Introduction to Heliophysics

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Total Force.

Having since had occasion to examine the disturbances of the Declination at the same two stations in the three succeeding years 1846, 1847 and 1848, I have had the satisfaction of finding that the observations of these years confirm every deduction which

period

Phil. Trans. Royal Soc. **142**, 103 (1852)

rison of the frequency and amount of the disturbances in *different years*, apparently indicating the existence of a *periodical variation*, which, either from a causal con-

some periodical affection of an outer envelope, (the photosphere,) of the sun; and it is certainly a most striking coincidence, that the period, and the epochs of minima and maxima, which M. Schwabe has assigned to the variation of the solar spots, are absolutely identical with those which have been here assigned to the magnetic variations.

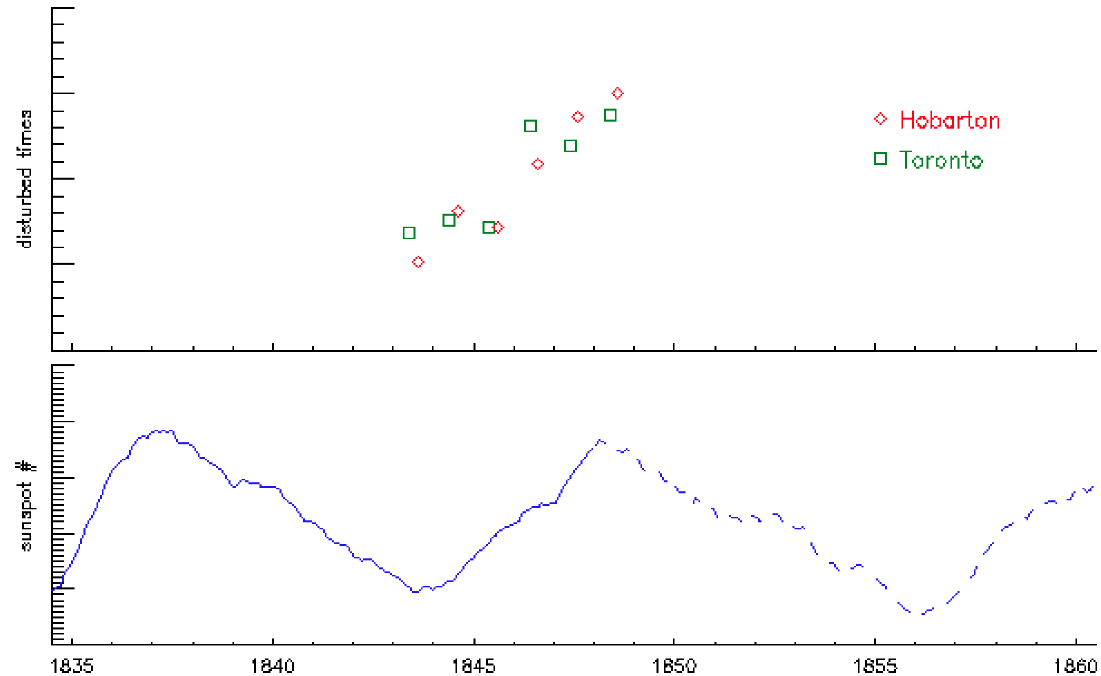
tion into the laws of the disturbances of the Inclination and of the Total Force, for which I have not yet been able to command the necessary leisure.

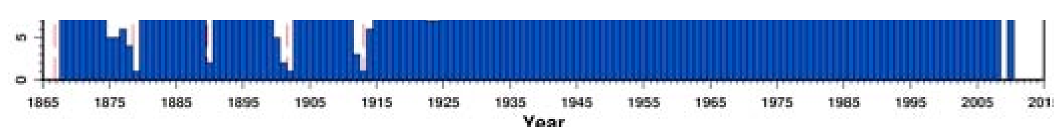
Edward Sabine
(1788-1883)

- 1839+ : Helped establish global network of magnetic observatories

- 1852: Discovers correlation between disturbed times (@ Earth) and cycle of sunspots discovered previously by Schwabe (1843)

- 1861 – 1871: President of Royal Society (UK)





William Thomson
aka. Lord Kelvin
(1824 – 1907)

ether, we cannot say that the sun might not be 1000, or 10,000, or 100,000 times as intense a magnet as the earth. It is, therefore, a perfectly proper object for investigation to find whether there is, or is not, any disturbance of terrestrial magnetism, such as might be produced by a constant magnet in the sun's place with its magnetic axis coincident with the sun's axis of rotation. Neglecting for the present the seven degrees of obliquity of the sun's equator, and supposing the axis to be exactly perpendicular to the ecliptic, we have an exceedingly simple case of magnetic action to be considered: a magnetic force perpendicular to the ecliptic at every part of the earth's orbit and varying inversely as the cube of the earth's distance from the sun. The components of this force parallel and perpendicular to the earth's axis are ...

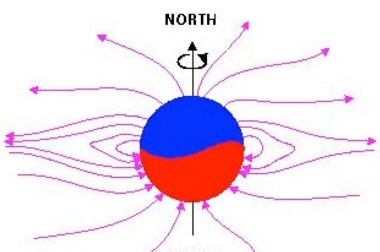
i.e. a dipole

- 1890 – 1895: President of Royal Society (UK)
- 1892 – publishes demonstration that sunspots **cannot** [sic] influence Earth's magnetic field

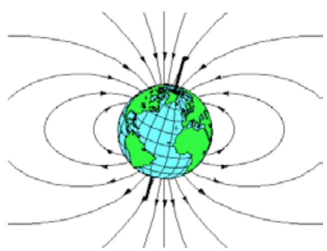
ergs per sec.) of the solar radiation. Thus, in this eight hours of a not very severe magnetic storm, as much work must have been done by the sun in sending magnetic waves out in all directions through space as he actually does in four months of his regular heat and light. This result, it seems to me, is absolutely conclusive against the supposition that terrestrial magnetic storms are due to magnetic action of the sun; or to any kind of dynamical action taking place within the sun, or in connection with hurricanes in his atmosphere, or anywhere near the sun outside.

It seems as if we may also be forced to conclude that the supposed connection between magnetic storms and sun-spots is unreal, and that the seeming agreement between the periods has been a mere coincidence.

We are certainly far from having any reasonable explanation of any of the magnetic phenomena of the earth; whether the fact that the earth is a magnet; that its magnetism changes vastly, as it does from century to century; that it has somewhat

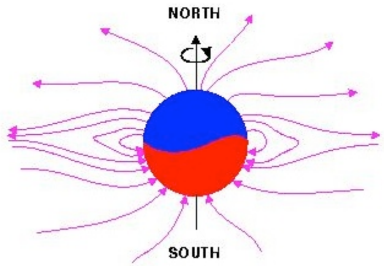


CORONAL MAGNETIC FIELD LINES AT SOLAR MINIMUM ACTIVITY



Nature **47**:1206 p.106 (1892)

Where did Kelvin go wrong?



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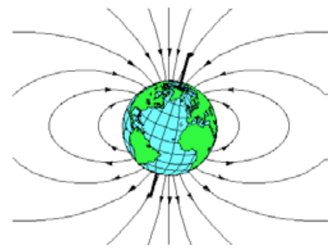
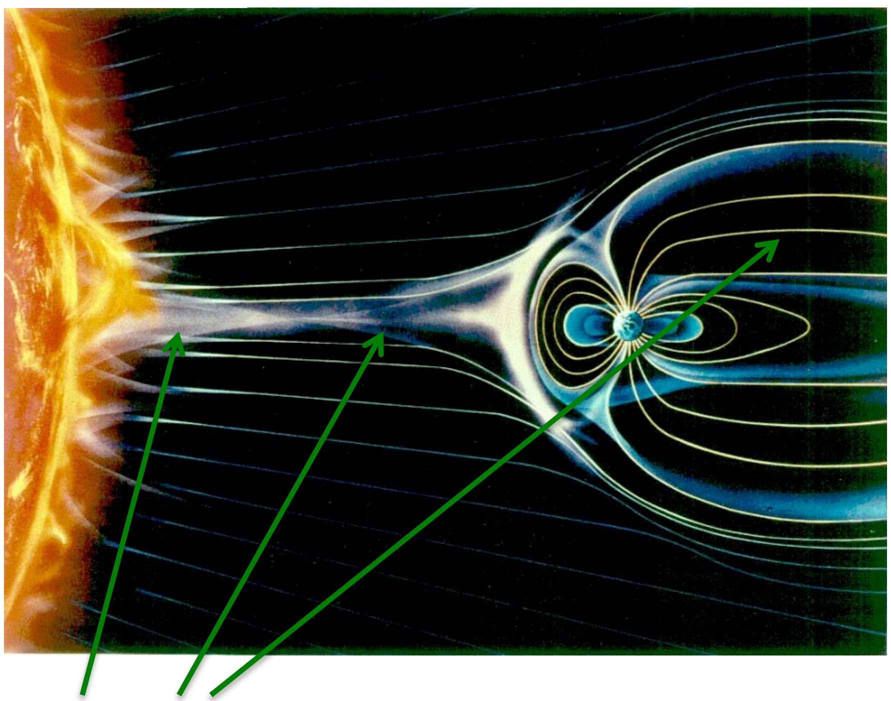
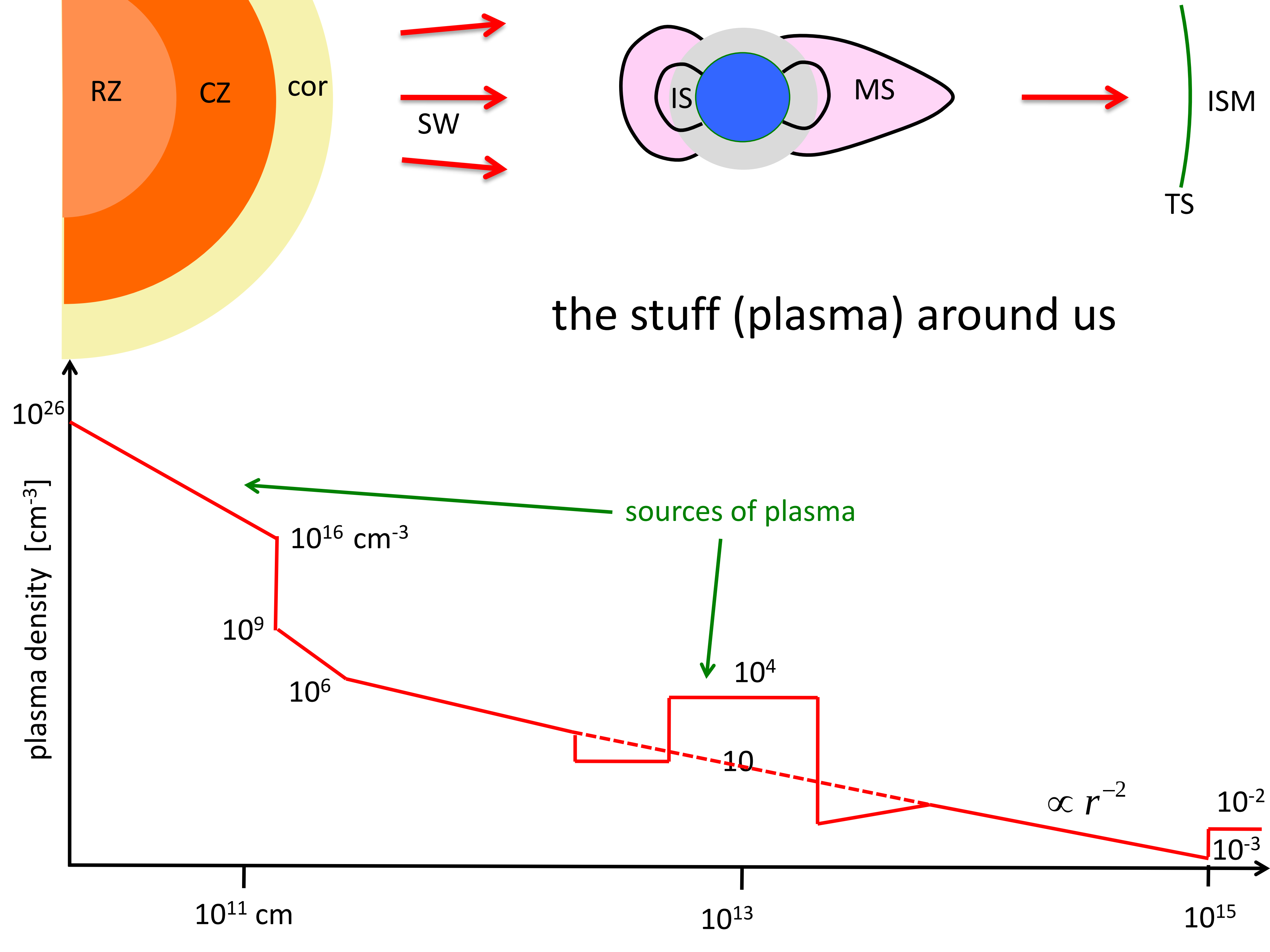


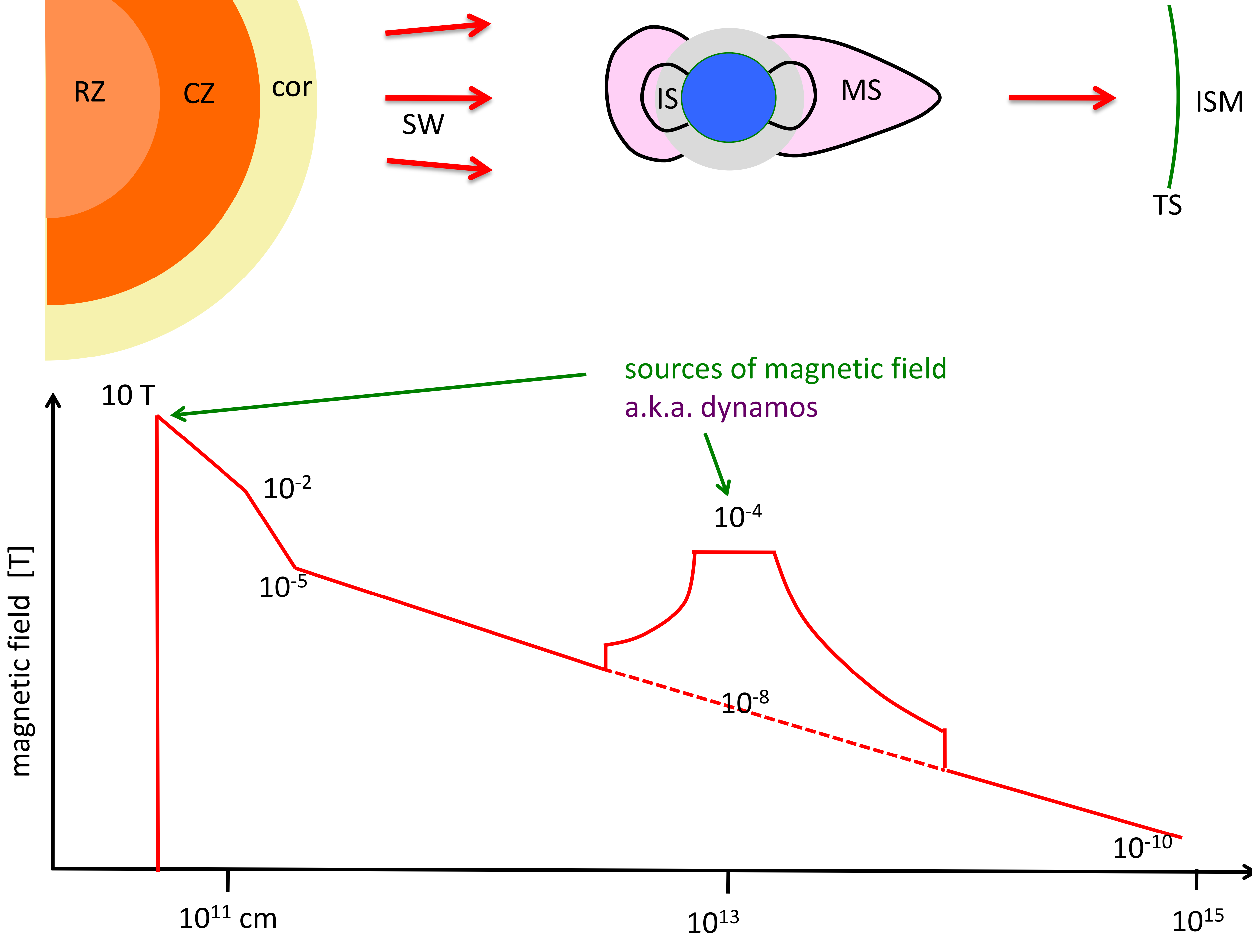
- wrong equations: ``Maxwell's"
- wrong magnetic fields
- too complex to model
- …



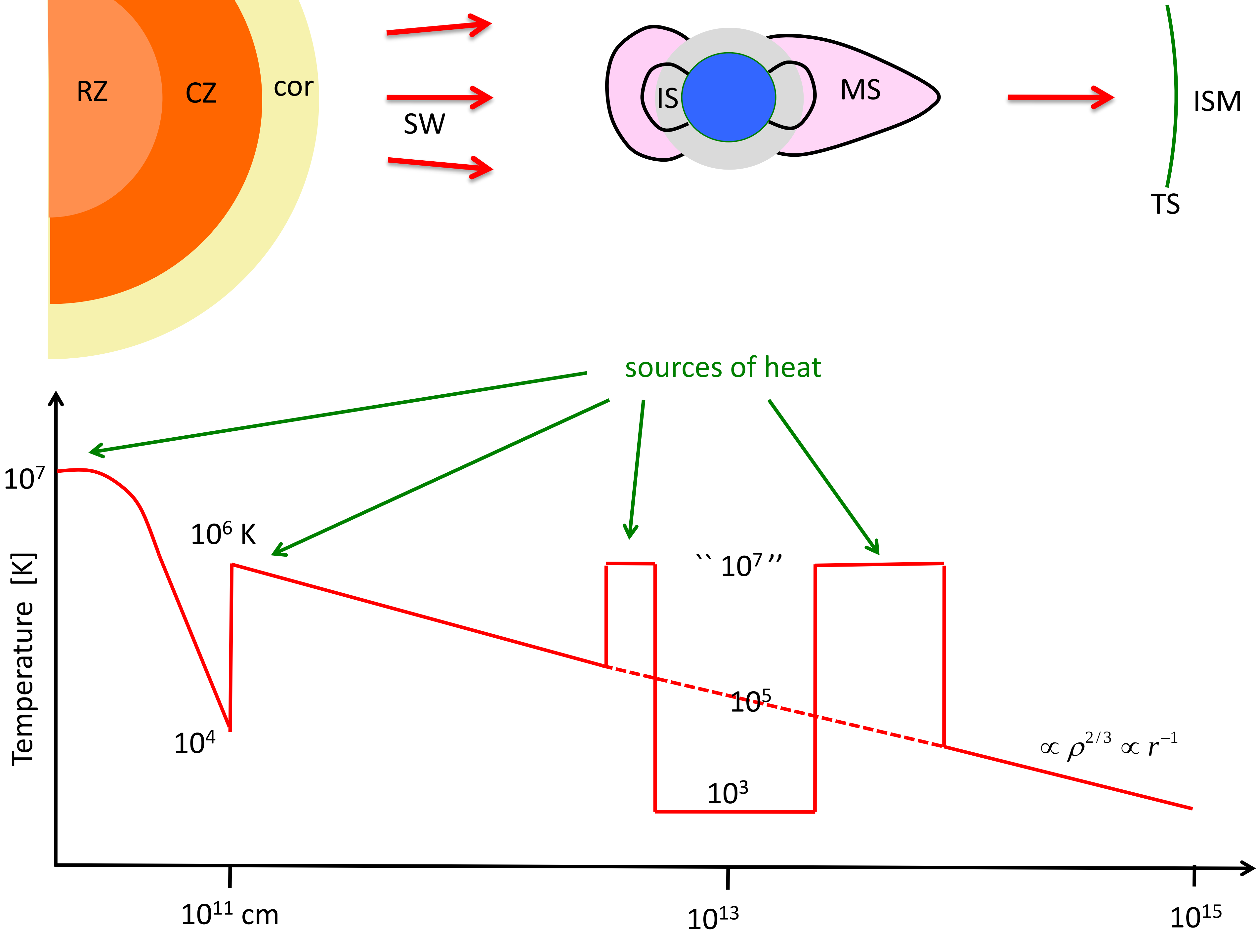
Stuff (plasma) – single system including Sun & Earth

the stuff (plasma) around us

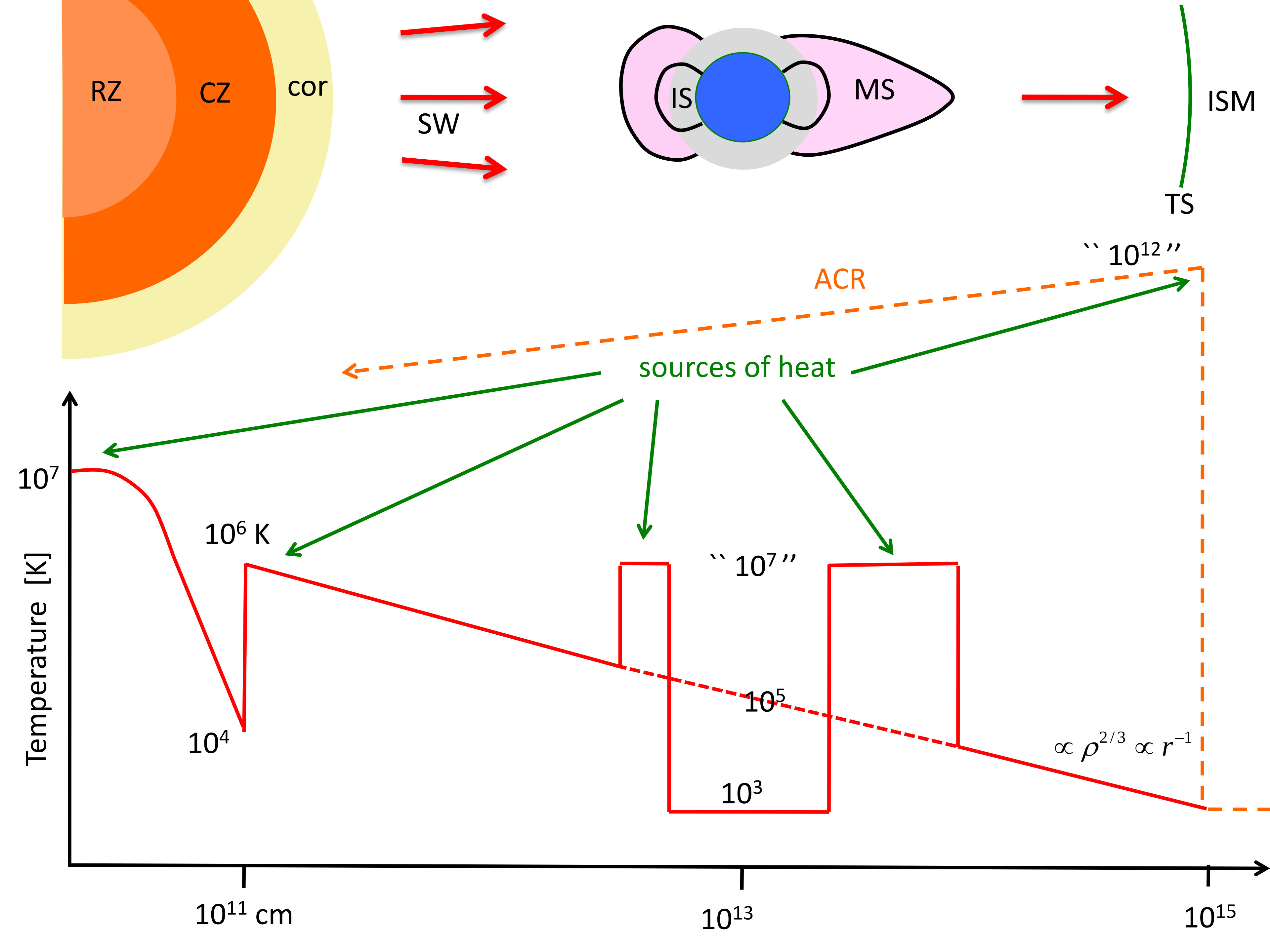




RZ
CZ
cor
SW
IS
MS
ISM
TS
sources of magnetic field
a.k.a. dynamos
10 T
10^{-2}
10^{-5}
10^{-4}
10^{-8}
10^{-10}
magnetic field [T]
10^{11} cm
10^{13}
10^{15}



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



RZ
CZ
cor
SW
IS
MS
ISM
TS
`` 10^12 ''
ACR
sources of heat
10^7
10^6 K
`` 10^7 ''
10^5
10^4
10^3
∝ ρ^{2/3} ∝ r^{-1}
Temperature [K]
10^11 cm
10^13
10^15

The Sun’s corona

- A heat source
- Source of the plasma flow = solar wind

- Are these unrelated features?

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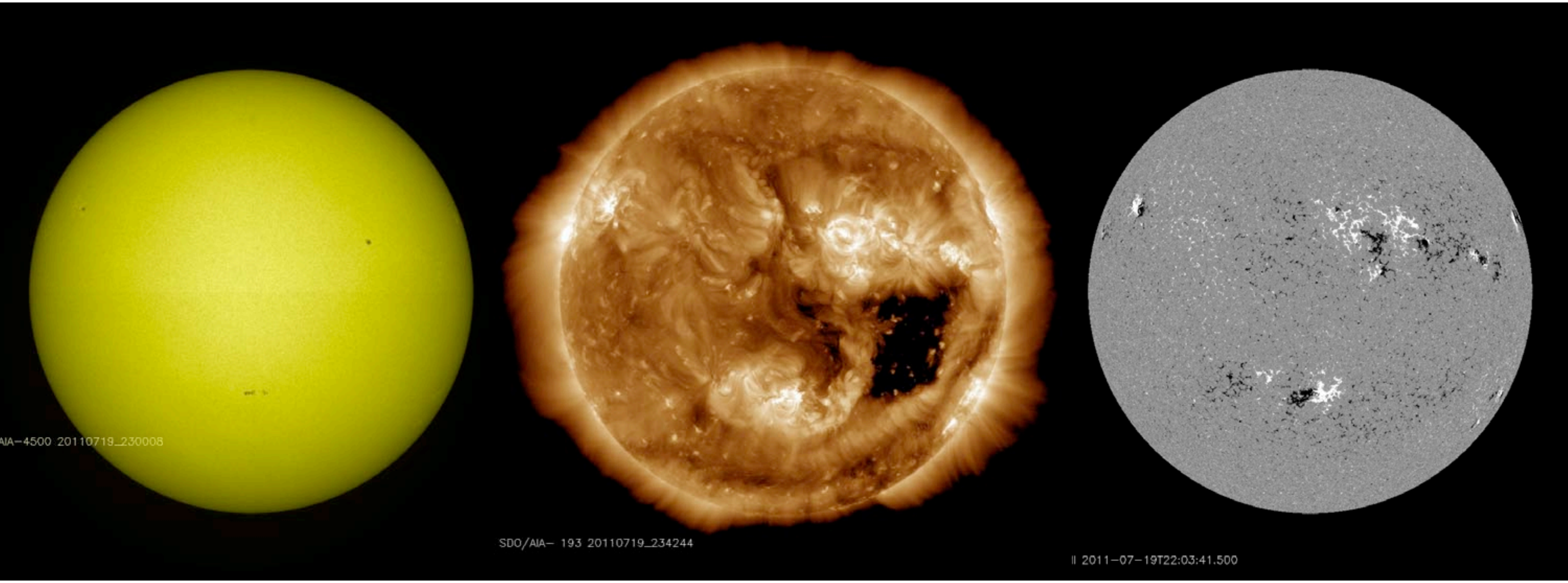
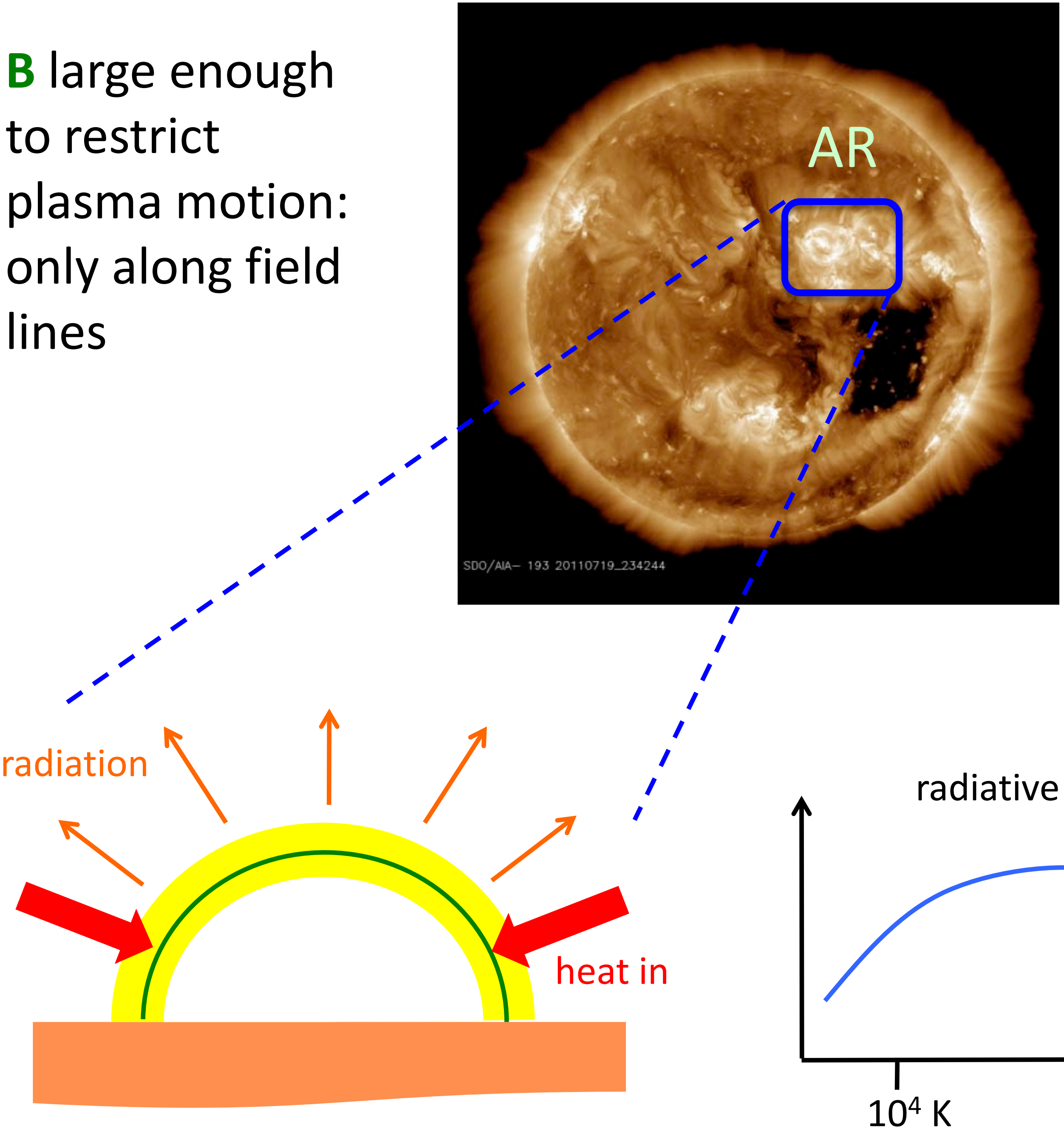


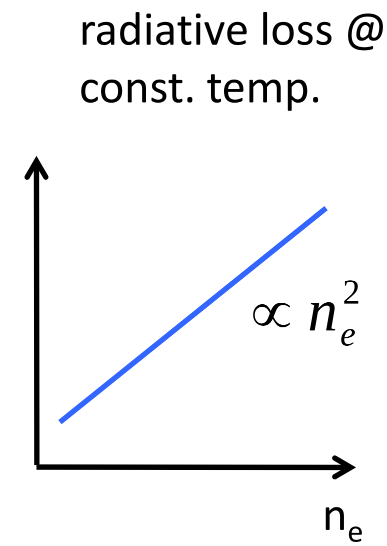
Coronal (EUV) imaging – the basics:

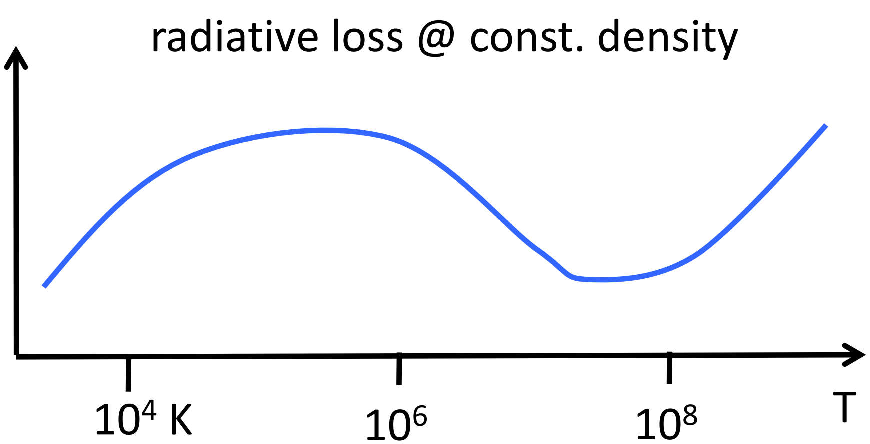
- what you see is all the same T (1.5 x 10^6 K)
- bright = dense plasma – n_e^2
- heating **can*** make plasma dense & thus bright
- heating is evidently magnetic

* if magnetic field lines are closed – magnetic bottle

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







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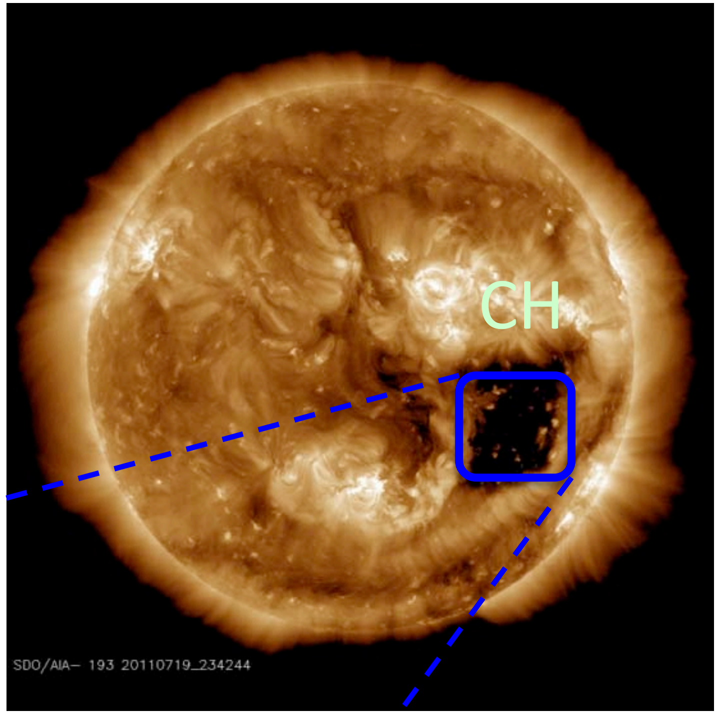
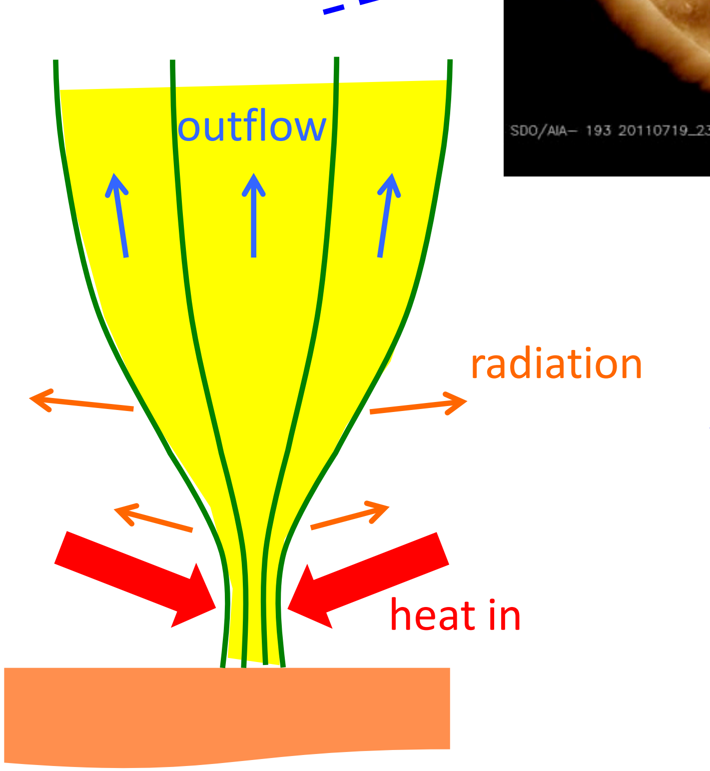




specific enthalpy

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

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

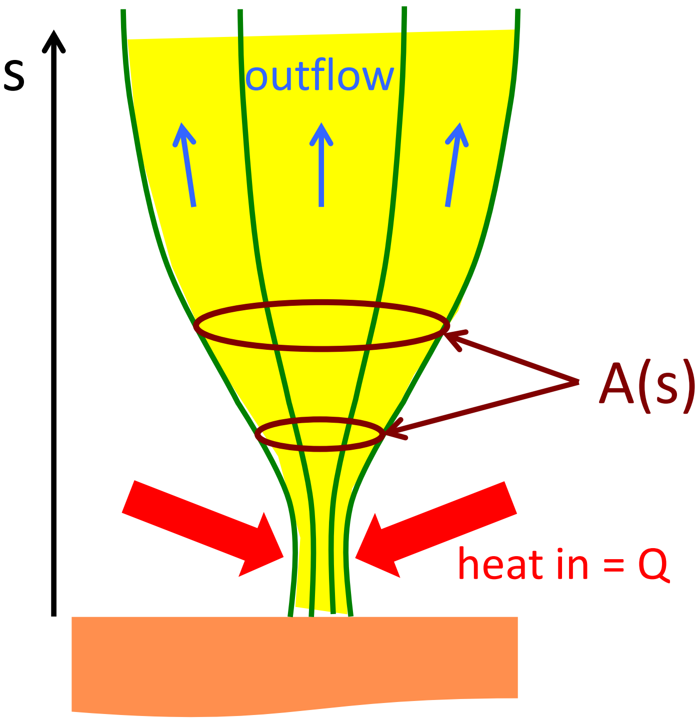
mass loss fixed & unknown

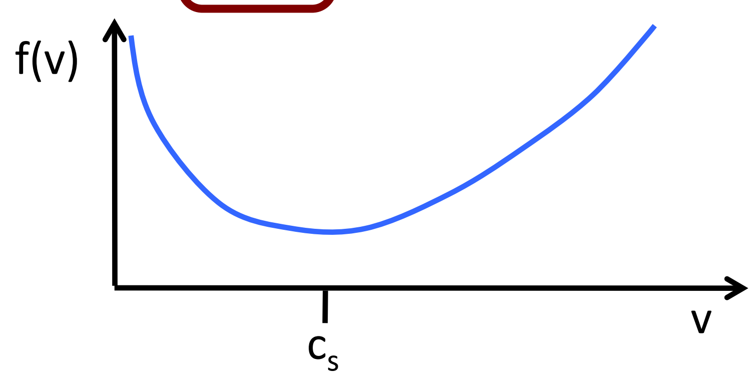
Simple case: Isothermal ... $\gamma \to 1$

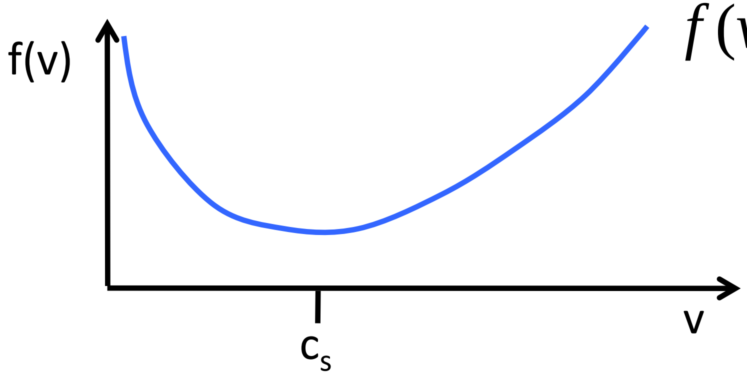
$$w(\rho) \propto \frac{\gamma}{\gamma - 1}\rho^{\gamma-1} \to c_s^2 \ln(\rho) + \text{const.}$$

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

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







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

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

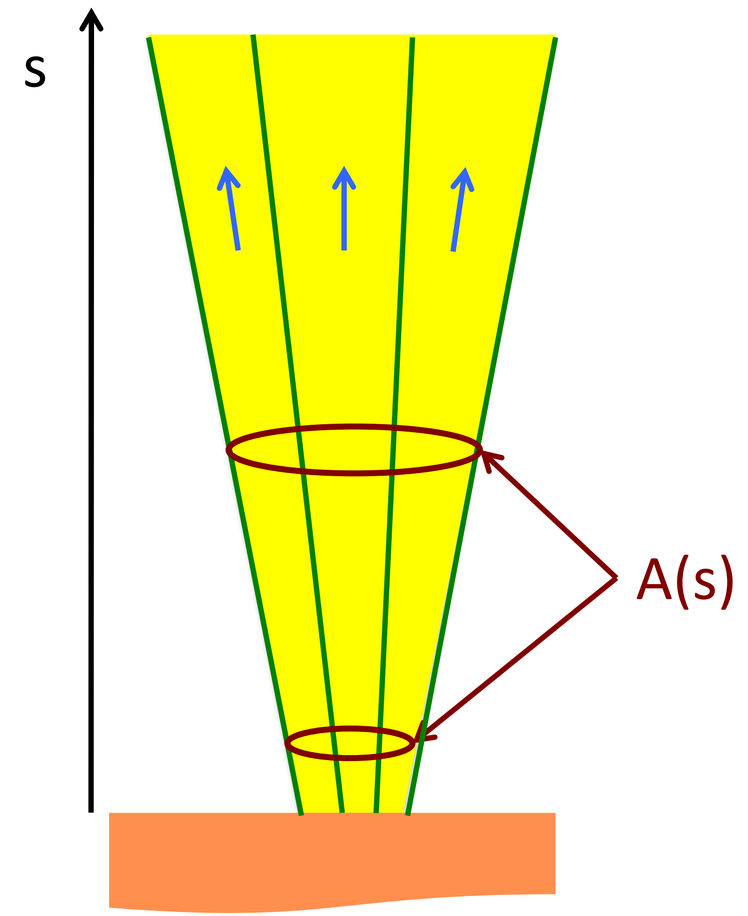
tube:

cone w/ vertical axis

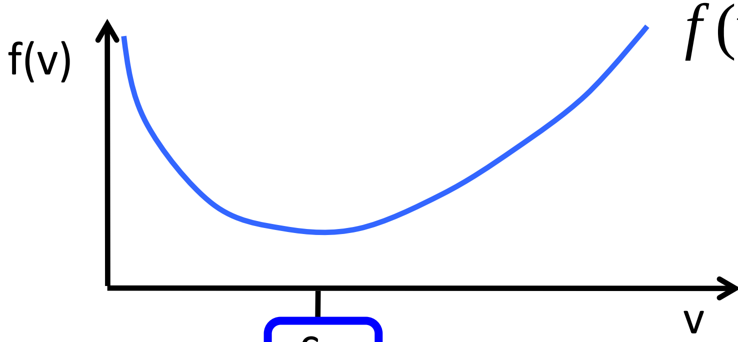
$A(s) \sim s^2$

$s = r$

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



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



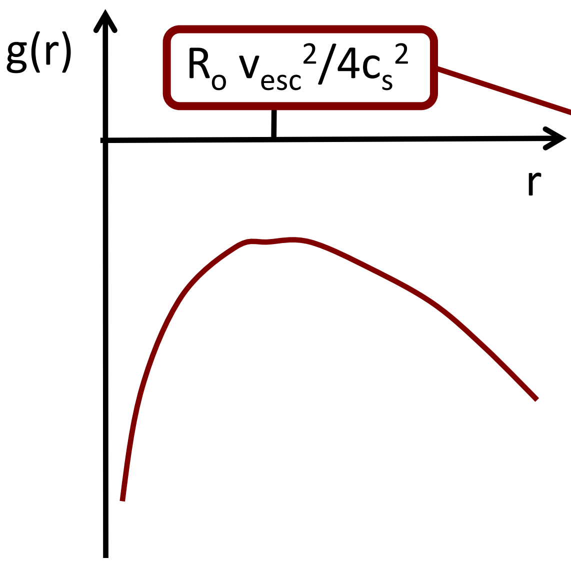
$$F(v,r)=f(v)+g(r)=\frac{Q}{\dot{M}}=\text{const.}$$

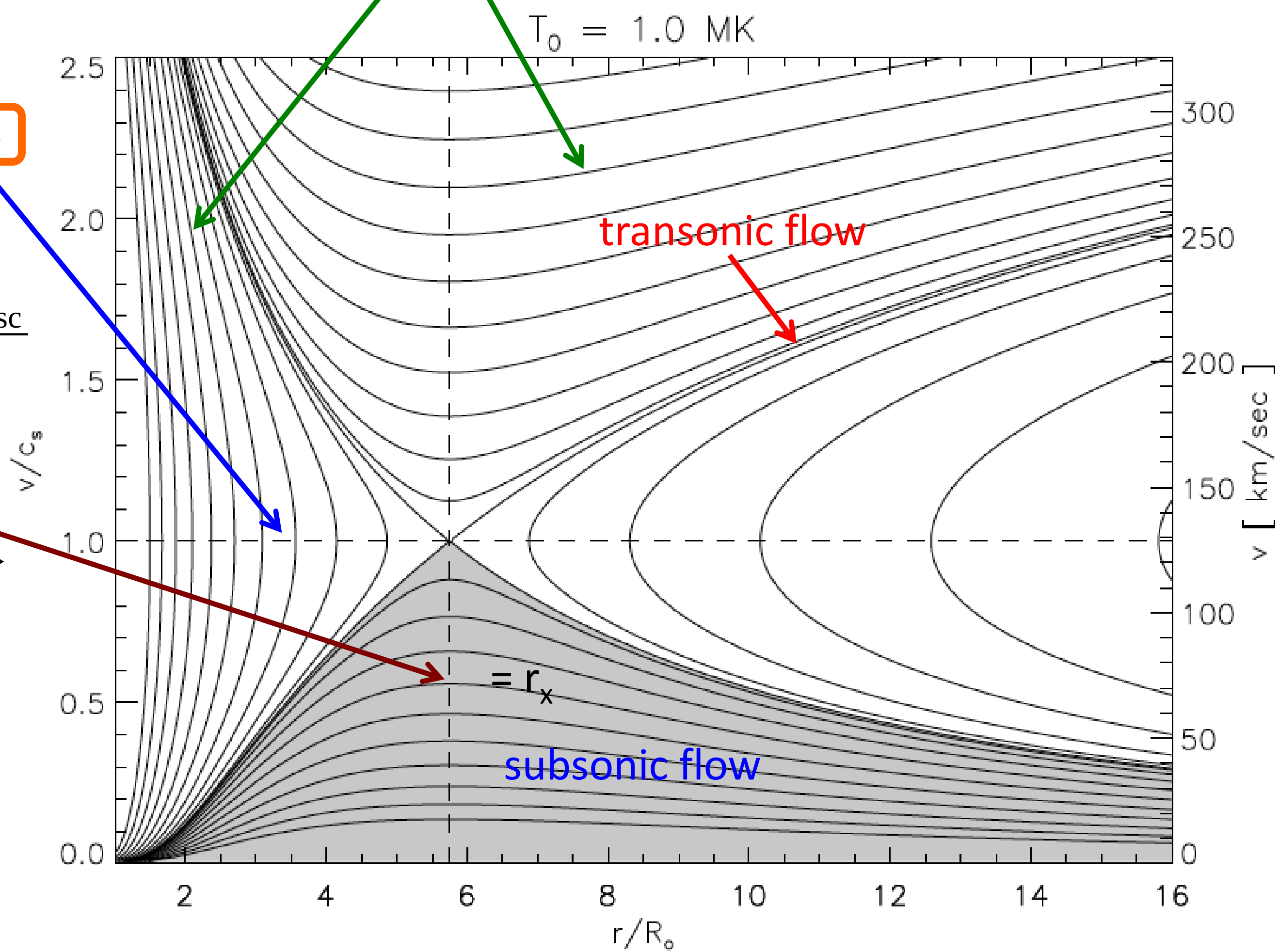
tube:

cone w/ vertical axis

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

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





tube:

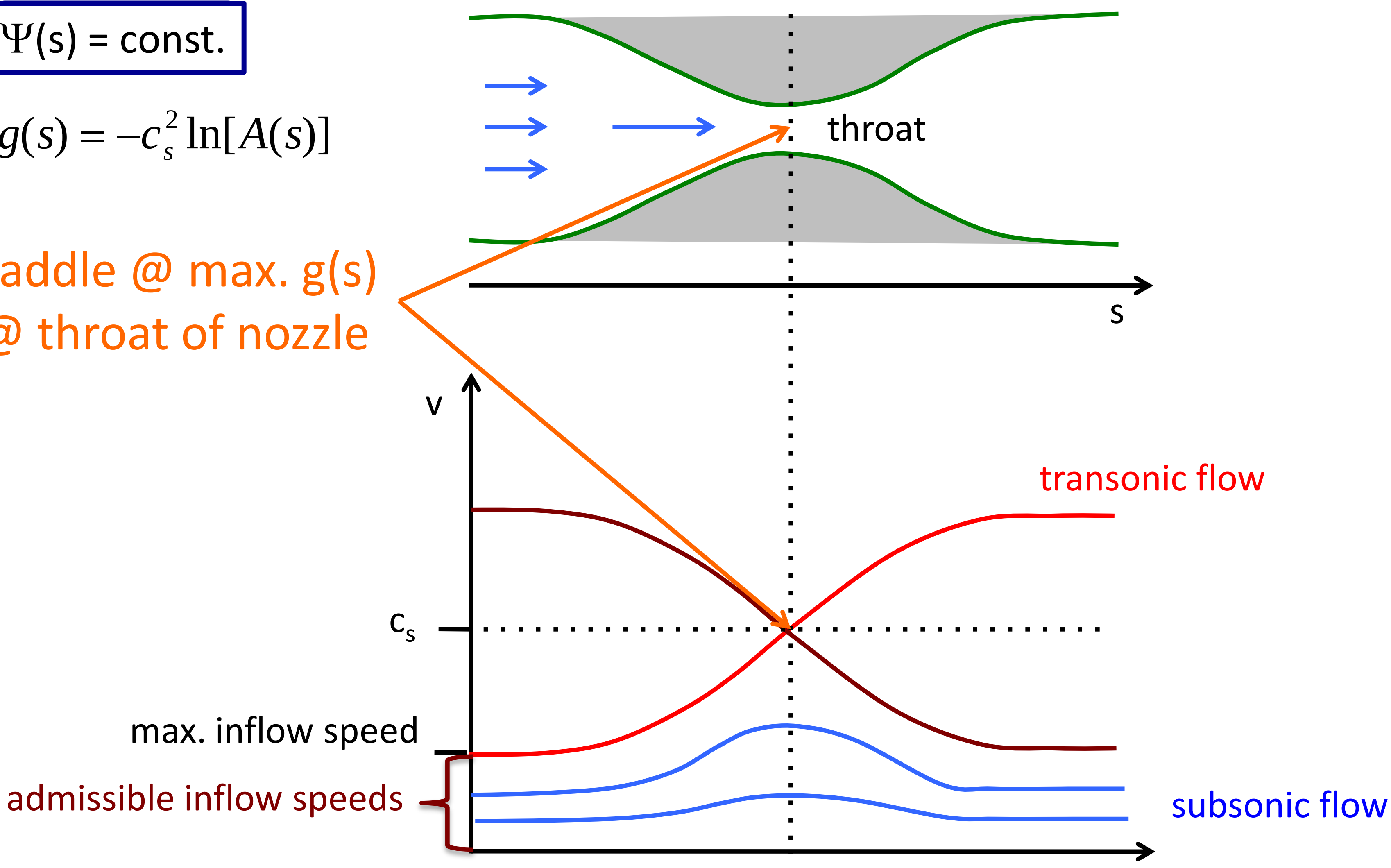
horizontal nozzle

$\Psi(s)$ = const.

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

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

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



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tube:

horizontal nozzle

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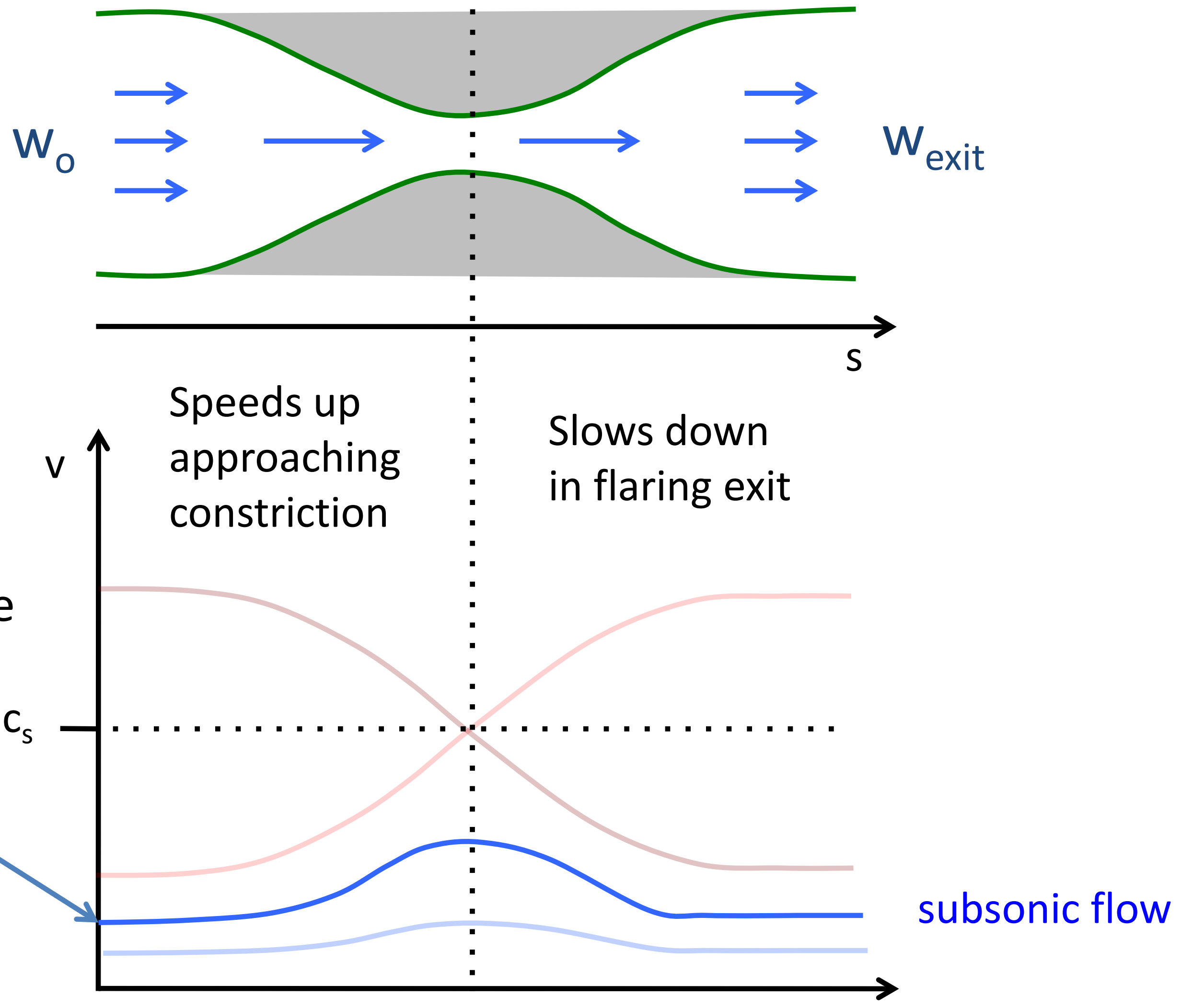


Inflow = mass loss rate

set by back-pressure

W_{exit}

tube:

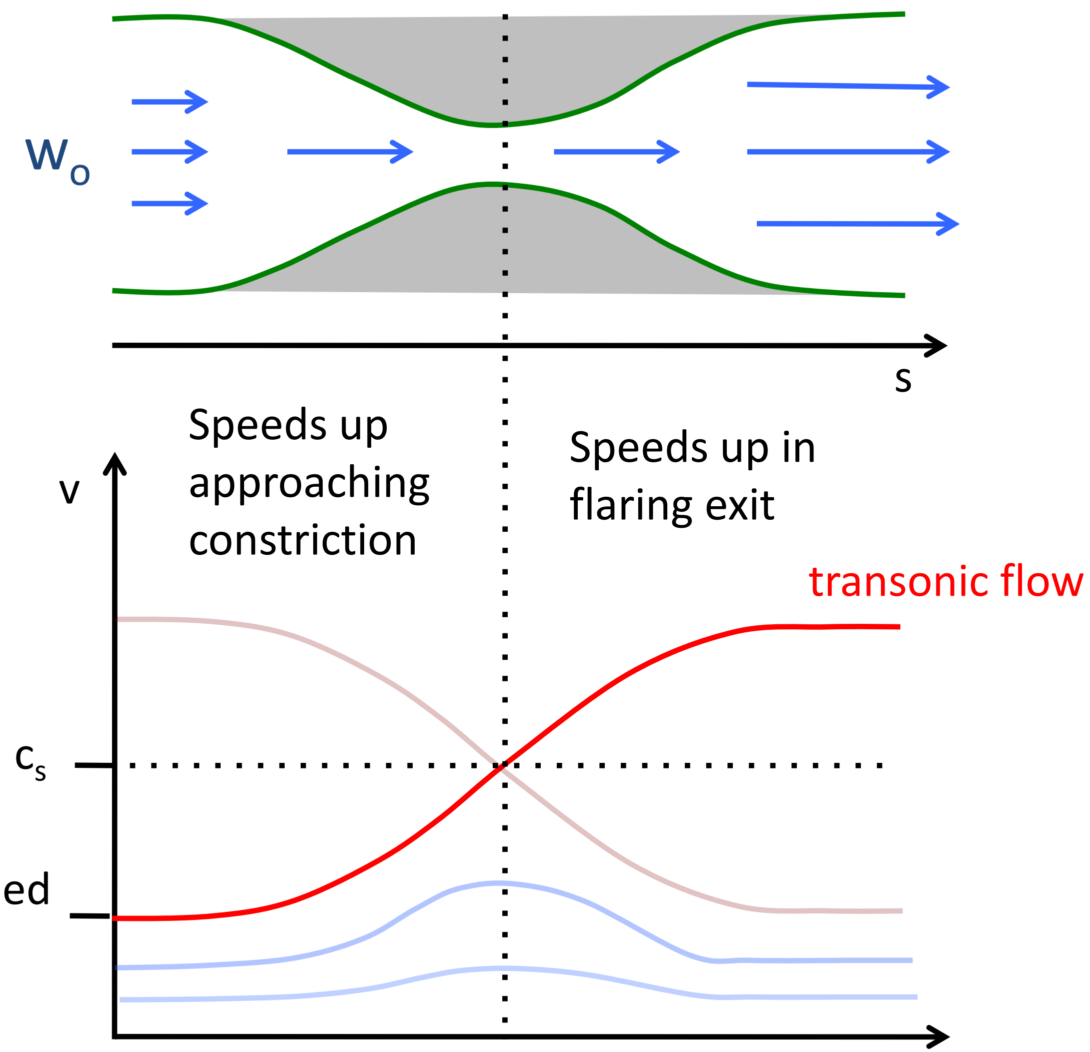
horizontal nozzle

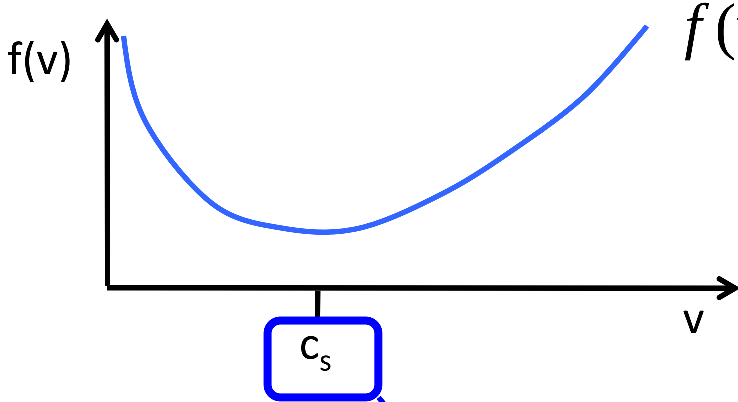
$\Psi(s)$ = const.

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

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

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

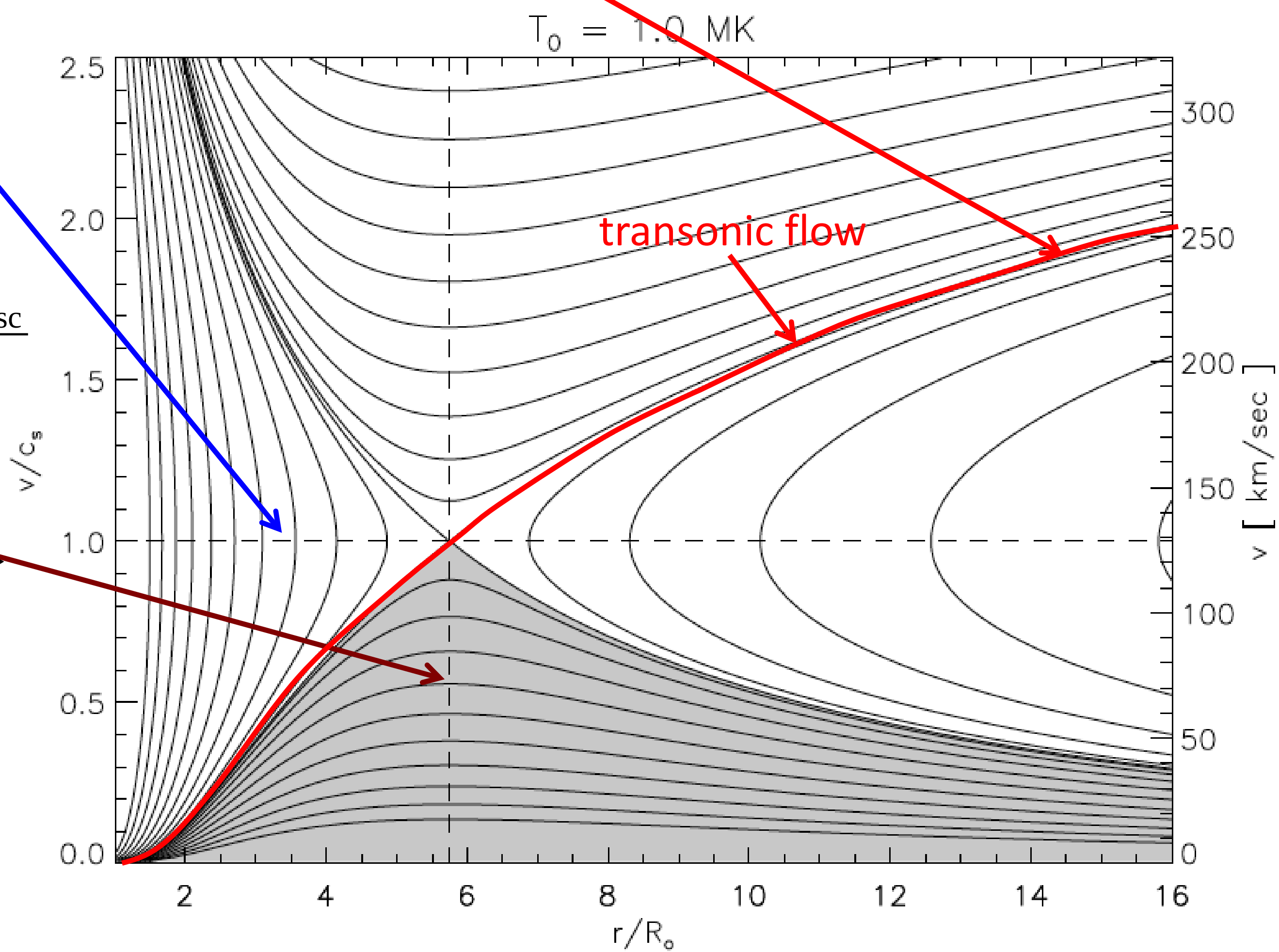




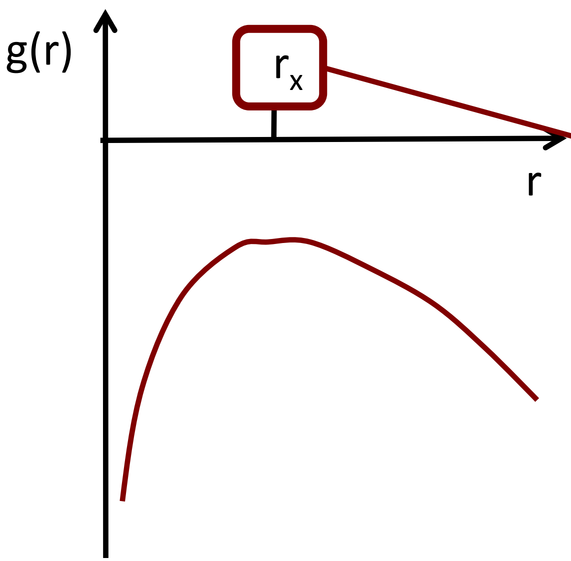
$$f(v) = \tfrac{1}{2}v^2 - c_s^2 \ln(v)$$

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

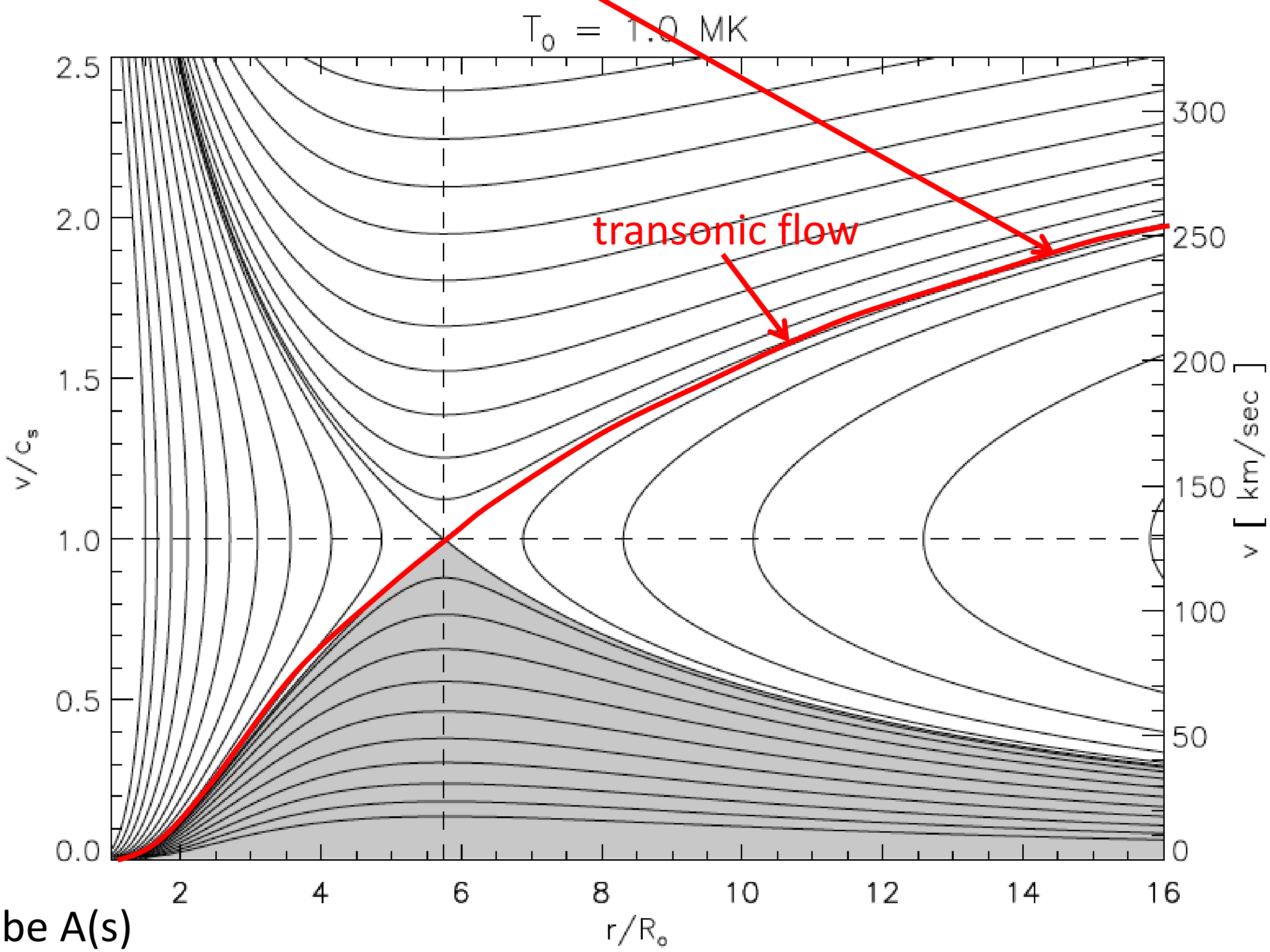
$$\rho(r_x) = \frac{\dot{M}}{A(r_x)c_s}$$

➔ 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

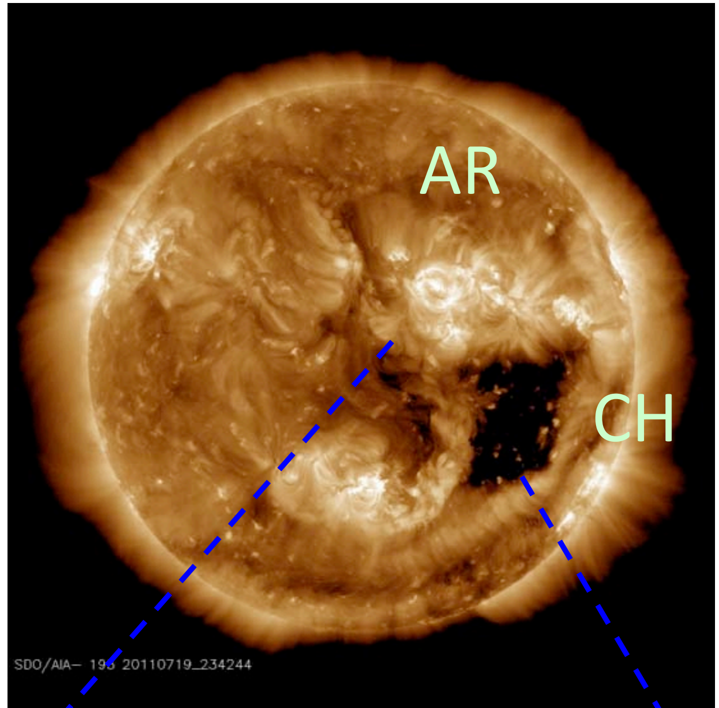
$$F_x = f(c_s) + g(r_x) = \frac{Q}{\dot{M}}$$

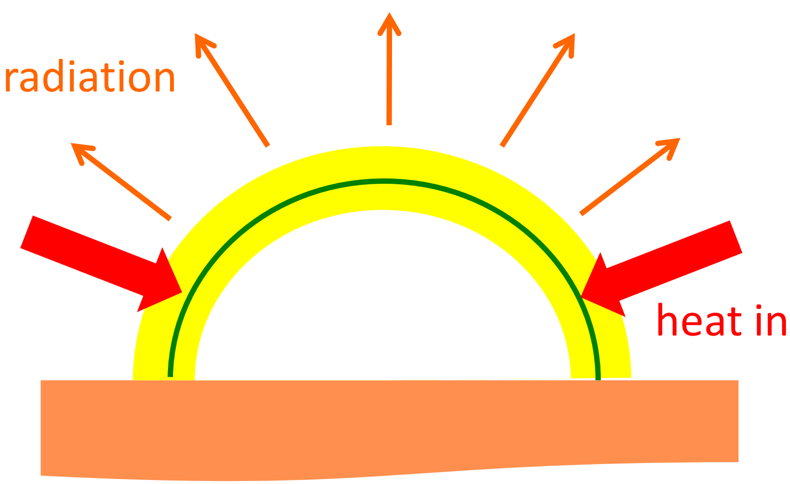


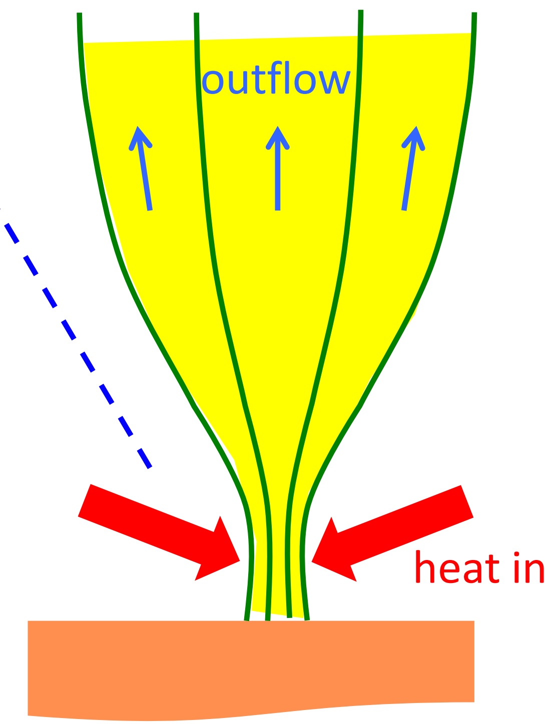
* … and geometry of flux tube A(s)

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)

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

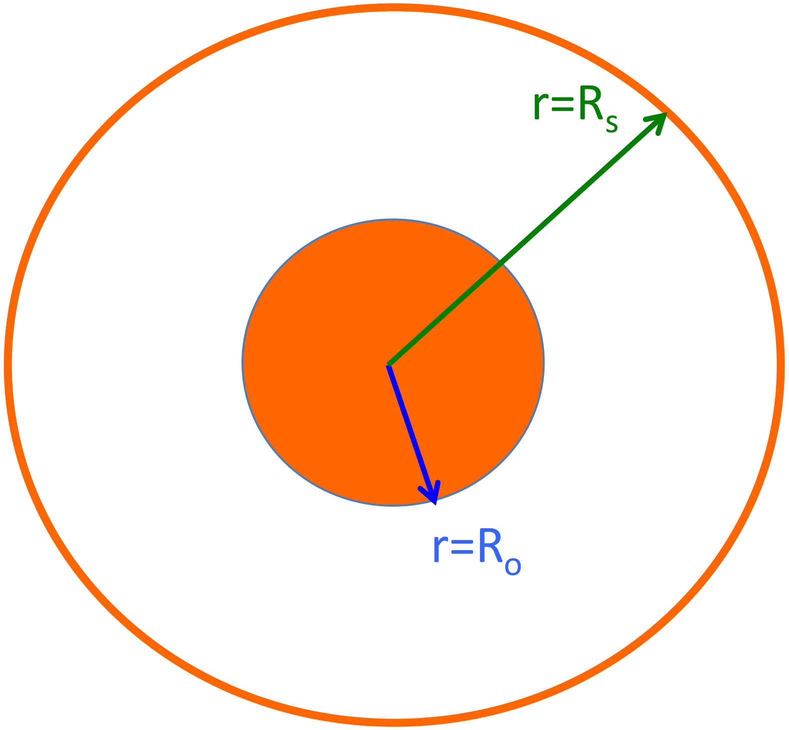
potential field
(cf. electrostatics)

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

harmonic potential
(cf. electrostatics in vacuum)

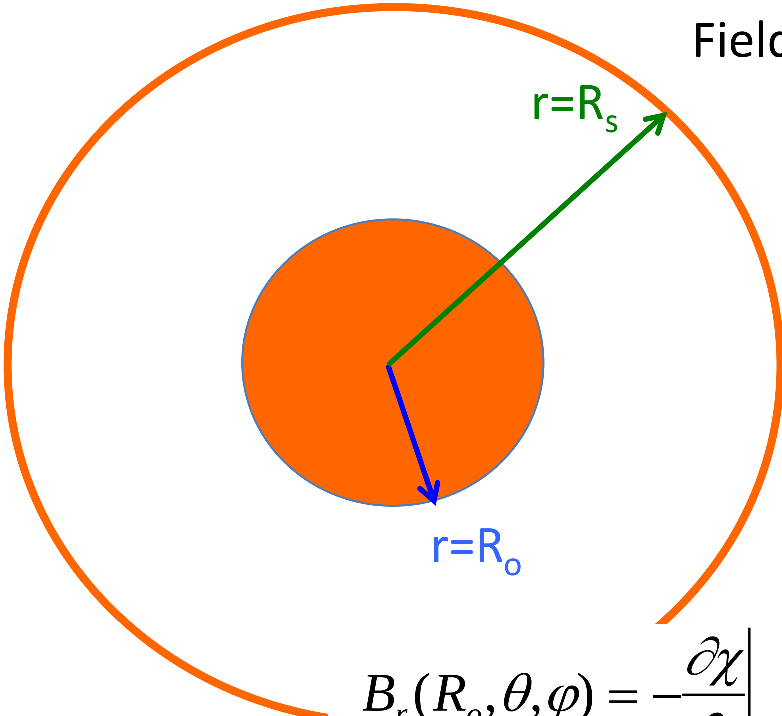
$$\mathbf{B} = -\nabla\chi \quad \& \quad \nabla^2\chi = 0$$

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

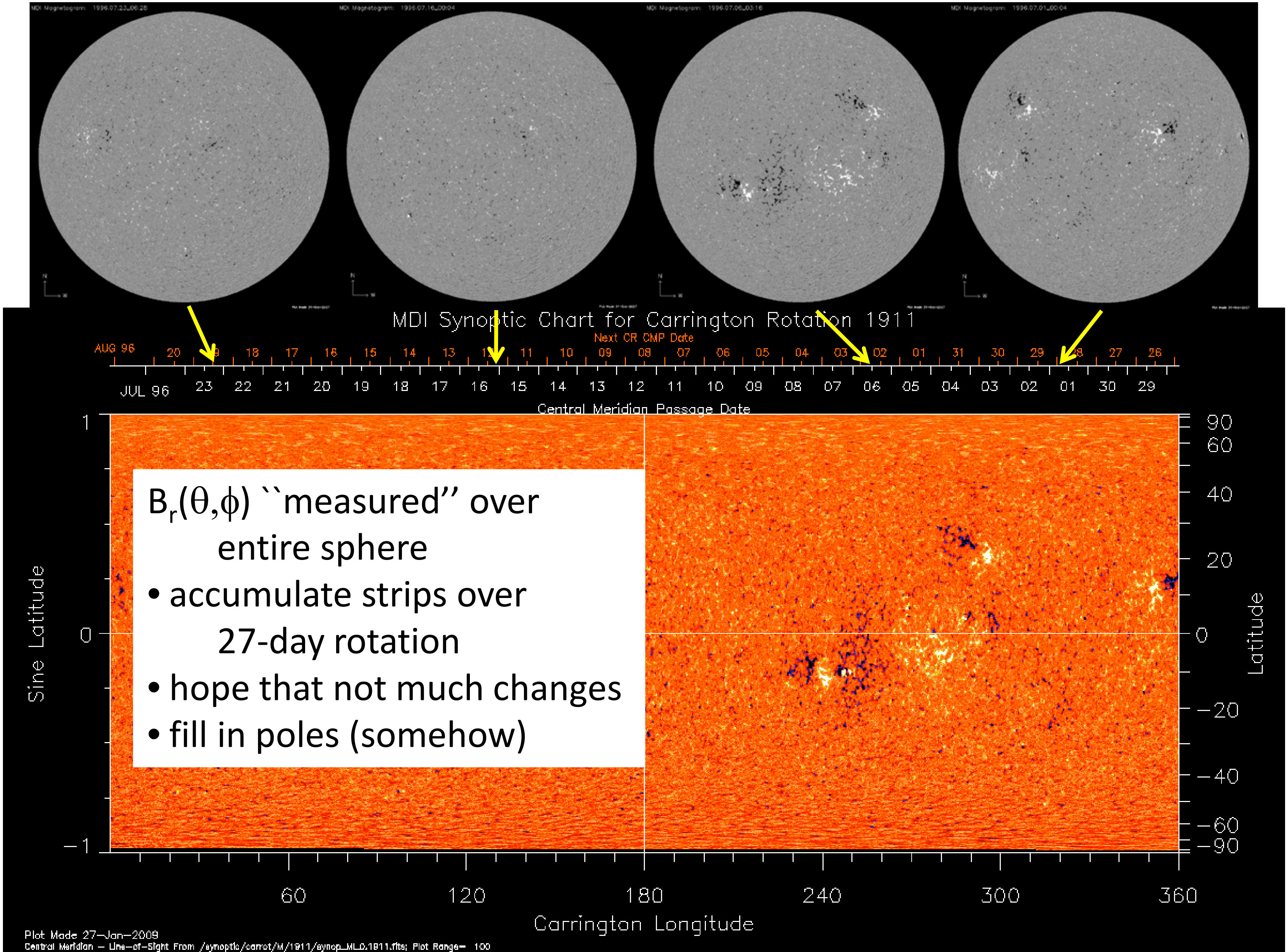
$$\chi(r,\theta,\varphi) = \sum_{l,m} A_{l,m}\left[\left(\frac{R_s}{r}\right)^{l+1} - \left(\frac{r}{R_s}\right)^{l}\right]Y_{l,m}(\theta,\varphi)$$

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

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

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

time

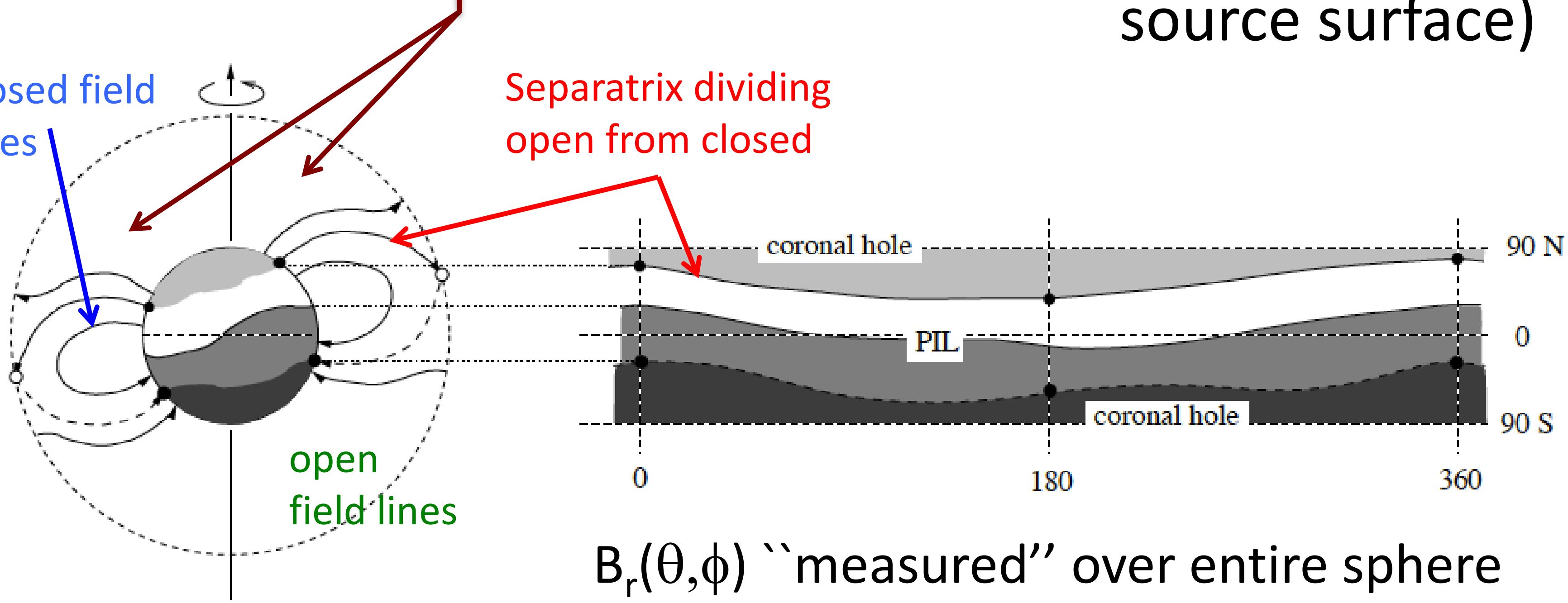


$B_r(\theta,\phi)$ ``measured'' over entire sphere

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

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

PFSS model
(potential field source surface)



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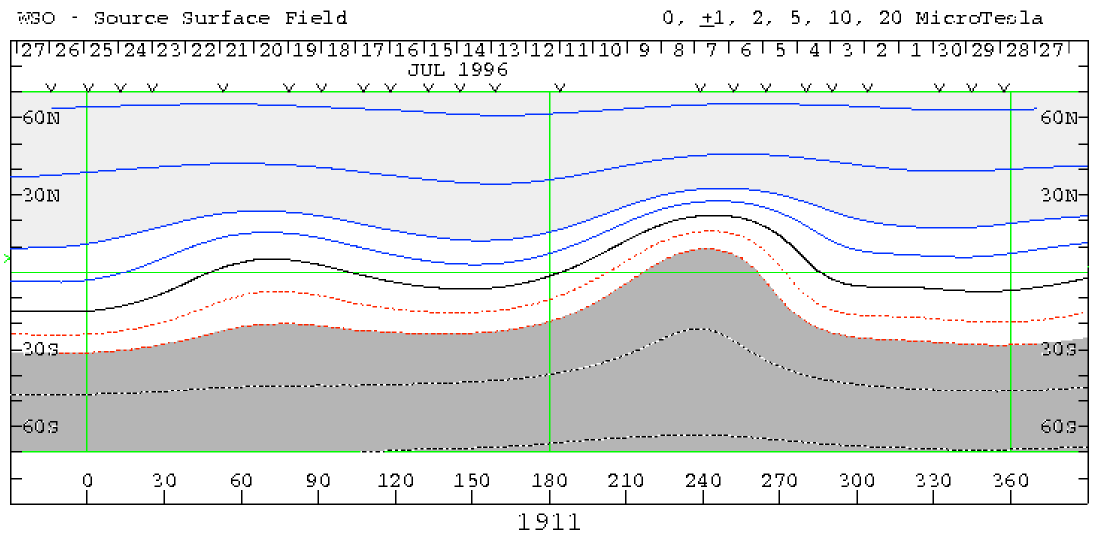
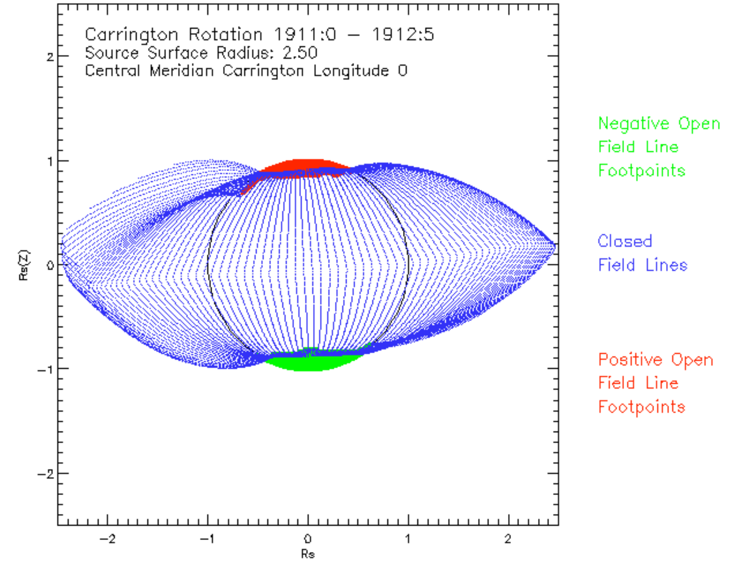
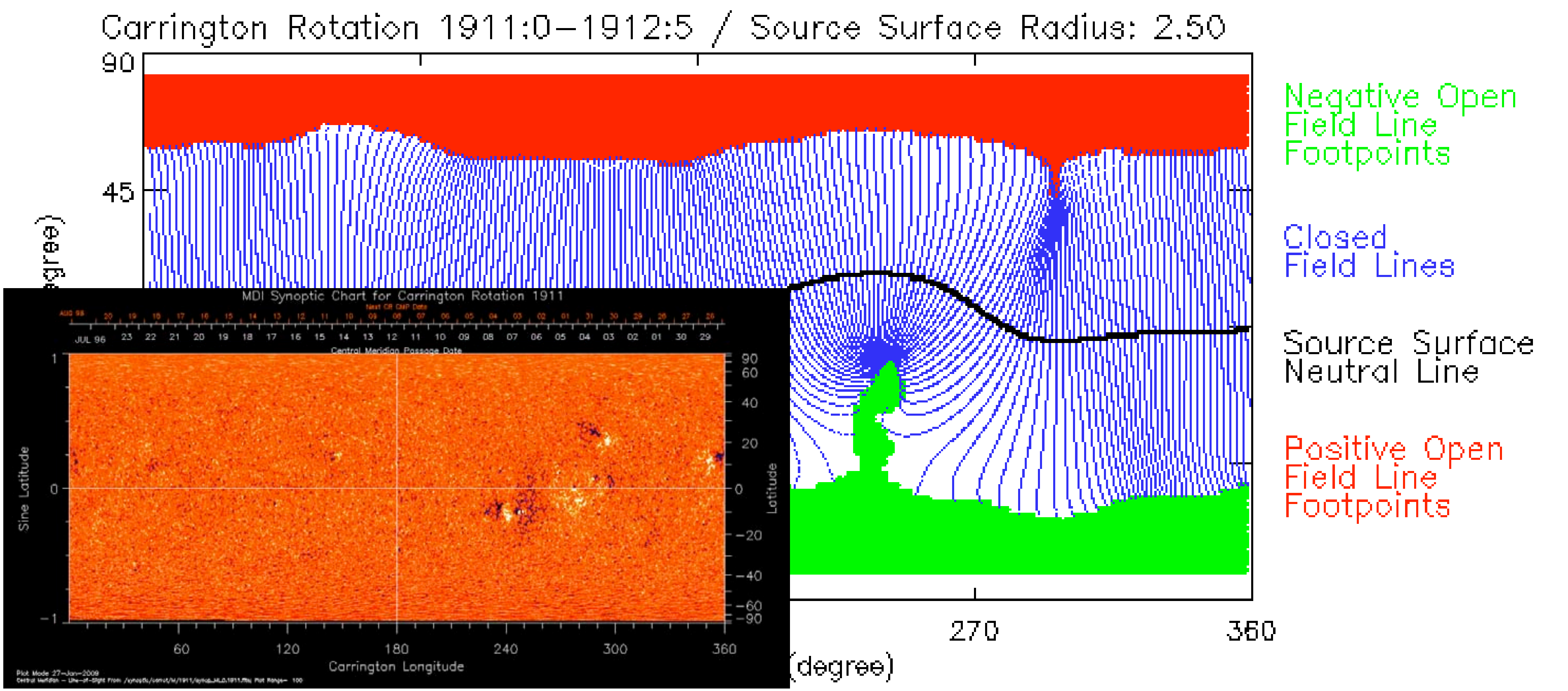
Solar wind flows from open field crossing $r=R_s$ … the `source' of the wind ➔ the `source surface'

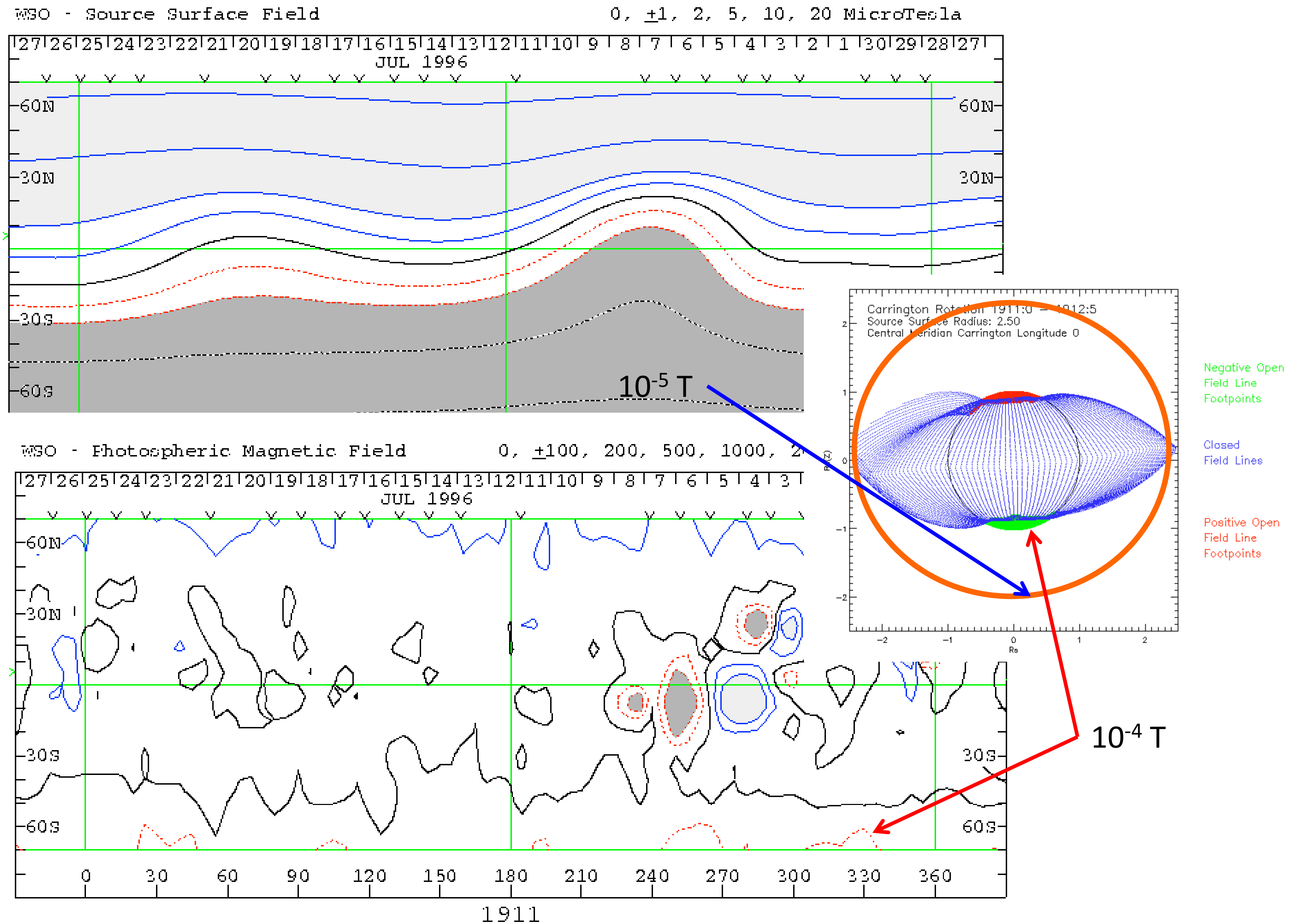
$B_r(\theta,\phi)$ ``measured'' over entire sphere

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


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
JUL 96
Central Meridian Passage Date
Sine Latitude
Latitude
Carrington Longitude
60 120 180 240 300 360



WSO - Source Surface Field
0, ±1, 2, 5, 10, 20 MicroTesla
JUL 1996
60N
30N
30S
60S
10^-5 T
WSO - Photospheric Magnetic Field
0, ±100, 200, 500, 1000, 2
JUL 1996
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
Negative Open Field Line Footpoints
Closed Field Lines
Positive Open Field Line Footpoints
10^-4 T

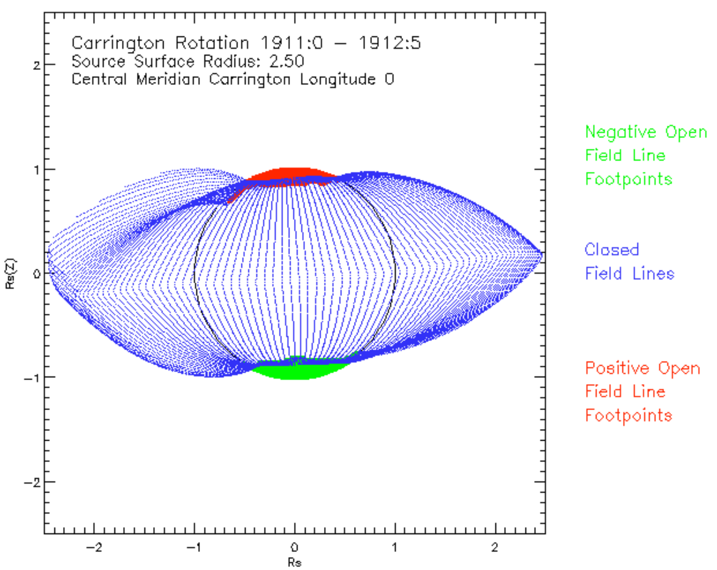
Assumptions of the PFSS

- No currents in coronal field (simplest equilibrium)

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

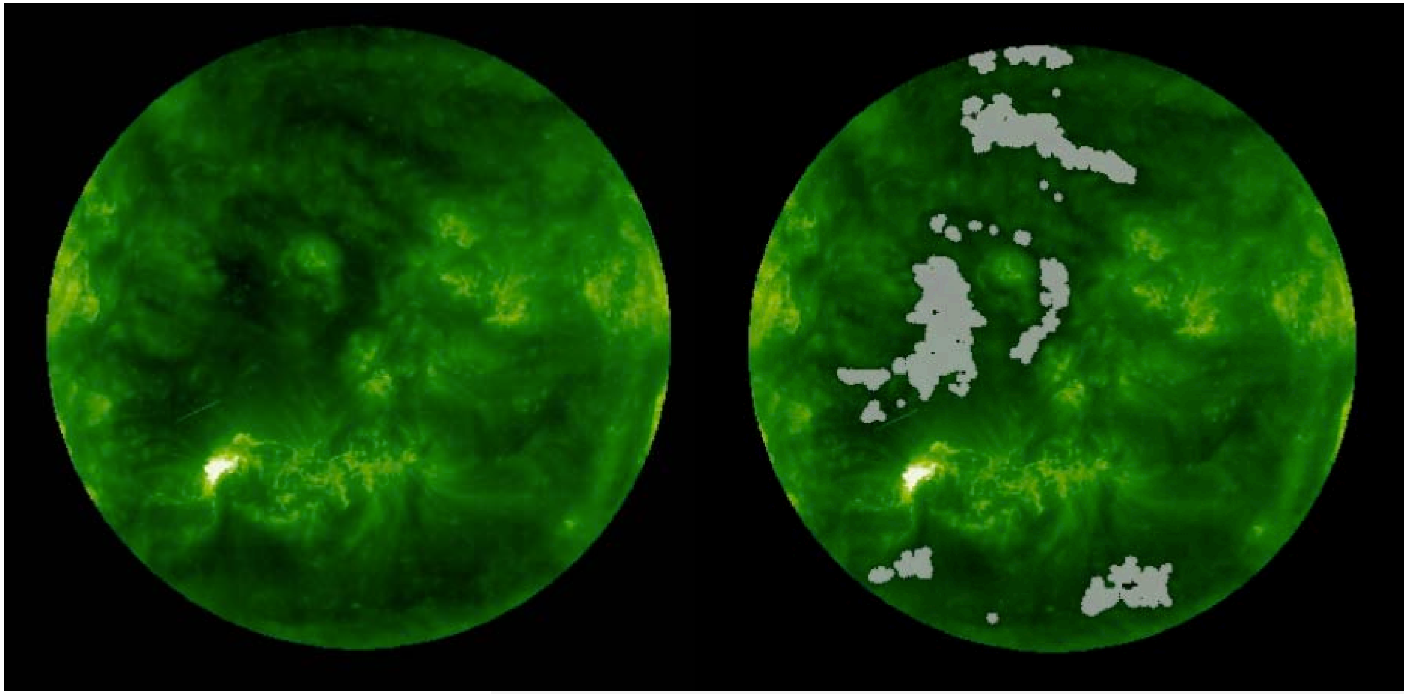
- Field becomes open (radial) @ fixed radius $r=R_s$

- Not much change during 27-day accumulation



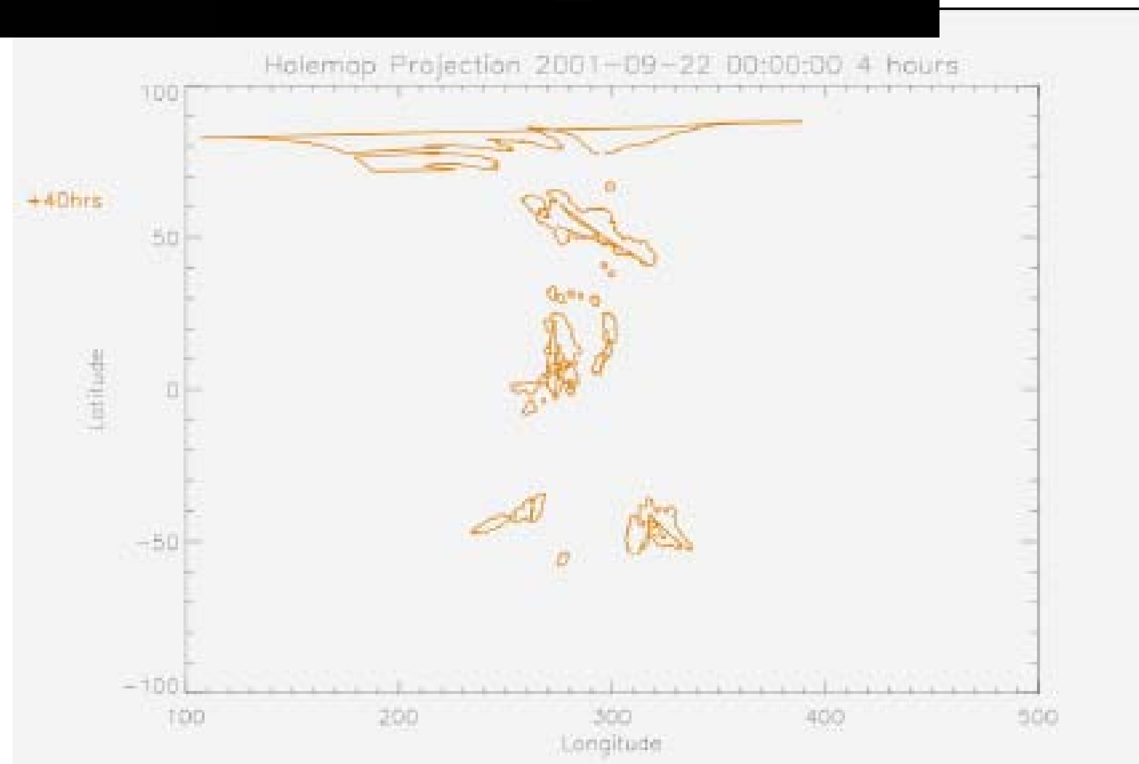
➔ **Model** distinguishing open/closed coronal field

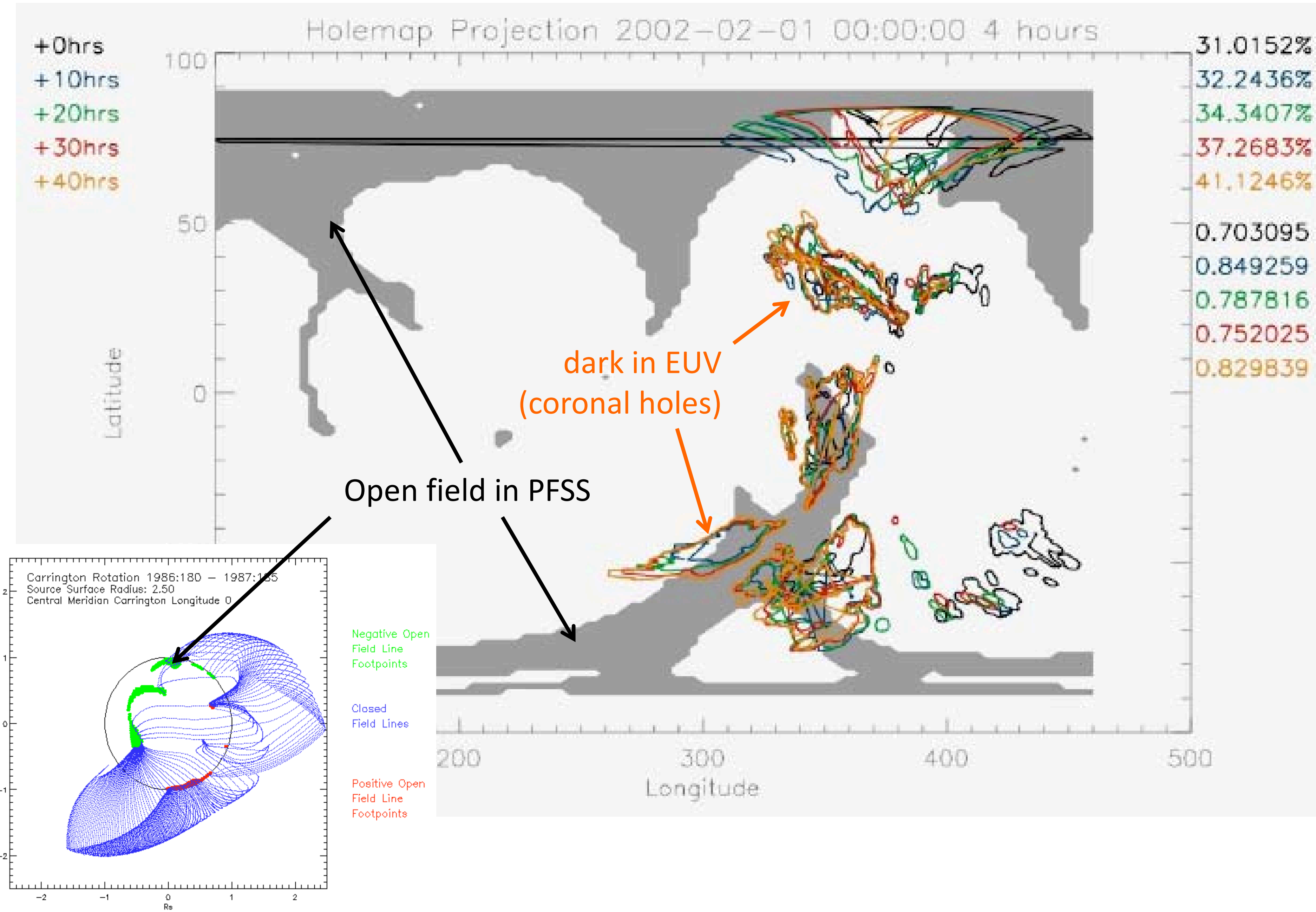
➔ Field **actually** open will be source of solar wind, less dense & dark in EUX & SXR



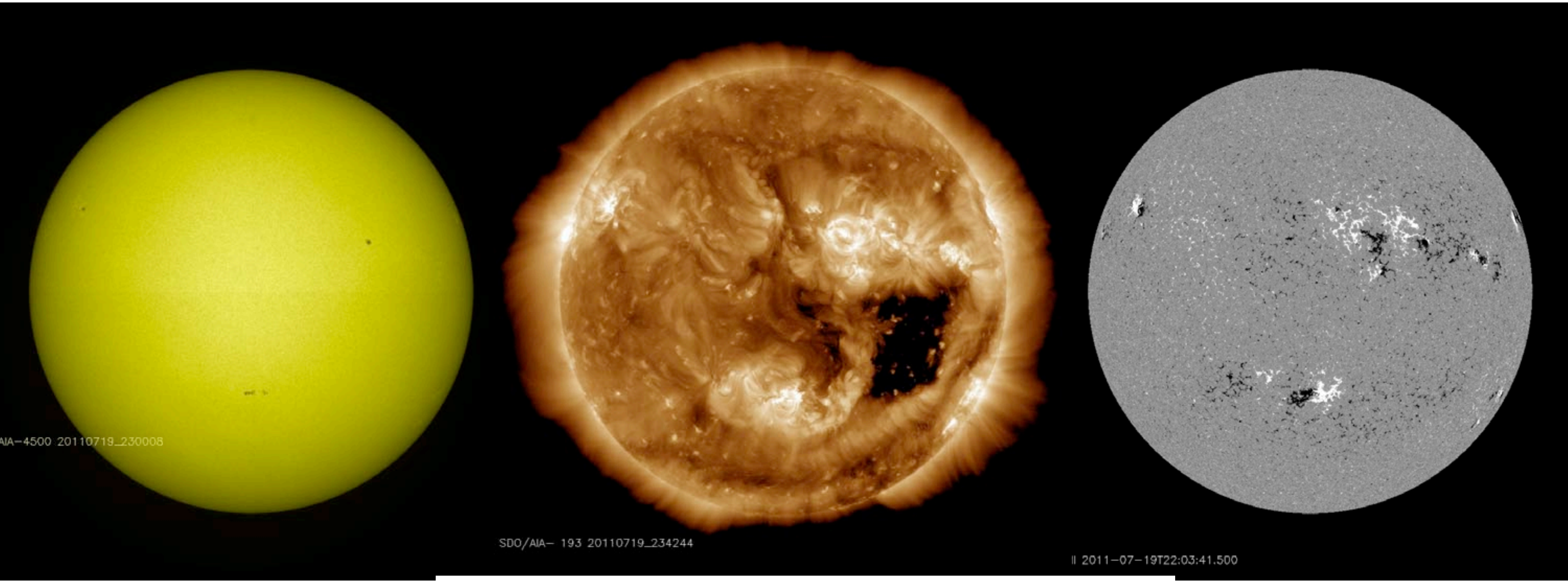
finding coronal holes

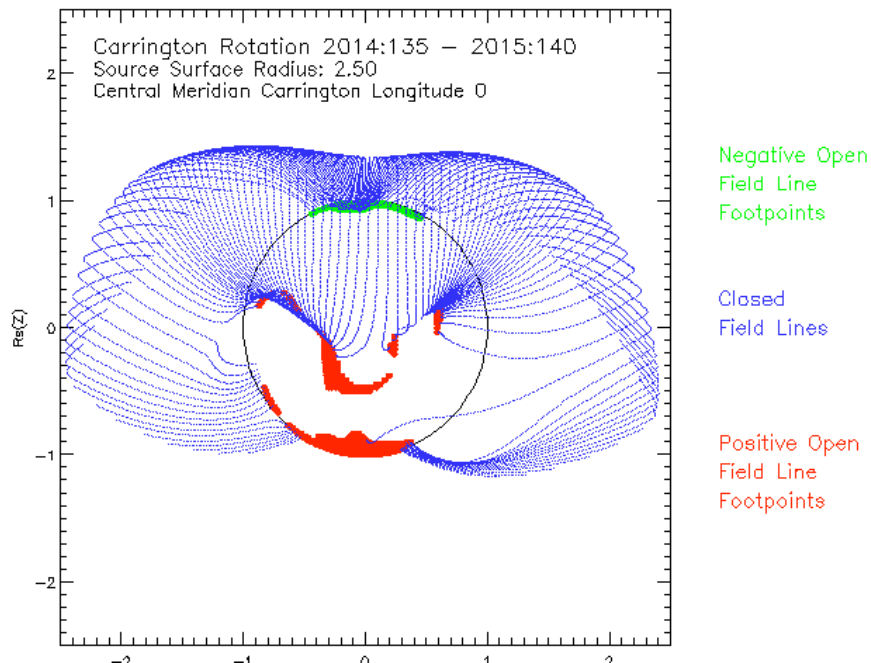
Dustin Hickey
Chris Lowder
Jiong Qiu & DWL





Holemap Projection 2002-02-01 00:00:00 4 hours
+0hrs
+10hrs
+20hrs
+30hrs
+40hrs
31.0152%
32.2436%
34.3407%
37.2683%
41.1246%
0.703095
0.849259
0.787816
0.752025
0.829839
Latitude
100
50
0
200
300
400
500
Longitude
dark in EUV
(coronal holes)
Open field in PFSS
Carrington Rotation 1986:180 – 1987:185
Source Surface Radius: 2.50
Central Meridian Carrington Longitude 0
Negative Open
Field Line
Footpoints
Closed
Field Lines
Positive Open
Field Line
Footpoints
Rs


AIA-4500 20110719_230008
SDO/AIA- 193 20110719_234244
I 2011-07-19T22:03:41.500


Carrington Rotation 2014:135 – 2015:140
Source Surface Radius: 2.50
Central Meridian Carrington Longitude 0
Rs(Z)
Negative Open Field Line Footpoints
Closed Field Lines
Positive Open Field Line Footpoints

Summary

- Heliosphere is a system of (mostly) plasma coupling Sun, & planets
- Includes sources of plasma, magnetic field & heat
- Corona is a source of heat & solar wind
- Energy dissipation drives flow along open field lines: the solar wind
- Coronal field composed of closed & open field according to conditions of magnetic equilibrium