Polar Magnetic Field Topology

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Solar Orbiter SAP science goal #4 + PHI stand-alone science meeting
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Objective 4: How does the solar dynamo work and drive connections between the Sun and the heliosphere?

4.1 How is magnetic flux transported to and re-processed at high solar latitudes?
   4.1.1 Study the detailed solar surface flow patterns in the polar regions, including coronal hole boundaries.
   4.1.2 Study the subtle cancellation effects that lead to the reversal of the dominant polarity at the poles.
   4.1.3 Explore the transport processes of magnetic flux from the activity belts towards the poles and the interaction of this flux with the already present polar magnetic field.
   4.1.4 Study the influence of cancellations at all heights in the atmosphere.

4.2 What are the properties of the magnetic field at high solar latitudes?
   4.2.1 Probability density function (PDF) of solar high-latitude magnetic field structures.
   4.2.2 Basic properties of solar high-latitude magnetic field structures.
   4.2.3 Probe the structure in deep layers of the Sun.

4.3 Are there separate dynamo processes acting in the Sun?

4.4 How are coronal and heliospheric phenomena related to the solar dynamo?
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## Polar magnetic field measurements

1. What are the difficulties?
2. Why is it important?
3. What do we know?
4. What can we expect from PHI?
5. How to operate PHI to maximize polar field information?
Problems in polar field diagnostics: $B_0$ max. 7°

Pole measurements are difficult

- foreshortening
- ambiguity removal tricky
- study of features with almost no change in viewing angle
- ground-based: low contrast hinders stable AO locking
- low photon flux (limb darkening)
- sampling higher layers
- highly inclined LOS wrt. solar vertical $\rightarrow$ simple inversions (ME-type) not applicable
- Zeeman effect: $||$ vs. $\perp$
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Fig. 1.—A typical drift scan plotted against scan angle $\phi/\phi_\circ$. The intensities plotted here have been corrected for zero point and normalized. Representative values of $\mu = \cos \theta$ are marked along the following half of the scan.
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Durrant et al. (1981)
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Problems

$7^\circ$ vs. $35^\circ$ - continuum intensity

Angle from Limb: $35^\circ$ vs. $7^\circ$
Angle from Limb: 35° vs. 7°

Problems

7° vs. 35° - Stokes V
The importance of measuring polar $B$

- Polar field is directly related to dynamo process (source of poloidal field)
- Polar $B$ field distribution responsible for coronal holes, polar plumes, X-ray jets, ... 
- Source of fast solar wind
- Slow solar wind likely to emanate from CH boundaries
Tsuneta et al. (2008)

Best polar field measurements

Tsuneta et al. (2008), Hinode SOT/SP

- low straylight, stable space environment
- B0 angle: 7° (2× per year)
- 4.8 s integration time $\rightarrow$ S/N ratio 1000 (increase to 2000 is possible)
(a) Continuum
Tsuneta et al. (2008)

(b) Stokes Q
Tsuneta et al. (2008)

(c) Stokes U
(e) Stokes V
Tsuneta et al. (2008)
Tsuneta et al. (2008)

Analysis method

- Milne-Eddington type inversions (MILOS code, Orozco Suárez et al., 2007)
- 10 free parameters:
  - $B$, $\gamma$, $\phi$ - magnetic field vector
  - $v_{\text{LOS}}$ - line-of-sight velocity
  - $S_0$, $S_1$ - source function & gradient
  - $\eta_0$ - ratio of line to continuum absorption coefficients
  - $\lambda_D$ - Doppler width
  - $a$ - the damping parameter
  - $\alpha$ - stray-light factor
  (similar to PHI onboard processing - no $\alpha$)
- $Q$, $U$, or $V$ signal $\geq 5\sigma$ (10.5% of all pixels)
Polar magnetic fields: Basic properties (4.2.2.)

Polar landscape (Tsuneta et al., 2008)
Results

- kG patches (unipolar) \perp solar surface (cf. plage / network at disk center)
- larger patches:
  - closer to pole (height effect?)
  - vertical (red)
  - coincide with polar faculae
  - 5-10 hours
- smaller patches
  - horizontal (blue)
  - 30 minutes
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Polar magnetic fields: Probability density functions (4.2.1)

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- red - $B_\perp$
- blue - $B_\parallel$
- black - total $B$
- dashed - $> 800 \text{ G}$
- solid - $> 300 \text{ G}$
Tsuneta et al. (2008)

(a) - strength distribution
- $B_\perp$ dominates strong fields
- $B_{||}$ dominates weak fields

(b) - energy distribution ($n \times B^2$)
- weaker fields carry more energy

red - $B_\perp$ blue - $B_{||}$ black - total $B$ dashed - $> 800$ G solid - $> 300$ G
Tsuneta et al. (2008)

- Polar magnetic fields: Probability density functions (4.2.1)

- **Intensity distribution**
  - Vertical fields are brighter (→ faculae)
  - $B_{\parallel}$ symmetric about $< I_C >$

- **Filling factor**
  - Small FF indicate unresolved structures AND/OR straylight (PSF)

- **Color Code**
  - Red - $B_{\perp}$
  - Blue - $B_{\parallel}$
  - Black - Total $B$
  - Dashed - $> 800$ G
  - Solid - $> 300$ G
Shiota et al. (2012): $B$-flux per patch number density
Shiota et al. (2012): $B$-flux per patch avg. flux density

Polar magnetic fields: Probability density functions (4.2.1)
Shiota et al. (2012): long-term study 2008-2012

vert. flux $> 10^{18}$ Mx

North pole vertical, large

Vert. flux $< 10^{18}$ Mx

North pole vertical, small

North pole horizontal
Small-scale dynamo vs. global dynamo

Study small-scale flux emergence

- small-scale surface dynamo
  \(\rightarrow\) no latitudinal dependence expected

- in-ecliptic measurements strongly biased:
  - foreshortening
  - sampled height layer
  - different sensitivity for \(B_\perp, B_\parallel\)
  - small deflections in near-vertical field

- evenly distributed measurements mandatory

\(\rightarrow\) If PDF of properties (number, size, flux) are significantly different at high latitudes
\(\Rightarrow\) strong support for weak features being due to global dynamo.
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→ If PDF of properties (number, size, flux) are significantly different at high latitudes
  ⇒ strong support for weak features being due to global dynamo.
Details of cancellation mechanism

Flux removal at the poles

- What is the main mechanism? (Anusha et al., 2016) (death by disappearance of unipolar features, cancellation of bipolar features, merging events)
- PHI will deliver better estimate flux removal rate
Polar magnetic fields: Study of polar magnetic features (4.1.4.1.)

Special polar magnetic features (e.g. jets)

Example: details of polar jets (Quintero Noda et al., 2016)
- inversion of Hinode SOT/SP data after removing PSF effect
- height-dependent inversion of Stokes profiles
- best currently available comb. of data + analysis method

Results
Faculae are ...
- hot plasma tubes with low line-of-sight velocities
- single polarity magnetic kG fields ⊥ solar surface
- slightly shifted wrt. continuum image towards the disc center
Polar magnetic fields: Study of polar magnetic features (4.1.4.1.)

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Results

Faculae are ...
- hot plasma tubes with low line-of-sight velocities
- single polarity magnetic kG fields \( \perp \) solar surface
- slightly shifted wrt. continuum image towards the disc center → result of hot wall effect
- ideal for combined measurements PHI & hi-res GB
How to optimize PHI for measuring polar $B$?

Wishlist for polar $B$-field (standalone) science

- max. solar latitude
- min. distance
- co-observations from Earth:
  - large $B_0$ angle
    (March-08: South pole, September-08: North pole)
  - ground-based support: Canary observatories
    September preferable; DKIST?
- HRT ME maps of all parameters
- few Stokes parameter maps
Selecting good orbits: example #14