The role of the chromospheric canopy in the formation of a penumbra

P. Lindner[1], C. Kuckein[2,3], S. J. González Manrique[1,2,3,4], S. Berdyugina[1], N. Bello González[1], L. Kleint[5], and T. Berkefeld[1]

[1] Leibniz-Institut für Sonnenphysik (KIS), Schöneckstr. 6, 79104 Freiburg, German
[2] Instituto de Astrofísica de Canarias (IAC), Vía Láctea s/n, 38205 La Laguna Tenerife, Spain
[3] Departamento de Astrofísica, Universidad de La Laguna 38205, La Laguna, Tenerife, Spain
[4] Astronomical Institute, Slovak Academy of Sciences, 05960 Tatranská Lomnica, Slovak Republic
[5] University of Geneva, CUI-SIP, 1205 Geneva, Switzerland

Abstract

The formation of a penumbra is a phenomenon that happens only under certain conditions. We investigate the existence of a chromospheric canopy as a necessary condition for penumbra formation. Spectropolarimetric observations from the GRIS@GREGOR instrument as well as imaging data from the BBI@GREGOR instrument of a sunspot with a partially developed penumbra are analyzed. Atmospheric parameters are obtained from inversions of the Ca I 10839 Å line, the Si I 10827 Å line and the He I 10830 Å triplet. We compare the photospheric and chromospheric magnetic topology of the side of a sunspot with a fully fledged penumbra to a side where it does not form.

In the deepest atmospheric layers, we find that the magnetic properties measured in the sunspot side where no penumbra is present are similar to those measured on the fully fledged sunspot side. Yet, in higher layers, the magnetic properties are different and this difference becomes more prominent towards higher layers. In the region showing no penumbra in continuum maps, thin filaments are seen in high-resolution images. Although in the deep photosphere, the 'ingredients' for penumbra formation seem to be present in the region with the disturbed canopy, no penumbra actually forms. As inclined magnetic fields in the deep photosphere are similar on each sunspot side, the existence of the penumbra is found to be discriminated by the conditions in the chromosphere. In addition, the presence of inclined photospheric fields in the region with the disturbed canopy and almost vertical chromospheric fields demonstrates that inclined fields in the chromosphere are not needed for the development of inclined fields in the photosphere. We question the penumbra formation scenario in which inclined magnetic fields in the photosphere fall from the canopy and favor a formation scenario, in which inclined fields emerge from below the surface and are blocked by the overlying canopy.

Data

Observations were conducted on 2020-10-16 with the GREGOR telescope (Schmidt et al. 2012), during a Science Verification Phase that followed a complete redesign of the optics laboratory (Kleint et al. 2020). The target was a sunspot showing a partially developed penumbra with the NOAA AR number 12776. During the observations, the AR was located south-east from the solar disk center with a μ value (cosine of the heliocentric angle) of 0.639. The sunspot showed a penumbra everywhere except on its left (East) side. Within two days following the observations, no complete penumbra formed on the East side.

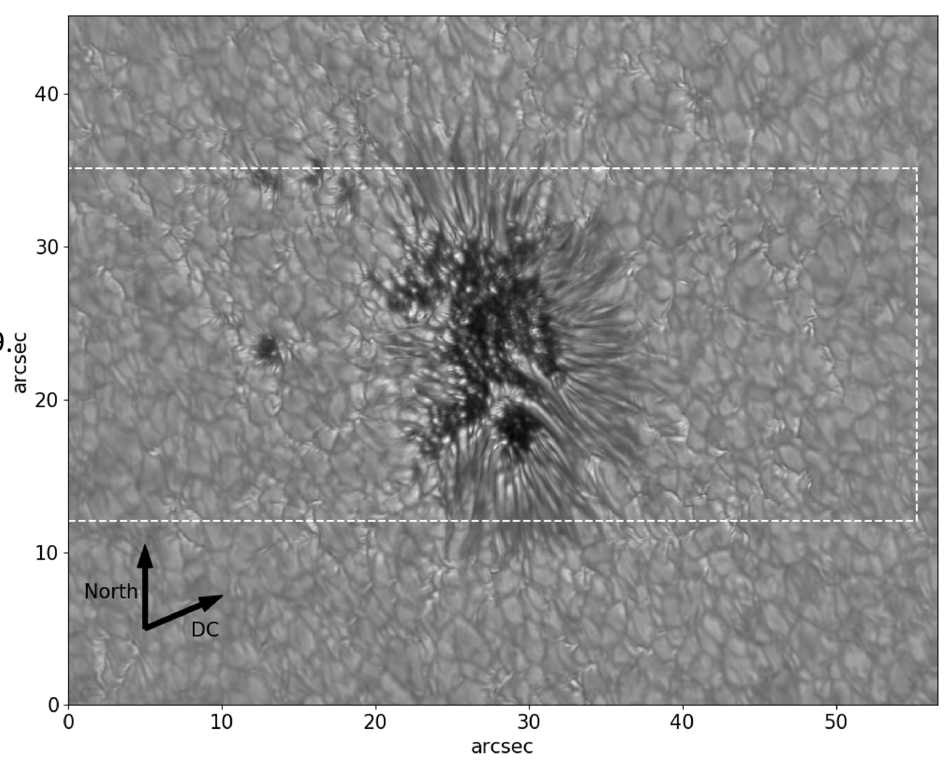


Fig. 1: Speckle-reconstructed image with the TiO filter (full BBI FOV). The GRIS FOV is depicted by the white dashed box.

Imaging data from BBI

Images were recorded using an adaptation of the GREGOR Broad Band Imager (BBI, von der Lühe et al. 2012). The two Andor Zyla cameras were equipped with a G-Band filter and a Titanium Oxide (TiO), also known as Titanium monoxide, filter centered at the TiO molecular band at 7057 Å.

Spectropolarimetric data from GRIS

Spectropolarimetric data were obtained with the GRegor Infrared Spectrograph (GRIS, Collados et al. 2012). The spectral range was chosen to be around the He I 10830 Å triplet. In addition to this helium triplet, the Si I 10827 Å line and the Ca I 10839 Å were observed within the spectral window.

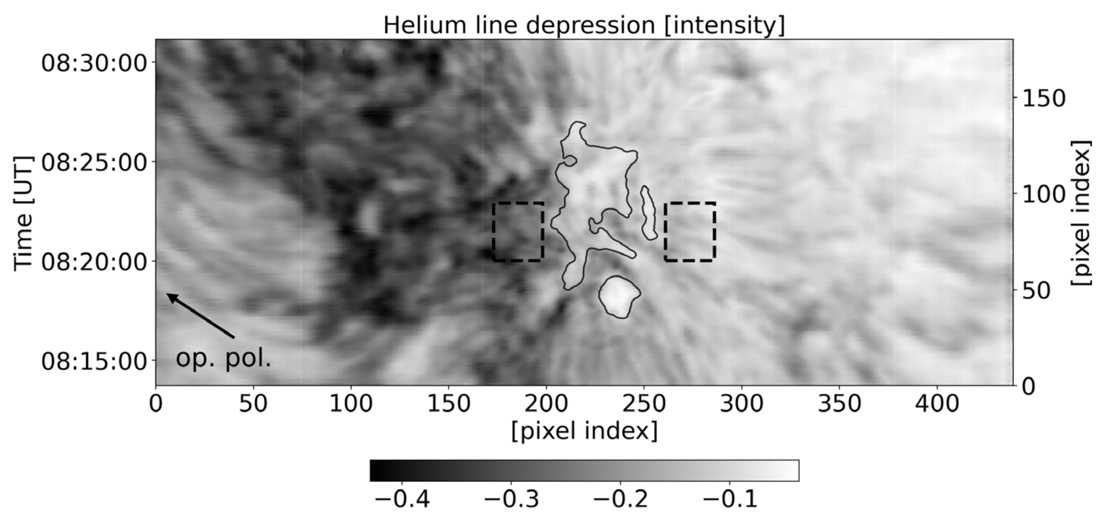


Fig. 2: Slit-reconstructed map from the GRIS instrument showing the line depression of the red component of the helium triplet. A dark extended structure is visible on the upper-left part of the image, which points towards the opposite polarity of the AR.

Inversions

The following inversion codes were used to obtain atmospheric parameters from the spectropolarimetric GRIS data:

- **VFISV** Milne-Eddington inversion code (Borrero et al. 2011) to invert the deep photospheric Ca I 10839 Å line
- **SIR** (Ruiz Cobo & del Toro Iniesta 1992) for a height-dependent inversion of the mostly photospheric Si I 10827 Å line
- **HAZEL** (Asensio Ramos et al. 2008) for an inversion of the chromospheric He I 10830 Å triplet assuming that the magnetic field and the velocity field is constant in height

Thin bright filaments (TBFs)

In the BBI and GRIS observations, no penumbra was visible on the left (East) side of the sunspot. Apart from granulation, thin bright filaments (hereinafter referred to as TBFs) were seen in BBI images, that are mostly aligned east-west, i.e. radially outward from the umbra. They are remarkably straight, almost no curvature is observed, and they seem to span multiple granules in some cases. The following characteristics were determined manually and by averaging over nine TBFs identified in the observations:

- Length: between 0.8 ″ and 2.2 ″ (average 1.4 ″)
- Width: seen as roughly 0.1 ″. This is in the range of the telescope diffraction limit λ/D of 0.10 ″ for TiO
- Lifetime: between 2 min and 10 min (average 4 min)

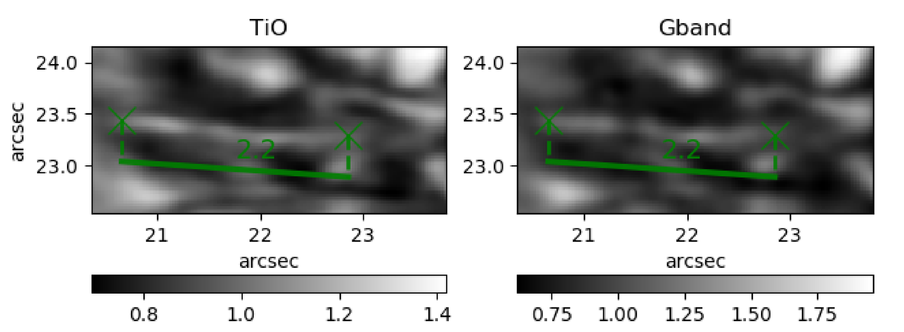


Fig. 3: Example of a thin bright filament (TBF). The location of this TBF is depicted as a magenta contour in Fig. 4

Topology of the magnetic field at different heights

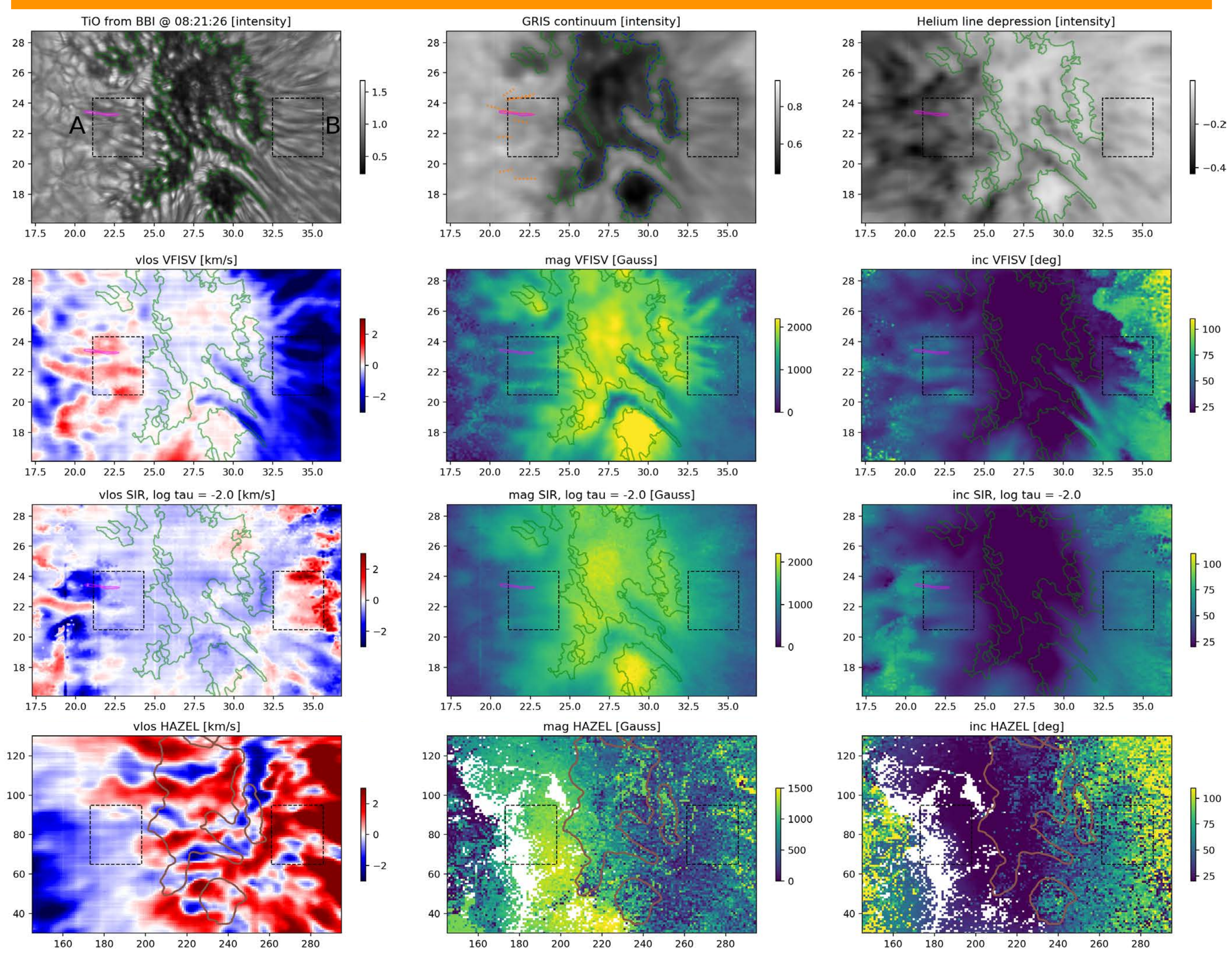


Fig. 4: Second to fourth row: Two-dimensional maps from the different inversions (VFISV, SIR, HAZEL). For the height-dependent SIR inversion, only one exemplary map at the optical depth value of $\log\tau$=-2.0 is shown. For the HAZEL inversion, some pixel are masked out in white because no successful inversion was possible with our inversion setup. The line-of-sight velocity, the magnetic field strength and the inclination of the magnetic field (in local reference frame) are shown for each inversion.

In order to understand why only TBFs formed on the East side of the sunspot instead of a fully developed penumbra, atmospheric parameters from the inversion results were analyzed. Interestingly, the deep photospheric magnetic field maps from the VFISV inversions showed filamentary structures (similar to a spine/intraspine) on both the East and the West side of the spot. Without looking at continuum images, it would be difficult to tell whether a penumbra is present on the East side or not.

The magnetic properties between two equally sized regions (depicted as black dashed boxes in Fig. 4) were compared in detail. Region A showed no penumbrae, but TBFs. Region B showed a regularly developed penumbra. Scatter plots showing the magnetic field strength versus the inclination (in local reference frame) were produced from the data at different heights. The scatter plots (Fig. 5) show that the distributions of region A and region B are similar for the deep photospheric VFISV results. In higher layers, the two distributions are different and the difference increases with height.

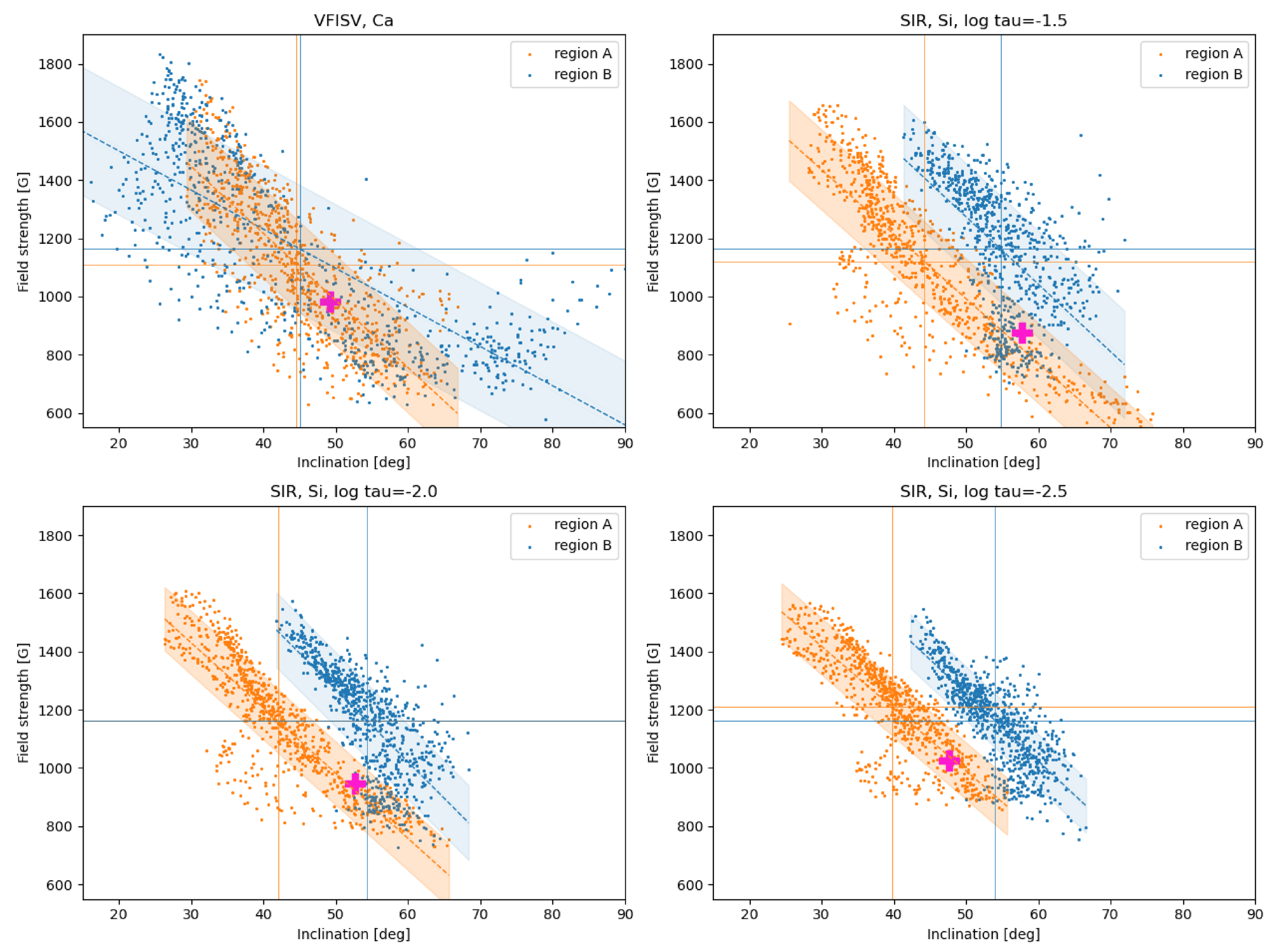
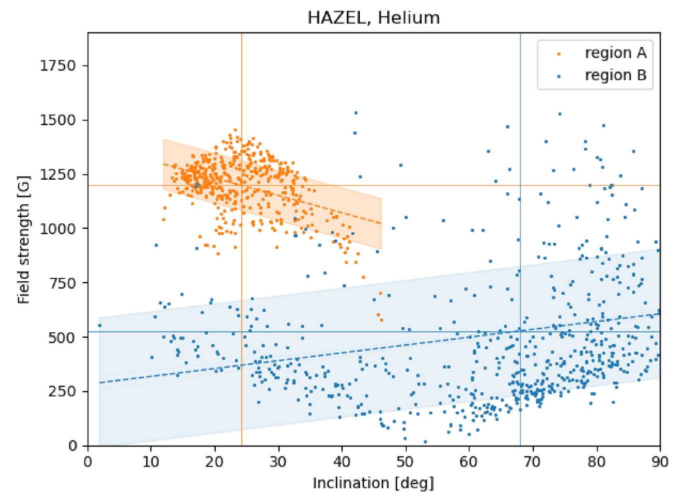


Fig. 5: Scatter plots characterizing the magnetic field topology in region A and region B for different atmospheric heights. The VFISV results from the Ca I 10839 Å line represent the data from the lowest layer (deep photosphere). The HAZEL results from the He I 10830 Å triplet represent data from the high chromosphere. Shaded areas depict the standard deviation from a linear fit. Vertical/horizontal lines depict the respective average inclination/field strength value. The magenta cross indicates the average value across the contour of the TBF shown in Fig. 3.



Summary and Conclusion

Comparing region A (showing no penumbra, but TBFs) and region B (showing a fully developed penumbra) we find that:

- Inclined (up to 70°) magnetic fields showing filamentation (similar to a spine/intraspine structure) are not only present in region B, but also in region A.
- The magnetic topology between region A and region B is similar in the deepest atmospheric layer, but becomes different in higher layers. The difference increases with height.
- In the chromosphere (showing the magnetic canopy), magnetic fields in Region A are almost vertical (average: 25°) , whereas they are almost horizontal (average: 70°) in region B.
- On the North-East side of the sunspot (in the direction where the opposite polarity of the AR is located), a dark extended structure is visible in the Helium line depression map.

We interpret these results as follows:

- It is not possible to reliable tell whether a penumbra is present or not by only looking at magnetic field maps.
- As inclined magnetic fields in the deep photosphere are similar on each sunspot side, the existence of the penumbra is found to be discriminated by the conditions in the chromosphere. We therefore surmise that a disturbance in the chromospheric canopy of the sunspot (dark extended structure in the Helium line depression map, almost vertical magnetic fields) is the reason why no penumbra formed on the East side of the sunspot. This is another hint towards an undisturbed chromospheric canopy being a necessary conditions for penumbra formation.
- We interpret the TBFs as flux tubes with mostly horizontal fields, that rise from below the surface. Since no chromospheric canopy is present in this region, they are not kept stably, but escape into higher layers or dissolve.
- As shown above for region A, inclined chromospheric magnetic are not needed for the stable development of inclined photospheric magnetic fields. We therefore question the 'top-down' penumbra formation scenario and favor the penumbra formation scenario in which inclined magnetic fields rise from the surface and are 'trapped' by an overlying canopy.

Leibniz-Institut für Sonnenphysik (KIS)

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