Polar Magnetic Field Topology

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Solar Orbiter SAP science goal #4 + PHI stand-alone science meeting
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SOP #4

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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Targets for PHI (stand-alone) high-res magnetic field measurements

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Outline

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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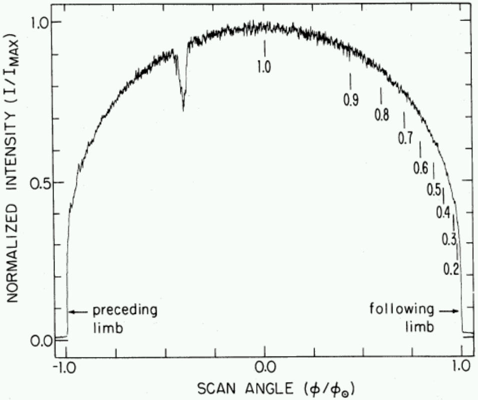

FIG. 1.—A typical drift scan plotted against scan angle $\phi/\phi_\odot$. The intensities plotted here have been corrected for zero point and normalized. Representative values of $\mu = \cos\theta$ are marked along the following half of the scan.

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Durrant et al. (1981)

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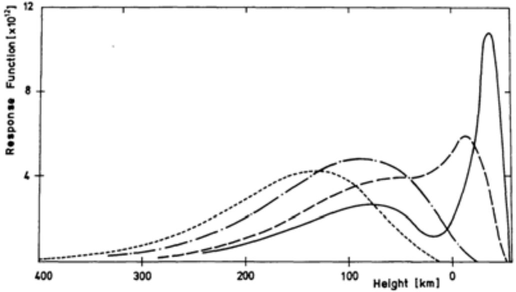

Fig.2. Temperature fluctuation response functions for continuum radiation seen at various heliocentric angles (——,μ=1.0; ---,μ=0.6; -.-.,μ=0.2; ...,μ=0.1). The abscissa gives the vertical height in the atmosphere; the optical path is 1/μ times this distance.

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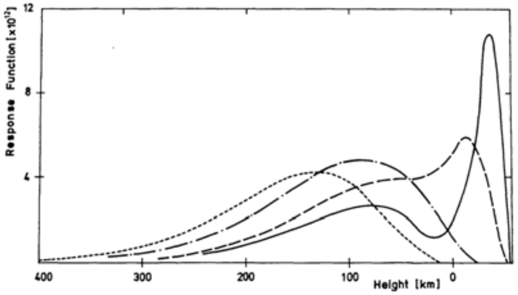

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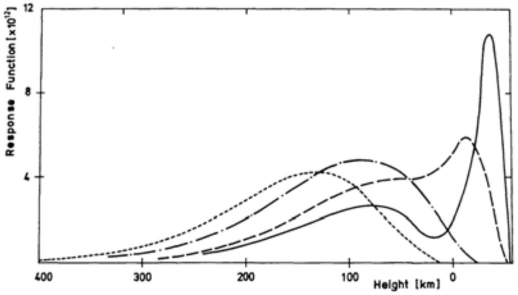

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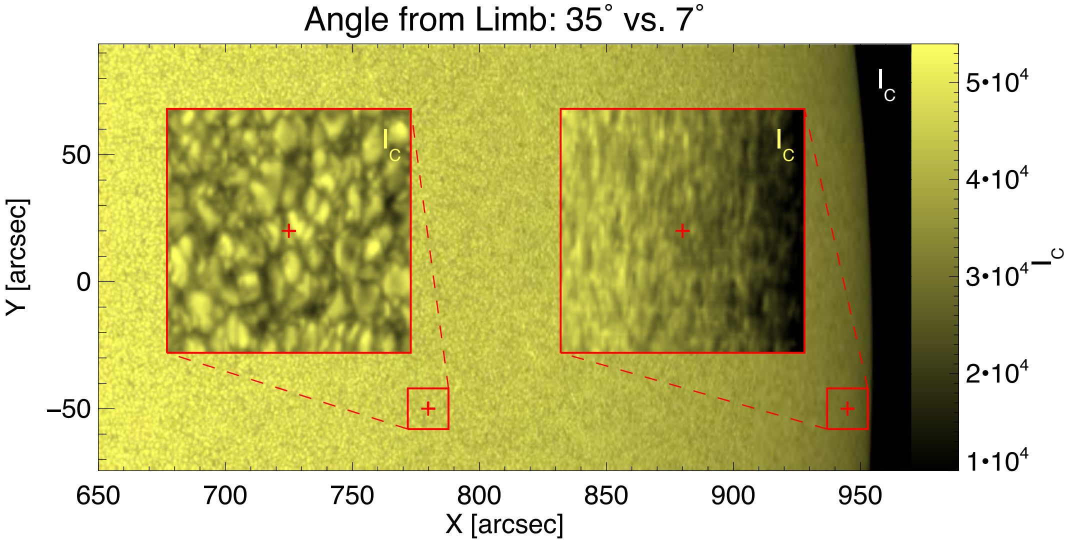
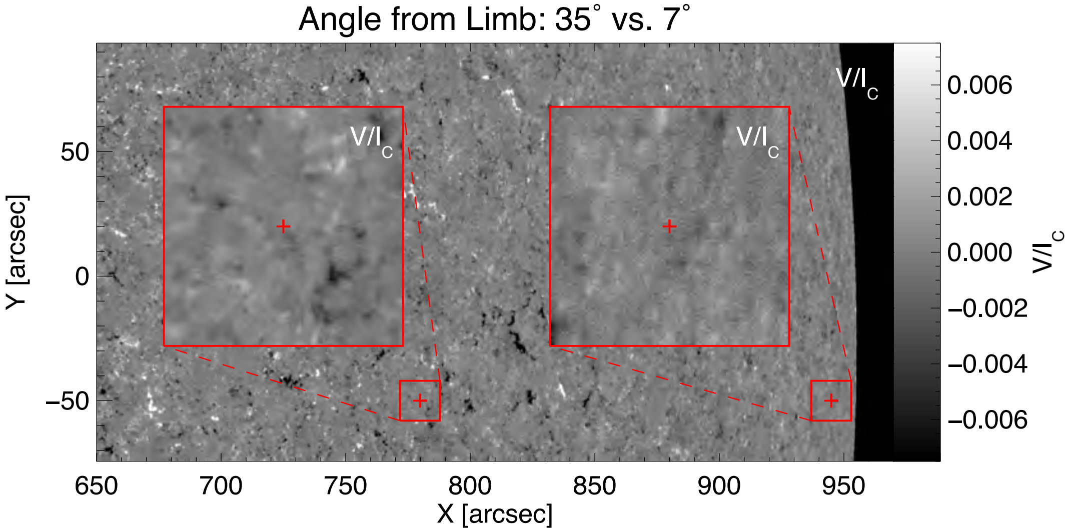
7° vs. 35° - continuum intensity



7° vs. 35° - Stokes *V*



The importance of measuring polar *B*

Relevance for *B* at polar latitudes

- 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

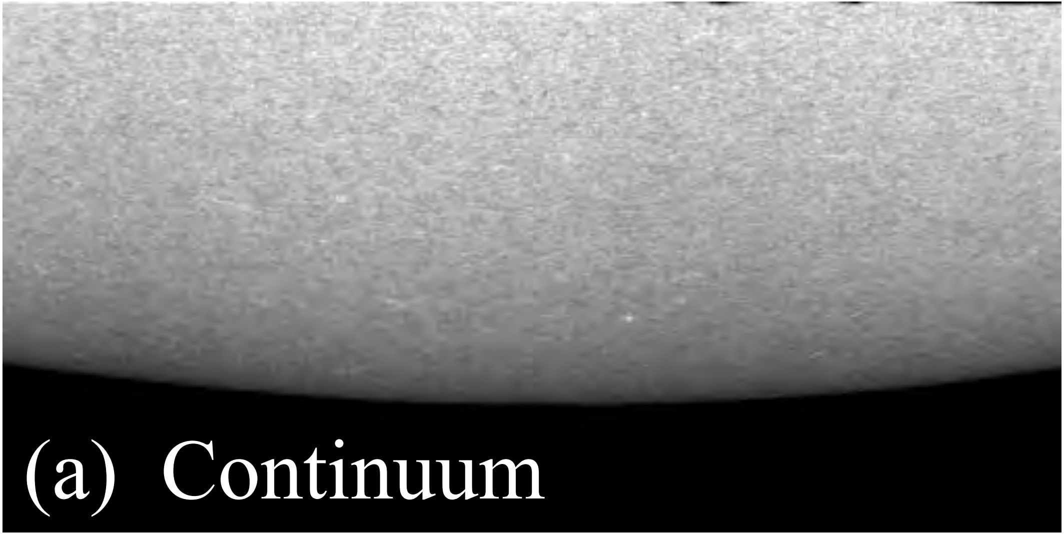
Tsuneta et al. (2008)

Best polar field measurements

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

- low straylight, stable space environment
- B0 angle: 7° ($2\times$ per year)
- 4.8 s integration time $\rightarrow$ S/N ratio 1000 (increase to 2000 is possible)

Tsuneta et al. (2008)



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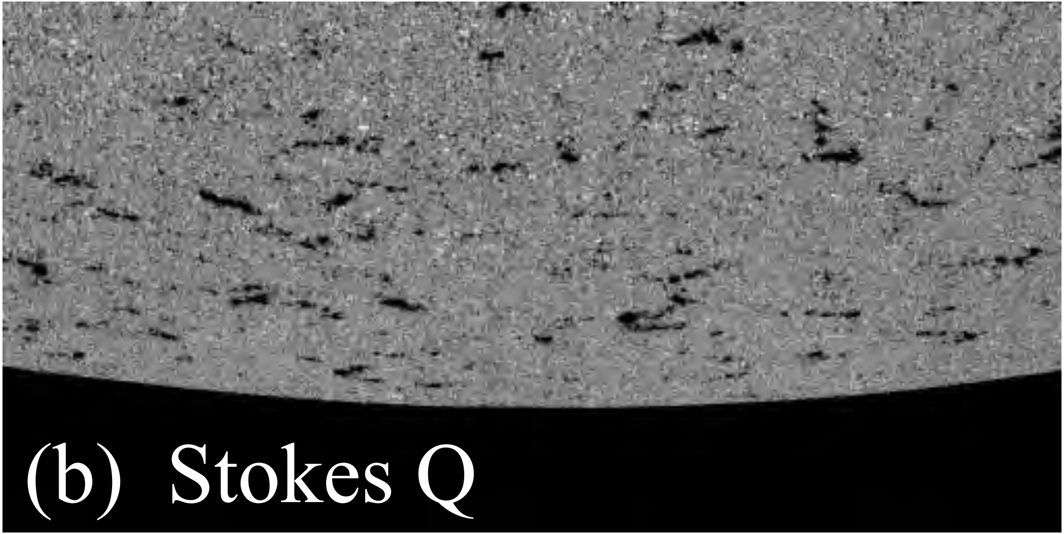

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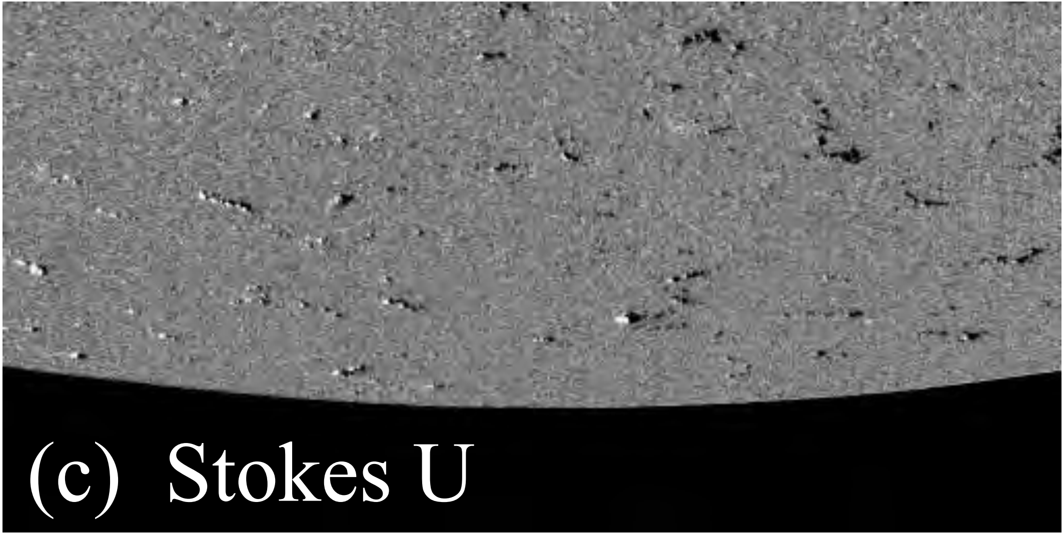

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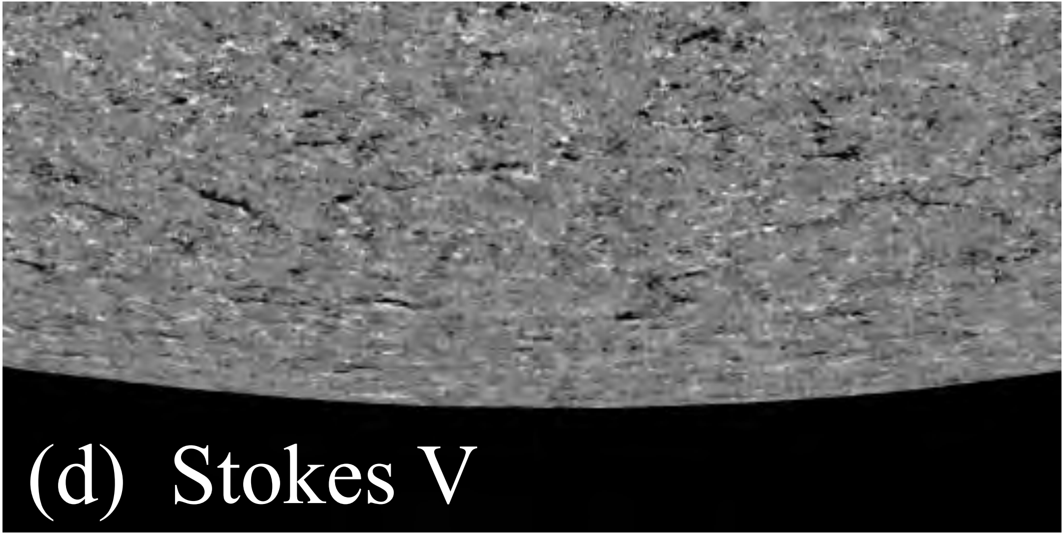

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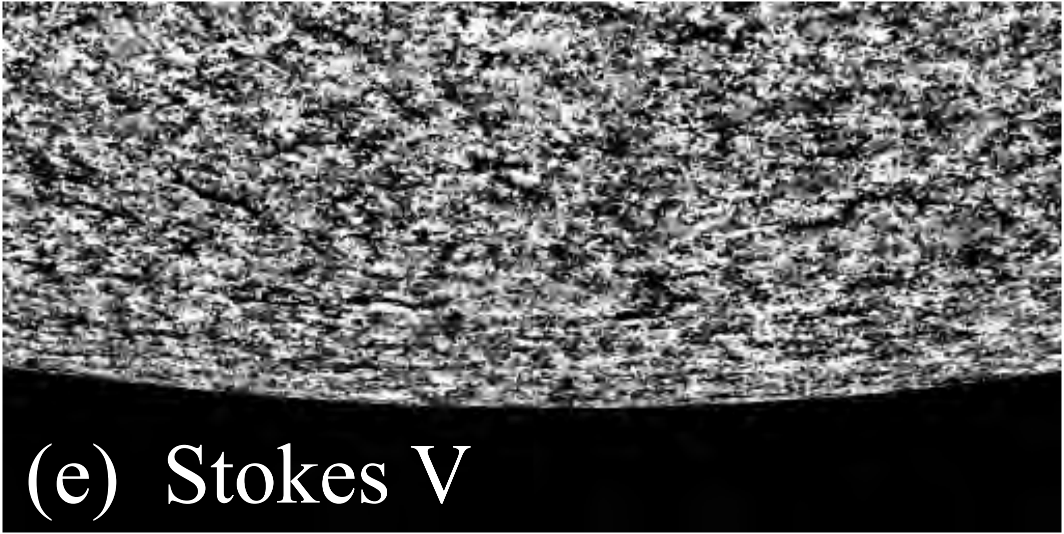

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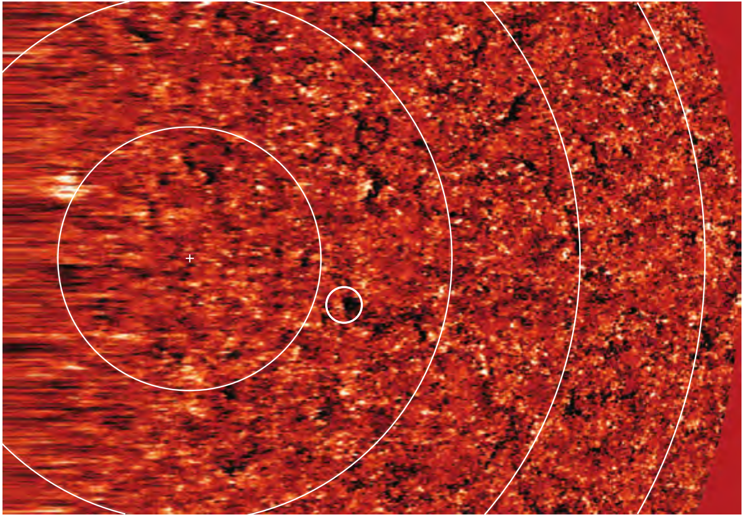


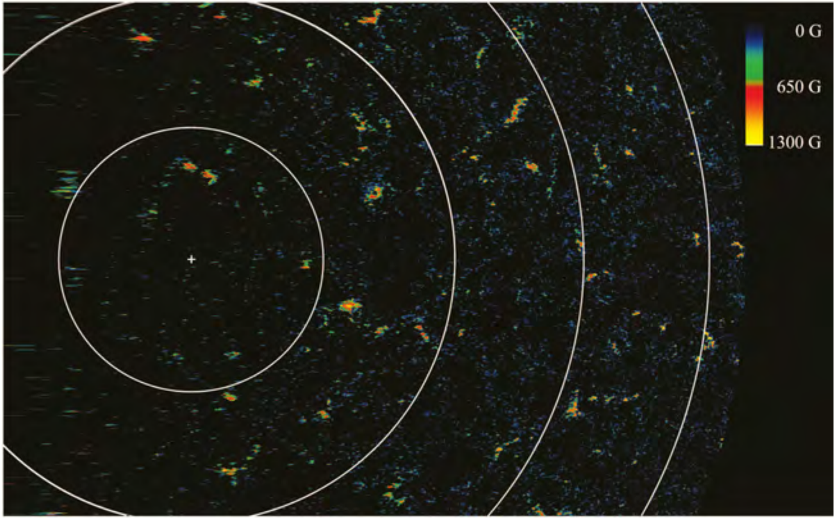
Tsuneta et al. (2008)

Analysis method

- Milne-Eddington type inversions (MILOS code, Orozco Suárez et al., 2007)
- 10 free parameters:
  - B, γ, ϕ - magnetic field vector
  - v_{LOS} - line-of-sight velocity
  - S_0, S_1 - source function & gradient
  - η_0 - ratio of line to continuum absorption coefficients
  - λ_D - Doppler width
  - a - the damping parameter
  - α - stray-light factor

  (similar to PHI onboard processing - no α)
- Q, U, or V signal $\geq 5\sigma$ (10.5% of all pixels)

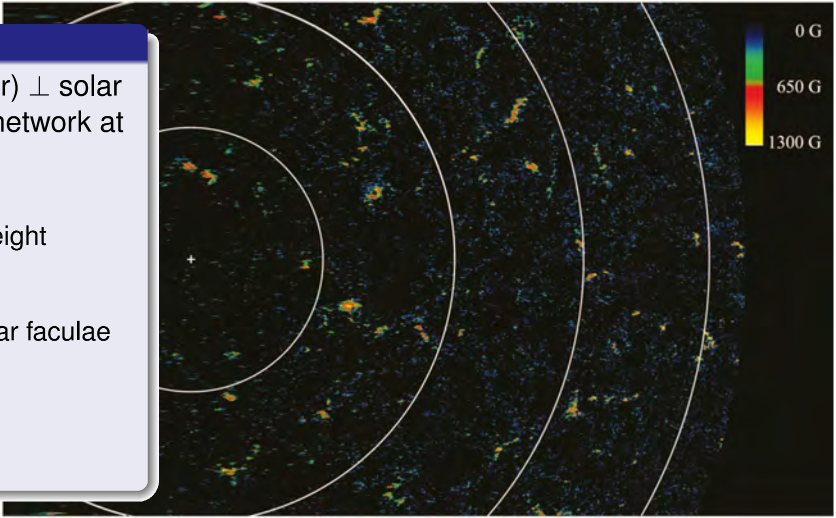
Polar landscape (Tsuneta et al., 2008)



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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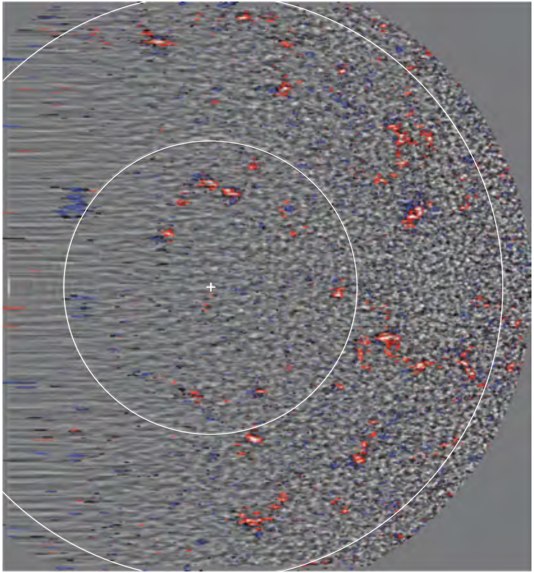

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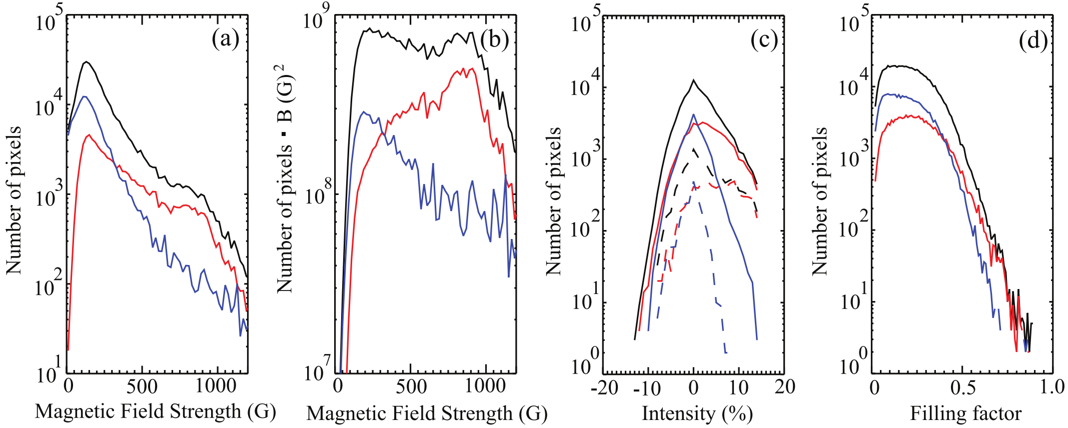

red - $B_\perp$ blue - $B_{||}$ black - total B dashed - $>$ 800 G solid - $>$ 300 G

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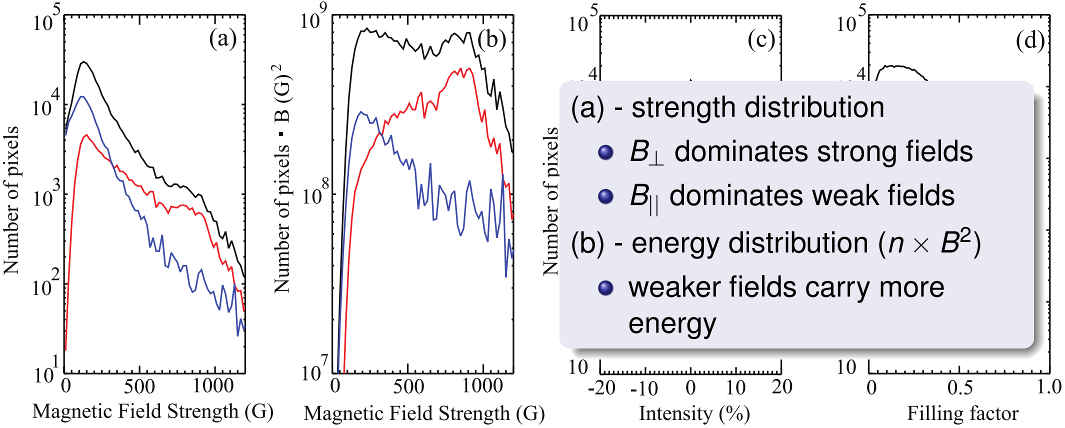

(a) - strength distribution

- $B_\perp$ dominates strong fields
- $B_{||}$ dominates weak fields

(b) - energy distribution ($n \times B^2$)

- weaker fields carry more energy

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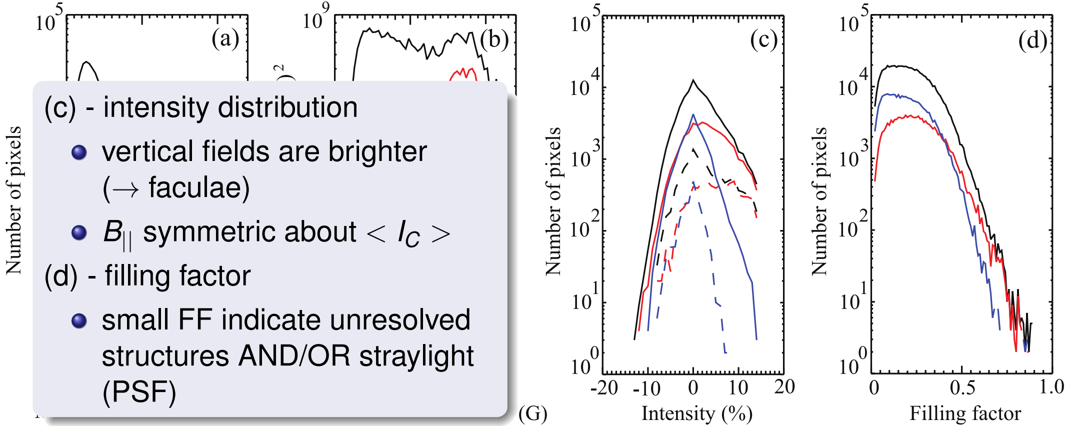

(c) - intensity distribution

- vertical fields are brighter ($\rightarrow$ faculae)
- $B_{||}$ symmetric about $< I_C >$

(d) - filling factor

- small FF indicate unresolved structures AND/OR straylight (PSF)

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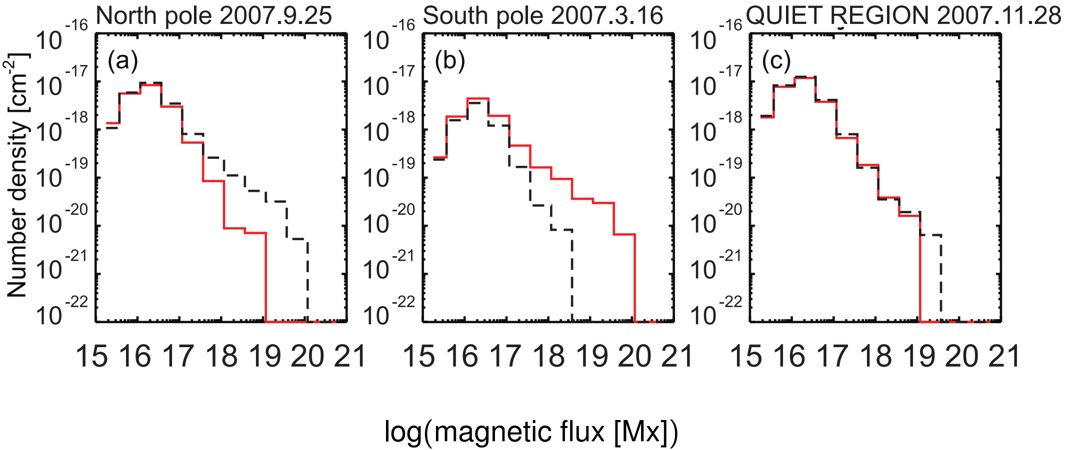
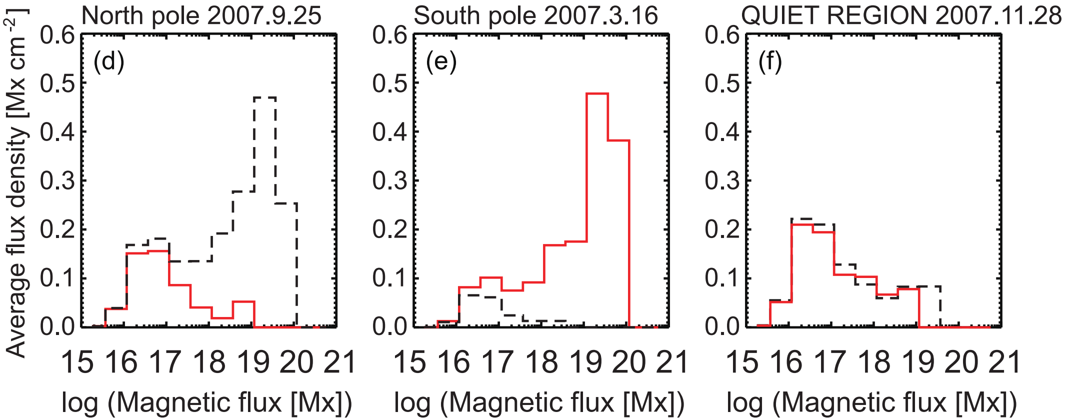
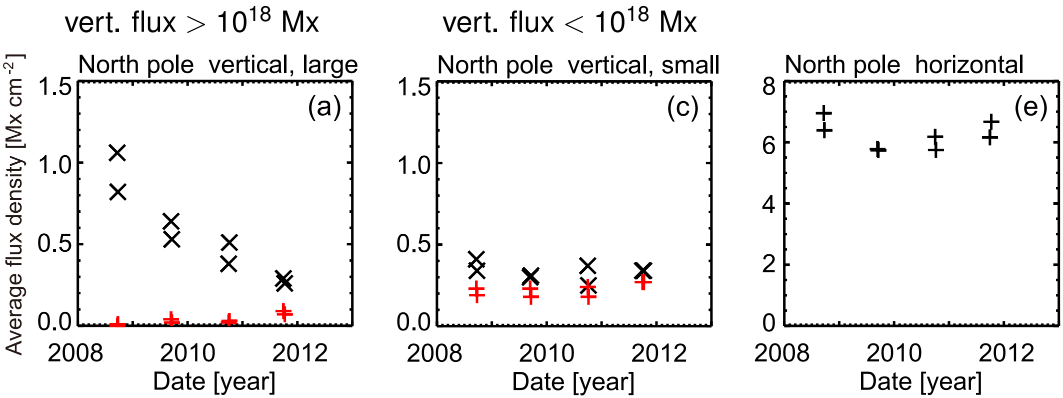
Shiota et al. (2012): *B*-flux per patch number density



Shiota et al. (2012): *B*-flux per patch avg. flux density



Shiota et al. (2012): long-term study 2008-2012



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 leyer
  - different sensitivity for $B_{\perp}$, $B_{||}$
  - 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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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

Special polar magnetic features (e.g. jets)

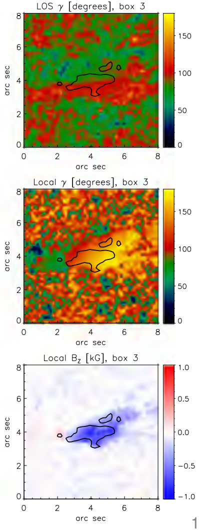
Example: details of polar jets (Quintero Noda et al., 2016)

- 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 $\perp$ solar surface
- slightly shifted wrt. continuum image towards the disc center



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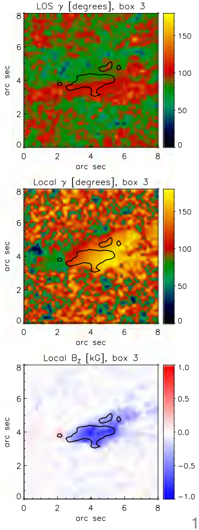
- single polarity magnetic kG fields $\perp$ solar surface
- slightly shifted wrt. continuum image towards the disc center $\rightarrow$ result of hot wall effect
- ideal for combined measurements PHI & hi-res GB

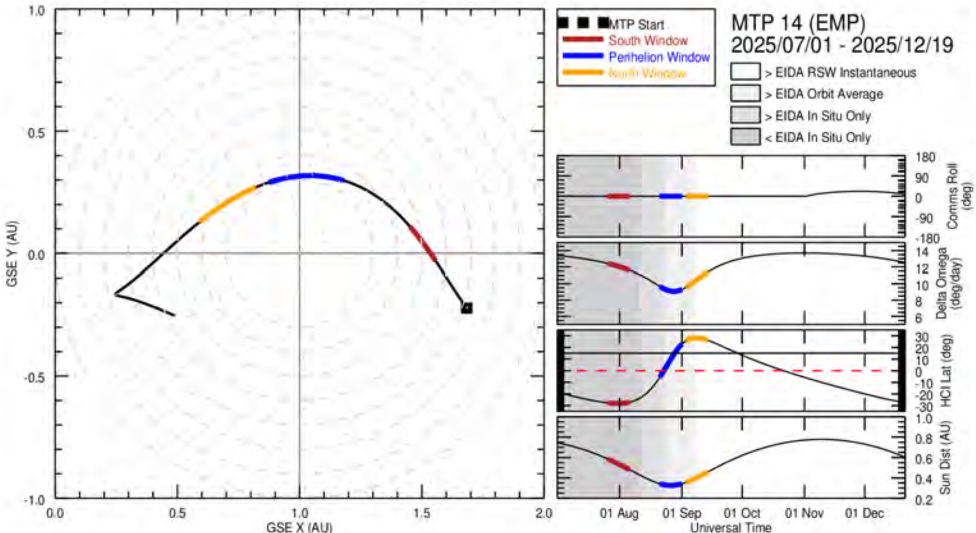


How to optimize PHI for measuring polar *B*?

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



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