Deciphering the process of penumbra formation

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transitions from pores to spots is triggered by magnetic field inclination exceeding 45 deg

such inclinations are found on boundaries of magnetic flux tubes with $\Phi$ of $1-7 \times 10^{20}$ Mx

this is in agreement with observed values of $\Phi$ in protospots

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Rezaei et al., 2012, A&A, 537, A19: $4 \times 10^{20}$ Mx

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we found observational support for this finding
there is no minimal magnetic flux necessary for a penumbra formation

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Stable umbra/penumbra boundary

Apparent motions of penumbral bright grains

Jurčák et al., 2015, A&A, 580, L1
Stable umbra/penumbra boundary

Vertical component of the magnetic field defines the boundary

- both magnetic field strength and inclination vary significantly along umbra/penumbra boundaries of developed sunspots
- the stronger the field is on the boundary, the more horizontal it is
- this results into a constant value of the vertical component of the magnetic field strength ($B_{\text{ver}}$) along the boundary
- possible weak dependence of $B_{\text{ver}}$ on the sunspot size

Penumbra formation

VTT data
G-band imaging (continuous)
GFPI spectropolarimetry (continuous)
Schlichenmaier et al. 2010, AN
Schlichenmaier et al. 2010, A&A
Rezai et al. 2012, A&A
Bello Gonzalez et al. 2012, A&A

Hinode data
G-band imaging (continuous)
spectropolarimetry (sparse)

Hinode 9, Belfast, 16 Sep 2015
Triggering the penumbra formation

Jurčák et al., 2014, PASJ, 66, 3
Forming umbra/penumbra boundary

Apparent motions of penumbral bright grains move the boundary towards the umbral core

Jurčák et al., 2015, A&A, 580, L1
Forming umbra/penumbra boundary
Change of its position

- The forming umbra/penumbra boundary migrates toward the sunspot centre.
- The mean distance to the umbral core decreases by approximately 20% in the first 4 hours.
- The umbra/penumbra boundary is stationary in developed sunspots.
- The mean distance to the umbral core fluctuates within ±1% of this distance.

Jurčák et al., 2015, A&A, 580, L1
Forming umbra/penumbra boundary
Evolution of the $B_{\text{ver}}$ on the UP boundary

- before the rapid evolution of penumbral filaments, the $B_{\text{ver}}$ is decreasing
- as the forming umbra/penumbra boundary migrates toward the sunspot centre, $B_{\text{ver}}$ increases
- $B_{\text{ver}}$ saturates around 1.3 kG when the umbra/penumbra boundary reaches a stable position

Jurčák et al., 2015, A&A, 580, L1
Forming umbra/penumbra boundary
Final stage – comparison with Hinode data

- the last GFPI scan (at 12:40 UT) is co-temporal with a Hinode scan of the region
- after the co-alignment of the studied umbra/penumbra boundaries, we found the vertical component of the magnetic field around 1.8 kG using Hinode data
- this value is comparable to the vertical component of the magnetic field strength on the umbra/penumbra boundaries of small developed sunspots
- the obtained discrepancy is partly caused the atmospheric stray. The main cause is a difference of resulting inclination values. We speculate that this difference might be due to limitations in the polarimetric calibration of the GFPI data
Penumbra formation at a pore boundary

- The penumbra develops at a boundary of a pore located close to the polarity inversion line (PIL).
- Total vertical magnetic flux is at maximum $9 \times 10^{19}$ Mx.

Hinode 9, Belfast, 16 Sep 2015
Penumbra formation at a pore boundary

The critical magnetic field inclination of 45 deg

- histogram of magnetic field inclination in the pore area
- at all times, the maximum inclination in the dark pore is below 45 deg
- this is matching the critical magnetic field inclination derived by Rucklidge et al. 1995, MNRAS, 273, 491
Conclusions

- the penumbra formation is triggered by large inclinations
- the magnetic flux is not a key factor for a penumbra formation, only favorable configuration of the magnetic field is necessary
- the motions of bright penumbral grains results into a migration of a forming umbra/penumbra boundary towards the sunspot centre
- the forming penumbra extends to umbral regions where $B_{\text{ver}}$ is smaller than the canonical $B_{\text{ver}}$ value around 1.8 kG
- this confirms the previously found canonical value of $B_{\text{ver}}$ on stable umbra/penumbra boundaries
- if $B_{\text{ver}}$ is everywhere smaller than the critical $B_{\text{ver}}$ value, the forming penumbra eventually dissolve the pore and orphan penumbra can be observed
- the penumbral mode of magneto-convection is suppressed by strong enough $B_{\text{ver}}$