Sunspot structure

Rolf Schlichenmaier
Kiepenheuer Institut für Sonnenphysik
Freiburg, Germany
www.leibniz-kis.de
1. Sunspot structure modelling

2. Umbral & penumbral fine structure & opposite polarity

3. Jurčák criterion (empirical law):
   a) magnetic property of U/PU boundary
   b) penumbra formation
| Name        | Year  | Description                                                                 |
|-------------|-------|-----------------------------------------------------------------------------|
| Hale        | 1908  | Sunspot manifest concentrated magnetic field                                |
| Evershed    | 1909  | Velocity field not vortical but radial                                     |
| Biermann    | 1941  | Magnetic field suppresses convection                                        |
| Hoyle       | 1949  | Heat dilution by fanning out                                                 |
| Jurčák      | 2011  | Vertical magnetic field hinders penumbral convection                         |
Global sunspot models

Key issues: Energy transport and stability!

Meyer, Schmidt, & Weiss 1977:
Fluting instability
Stability, if inclination of magnetopause large enough.
Magnetohydrostatic models

\[ \frac{1}{4\pi} \left( \nabla \times \mathbf{B} \right) \times \mathbf{B} = \nabla p - \rho \mathbf{g} \]

Based on:
- Schlüter & Temesvary 1958
- Chitre 1963
- Deinzer 1965

MHS models:
- Schmidt & Wegmann 1983
- Pizzo 1986, 1990
- Jahn 1989
- Jahn & Schmidt 1994

- Mixing length theory plus assumption of interchange convection
- Electric currents along sheets or in volume

Inconsistency: static field in convective stratification
Globally static with dynamic fine structure

Dynamic flux tube embedded in tripartite MHS model of Jahn & Schmidt 1994.

(Schl., Jahn, & Schmidt 1998)
Dynamic penumbral fine structure

- Instability driven by radiative heat exchange in photosphere.
  → Superadiabatic stratification beneath photosphere.

- Surplus gas pressure:

  \[ \frac{B^2}{8\pi} + p = \frac{B_b^2}{8\pi} + p_b \]

  \[ \Rightarrow H_{B_b^2/8\pi} \gg H_{p_b} \]

  \[ \Rightarrow p > p_b \]

  \[ \Rightarrow \nabla p \text{ accelerates plasma.} \]

  \[ \Rightarrow \nabla p \text{ sustained by radiative cooling.} \]

- Footpoint migrates inwards while plasma flows outwards.

Moving tube model:
- Evershed flow by rising flux tube
- Hot upflow migrating inwards, cooler radial outflow
- Horizontal tube in more vertical background

(Schl., Jahn, & Schmidt 1998)
Penumbral filament as moving flux tubes

- Penumbral grain
- PG tails
- PG inward migration
- Evershed flow
- Downflow in outer PU
- Uncombed penumbra
- Surplus brightness of PU
- Formation of penumbra

- Footpoint of tube
- Radiative cooling
- Footpoint migration
- Flow along tube
- Sea serpent solution
- Tube in background
- Hot upflows
- Angle of magnetopause

10 km/s
4 Mm

Temperature [1000 K]
U: local magneto-convection

Schüssler & Vögler 2006:
- local magneto-convective bubble in vertical magnetic field
- 'flux expulsion' á la Weiss (1964)
- umbral dots

GREGOR, BBI, 486nm, KISIP reconstructed
PU: Mag-con elongated cell

(Rempel 2012)
Opposite polarity in penumbra

Magnetic neutral line (spot at 30 deg):
- Multi-lobe V profiles
- Two components of opposite polarity along LOS necessary!

see also: Sanchez Almeida & Lites 1992

Stokes-V in Fe I 1564.8 nm

Amplitude asymmetry

1950 G

4-lobe profile

3-lobe profile
Penumbral downflows

Spot at 3 degree, line wing Doppler shift, Hinode-SP (Franz & Schl. 2009)

more downflows:
Joshi et al. 2011
Scharmer 2011
Scharmer & Henriques 2012
Scharmer et al. 2012
Tiwari et al. 2013
Temporal evolution of lateral downflows in penumbral filaments and their tem- peral evolution: Joshi et al. 2012
Scharmer et al. 2011
Scharmer & Henriques 2012
Scharmer et al. 2012
Tiwari et al. 2013

Esteban et al. 2016:
inner upflow,
outer downflow and lateral downflows
Opposite polarity: spot at disk center

Opposite polarity throughout the penumbra
(Sanchez Almeida 2005, Franz & Schl. 2013, Ruiz Cobo & Asensio Ramos 2013)

(SP@SOT Hinode)

Fig. 6, Rempel 2012
Three-lobe V profiles in Fe I 630 nm

$v_{\text{dop}}$ : line wing shift of Stokes-I
Three lobe profiles are redshifted.

Franz & Schl. 2013
Three-lobe V profiles in deep photosphere

Deep forming line with GRIS@GREGOR shows much less signals of opposite polarity than expected from mid-photosphere line with Hinode-SP.

Franz et al. 2016
0.08 arcsec with GREGOR-BBI

- Filamentary light bridges with elevated dark lane (Lites et al. 2004) associated with upflows (Rouppe van der Voort et al. 2010)

- Light bridge with elevated plateau and unconnected 'Y'-shaped dark lanes (new type)

NOAA 11757, 589 nm, 9 deg
Central dark lanes and their branches:

- Dark lanes in most cases have branches.
- Dark lanes extend along the light bridge of the middle pore at different heliocentric angles and (ii) viewed along the light bridge. Viewed in a spot close to disk centre.

- Dark lane extends along the light bridge of the middle pore. At (i) observed at large heliocentric angles and (ii) viewed along the light bridge. The spot in Fig. 7 is at heliocentric angle: 41 degree.

Scharmer et al. (2002) called them hairs, and Lites et al. (2004) ascribed their triangular structure to the projection effects of elevated light bridges. Such lateral bright and dark lanes could correspond to hot upflow and cold downflow areas, respectively. The triangular shape is a result of piled-up matter (Schüssler & Vögler 2006), while the central dark lane is at its upper ridge. The lateral slopes and junctions of dark lanes are also prominently visible in the wide arrow marks the direction to disc centre. The small arrows indicate the three light bridges referred to in the text. The white box corresponds to the larger arrow marks the direction to disc centre. The small arrows indicate the three light bridges referred to in the text. The white box corresponds to the large arrow marks the direction to disc centre.
Light bridge fine structure

'Y'-shaped dark lanes appear like penumbral grains.

→ inclined magnetic field (field lines wrap around light bridge)
Bright 'dots' are connected by dark lane.

→ Light bridges exist at lower intensity levels!

→ Faint light bridges

Question: Are all umbral dots connected by dark lanes?
The Jurčák criterion

Prior to 2011:
- U-PU boundary defined by intensity threshold
- Magnetic field quantities vary smoothly across the boundary.

Jurčák 2011: "The vertical component of the magnetic field is constant along the U/PU boundary."

→ Chandrasekhar 1961 ('Hydrodynamic and magnetodynamic stability'): Magneto-convection in inclined field
   → Onset of convection depends on vertical component
   → Horizontal component 'just' shapes

→ Jurčák et al. 2017, in prep.: Statistical proof of empirical law.

"In fully-fledged sunspots, $B_{\perp} = 1860$ G invariant along the U/PU boundary"

- Hinode/SP measures all sunspots in an identical way.
- Hinode/SP spot data with 'simple' inversion
- Transform to local frame
- Contour of $B_{\perp} = 1860$ G
Fig. 4. Analogous to Fig. 3, bifurcations $2U_a, c)$ and $7U_b, d)$. The solible black line in $B$ plots mark the vertical component of the magnetic field strength.

Using the resulting values of magnetic field strength and inclination, I derive the vertical component of the magnetic field ($B_{ver}$) on the inner penumbra boundaries. In Fig. 4, the $B_{ver}$ is shown along $2U$ and $7U$ boundaries. The $B_{ver}$ does not show any azimuthal variations along these boundaries, although both $B$ and $\gamma$ vary. There are some local fluctuations of $B_{ver}$ that are caused by fine structure at the inner penumbral boundaries. At the $2U$ boundary (Fig. 4c), the vertical component of the magnetic field drops by 300 G in regions where the bright penumbral filaments protrude deeply into the umbra, $\psi = [-170^\circ, 170^\circ]$. At the $7U$ boundary (Fig. 4d), similar decrease in $B_{ver}$ can be seen around $\psi = -40^\circ$, which corresponds to a small intrusion into the penumbra.

In Table 5, I show the median value of $B_{ver}$ at the studied boundaries along with their standard deviations. The uncertainties are significantly lower than those of the magnetic field strength listed in the second column of Table 4, because the vertical component of magnetic field does not vary along the boundaries. The average uncertainty is 190 G including all listed inner penumbral boundaries and 170 G, if the 5U boundary is omitted (the origin of the high $\sigma_{ver}$ on this boundary is unknown). Using the average errors of $B$ and $\gamma$ computed by the inversion code, the error of $B_{ver}$ is 98 G.

The value of $B_{ver}$ on the inner penumbral boundary is usually not specified in previous studies, but using the average values of $B$ and $\gamma$ from azimuthal averages, the vertical component of the magnetic field strength would be comparable to the values listed in Table 5.

5. Discussion

In Fig. 5, I show the dependence of magnetic fields strength on the cos($\gamma$) both inner and outer penumbral boundaries. The model dependence is $B_{ver}$.

Jurčák 2011
...other sunspots

Jurčák, Rezaei, Bello González, Schl. in prep.

$B_\perp = 1860$ G
Time evolution of boundary

HMI:
Disk passage of AR 11591
\( B_\perp = 1700 \text{ G} \)

Markus Schmassmann,
master thesis @KIS in prep. 2017
\( B_{\text{vertical}} \) constant, \( B \) not!
Empirical law of U/PU boundary

Empirical law for stable sunspots (Jurčák law):

1. An invariant value of the vertical component of the magnetic field discriminates between the umbra and penumbral mode of magneto-convection.
2. The exact value of this invariant depends on the measurement process. With our data and inversion method, we find a value of 0.19 T.

Meaning of invariancy: No dependency on
- phase in solar cycle
- on evolutionary stage
- size of sunspot

Conjecture: Jurčák criterion
Contour of $B_\perp = 0.19$ T trespasses the umbra.
Then, penumbra is susceptible to develop.
I.e.: For penumbra to develop 2 conditions are necessary:
   (1) $B_\perp < 0.19$ T
   (2) Magnetic field needs to be inclined.
...evolving regions

$B_\perp = 1860$ G

Jurčák, Rezaei, Bello González, Schl. in prep.
Jurčák et al. 2017

Formation of orphan penumbra, because vertical component of magnetic field is smaller than the Jurčák value.

Umbra converts into penumbra.
Open issues

• Does the Jurčák criterion also apply to stable pores?
• How is the Jurčák criterion linked to plasma beta and/or equipartition field strengths?
• Do the field lines with $B_\perp > 0.19$ T form the main component of the AR, which is anchored up in the corona connecting the two AR polarities?
• Where does the strong field come from?

Wentzel 1992
....ende...