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

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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

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

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

\[ n_e n_H \Lambda(T) = p^2 \frac{\Lambda(T)}{k_b T^2} \]
Need 1d: include thermal conduction to move heat to chromosphere.

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

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

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

\[ 0 = h - p^2 \frac{\Lambda(T)}{k_B T^2} + \frac{\partial}{\partial \ell} \left( k \frac{\partial T}{\partial \ell} \right) \]
TR: $h < \text{rad}$

Corona: $h > \text{rad}$
Below the TR – hairy details

Vernazza et al. 1981

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

![Diagram showing the temperature and height (km) distribution with various ionization levels and temperatures.](image)

- Photosphere
- Temperature minimum
Heating is Magnetic

Pevtsov et al. 2003

\[ L_X, \text{ erg s}^{-1} \]

\[ \text{Magnetic flux, Mx} \]
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 μ-waves

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

Monthly Averages

F10.7 = flux @ $\lambda = 10.7$ cm (f=2.8 GHz)

Hathaway 2010
B large enough to restrict plasma motion: only along field lines

wind: from open flux

specific enthalpy

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

adveotive energy loss –

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

>> radiative loss
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 ... $\gamma \to 1$

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

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

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

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

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

tube: cone w/ vertical axis

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

\[ R_o v_{\text{esc}}^2 / 4c_s^2 \]

\( T_0 = 1.0 \text{ MK} \)

transonic flow

subsonic flow

\( r_* \)
tube:

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

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

saddle @ max. $g(s)$

@ throat of nozzle

$s$-throttle

$\Psi(s)$

$v$

$\max.$ inflow speed

admissible inflow speeds

transonic flow

subsonic flow
tube: horizontal nozzle

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

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

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

Inflow = mass loss rate

set by back-pressure

$W_{\text{exit}}$

subsonic flow

Speeds up approaching constriction

Slows down in flaring exit
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

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

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

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

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

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

\( T_0 = 1.0 \text{ MK} \)

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

Mass loss rate is set by heating rate*

density everywhere is set by mass loss rate

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 \( A(s) \)
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...

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

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

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

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

(cf. electrostatics)

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

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

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

Field: purely radial @ \( r = R_s \) \hspace{1cm} (by fiat)

\[ (B_\theta, B_\varphi) = 0 \implies \begin{pmatrix} \frac{\partial \chi}{\partial \theta} \\ \frac{\partial \chi}{\partial \varphi} \end{pmatrix} = 0 \]

\[ \implies \chi(R_s, \theta, \varphi) = 0 \text{ Dirichlet} \]

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

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

- Observe \( B_r(\theta, \phi) \) @ photosphere
- decompose w/ spherical harmonics
- coeffs. \( \Rightarrow A_{l,m} \)
$B_r(\theta,\phi)$ "measured" over entire sphere
- accumulate strips over 27-day rotation
- hope that not much changes
- fill in poles (somehow)
The PFSS model
(potential field source surface)

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

- closed field lines
- Separatrix dividing open from closed
- 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)

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

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

Heliosphere

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

Source surface

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

Super-radial expansion

Parker Spiral
$r = R_\odot$

$r = 2.5 R_\odot$
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
the stuff (plasma) around us

plasma density [cm\(^{-3}\)]

- RZ
- CZ
- cor
- SW
- IS
- MS
- ISM
- TS
sources of magnetic field a.k.a. dynamos

magnetic field [T]

<table>
<thead>
<tr>
<th>10 T</th>
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<tbody>
<tr>
<td>10^{-5}</td>
</tr>
<tr>
<td>10^{-2}</td>
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<tr>
<td>10^{-8}</td>
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</tbody>
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distance [cm]

| 10^{11} |
| 10^{13} |
| 10^{15} |
Temperature \[K\] vs. Distance [cm]

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

Sources of heat:

- \[\propto \rho^{2/3} \propto r^{-1}\]

Temperature values:
- \(1 \times 10^7\) K
- \(1 \times 10^6\) K
- \(1 \times 10^4\) K
- \(1 \times 10^3\) K

Distance values:
- \(1 \times 10^{11}\) cm
- \(1 \times 10^{13}\) cm
- \(1 \times 10^{15}\) cm
Temperature $[K]$ plot with sources of heat indicated. The diagram shows a relationship $\propto \rho^{2/3} \propto r^{-1}$ and different temperature and distance scales.
Vol. III fig. 9.1
The Heliosphere’s Interstellar Interaction: No Bow Shock


Science May 10, 2012

**Result from IBEX**

\[ v_{fms} = 26.8 \text{ km/s} \]

\[ v_{fms} = 21.4 \text{ km/s} \]
Summary

• Corona: because there is heating – reaches high T because radiation cannot balance heating so conduction is needed
• More heat \( \rightarrow \) higher density
• Wind: because there is heating – advective energy flux balances heating
• Creates heliosphere