Introduction to Heliophysics

Dana Longcope
Montana State University
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)

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)
William Thomson aka. Lord Kelvin (1824 – 1907)

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

"...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, respectively, zero..."

i.e. a dipole

\[\text{ergs per sec.}\] 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

*Nature 47:1206 p.106 (1892)*
Where did Kelvin go wrong?

- wrong equations: ``Maxwell’s”
- wrong magnetic fields
- too complex to model
- ...

Stuff (plasma) – single system including Sun & Earth
the stuff (plasma) around us
Temperature [K] \( \propto \rho^{2/3} \propto r^{-1} \)
Sources of heat:

- Temperature \( T \) [K]: \( \propto \rho^{2/3} \propto r^{-1} \)
- \( 10^7 \) K
- \( 10^6 \) K
- \( 10^5 \) K

Regions:
- RZ
- CZ
- IS
- MS
- ISM
- TS

Distance:
- \( 10^{11} \) cm
- \( 10^{13} \) cm
The Sun’s corona

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

• Are these unrelated features?

(vol. I, Ch. 9)
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

radiation

heat in

radiative loss @ const. density

radiative loss @ const. temp.

\[ \propto n_e^2 \]

\[
\begin{array}{c}
10^4 K \\
10^6 \\
10^8
\end{array}
\]
B\,\text{large enough to restrict plasma motion: only along field lines}

Advecive energy loss – 
\[ \frac{1}{2} \rho v v^2 + \rho v w(\rho) \]

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

\( \text{specific enthalpy} \)

>> radiative loss
Bernoulli’s law: \( \frac{Q}{M} = \text{const.} \)

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

mass loss fixed & unknown

Simple case: Isothermal ... \( \gamma \to 1 \)

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

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

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

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

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

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

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

**subsonic flow**

**transonic flow**

\( T_0 = 1.0 \text{ MK} \)
tube: horizontal nozzle

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

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

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

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

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

$w_\text{exit}$

$w_\text{o}$

Speeds up approaching constriction

Speeds down in flaring exit

V

$c_s$

Subsonic flow
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

$V$

$s$

$w_o$

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?)

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

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

potential field
(cf. electrostatics)

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

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

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

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

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

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

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

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

**PFSS model**
(potential field source surface)

Solar wind flows from open field crossing \( r = R_s \) ...
... the `source' of the wind
→ the `source surface'

- 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
finding coronal holes

Dustin Hickey
Chris Lowder
Jiong Qiu & DWL
Open field in PFSS
dark in EUV (coronal holes)
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