Mysterious motion of penumbral grains

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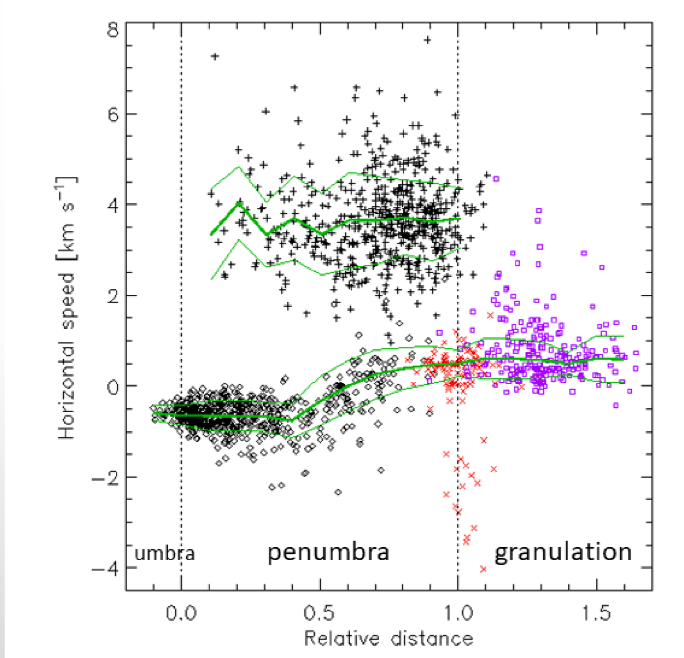
It has been known for a long time that bright heads of penumbral filaments, penumbral grains (PGs), are moving. Their movements are oriented toward the umbra (inwards) in the inner penumbra and away from the umbra (outwards) in the outer penumbra. The inward motion was first explained by Schlichenmaier et al. (1998, A&A 337, 897) as an apparent motion of the intersection of a rising flux tube with the visible surface. In a more recent model by Tiwari et al. (2013, A&A 557, A25), penumbral filaments are magnetoconvective cells distributed everywhere in the penumbra and embedded in a background magnetic field whose inclination increases with the distance from the umbra. PGs are places where hot plasma emerges to the surface, but their motion is not considered in that model. Sobotka & Puschmann (2022, A&A 662, A13) have shown that PGs motions change their orientation from inwards to outwards in the middle penumbra and their outward speed gradually increases with distance in the outer penumbra. They suggested that the apparent motions of PGs may be affected by the inclination of surrounding magnetic field. In the present work we use spectropolarimetric observations of sunspot penumbrae to compare magnetic inclinations inside PGs with those in their surroundings. We show that inward-moving PGs mostly have magnetic inclination larger than that in the surroundings and the inclination in outward-moving PGs is usually smaller than the surrounding one. Consequently, rising hot plasma surrounded by a less inclined magnetic field may adapt its trajectory to be more vertical, causing the apparent motion inwards. Oppositely, it may be dragged by the surrounding more horizontal magnetic field such that its crossing point with the surface moves outwards.

1 Horizontal speeds vs. position
Sobotka & Puschmann 2022, A&A, 622, A13

- ◊ – penumbral grains (PGs), + – dark bodies of filaments, x – penumbral border, □ – G-band bright points
- PGs: the mean speed increases gradually with relative distance d from −0.7 km/s inwards ($d \leq 0.4$) to 0.4 km/s outwards ($d = 0.8$). The direction of PGs motion changes at $d \approx 0.6$
- **Why do PGs move inwards in the inner penumbra and outwards in the outer penumbra?**



Green lines: mean values ± σ

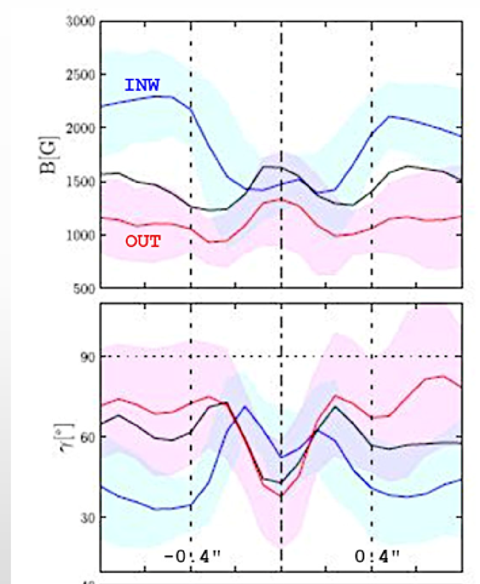
2 Filament model (Tiwari et al. 2013, A&A, 557, A25): transversal cuts of PGs in *B* and γ

The inclination γ of background magnetic field increases gradually with the distance from the umbra, so that:

- Inner penumbra: γ(PG) > γ(surroundings)
- Outer penumbra: γ(PG) < γ(surroundings)

The inclination of surrounding field might affect ascending flows thus the apparent motions of penumbral grains.

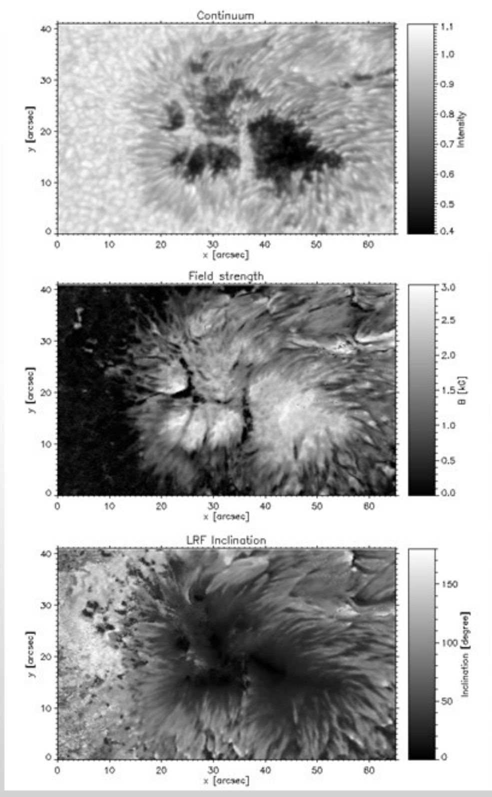
Is it really the case? Do inward-moving PGs have their magnetic inclination larger and outward-moving PGs smaller than that in the surroundings?



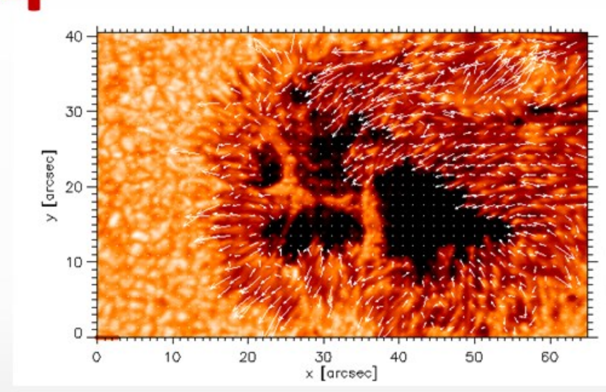
Credit: Tiwari et al. 2013

3 Observations: AR 13014 "Monika"

- A complex sunspot observed on 18 May 2022 at position −375"E, 390"N, (μ = 0.82)
- GREGOR solar telescope (D = 1.5 m) Tenerife, adaptive optics, spectrograph GRIS, imaging
- Spectropolarimetric scan in lines Si I 1082.7 nm and Ca I 1083.9 nm, 08:29–08:48 UT, scale 0.135"/pix, FOV 65" x 41", mediocre seeing
- Simultaneous series of 200 broadband images in TiO band (751 nm), scale 0.050"/pix, FOV 77" x 60", cadence 5.5 s, resolution 0.3"–0.4"
- Inversions of I,Q,U,V line profiles to obtain the map of magnetic-field vector (SIR code)

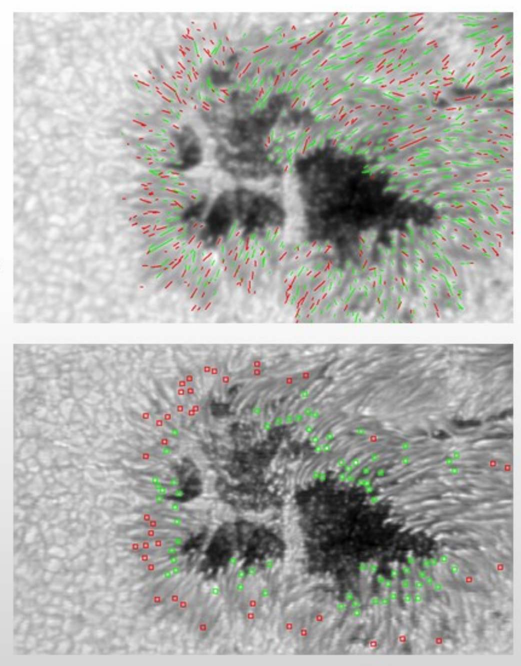


4 AR 13014: Motions of PGs derived from the series of TiO images



← Local correlation tracking (LCT)

Feature tracking (green: inwards, red: outwards) →



We cannot associate all the detected PGs directly with the magnetic inclination map, scanned during 19 min, because we can consider only those PGs that were present when the given part of the map was scanned. Instead, we find PGs in the enhanced GRIS continuum map and use the feature-tracking and LCT results just to distinguish between the inward and outward-moving PGs. →

5 AR 13014: Magnetic inclination in PGs and surrounding field

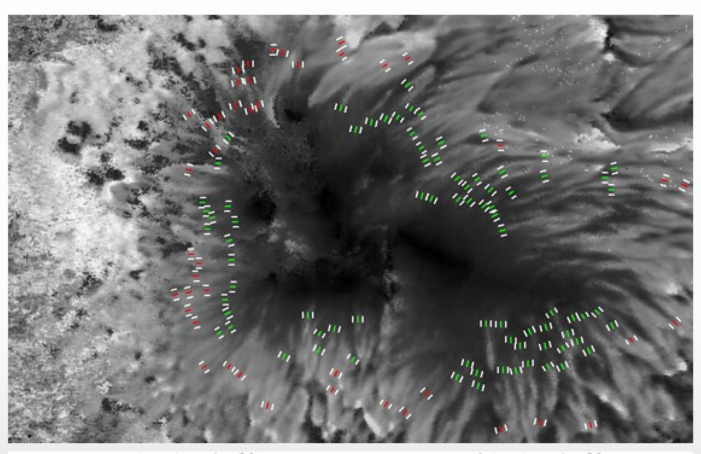
Inclination map with PGs represented by short (0.6") line segments directed along the local magnetic azimuth (green: inwards, 80 PGs; red: outwards, 44 PGs) →

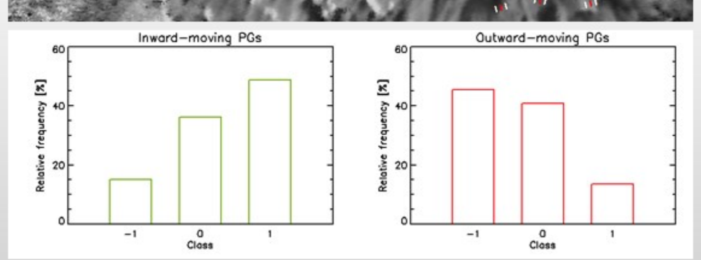
Mean inclination along the PG lines and mean inclinations along two parallel lines (white) on opposite sides of the PG line at distance 0.5" are compared and classified:

- class −1 : γ(PG) < γ(both sides) "U"
- class 0 : all other cases (unresolved)
- class 1 : γ(PG) > γ(both sides) "∩"

Populations of PGs in the classes →

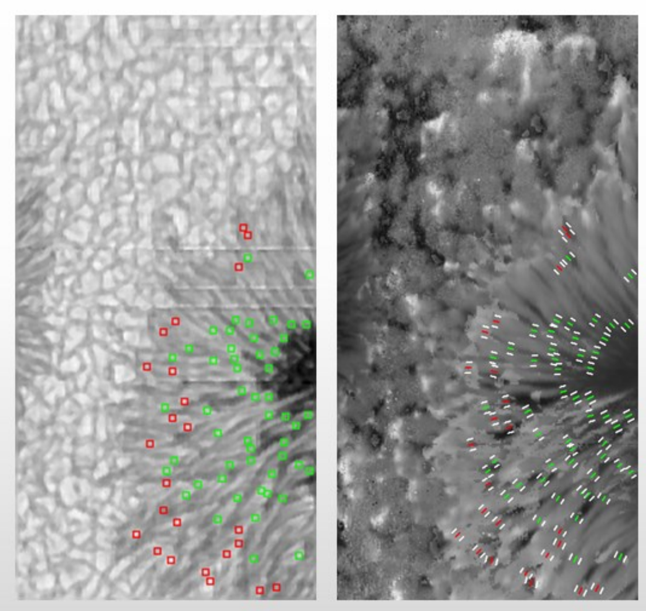
Inwards: most frequent **γ(PG) > γ(surr.)**
Outwards: most frequent **γ(PG) < γ(surr.)**





6 Observations: AR 12674, retrieved from https://archive.sdc.leibniz-kis.de/

- Penumbra of a spot observed on 3 Sep 2017 at position −248"E, 91"N, (μ = 0.96)
- GREGOR solar telescope (D = 1.5 m) Tenerife, adaptive optics, spectrograph GRIS
- Two scans in lines Fe I 1564.9 and 1566.2 nm, 08:43 and 08:54 UT, scale 0.135"/pix, mediocre seeing, scan 2 is of better quality
- Inversions of I,Q,U,V line profiles to obtain the map of magnetic-field vector (SIR code)
- PGs are identified in both scans to find their direction of motion. The magnetic inclination of PGs and their surroundings are compared in scan 2; 52 inward (green) and 24 outward moving (red) PGs.



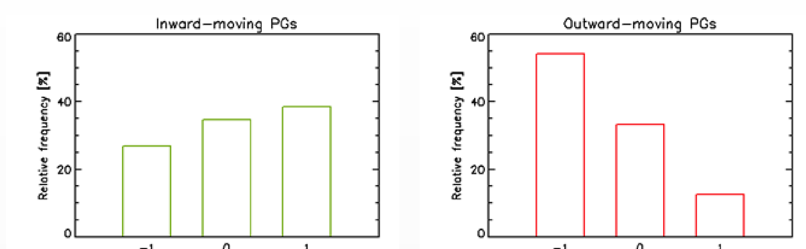
Scan 2: continuum and LRF inclination with PGs positions

7 Comparison of magnetic inclination of PGs and surrounding field

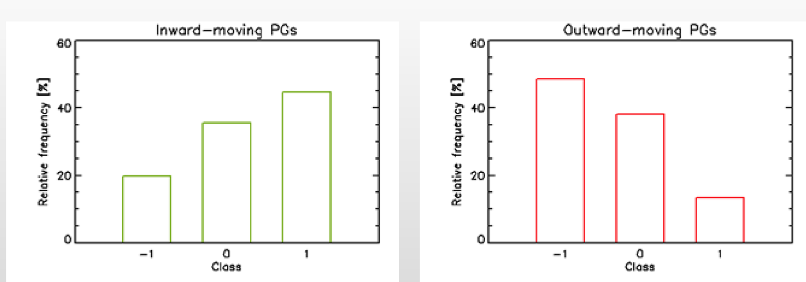
The sample of 132 inward-moving (INW) and 68 outward-moving (OUT) penumbral grains in two different sunspots shows that

- **γ(PG) > γ(surr.)** – Class 1 is the most frequent case for **INW** PGs and
- **γ(PG) < γ(surr.)** – Class -1 is the most frequent case for **OUT** PGs,

so that the difference of PGs and surrounding-field inclinations possibly affects the orientation of PGs motions.



AR 12674

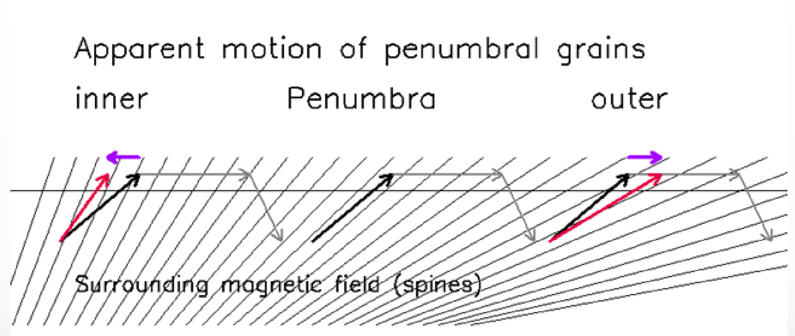


AR 13014 and AR 12674 together

8 Discussion

PGs moving inwards:
Rising hot plasma surrounded by a less inclined magnetic field in the inner penumbra may adapt its trajectory to be more vertical.

PGs moving outwards:
Rising hot plasma in the outer penumbra may be dragged by the more inclined surrounding field to a more horizontal trajectory.



More data with a better spatial resolution and numerical simulations of magneto-convection will be helpful to confirm this hypothesis.

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