Magnetic field measured at different levels in the solar atmosphere and magnetic coupling

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Magnetic field is the source of Sun’s activity, which is best visible in the outer atmosphere. Field couples all atmospheric layers: Need to know magnetic field from convection zone to Corona! Major problem: Magnetic field not well known in upper atmosphere.
Measuring solar magnetic fields: techniques

- Gyroresonant emission: Radio obs. of strong fields (>250 G)
- Bremsstrahlung emission: Radio
- Coronal loop oscillations: EUV, coronagraphy (Nakariakov, next talk)
- Zeeman effect: spectro-polarimetric observations UV - IR
- Faraday rotation: radio obs.
- Scattering polarization: coronagraphy
- Hanle effect: spectropolarimetric observations UV - IR

Polarisation!
Magnetic field in photosphere

- **2 main components:**
  - strong fields (flux tube fields: sunspots, faculae, network)
  - weak fields (turbulent fields)

- **Measurement techniques:**
  - Zeeman effect (strong fields)
  - Hanle effect (weak fields)
  - Proxies (e.g. G-band)

V. Zakharov
Inversions: 3-D photospheric field

- Inversion codes deduce $B(x,y,z)$ from Stokes profiles (e.g., Auer et al. 1977, Keller et al. 1990, Ruiz Cobo & Del Toro 1992, Socas Navarro et al. 1998).

Quiet Sun fields: weak or strong?

Hot topic: controversial results

- **Network**: kG fields (Stenfö 73)
- **Internetwork**: Results depend on technique
  - Zeeman in visible: mainly strong (kG fields, i.e. flux-tube like)
  - Zeeman in IR: weak (<500 G)
  - Hanle: large flux in turbulent B
- **Comparison visible vs. IR**
  - Systematic errors when inverting Fe I 6302 & 6301 (Collados et al.)
Hanle measurements

- Depolarisation of Sr I resonance line gives $<B> = 40$-60 G hidden turbulent field (Trujillo Bueno et al. 2004) ➔ less magnetic energy density than the strong field.

- Trujillo Bueno et al.: if exponential PDF of magnetic field obtained from simulations is used, then the weak internetwork field magnetic energy density is larger than that in the network field (flux tube field).

➤ Consider the simulation PDFs more carefully
Radiation-MHD Simulations of small-scale magnetic fields

Box: 6000x6000x1400 km
Grid scale: 10x10x14 km
Initial condition: B=200 G, homogeneous unipolar field
Details: Vögler et al. 2004, 2005, Vögler 2004
horizontal cuts near surface level

Vögler et al. 2003
Radiation-MHD Simulations of small-scale magnetic fields

Log(|B|) for a homogeneous initial field of 10 G.

Brighter is stronger field.
Complex PDF of B shows more or less exponential drop-off at large B values.
Synthetic vs. Observed Field Strength PDFs (Probability Distribution Functions)

Synthetic: $B(t=0)=10G$

Observed

- Internetwork: Vögler et al. 2005
- Internetwork: Khomenko et al. 2003

Exponential drop in PDF over the field strength range covered by 1.56 μm observations

- Red: 10 km
- Black: 20 km

Splitting, [Å]

7808 profiles
Stokes V

Splitting, [G]

Vögler et al. 2005, Khomenko et al. 2003
Quiet Sun fields: weak or strong?

- Internetwork: comparison with simulations:
  - Compare distribution of Stokes V amplitudes of simultaneously measured visible and IR lines with same quantity from simulations
  - vis & IR lines reproduce simulations for $<B> = 20G$

Khomenko et al. 2005
**Quiet Sun fields: why are they of interest for magnetic coupling?**

- Hanle effect interpreted in terms of exponential PDF (based on MHD simulations) gives larger energy in internetwork than in network field (Trujillo et al 04)

- Actual MHD PDF shows 2 distinct regimes:
  - Rapid drop at weak fields: turbulent field
  - Slow drop at strong fields: flux-tube-like fields

→ Most of the magnetic energy is in the strong flux-tube field
Extrapolations of magnetic field from photospheric magnetograms

Important help for knowing magnetic field in corona

Hurdles:
1. 180° ambiguity in vector field
2. Field not ff in photosphere, etc.
3. Large resources needed for realistic extrapolations

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Wiegelmann 2005
Why are Coronal Holes not visible at transition region temperatures?

CH and QS in EIT Fe XII & MDI + overlaid magn. loops (for B > 20G): Many more long loops in QS than in CH. Small loops equally present in both regions. T~L^{1/3}: hot loops depleted in CH, cool loops equally present in QS and CH

Wiegelmann+Solanki 2004
B in fast solar wind source region

Tu, et al., Science, 2005
Chromospheric magnetism

- **Zeeman effect:**
  - Hβ from Huairou observatory (many papers by H. Zhang and his group)
  - Ca IR triplet (Socas Navarro & co-workers)
  - He 10830 (Harvey & Hall 1971, Rüedi et al., Penn & Kuhn, Solanki et al., Socas Navarro et al)
  - Na I D lines (Eibe et al. 2002)

- **Hanle effect:**
  - Ca I and Sr II lines (Bianda et al.)
  - He 10830 (Trujillo Bueno et al., Lagg et al.)
Bao & Zhang (2003):
- chromospheric magnetic field from Hβ filament
- LOS-field: 40-70 G
- evidence for twisted magnetic configuration inside the filament

Measurements in Chromosphere & Photosphere

Solar Magnetic Field Telescope in Huairou Solar Observing Station
Structure of Magnetic Loops

Magnetic loops deduced from measurements of He I 10830 Å Stokes profiles in an emerging flux region.

Left projection: Field strength
Right projection: Vertical velocity

Solanki et al. 2003
Testing Magnetic Field Extrapolations

- Non-linear force-free fields reproduce the loops reconstructed from observations better than the linear force-free ones and far better than potential fields.
- Loops harbour strong currents while still emerging.

Wiegelmann et al. 2004
Current sheets

Multiple large current sheets found, but not very common

13may01.014, avg.fit=2.38
atm_archive/atm_13may01.014_v01_1comp/input.ipt

OBSERVATION
13may01.014; observation in one of three formats: 1) sav
2) h5 -- these cannot be used for analysis (may be only a vector containing xmin,xmax of the
3) mfh -- including ymin,ymax of the

WL_RANGE 10825. 10835. ;WL-range to be used for analysis (may be only a
XPOS 0 150 ;two-elements vector containing xmin,xmax of the
YPOS 0 100 ;two-elements vector containing ymin,ymax of the
STEPX 1 ;step size for going from xmin to xmax
STEPY 1 ;step size for going from ymin to ymax
AVERAGE 1 ;if 1 then average observation over the stepx/stepy
SCANSIZE 0 ;stepsize of multiple scans within one observation
SYNTH 0. ;if 1 then create synthetic profile
NOISE 0. ;noise level for adding artificial random noise
SMOOTH 0 ;ssmooth-value for profiles and smooth-method:
STRAYPOL_AMP 0.0 ;amplitude for stray-polarization (only used for
CCORR 1. ;factor for I (constant continuum correction)
STRAYPOL_CORR 100.0000 B ;iteration steps and orientation of
NCOMP 1 ;number of components
BFIEL 000.00 0.00 2000.00 4 100 4 ;magnetic field value in Gauss
AZIMU 1.00 -90.00 90.00 3 100 3 ;azimut of B-vector [deg]
GAMMA 1.00 0.00 180.00 2 100 2 ;inclination of B-vector [deg]
VELOS 0.00 -20000.00 50000.00 1 10 1 ;line-of-sight velocity in m/s
VDAMP 0.35 0.00 0.70 0 100 1 ;damping constant (Voigt only)
VDOPP 0.10 0.01 0.70 1 100 1 ;doppler broading (Voigt only)
EZERO 1.00 0.00 10.00 0 100 -1 ;amplitude of components of propagat
SGRAD 1.00 -4.00 8.40 1 100 1 ;gradient of source function
ALPHA 0.50 0.01 0.99 0 100 0 ;Filling factor for this component
USE_LINE He ;Lines to be used for this component. This allows to
IQUV_WEIGHT 1. 1. 1. 1. 1. 1. 1. 1. ;4-element vector defining relative weighting
WGT_FILE he_default.wgt ;file with WL-dependent weighting function for IQUV
PROFILE voigt ;functional form for pi- and sigma components of MAG
MAGOPT 1 1 ;include magneto-optical effects (dispersion
USE_GEFF 1 1 ;use effective Lande factor (=1) or real Zeeman
CODE FORTRAN ;PIKAIA code to use. Available: FORTRAN (=fast) or
METHOD 0 ;minimization method: PIKAIA or POWELL (fast)
NCALLS 400 00 ;number of iterations in PIKAIA routine / max.

0 5 10 15 20 25
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Radio Measurements

- **Bremsstrahlung**: from collisions of e\(^-\) with ions \(\rightarrow\) e\(^-\) density diagnostic tool. Polarisation: weak longitudinal B fields

- **Gyroresonance**: emission from nonrelativistic thermal plasma at low harmonics of the electron gyro-frequency, \(f_B = 2.8 \times B \text{ MHz}\)

- **Gyrosynchrotron**: emission by mildly relativistic e\(^-\) at harmonics 10-100 of the gyrofrequency

- **Plasma emission**: caused by electrostatic Langmuir waves

*White (2002)*
Coronal Zeeman effect

- Coronagraphic measurements in Fe XIII 1074.7 nm (Lin et al. 2000)
- Coronal Multi-channel Polarisimeter: (CoMP; Sac Peak): IQUV
- **Problem:** LOS integration.
- **Possible solution:** vector tomography (Inhester et al.)

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Atom alignment; scattering polarization.

90° ambiguity

measurements in the sub-Gauss range expected

S. Tomczyk, 2004

FeXIII 1074.7 Line-of-Sight Velocity 4/21/05

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ATST: measurements in the sub-Gauss range expected

90° ambiguity

measurements in the sub-Gauss range expected

S. Tomczyk, 2004
Conclusions

- **Magnetic field measurements in photospheric layer** are of a high standard
  - Still open questions: structure and strength of the field in the very quiet Sun (internetwork and turbulent field)

- **Rapid recent progress in study of chromospheric magnetism**
  - Many open questions: E.g., how common are chromospheric current sheets and how are they related to flares and coronal heating

- **Progress in coronal field measurement needed**
  - Improved radio data (FASR, 2009)
  - Development of other techniques, incl. UV Hanle effect measurements (e.g. Solanki et al. 2006)