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 $T (1.5 \times 10^6 \text{ K})$
• 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.

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

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

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

\[ \Delta(T)/k_b T^2 \]

Unstable

Heat

Balance

Loss @ fixed pressure
balance: (RTV)

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

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

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

more heating \((h)\)

\(\Rightarrow\) little hotter
much brighter

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

corona: \(h > \text{rad}\)

TR: \(h < \text{rad}\)
Below the TR – hairy details

Vernazza et al. 1981

- Radiation: not optically thin
- Ionization level varies with T
Heating is Magnetic

Pevtsov et al. 2003

![Graph showing magnetic flux and heating rate relation]
Field varies – corona varies

GOES 1-8 Å

×50
X-rays: highly variable – flares

do smaller flares heat the corona?
Corona produces EUV & X-ray
Corona produces $\mu$-waves
\[ \frac{1}{2} \rho v^2 v^2 + \rho v w(\rho) \]

>> radiative loss

Advective energy loss –

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

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

Wind: from open flux

specific enthalpy

\[ w(\rho) \propto \frac{\gamma}{\gamma - 1} \rho^{\gamma - 1} \]
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 ... $\gamma \rightarrow 1$

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

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

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

\[ g(s) = -c_s^2 \ln[A(s)] - \frac{R_0 v_{\text{esc}}^2}{2r(s)} \]

tube: cone w/ vertical axis

\[ A(s) \sim s^2 \quad s = r \]

\[ g(r) = -2c_s^2 \ln(r) - \frac{R_0 v_{\text{esc}}^2}{2r} \]
$f(v) = \frac{1}{2}v^2 - c_s^2 \ln(v)$

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

$g(r) = -2c_s^2 \ln(r) - \frac{R_0 v_{\text{esc}}^2}{2r}$

 Tube: cone w/ vertical axis

$A(s) \sim s^2$

$s = r$

$R_0 v_{\text{esc}}^2 / 4c_s^2$

$= r_x$

Transonic flow

Subsonic flow
tube: horizontal nozzle

\[ \Psi(s) = \text{const.} \]

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

saddle @ max. \( g(s) \)

@ throat of nozzle

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

horizontal nozzle

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

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

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

Inflow = mass loss rate

set by back-pressure

$W_{\text{exit}}$

Subsonic flow

Speeds up approaching constriction

Slows down in flaring exit

$W_0$
tube:
- horizontal nozzle
- $\Psi(s) = \text{const.}$

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

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

max. inflow speed

$\Psi(s)$

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

Speeds up approaching constriction

Speeds up in flaring exit

transonic flow
\[ f(v) = \frac{1}{2} v^2 - c_s^2 \ln(v) \]

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?)

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

* ... 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...

\[(\nabla \times \mathbf{B}) \times \mathbf{B} = 0\]

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

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

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

potential field
(cf. electrostatics)

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

harmonic potential
(cf. electrostatics in vacuum)
\[ \mathbf{B} = -\nabla \chi \quad \& \quad \nabla^2 \chi = 0 \]

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)

\[ (B_\theta, B_\phi) = 0 \quad \Rightarrow \quad \left( \frac{\partial \chi}{\partial \theta}, \frac{\partial \chi}{\partial \phi} \right) = 0 \]

\[ \Rightarrow \chi(R_s, \theta, \phi) = 0 \quad \text{Dirichlet} \]

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

Observe \( B_r(R_o, \theta, \phi) \) @ photosphere

• decompose w/ spherical harmonics
• coeffs. \( \Rightarrow A_{l,m} \)
$B_r(\theta, \phi)$ ``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 \( \Rightarrow \) 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. \( \Rightarrow A_{l,m} \)
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 EUX & SXR
Parker Spiral

\[ \vec{B} = B_R \hat{R} + B_\phi \hat{\phi} \]
\[ \vec{V} = V_R \hat{R} \]

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

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

Heliosphere

1 AU

HCS
\[ r = R_{\odot} \]

\[ r = 2.5 \ R_{\odot} \]
cosmic rays

- Originate far away in galaxy – in supernova remnant shocks
- Enter solar system isotropically
- No collisions with SW particles
- Deflected by SW $B$
  - Advected outward
  - Diffused by $B$ fluctuations
  - Drift:

\[
v_d = \frac{pcw}{3q} \nabla \times \left( \frac{B}{B^2} \right)
\]

\[
\approx \frac{2pcw}{3q} \frac{B}{B^3} \times \nabla B
\]
Effect on cosmic rays

Vol. III fig. 9.4
The wind through the cycle
Effect of a "warped" HCS

Vol. III fig. 8.6

Vol. III fig. 8.7
plasma density \([\text{cm}^{-3}]\)

Sources of plasma:

- \(10^9\)
- \(10^6\)
- \(10^4\)

the stuff (plasma) around us

Graph showing plasma density decreasing with distance, \(\propto r^{-2}\)

Regions:

- RZ
- CZ
- cor

Situations:

- SW
- ISM
- TS

Distance:

- \(10^{11}\) cm
- \(10^{13}\) cm
- \(10^{15}\) cm
sources of magnetic field
a.k.a. dynamos

RZ
CZ
cor

SW

ISM

TS

magnetic field [T]

$10^T$

$10^{-2}$

$10^{-5}$

$10^{-8}$

$10^{-10}$

$10^{11}$ cm

$10^{13}$

$10^{15}$
Temperature $[K] \propto \rho^{2/3} \propto r^{-1}$

Sources of heat:

- $10^7$ K
- $10^6$ K
- $10^5$
- $10^3$

Regions:

- RZ
- CZ
- cor
- IS
- MS
- ISM
- TS

Distances:

- $10^{11}$ cm
- $10^{13}$ cm
- $10^{15}$ cm
Temperature [K] vs. distance [cm]

- `\(10^6 \text{ K}\)`
- `\(10^4 \text{ K}\)`
- `\(\sim 10^7\)`
- `\(10^5\)`
- `\(10^3\)`

\(\propto \rho^{2/3} \propto r^{-1}\)

Sources of heat:
- ACR
- MS
- IS

RZ, CZ, cor, SW, ISM, TS, ACR

Red arrows indicate flow directions.
Vol. III fig. 9.1
The Heliosphere’s Interstellar Interaction: No Bow Shock


Result from IBEX

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

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