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High-resolution imaging and near-infrared spectroscopy of penumbral decay

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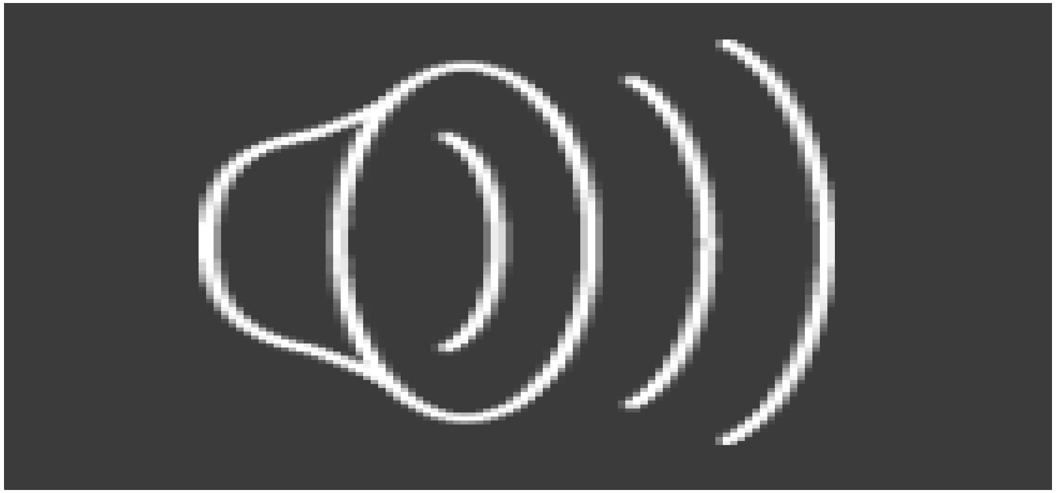
Relation between decaying sunspot penumbra and flux emergence

- Künzel (1969) found that the polarity, magnetic field strength, and size of a neighboring spot influence the penumbra of the sunspot. He also noticed that no penumbra forms between the spots of same polarity.
- Flux emergence in the vicinity of a sunspot inhibits the formation of a stable penumbra as demonstrated by Schlichenmaier et al. (2010) and Rezaei et al. (2012).
- Lim et al. (2013) observed the formation of a non-radial penumbra in a flux emergence region with pre-existing chromospheric canopy. Murabito et al. (2017) observed that a stable penumbra was formed in a sunspot at the site facing region of flux emergence.
- These sometimes contradictory findings lead to the question what role does magnetic flux emergence and its interaction with with photospheric plasma play in the decay of sunspot penumbrae?
- In present work, we provide an answer to this question. We present high-resolution GREGOR observations of a decaying sunspot, where the decaying penumbra faces the flux emergence site.
- We combine high-resolution spectropolarimetric and imaging data.
- We scrutinize the three-dimensional velocity and magnetic fields of the sunspot and its surroundings.

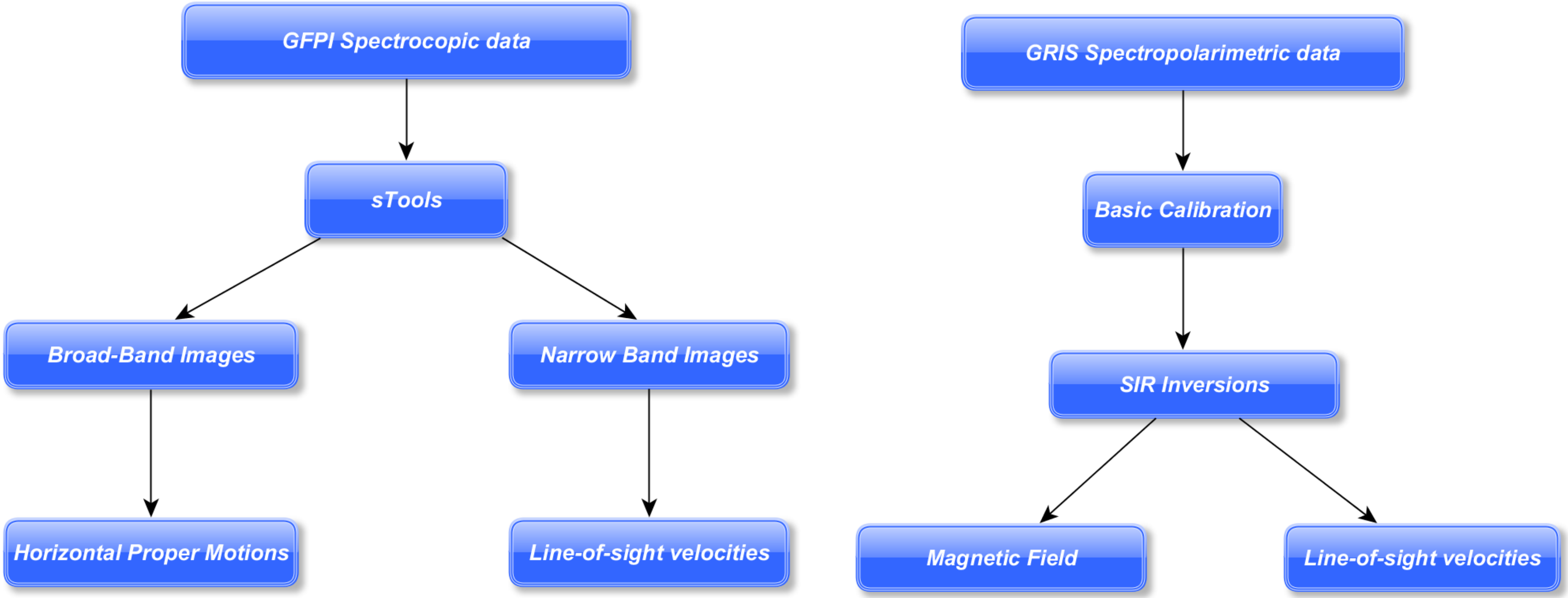
GREGOR observations

- GFPI – Imaging Spectroscopic data in the Fe I 617.3 nm line
- One line scan ~ 24 s
- ~ 100 scans starting at 08:52 UT on September 24
- FOV of $56'' \times 42''$
- Level 1 & Level 2 MOMFBD data

- GRIS - IQUV Stokes spectra in 1083.0 nm spectral range
- Si I 1082.7 nm (photosphere)
  He I 1083.0 nm (chromosphere)
  Ca I 1083.9 nm (photosphere)
- Two scans: 09:02 UT and 10:30 UT
- 360/300 steps covering FOV of $62'' \times 52''$ / $62'' \times 42''$

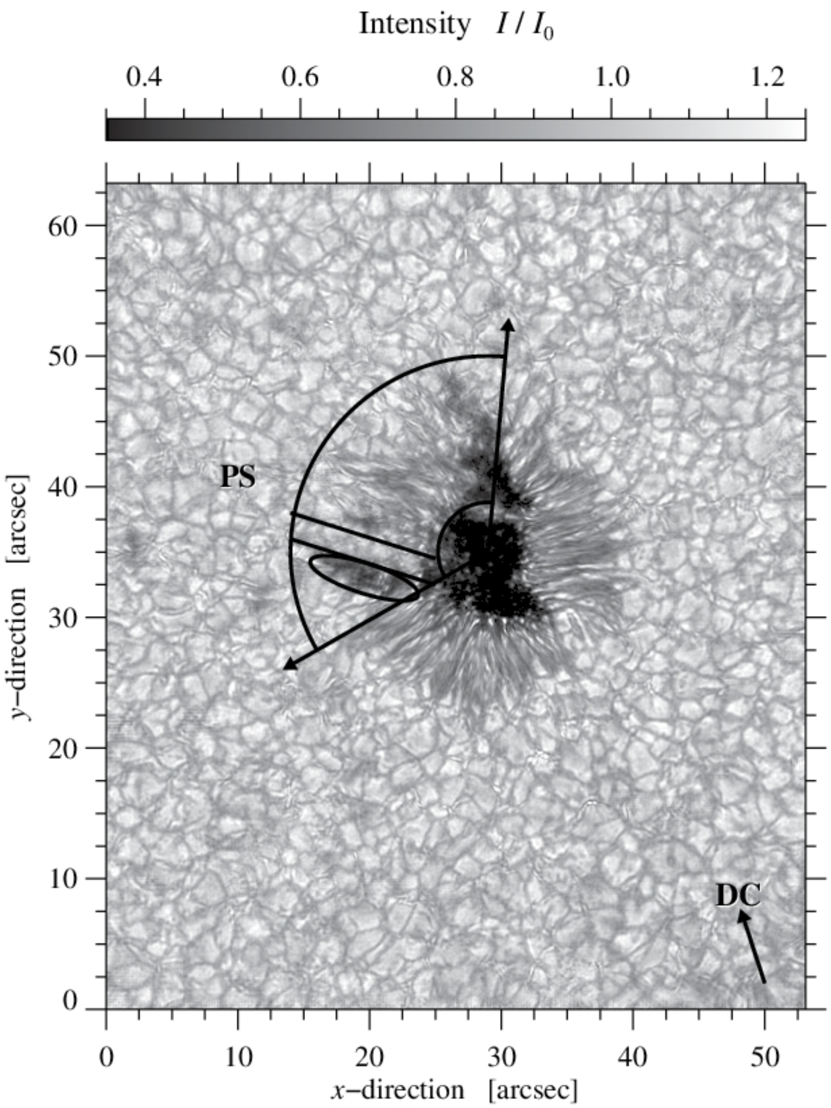


Data analysis



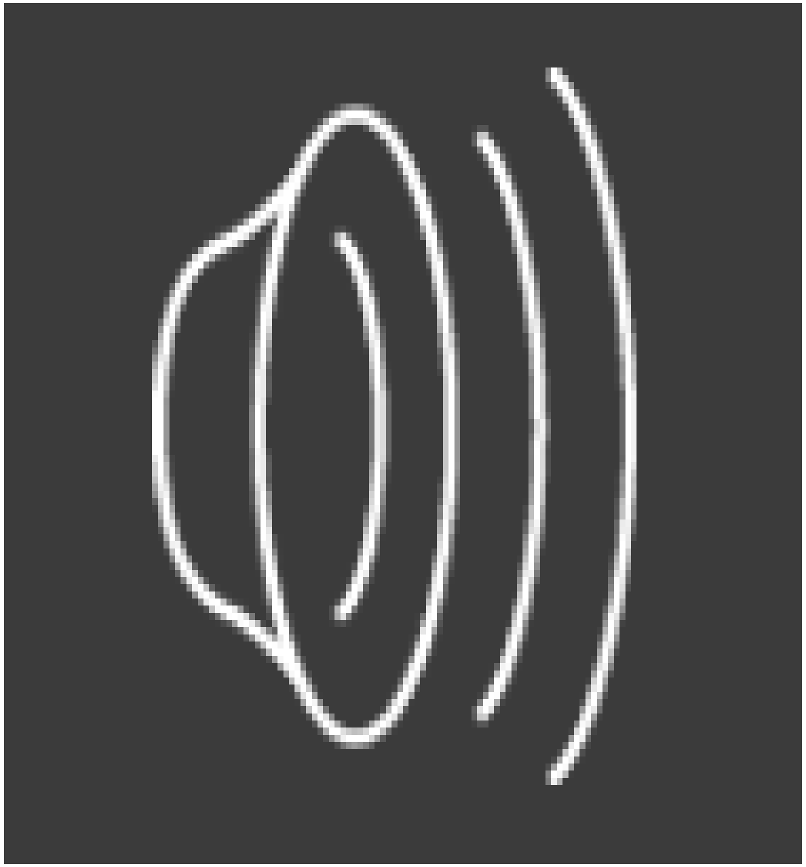
- GFPI data-pipeline: sTools
- MOMFBD for level 2 GFPI data
- LCT for horizontal proper motions and line-core fitting for LOS velocities
- SIR inversions for GRIS Si I and Ca I spectral lines

Leading Sunspot in NOAA 12597



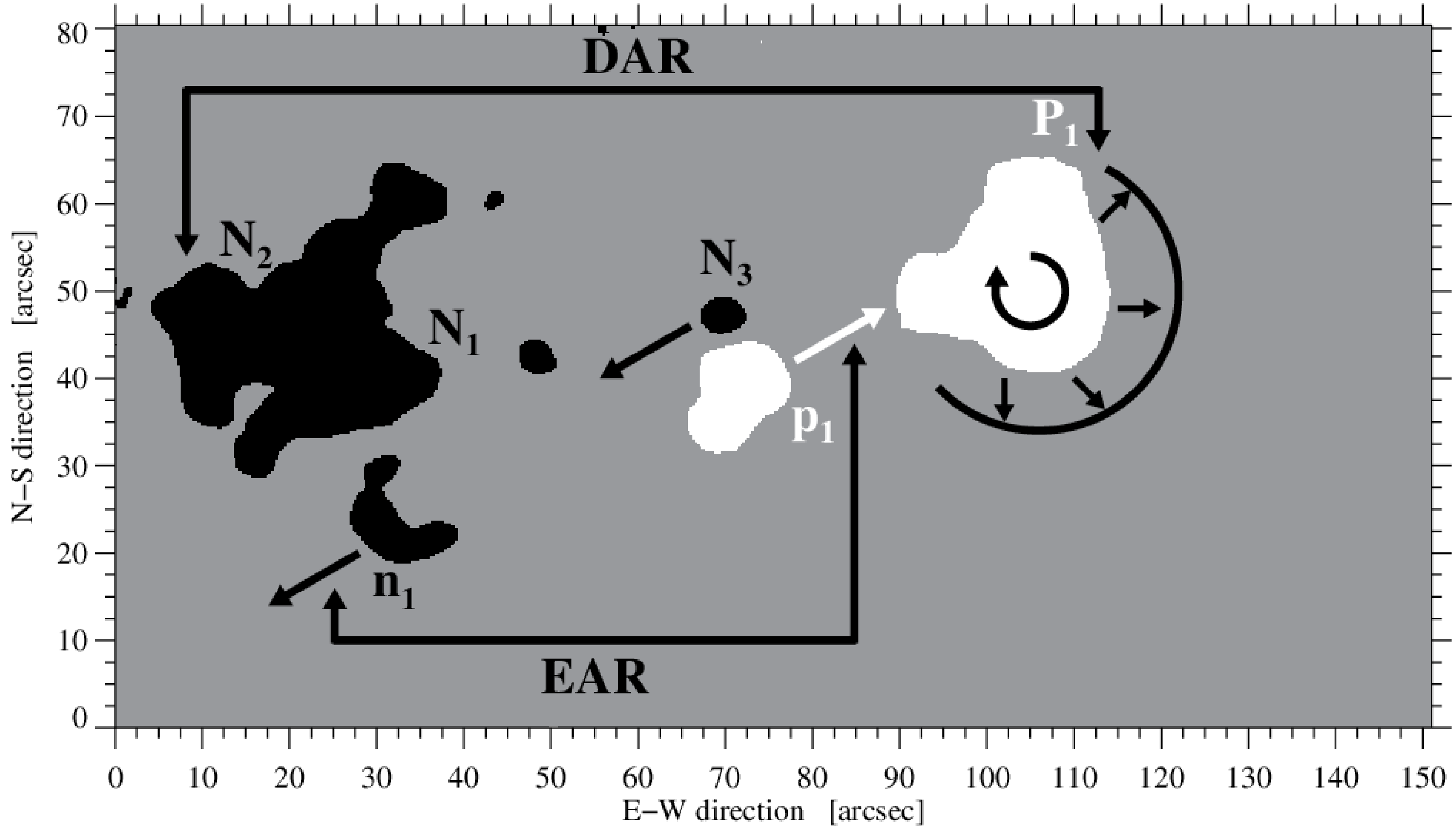
- Speckle-restored blue continuum image from HiFI observed at 08:50 UT on 2016 September 24.
- Leading spot in NOAA 12597
- The two black arcs mark the penumbral sector PS facing flux emergence site
- The arrow in the lower right corner points to solar disk center DC.
- The black oval and the two parallel lines inside the PS indicate the elongated dark umbral core, and the peumbral gap, respectively,

Leading Sunspot in NOAA 12597



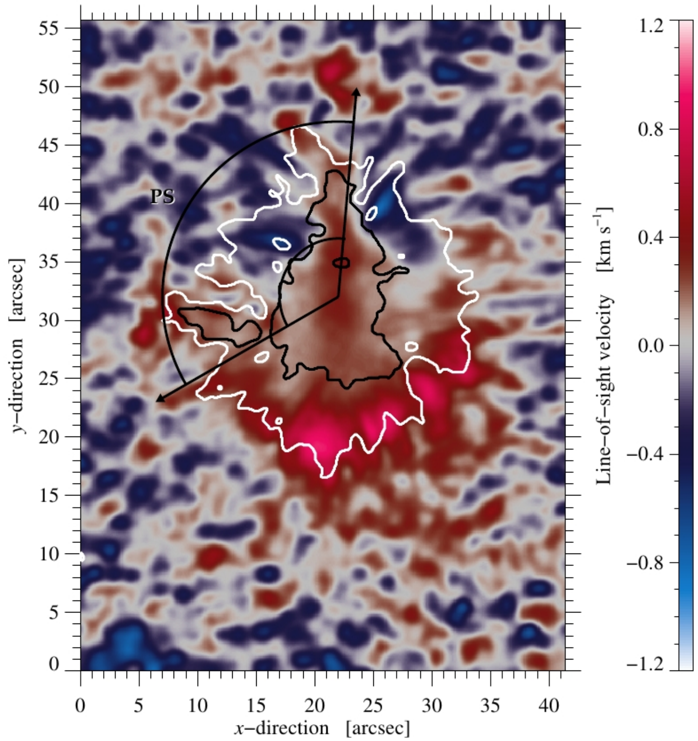
- GREGOR observations at 08:52 UT on 2016 September 24
- Active region appeared in south east near disk center on 2016 September 22.
- Position on 2016 September 24 (110", -350") and classified as β-group
- Focused on the leading spot
- Mature sunspot with decaying penumbra
- SDO – continuum, LOS magnetogram, and 1600 nm UV and 171 nm EUV images
- Boxes are FOV covered by GFPI, GRIS, and HiFI

Evolution on the day of GREGOR observation

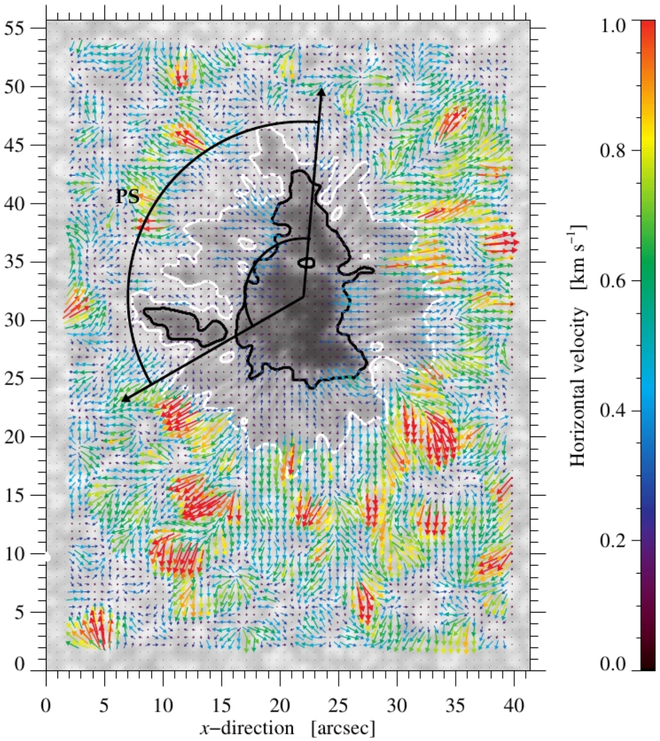


- The sketch is based on the HMI magnetogram observed at 09:00 UT on 2016 September 24.
- Black and white areas mark the negative and positive polarities, respectively.
- Arrows indicate the direction in which different features moved over the course of the day.
- The black semi-circle denotes the region around P1 with moat flow and MMFs.
- The black lines with vertical arrows mark the extent and features belonging to DAR and EAR

3D velocity field from GREGOR GFPI Doppler & LCT

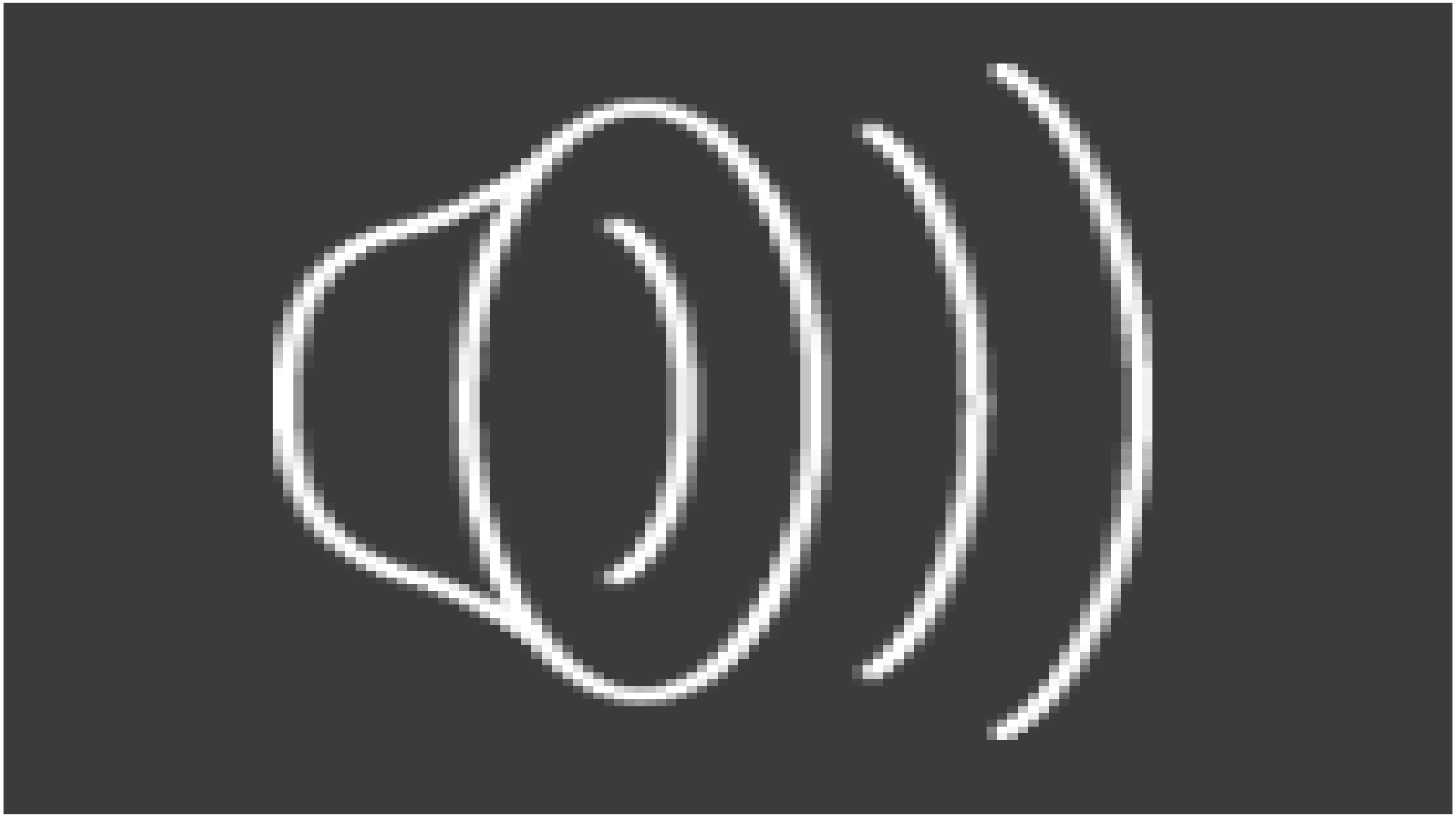


- Evershed flow around the sunspot - moat flow in the seen in the limb-side penumbra
- PS flows deviated from the usual penumbral flow pattern.
- The gap displayed a flow pattern resembling that of granulation.
- The elongated umbral core in the PS possessed a velocity pattern similar to that of the umbra of sunspot.



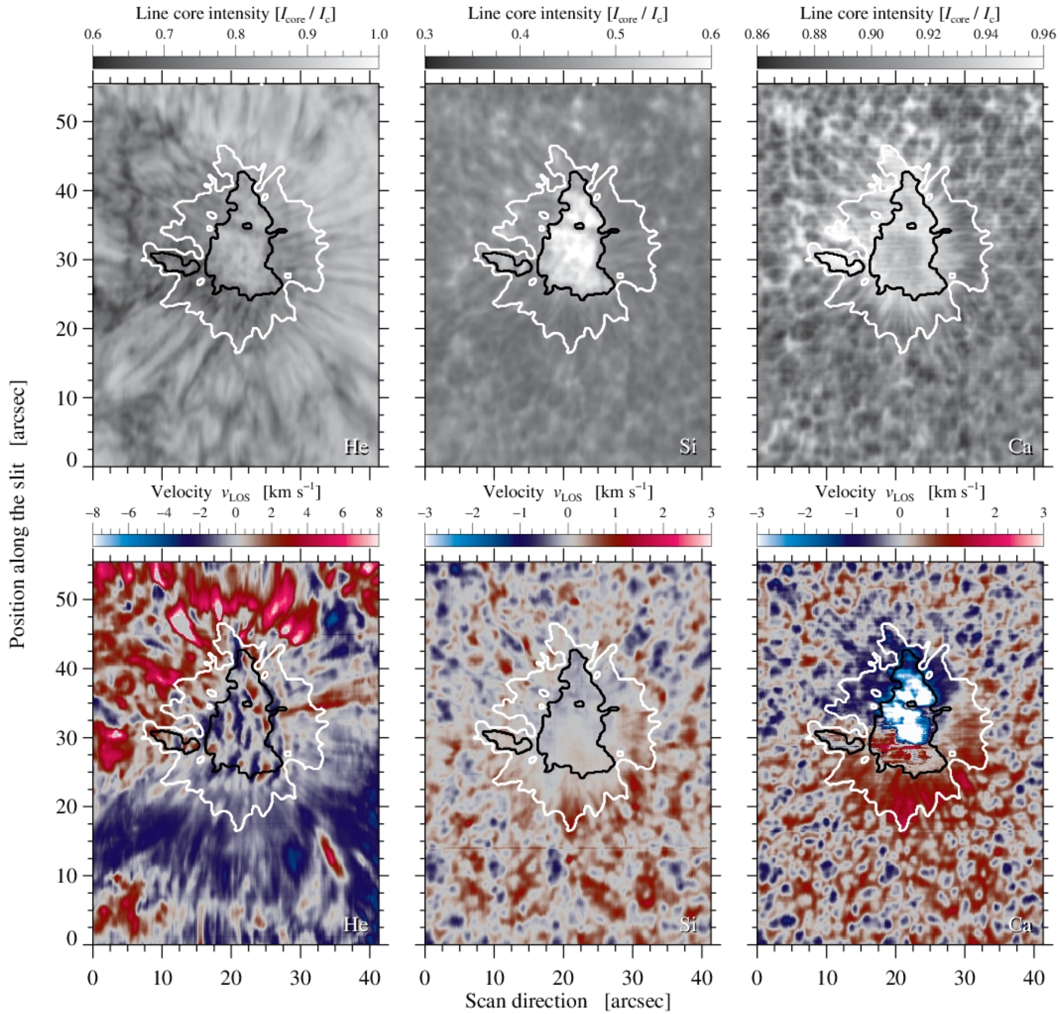
- Global granular flow pattern within the quieter part of the FOV.
- The moat flow partly encircled spot.
- However, the moat flow was absent in the PS containing the elongated umbral core.
- Proper motions were diminished in that region.

3D velocities



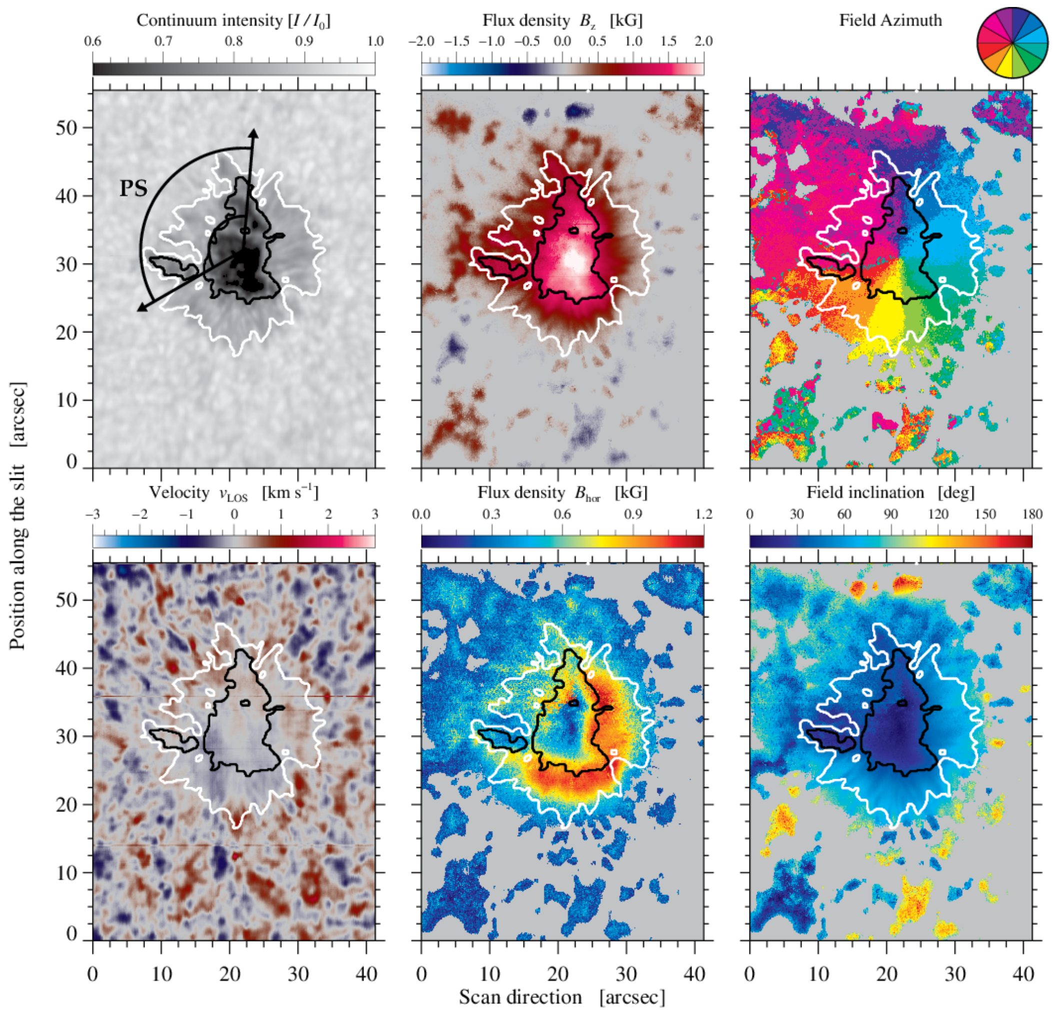
LOS velocity and line-core time-lapse movie

Photospheric to chromospheric velocities



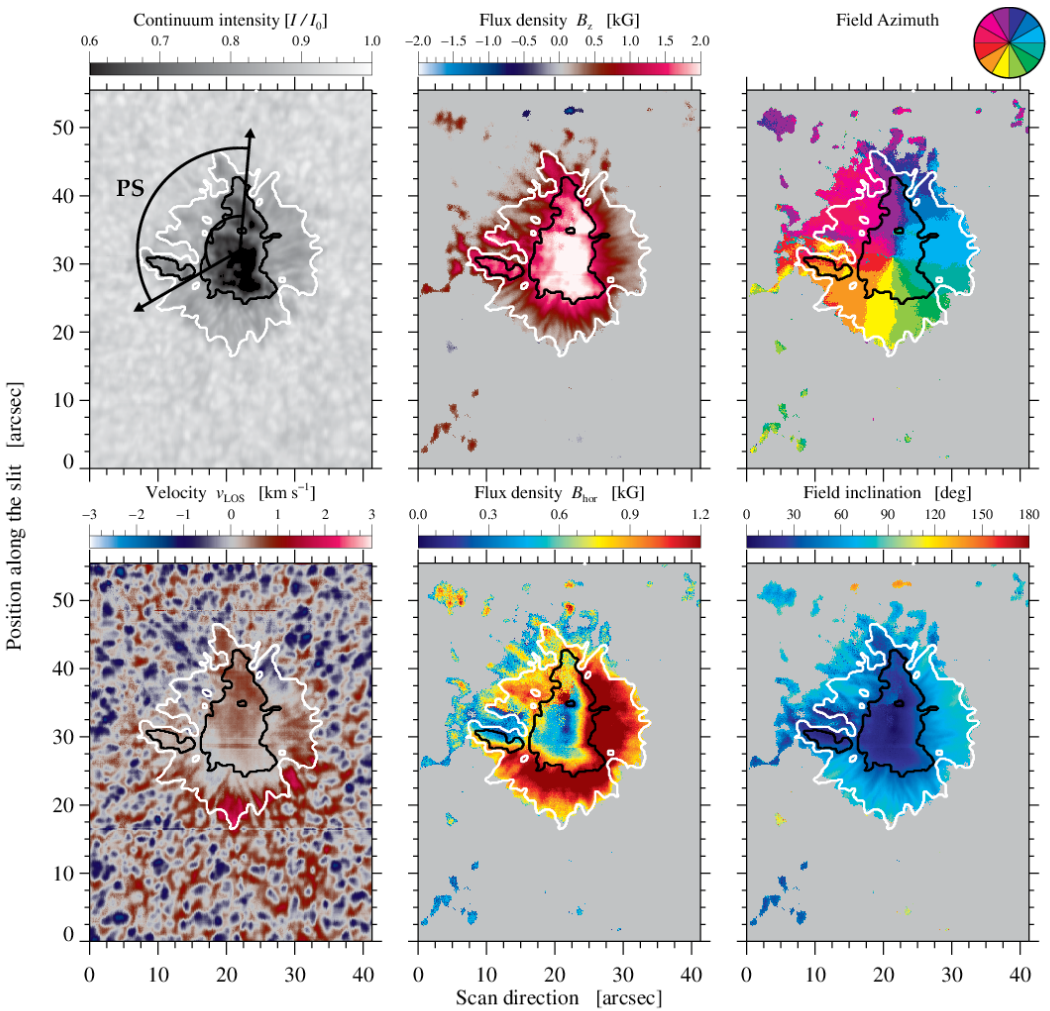
- Line core intensity and LOS velocities for three lines
- Si I and Ca I lines represent upper and lower photosphere show granulation pattern, signatures of Evershed flow.
- Inverse Evershed flow, more filamentary structure in He I map.
- He I line-core intensity did not show any (super)penumbral filaments above PS but did show a very perturbed penumbral structure.
- Bright features in the Ca I line-core intensity near PS exhibited blueshifts.
- The decaying sunspot in the Si I LOS velocity map very low velocities.
- Strong downflows are present in the He I map, where the PS faces the EAR

Magnetic field: Si I line



- The vertical magnetic flux density B_z was positive for the leading spot
- MMFs were present in the vicinity of the spot.
- B_z for elongated umbral core in the PS was higher than the rest of penumbra and PS.
- B_{hor} for the PS facing the EAR was lower than rest of penumbra

Magnetic field: Ca I line



- B_z smaller areal extent with only few signs of MMFs.
- The elongated umbral core in the PS possessed a strong B_z in the Ca I line as well.
- Lowest values of B_{hor} in the gap intruding into the PS
- PS enclosed a patch with higher B_{hor} values, but still lower than rest of the penumbra.

Average profiles umbra and elongated umbra

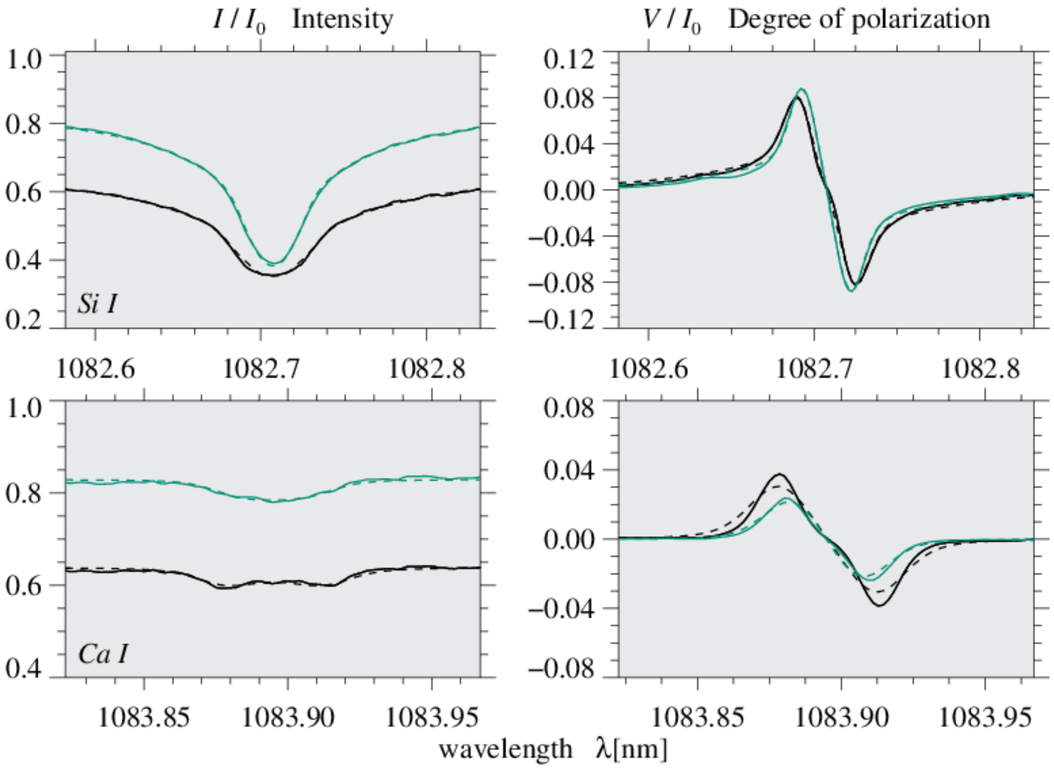
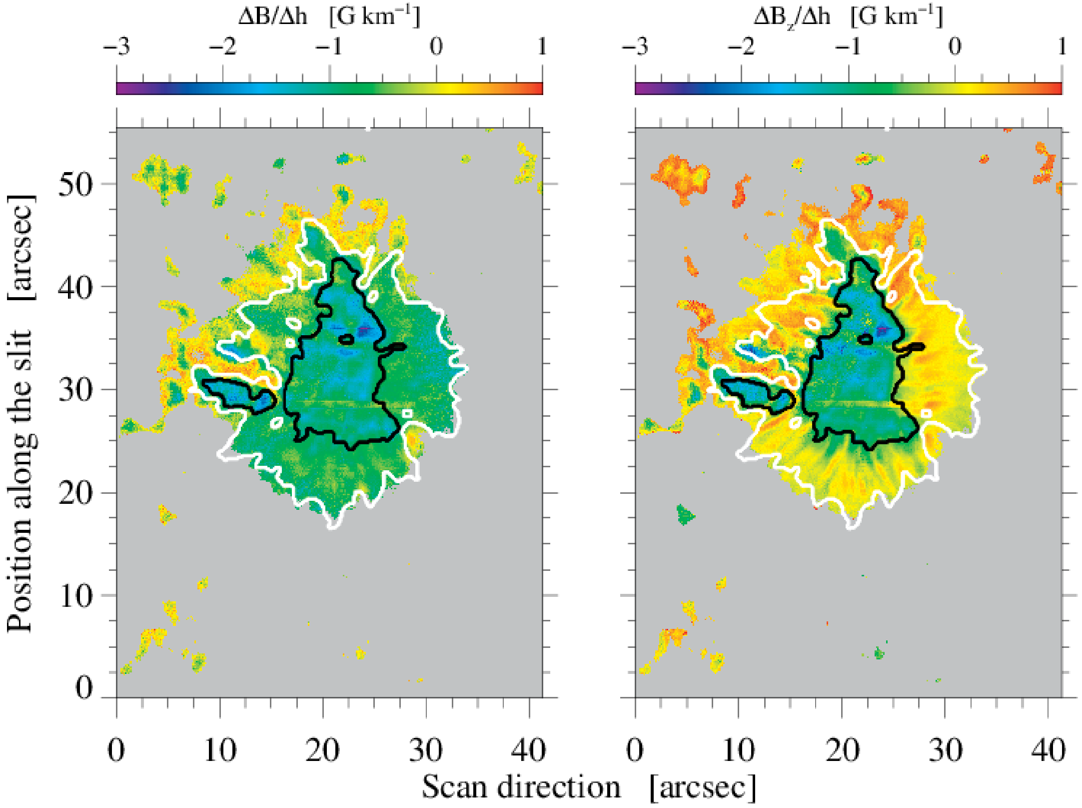


Table 1. Average magnetic field properties derived from SIR for umbra, elongated umbral core, penumbral sector PS, and the remainder of the penumbra for both the Si I and the Ca I spectral lines and for both GRIS scans.

Features	$B_z \pm \sigma_{B_z}$ [kG]	$B_{hor} \pm \sigma_{B_{hor}}$ [kG]	$\gamma \pm \sigma_\gamma$ [deg]
		Si I – Scan I	
Umbra	1.62 ± 0.23	0.61 ± 0.22	21.25 ± 8.38
Elongated Umbra	0.99 ± 0.12	0.48 ± 0.15	26.15 ± 8.85
Penumbral Sector	0.83 ± 0.24	0.57 ± 0.15	35.31 ± 10.30
Penumbra	0.59 ± 0.42	0.75 ± 0.22	56.80 ± 14.53
		Si I – Scan II	
Umbra	1.53 ± 0.20	0.65 ± 0.22	23.29 ± 8.60
Elongated Umbra	1.02 ± 0.10	0.48 ± 0.13	24.99 ± 6.62
Penumbral Sector	0.76 ± 0.24	0.55 ± 0.16	37.04 ± 11.50
Penumbra	0.61 ± 0.41	0.70 ± 0.21	54.50 ± 14.96
		Ca I – Scan I	
Umbra	1.94 ± 0.22	0.71 ± 0.27	20.20 ± 7.86
Elongated Umbra	1.30 ± 0.27	0.69 ± 0.27	27.80 ± 13.65
Penumbral Sector	0.94 ± 0.43	0.74 ± 0.22	40.81 ± 17.62
Penumbra	0.61 ± 0.50	1.05 ± 0.24	64.57 ± 16.38
		Ca I – Scan II	
Umbra	1.87 ± 0.22	0.78 ± 0.29	22.77 ± 9.17
Elongated Umbra	1.43 ± 0.20	0.75 ± 0.22	27.68 ± 9.89
Penumbral Sector	0.80 ± 0.40	0.83 ± 0.22	48.62 ± 17.41
Penumbra	0.63 ± 0.51	1.02 ± 0.24	63.16 ± 18.31

Magnetic field gradient



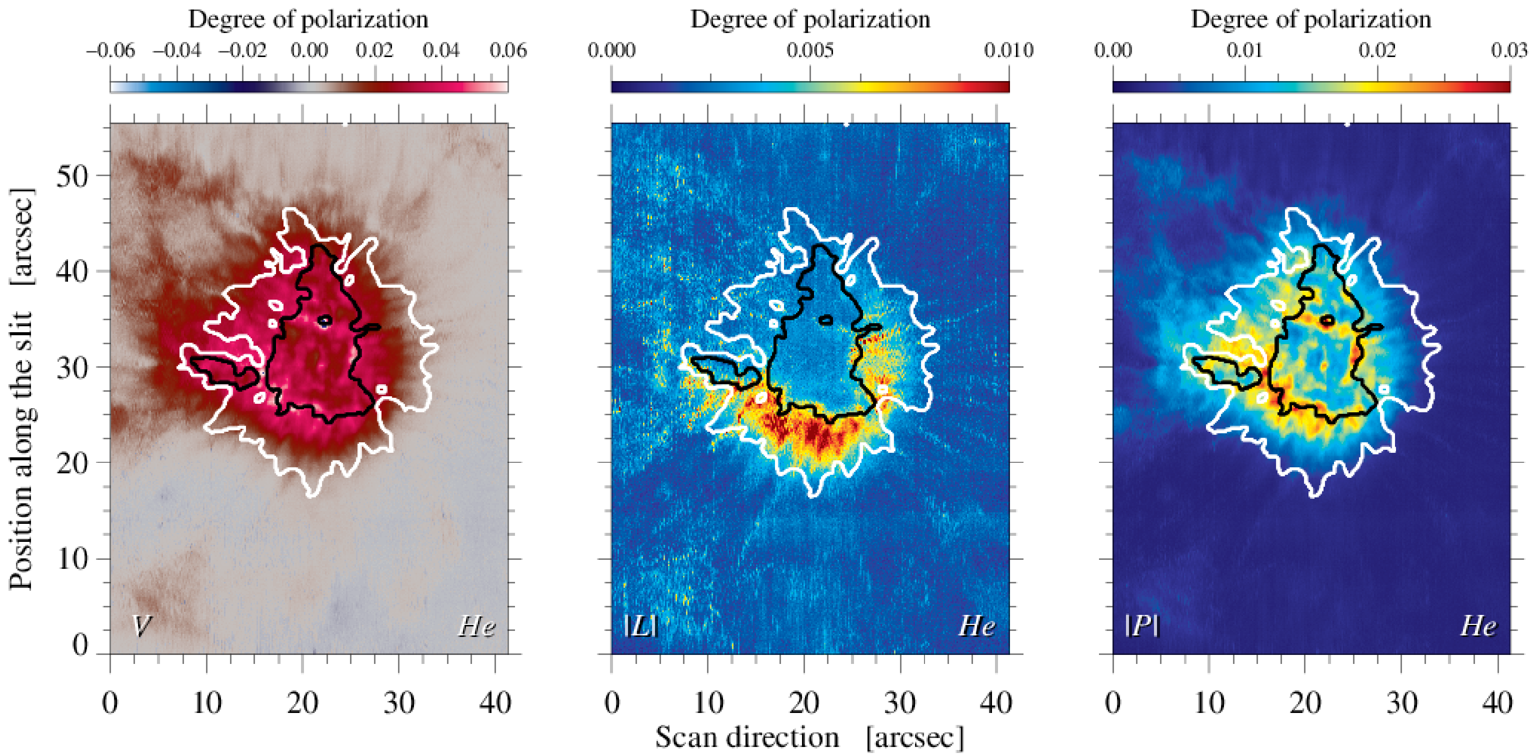
- Divided the difference of total B and B_z for the Si I and Ca I lines by the height difference of both lines (Balthasar & Gömöry, 2008).
- Si I line originates roughly about 350 km higher in the atmosphere than the Ca I line.
- The negative values indicate that the field strength decreases with height.
- At the penumbra-granulation border, the field strength increased with height.
- The magnetic field is less inclined higher in the atmosphere.

Decaying penumbra and flux emergence

- What role does magnetic flux emergence and its interaction with photospheric plasma play in the decay of sunspot penumbrae?
- We presented high-resolution spectroscopic and polarimetric observations of a decaying sunspot.
- Before the time of the GREGOR observations, the sunspot contained light-bridges indicating the start of its fragmentation.
- Concurrently, a new flux system emerged in the already established flux system
  → disrupting the quiet environment needed for stable penumbra
- An elongated, dark umbral core appeared within the decaying penumbral sector
  → slow changes of the magnetic field topology introduced by flux emergence can induce the transformation of penumbral to umbral magnetic fields
- The flow and magnetic field properties of this penumbral sector facing flux emerging site exhibited weak Evershed flow, moat flow, and horizontal magnetic fields.
- The continuous flux emergence likely altered the convection pattern in the surrounding → accelerated the decay of penumbral filaments and led to rotation of leading sunspot.


Thank you!

Next steps!!



Degree of polarization
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Degree of polarization
0.000 0.005 0.010
Degree of polarization
0.00 0.01 0.02 0.03
Position along the slit [arcsec]
0 10 20 30 40 50
V
He
|L|
He
|P|
He
0 10 20 30 40
Scan direction [arcsec]