Depth-dependent Inversion of a Sunspot:  
II. Global Properties

Sanjiv K. Tiwari,
(M. van Noort, A. Lagg, S. K. Solanki)

Max Planck Institute for Solar System Research, 
Katlenburg-Lindau, 37191, Germany

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Introduction & Motivation

- Sunspot fine structure: umbral dots, light bridges, penumbral filaments and spines, peripheral downflows etc.
- They are all dynamically evolving, what makes sunspot stable?
- Other issues:
  - magnetic canopy structure; thermal-magnetic relationships;
  - the Evershed flow: (magneto-) convection or siphon flow;
  - global twist, equilibrium of sunspots etc.
- Considerable advances have been achieved theoretically (Rempel et al. 2009) and observationally (Westendorp Plaza et al. 1998, Mathew et al. 2003) for last two decades. BUT controversies exist!
- Investigating global properties of sunspots, still important! Revisit with much better data and inversion scheme

Some Instructive reviews:
Solanki, 2003; Borrero & Ichimoto, 2011; Rempel & Schlichenmaier, 2011
Data

- NOAA AR 10933, observed from SOT/SP onboard Hinode

- The sunspot was observed very close to disk center ($\mu=0.99$) on 05 Jan 2007 at 1213 UT.

- The spectral lines used for polarimetric measurements are the doublet Fe I 6301.5 and 6302.5 Å.
Inversion

SPINOR (Frutiger et al., 2000; Solanki, 1987):
Comparison with pixel to pixel inversion (Tiwari, SGS, 03 July 2012)

• 2D maps of spectro-polarimetric data can be inverted simultaneously

• accounts for telescope diffraction psf

• self-consistent solution, very accurate Stokes profile’s fitting

• stable to spatial oversampling of the data; can resolve structures up to diffraction limit (van Noort et al., 2013, A&A)

• log(τ) node positions: -2.5, -0.9, 0

• Free parameters: temperature, magnetic field strength, inclination, azimuth, line-of-sight velocity, micro turbulent velocity
Global properties
B & γ with radius
B vs γ
Field azimuth and twist
$V_{\text{los}}$ & $T$ with radius
T vs B
$T$ vs $V_{\text{los}}$
B vs $V_{\text{los}}$
Summary

- Field gradient in umbra -1.3G/km; positive gradients in inner-middle penumbra, canopy outside the penumbra

- B vs γ: anti-correlated for γ<90°; correlated for γ>90° (tails of penumbral filaments)

- Magnetic field: 1kG@penumbra, more horizontal fields in deeper layers

- Darker regions contain stronger fields in general (but see trunk shape, and penumbral population)

- In penumbra a positive correlation between T & B seems to be present accounting for heads of penumbral filaments (Tiwari et al, 2013)

Summary contd..
Summary contd..

- Dominant upflows in inner penumbra, downflows in outer, consistent with the Evershed flow continuing into canopy (Solanki et al. 1999)

- Average twist is weak, -3.8deg; increase with radius?

- Downflowing mass flux 2.5 times more than upflows probably accounting for corrugated tau surface

- Upflows hotter than downflows: evidence of convection

- Upflows/downflows have weaker/stronger fields: siphon flow?
Thanks!