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

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

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

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

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

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

more heating \( (h) \) ➞ little hotter much brighter

radiation
direction
heat in

conduction

[Graph showing power & flux vs. \( r \), with corona: \( h > \text{rad} \) and TR: \( h < \text{rad} \).]
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

photosphere

temperature minimum
Heating is Magnetic

Pevtsov et al. 2003

![Graph showing correlation between Magnetic flux and X-ray luminosity.](image)
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

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

Hathaway 2010

Nobeyama Radio Heliograph 17GHz (R+L)

2011-07-19 02:44:35.084
\[ \frac{1}{2} \rho v \nu^2 + \rho v w(\rho) \ll \text{radiative loss} \]

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 ...
$\gamma \to 1$

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

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

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

Bernoulli’s law: $\frac{Q}{M} = \text{const.}$
\[ f(v) = \frac{1}{2} v^2 - c_s^2 \ln(v) \]

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

tube:
- Cone with vertical axis
- \( A(s) \sim s^2 \)
- \( s = r \)

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

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

"tube: cone w/ vertical axis"

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

\[ A(s) \sim s^2 \]

\[ s = r \]

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

transonic flow

subsonic flow

\[ T_0 = 1.0 \text{ MK} \]
tube: horizontal nozzle

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

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

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

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

transonic flow

subsonic flow

max. inflow speed

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

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

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

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

Speeds up approaching constriction

Speeds up in flaring exit

transonic flow

max. inflow speed
\[ f(v) = \frac{1}{2}v^2 - c_s^2 \ln(v) \]

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

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

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

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

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

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

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

(cf. electrostatics)

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

(cf. electrostatics in vacuum)
B = −∇χ \quad & \quad ∇^2 χ = 0

potential field outside
sphere \quad r=R_o

r=R_s

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)

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

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

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

Observed (Neumann)

- Observe \( B_r(\theta, \phi) \) @ photosphere
- Decompose w/ spherical harmonics
- Coeffs. \( \Rightarrow A_{l,m} \)
B_r(θ,φ) "measured" over entire sphere

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

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'}
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
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
the stuff (plasma) around us

\[ \text{plasma density [cm}^{-3}] \]

\[ 10^{26} \]

\[ 10^{16} \text{ cm}^{-3} \]

\[ 10^9 \]

\[ 10^6 \]

\[ 10^4 \]

\[ 10^{-3} \]

\[ \text{sources of plasma} \]

\[ \propto r^{-2} \]

10^11 cm

10^{13}

10^{15}
sources of magnetic field
a.k.a. dynamos

magnetic field [T]

$10^T$

$10^{-2}$

$10^{-5}$

$10^{-8}$

$10^{-10}$

$10^{-15}$

$10^{11}$ cm

$10^{13}$

$10^{15}$

RZ

CZ

cor

SW

ISM

TS
\begin{align*}
\text{Temperature} & \quad [\text{K}] \\
10^4 & \\
10^6 \text{ K} & \\
10^7 & \\
\alpha \rho^{2/3} & \approx r^{-1}
\end{align*}
Vol. III fig. 9.1
The Heliosphere’s Interstellar Interaction: No Bow Shock

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. Zank6

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