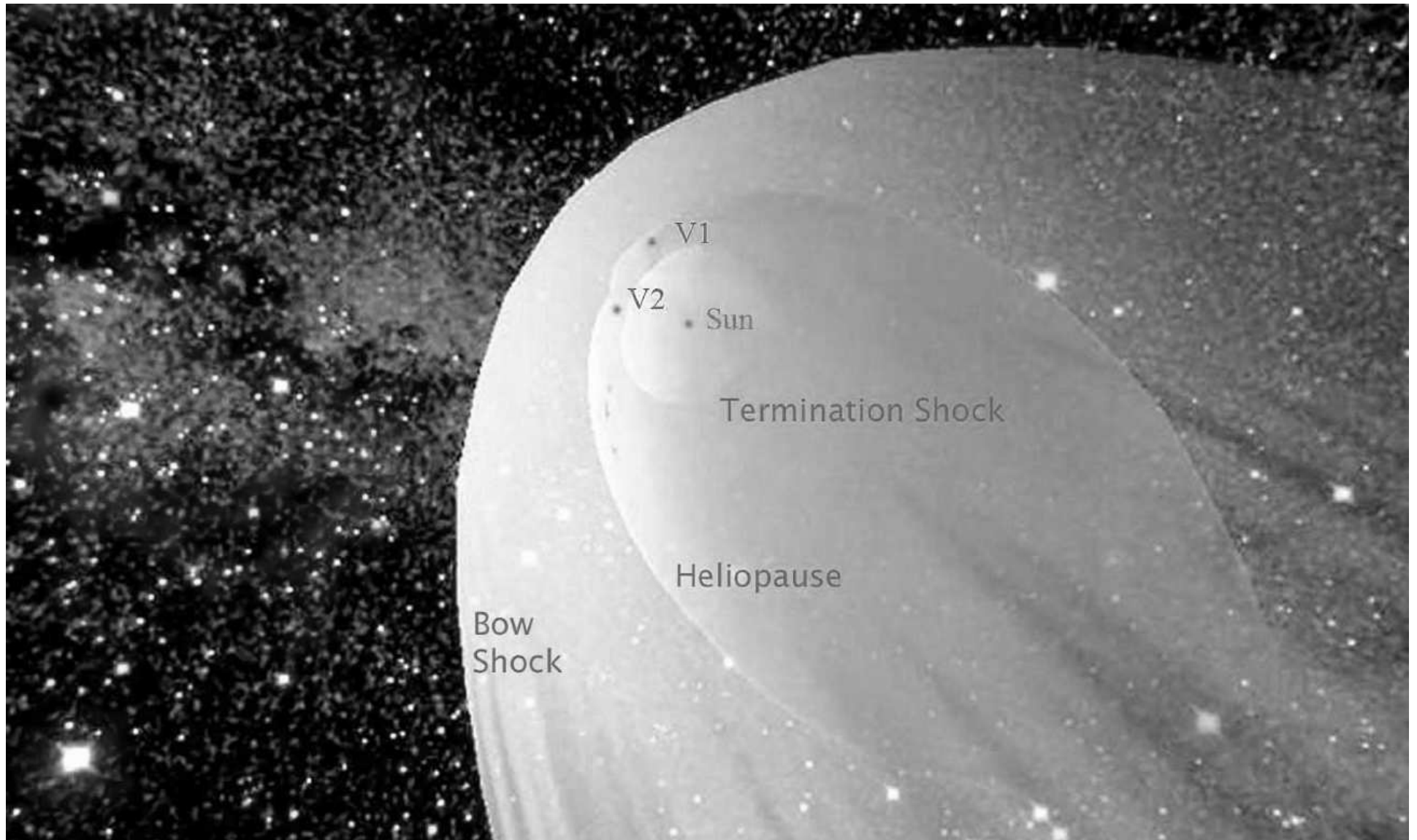












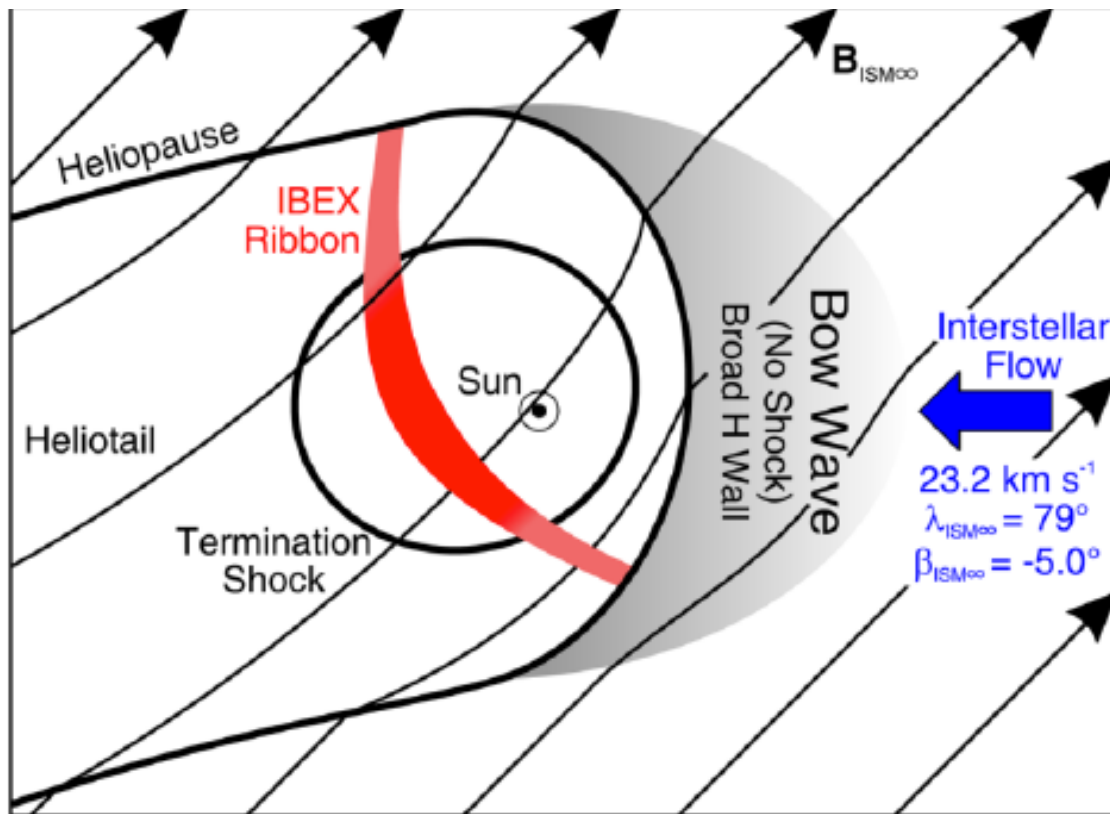
Vol. III fig. 9.1

# The Heliosphere's Interstellar Interaction: No Bow Shock

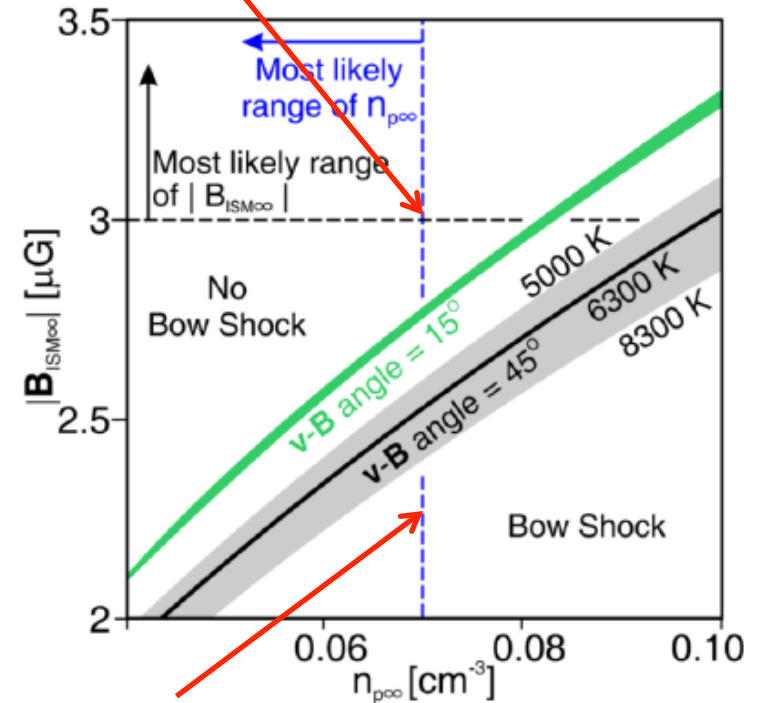
Science May 10, 2012

**Result  
from  
IBEX**

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



$v_{fms} = 26.8 \text{ km/s}$



$v_{fms} = 21.4 \text{ km/s}$

# 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