Evolution of penumbral filaments in forming sunspot

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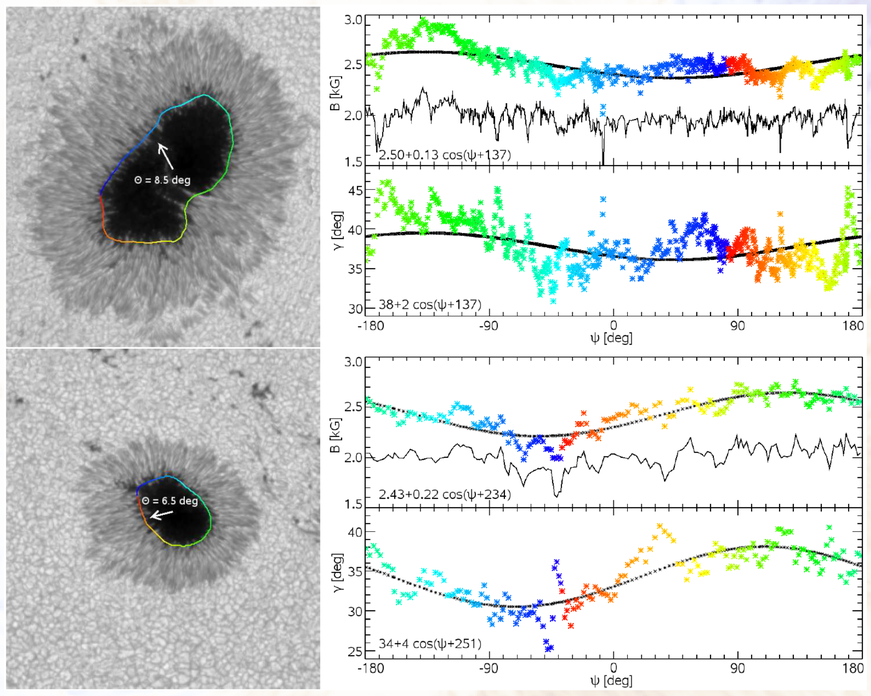
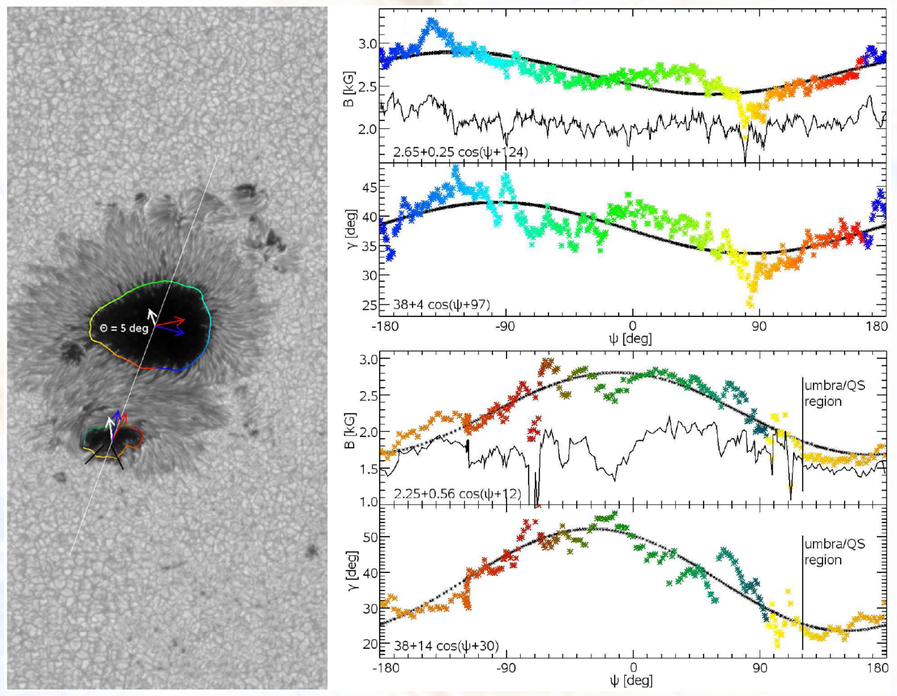
Hinode data (motivation)

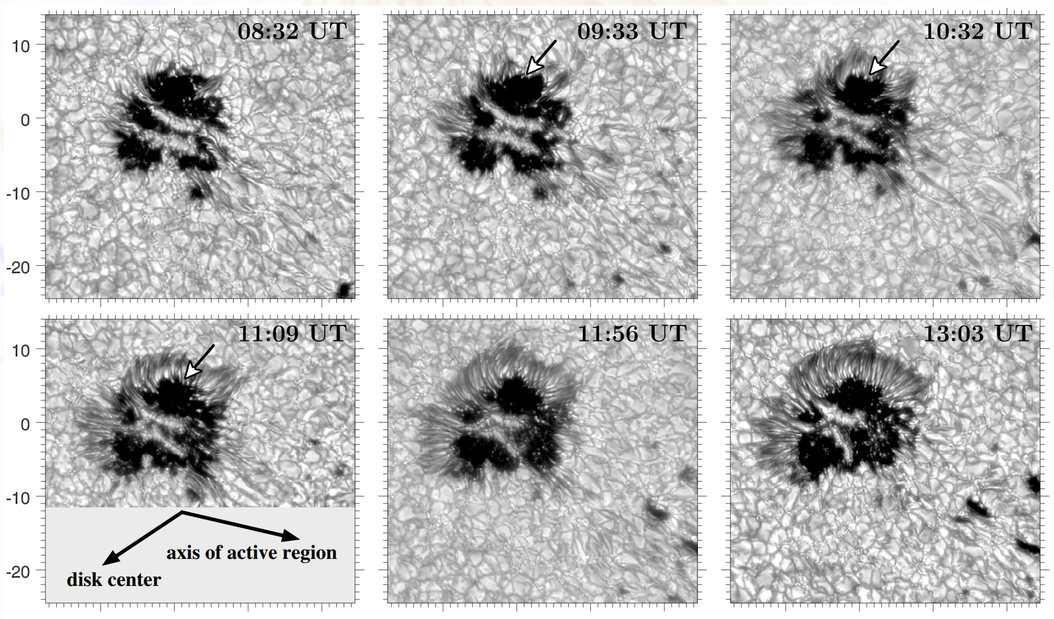


Static Hinode SP scans show that the magnetic field strength and inclination (coloured symbols) vary on the umbra/penumbra boundaries. However, the vertical component of the magnetic field strength (solid line) is constant there and not dependent on the umbra size. The lower sunspot has 3.3 times smaller umbral area, but the vertical component of the magnetic field is around 2 kG on both boundaries. [1]

There is fully developed penumbra around the larger umbra, where the vertical component of the magnetic field is again around 2 kG on the boundary. The smaller umbra of opposite polarity has only partially developed penumbra. On the umbra/QS boundary we observe weaker and more vertical magnetic field compared to the umbra/penumbra boundaries. ***Possibly, once the penumbral filaments develop, they protrude deeper into the umbra until they reach the value of 2 kG of vertical component of the magnetic field strength, where the stable umbra/penumbra boundaries are located. Therefore, it is necessary to follow the evolution of penumbral filaments and changing conditions on the umbra/QS and umbra/penumbra boundary.***

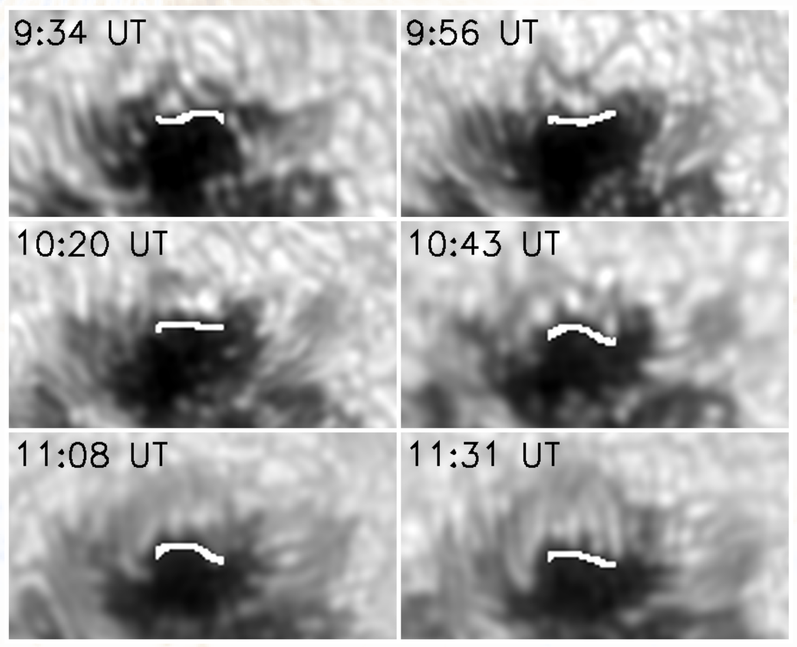


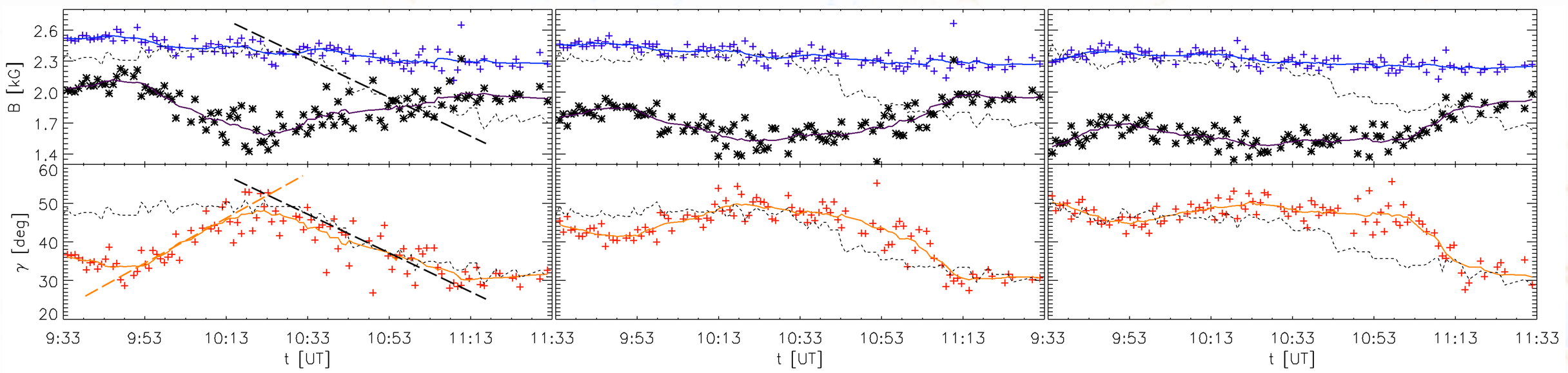
VTT (GFPI) data



On June 4, 2009, we observed a pore with developing penumbra in active region NOAA 11024. We show snapshots of the penumbra evolution using speckle reconstructed G-band images. [2]
We focused on a segment of penumbra forming between 9:30 and 11:30 in the area marked by arrows.

Intensity maps (GFPI@VTT, [3]) show the evolution of the penumbral segment and the radial position of umbra/QS and umbra/penumbra boundary, respectively. Consecutive images are cross-correlated and aligned. Average values of plasma parameters are taken from pixels on the boundary, which is marked by the white line (corresponding to 55 % of the mean QS intensity). As the penumbra forms, the white line migrates towards the umbra. We analysed 104 GFPI scans.





Plots showing the temporal evolution of magnetic field strength (blue symbols), local reference frame inclination (red symbols), and vertical component of the magnetic field (black symbols) on the umbra/QS boundary which changed into umbra/penumbra boundary. The solid lines mark 10 minutes smoothed values of the plasma parameters. The thin dashed lines show the mean radial position of the pixels on the boundary (illustrates the motion of the boundary towards the umbra). The thick dashed lines in the right plot illustrate the increase of magnetic field inclination preceding the penumbra formation (orange dashed line) and the radial movement of the umbra/penumbra boundary towards umbra that starts right after the penumbra formation (black dashed lines). From left to right, we compare the evolution of plasma parameters on boundaries defined as 50 %, 55 %, and 60 % of the mean QS intensity.

Conclusions

- Magnetic field inclination on stable umbra/penumbra boundaries is typically around 35°, although the value is dependent on the size of the umbra and varying along the boundary. On umbra/penumbra boundary, the vertical component of the magnetic field is constant and only slightly dependent on umbral size [1].
- Theoretical models describing formation of the penumbra predict a critical value of magnetic field inclination around 45° when the filamentary magneto-convection sets in [4, 5]. This has not yet been confirmed observationally.
- We present for the first time the temporal evolution of magnetic field strength and inclination on the changing umbra/QS boundary and umbra/penumbra boundary.
- We find that umbra/penumbra boundary is migrating inwards towards the umbra as the penumbral segment forms.
- In the studied region of the evolving proto-spot, the segment of penumbra start to form around 10:20 UT. This can be seen in continuum intensity maps and also on the mean radial position of the umbra/penumbra boundary, which starts to move at this time towards the umbra.
- On the studied umbra/QS boundary, we observe a significant increase of magnetic field inclination preceding the onset of penumbra formation. This trend is more apparent in the darker regions, i.e., on boundary defined as 50 % of the mean QS intensity (left plot in the figure above), although a slight increase of inclination can be seen also in the middle and right plots, where we display plasma parameters on boundary defined as 55 % and 60 %, respectively.
- The critical value of magnetic field inclination is around 50° independently on the boundary definition. The field is even more horizontal than the theoretically predicted critical value, but the uncertainties of the derived inclinations are higher than 5°.
- At the moment when the filamentary convection sets in, the vertical component of the magnetic field (B_{ver}) is around 1500 G. In time, the umbra/penumbra boundary moves into regions with more vertical field, which leads to increase of B_{ver}. This increase saturates (in last 20 minutes) at about 2000 G, which is in agreement with the conditions found in stable sunspots.

References

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