Tutorial: The magnetic Connection between the Sun and the Heliosphere

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The connection between Sun and Earth ...
Overview

- From ideal to real ...
- Five pieces of the puzzle:
  1) The “streamer belt” of a model Sun
  2) Evolution of the Sun-heliosphere coupling
  3) Source regions of the solar wind
  4) Forecasting the quiescent solar wind
  5) Powering the solar wind (and the corona)
- Conclusions and some questions
An ideal world: solar/heliospheric model

- The large-scale coronal magnetic configuration can be approximated by a potential field below a “source surface” (1969).

- The surface magnetic field is dispersed and advected to a good approximation as a scalar (1964).

- The heliospheric/ecliptic magnetic configuration can be reasonably approximated by the “Parker spiral” (1958).
Simulation of the solar cycle

Visualizing the evolution of the solar wind source domains, as seen in a ‘corotating’ frame, over 1-1.5 magnetic cycles:

<table>
<thead>
<tr>
<th>Surface view</th>
<th>Surface grid</th>
<th>Source-surf. grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equatorial</td>
<td>Equatorial</td>
<td>Equatorial</td>
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<tr>
<td>40° North</td>
<td>40° North</td>
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<tr>
<td>90° North</td>
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<td>90° North</td>
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Surface $\phi$-$\theta$ map and neutral line: Streamer belt still: From ‘Earth’: Streamer belt envelope (27-d syn. Bartels frame):
Simulating photospheric activity

Relatively recent essential additions:
- magneto-convective coupling
- magneto-chemistry: fragmentation and collisions
- ephemeral-region population
Effects of large-scale flows

Differential rotation and meridional flow only, as viewed from 40°N
Large-scale solar field depends on source function, dispersal, meridional flow, and differential rotation.

- Good approximation of large-scale flux patterns, including polar fields.
The Sun through the cycle

- Total flux
- Flux in activity belt
- Polar-cap flux (>60°)
- Absolute
- Net
- Positive only
The large-scale coronal field is mostly potential.

It can be approximated remarkably well by an *electrostatic model*:
- charge distribution on the solar photosphere
- within a perfectly conducting sphere of ~5 \( R_\odot \).

**SOHO/EIT 284Å with overlay of open-field boundaries from a PFSS model for different \( R_{ss} \) (see other examples at www.lmsal.com/forecast).**
The “current sheet” for a model Sun

- The neutral line drifts around a 27-d synodic rate, as observed. *No magic needed!*

- Model:
  - One neutral line 90% of the time.
  - One additional polarity island: 10% of the time
  - Only ~30 islands throughout a full magnetic cycle.
  - Islands commonly pinch off from, and re-merge with, the neutral line.
  - Very few islands form at cusp: *the quiescent corona rarely blows bubbles.*
MHD sim. shows disconnected field in current sheet

Flux emergence in a dipolar field

Courtesy Pete Riley
MHD simulation shows disconnected field in current sheet.

MHD sim. shows disconnected field in current sheet

Red: initially closed; Blue: opened field
Black: initially open; green/cyan/yellow: successive openings/c closings
Circled: foot point of field line that closes and reopens
Boxed: foot point of field line that opens

White areas: field is not connected to the Sun at 30 solar radii (Lionello et al., 2005; ApJ 625, 463).

All Such regions are adjacent to the current sheet.
Successive cycles often differ strongly:

![Graph showing sunspot cycles over time](image)
Consequently the total flux on the Sun is modulated:
Polar-cap (>60°) absolute flux

And the polar-cap field “capacitor” does not simply alternate in strength or even polarity:

- Traditional model: no decay
- No polar polarity inversion?
What if flux “decayed” by, e.g., 3D transport?

The polar-cap flux behavior signals something is missing from our understanding:

- Half life: 2.8 yr

![Graph showing polar flux over time (1700-2000 years).](chart)
What if flux transport were modified?

With polar-cap behavior ‘regularized’*, the heliospheric and cosmic-ray fluxes are roughly anti-correlated:

* For example by introducing 3D flux transport (Schrijver & DeRosa, Baumann et al.) or by modulating flux transport (Wang et al., Schrijver et al.).
Source regions of the solar wind

Perspective changes over the past few years:

- Much of the IMF is rooted in active regions (even sunspots).
  - Luhmann et al., 2002, JGR 107, 10.1029
  - Neugebauer et al., 2002, JGR 107, A12, 13-1
  - Schrijver and DeRosa, 2003, SPh 212, 165

- Heliospheric field from up to a dozen source regions at cycle maximum (may be connected by thin channels).

- Much of the slow wind originates in the ARs whose fields generally lie near the cusp at low (i.e., IMF) latitudes.
Data assimilation into a global model

Assimilating (“inserting”) magnetograms into the model:
“Sources” of heliospheric field

- Magnetic plage regions
- Heliospheric field foot points

- ✔ Heliospheric field originates in coronal holes
- ✔ AND in active regions!
✓ IMF originates in coronal holes over unipolar network

AND in young and mature active regions!
At solar maximum, 30-50% of the interplanetary magnetic field connects directly to active regions (incl. sunspots)

Model: field open to the heliosphere

SOHO
MDI 2001/03/13 00:00:30

TRACE
171A 2001/03/13 00:13:10
At solar maximum, 30-50% of the interplanetary magnetic field connects directly to active regions (incl. sunspots).

*Model: field open to the heliosphere*
Sources of heliospheric field
(all directions from the Sun)

- Latitudes above 30 degrees contribute 20 to 80% of the total heliospheric flux.
IMF: plage vs. activity belt

- Latitudes above 30 degrees contribute no more than 40% of the IMF
- Some 30-50% of the IMF at cycle maximum originates in magnetic plages.
Streamers and the solar wind

Ulysses First Orbit

Ulysses Second Orbit

SWOOPS

Speed [km s⁻¹]

Outward IMF
Inward IMF

S
N

Average Monthly and Smoothed Sunspot Number

How important is the small stuff (I) ?

- Quiet-Sun “magnetic carpet”:
  - Large-scale patterns survive for months or more
  - Network flux concentration survive for at most a few days, and magnetic connections much less than a day, owing to emergence of many small bipoles (“ephemeral regions”)

![Image of magnetic patterns]

![Image of magnetic connections]
How important is the small stuff (II)?

- A “magnetic canopy” was thought to separate the strong network field from essentially field-free regions around the network in a closed-vault geometry. But then:
  - “Weak field” away from the network discovered in the mid 70s
  - Maybe “weak field,” but lots of flux: ~5 — 50 Mx/cm², on average ~20 Mx/cm²
  - Maybe not “weak,” but merely “small”: $10^{16-17}$Mx compared to $10^{18-19}$Mx?
The “intranetwork field” steals flux from the network, so that the field geometry is inconsistent with the classical canopy concept, while the connectivity into corona & heliosphere changes on minute-to-hours time scale!

Oh, and much of the quiet-Sun corona is not low-\(\beta\)!

(Schrijver and van Ballegooijen, 2005; also Hansteen …)
Photosphere-corona connection

- The “intranetwork field” steals flux from the network, so that
- the field geometry is inconsistent with the classical canopy concept.

Potential field above unipolar network and mixed-polarity intranetwork; side and top view
‘Incomplete knowledge’:

Having observations of only $\frac{1}{4}-\frac{1}{3}$ of the solar surface introduces substantial uncertainties (2nd half of the movie) not seen in a model with perfect knowledge (1st half of the movie).

Note the substantial field deflections from the sub-solar point to the photosphere!
The polarity pattern of the heliospheric field is forecast accurately more than a month into the future.

Not surprising: this pattern is dominated by the largest scales, which evolve slowly.

Around spot maximum, the source strength of the source-surface heliospheric field can be forecast accurately only a few days ahead of time, because (a) active regions evolve quickly, and (b) active regions are seen too late.
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The extended stellar atmosphere
- Cycle maximum: 30-50% of the IMF from ARs,
- significantly non-potential ~10-30% of the regions on the surface,
- with the wind perturbed by wide-angle CMEs ~15-20% of the time (during non-potential phases of ARs), and
- inadequate knowledge of much of the solar surface:
- PFSS source-region mapping must fail ~20% of the time.
Wang-Sheeley/Arge-Pizzo wind modeling ...
Wang-Sheeley/Arge-Pizzo wind modeling …

- Arge/Pizzo (2000) model:
  - Arge/Pizzo – field expansion (ratio of base to source-surface field strengths):
    \[ C = 0.34 - 0.39 \text{ for 3-yr for sunspot numbers 10-25} \]
  - Our model – base flux density over average source-surface flux density:
    \[ C = 0.38 \text{ for 3-yr for sunspot numbers 30-115.} \]
    Eliminate the worst 17%, then \( C = 0.71 \)

- Wind speed: \( v = a + b \left( \frac{B_{ss}}{B_{ph}} \right)^c \)
  - Arge/Pizzo: \( a = 270 \text{km/s}, \quad b = 410 \text{km/s}, \quad c = 0.4 \)
  - Our model: \( a = 280 \pm 40 \text{km/s}, \quad b = 1000 \pm 200 \text{km/s}, \quad c = 0.49 \pm 0.10 \)
    (Note: \( b \) is sensitive to magnetogram resolution)

- Wind interaction: \( v_{ij} = \left[ \frac{(v_i - d) + (v_j - d)}{2} \right]^{-1/d} \)
  - Arge/Pizzo: \( d = 2 \)
  - Our model: \( d \in [-2, 2] – \text{unconstrained!} \)
All rotating stars with convective envelopes exhibit atmospheric magnetic activity.
Hypothesis:

Stellar dynamos are like that of the Sun, except for the frequency of active-region emergence.
Activity, rotation, and saturation

A star at 30x solar rate of flux injection is of merely moderate activity:

\[ \frac{\Phi}{\Phi_\odot} \approx 10 \]
Simulations of activity

Simulated “Sun” from 40°N:

Present Sun

Active star (30x higher rate of flux injection), from 40°N:

Young Sun at ~500 Myr?
Wind from the once and future Sun

- Combination of solar and stellar observations constrains mass loss and angular momentum loss of the Sun in the distant past and future, and
- raises the question whether the mechanism which drives the wind also contributes significant power to (long) loops.
Sun-like star

Cycle maximum

Surface field

Corona (for YOHKOH’s SXT)

Traced field lines
30x solar emergence rate

Surface field

Corona (for YOHKOH’s SXT)

Traced field lines
Simulated magnetic field on a star like AB Dor (K0V, 15pc, 20-30Myr, P=0.51d), just prior to “cycle maximum”

by MacKay, Jardine, Collier Cameron, Donati, Hussain (2004)
Asterospheres

Combine observed Ly $\alpha$ profiles with models of wind-ISM interaction to derive mass loss rates:

- Observed after inter-/circumstellar absorption
- Model stellar profile
- Asterospheric absorption
The mystery of magnetic braking

\[ \phi_A (R_{ss} \phi_*) \]
Model: astrospheric field

\[ \phi_A \propto v_A^{1/2} \Omega \]
Inferred: astrospheric field

\[ \beta = 1 \]
Theory: field balances flow

\[ R_A (\dot{M}, \Omega) \]
Inferred: mass loss

\[ \dot{M} (v_\infty, \phi_*) \propto \phi_* \]
Inferred: mass loss

\[ F_X (\phi_*) \]
Observed: flux-flux

\[ \Omega(t) \]
Observed: rotation-age

\[ \dot{M} (v_\infty, F_X) \]
Observed: mass loss

\[ L (\dot{M}, R_A, \Omega) \]
Theory: angular momentum

\[ R_{ss} (\phi_*, v_A, \Omega) \]
Inferred: source surface

\[ R_{ss} \propto v_A^{-0.5} \phi_*^{0.9} \]
Observed: surface field

\[ \dot{M} (v_\infty, \phi_*) \propto \phi_* \]
Inferred: mass loss

\[ R_A \propto v_\infty^{0.5} \]
Observed: surface field

\[ L (\dot{M}, R_A, \Omega) \]
Theory: angular momentum
The mystery of magnetic braking

\[ R_{ss} \propto V_A^{-0.5} \phi_*^{0.9} \]

\[ \phi_A \propto V_A^{1/2} \Omega \]
Inferred: astrospheric field

\[ \phi_* \propto \Omega^3 \]
Observed: surface field

\[ R_A \propto V_\infty^{0.5} \]

\[ M(V_\infty, \phi_*) V_\infty^2 \propto \phi_* V_\infty^2 \]
Inferred: wind power

Q: Why do surface and astrospheric fields scale differently with activity?
A: Coronal field is forced open lower as activity decreases
   (causes: field expansion in a dipolar geometry and wind acceleration).
Model solar corona, based on observed magnetic field, rendered for YOHKOH/SXT Al/Mg filter


\[ F_H = 8 \times 10^4 B^{1.0\pm0.3}(10^{10}/2L^{1.0 \pm 0.5} \pm 1) \text{ ergs/cm}^2/\text{s} \]
The appearance of the corona depends on the properties of coronal heating.

These sample images show some of the “worst-fit” cases.
Model solar corona, based on observed magnetic field, rendered for YOHKOH/SXT Al/Mg filter.


\[ F_H = 8 \times 10^4 B^{1.0 \pm 0.3}(10^{10}/2L^{1.0 \pm 0.5} + 1) \text{ ergs/cm}^2/\text{s} \]
Conclusions and some questions

- PFSS-like modeling works well most of the time.
- Reconnection through the neutral-line/current-sheet can likely take care of the evolution of the heliospheric flux.
- Much of the IMF connects directly to ARs (& spots).
- Much of the fast wind is likely rooted in dynamic small-scale field. What does that imply for, e.g., the Solar Probe?
- Does the wind driver also dominate in long closed loops?
- How best to improve understanding of wind driver(s)? At least, improve our understanding of photosphere-heliosphere coupling
  - better coverage of the full sphere (Sentinels & FarSide); inclusion of major current systems in active-region coronae (Solar-B, SDO, & GBO); long-term sampling of inner heliosphere (IHS, Orbiter); improved understanding of polar-cap behavior (Orbiter); …