The relation between magnetic field inclination and apparent motion of penumbral grains

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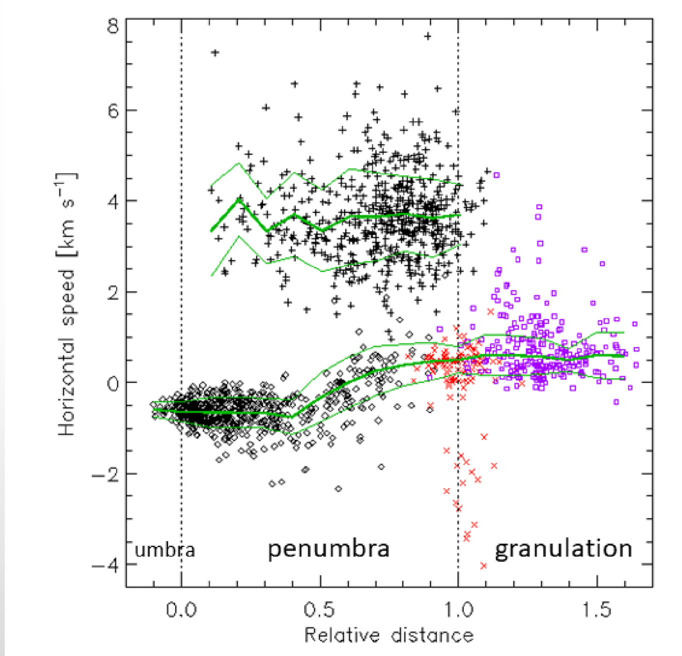
1 Horizontal speeds vs. position

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

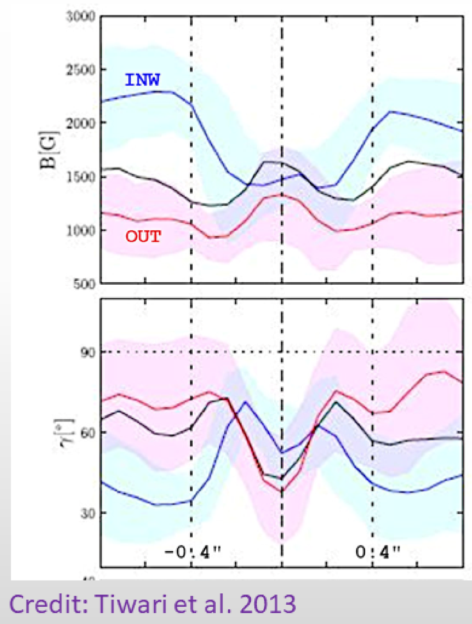
2 Filament model (Tiwari et al. 2013, A&A, 557, A25): transversal cuts of PGs in *B* and γ

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?



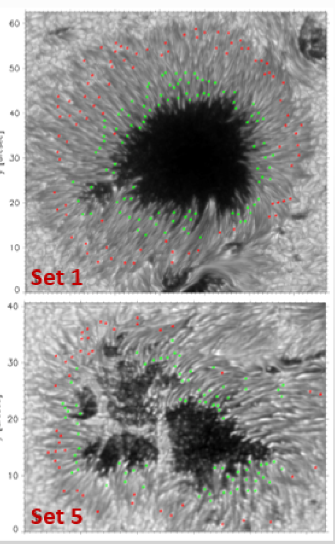
Credit: Tiwari et al. 2013

3 Observations

Sobotka, Jurčák, Castellanos Durán, and García-Rivas (2024, A&A, 682, A65)

Spectropolarimetric scans of well-developed penumbrae with spatial sampling 0.16" and better, μ > 0.8, simultaneous time series of broadband or continuum images.

Data set	1	2	3	4	5
Date	2006-12-10	2007-05-01	2012-05-05	2017-09-03	2022-05-18
Time UT	11:56–12:57	21:44–22:24	08:11–09:00	08:43–09:05	08:29–08:48
Active region	10930	10953	11471	12674	13014
Position μ	0.92	0.99	0.92	0.96	0.82
Instrument	SOT–SP	SOT–SP	CRISP	GRIS	GRIS
Spectral lines	Fe I 630.2	Fe I 630.2	Fe I 617.3	Fe I 1564.9	Si I 1082.7
[nm]	Fe I 630.3	Fe I 630.3	-	Fe I 1566.2	Ca I 1083.9
Sampling	0.″16	0.″16	0.″059	0.″135	0.″135
Inversion code	SPINOR–2D	SPINOR–2D	SIR	SIR	SIR
$\tau_{500\,nm}$	0.16	0.16	1.0	1.0	1.0
Broadband	G band	continuum	continuum	none	TiO band
wavelength	430.9 nm	450.4 nm	617.4 nm	-	750.7 nm
cadence	120 s	30 s	56.5 s	(2 scans)	5.47 s
sampling	0.″109	0.″054	0.″059	-	0.″050



Determination of inward and outward motions of PGs using LCT and feature tracking.

4 Magnetic inclination in penumbral grains and surrounding field – Set 5:

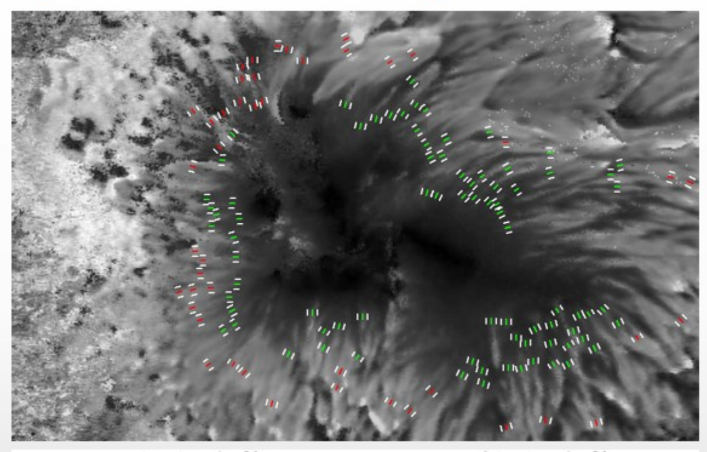
Inclination map with PGs represented by short (0.6") line segments directed along the local magnetic azimuth (green: inwards, 80 PGs; red: outwards, 44 PGs) →

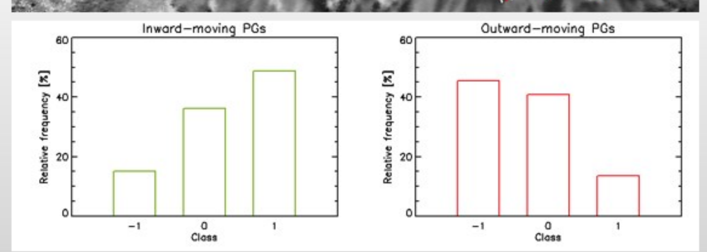
Mean inclination along the PG lines and mean inclinations along two parallel lines (white) on opposite sides of the PG line at distance 0.5" are compared and classified:

- **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.)**





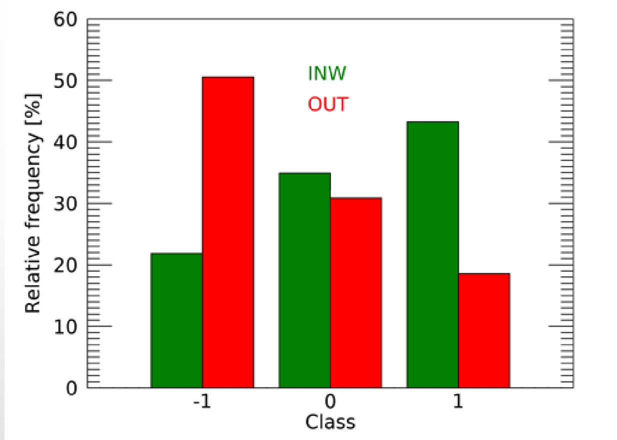
5 Results of observations – all 5 data sets

The sample of 444 inward-moving (INW) and 269 outward-moving (OUT) penumbral grains in five different sunspots shows that

- **γ(PG) > γ(surr.)** – Class 1 is the most frequent case (43%) for **INW** PGs and
- **γ(PG) < γ(surr.)** – Class -1 is the most frequent case (51%) for **OUT** PGs,

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

But there are many unsolved cases – can numerical simulations make it clearer?



6 Numerical simulations

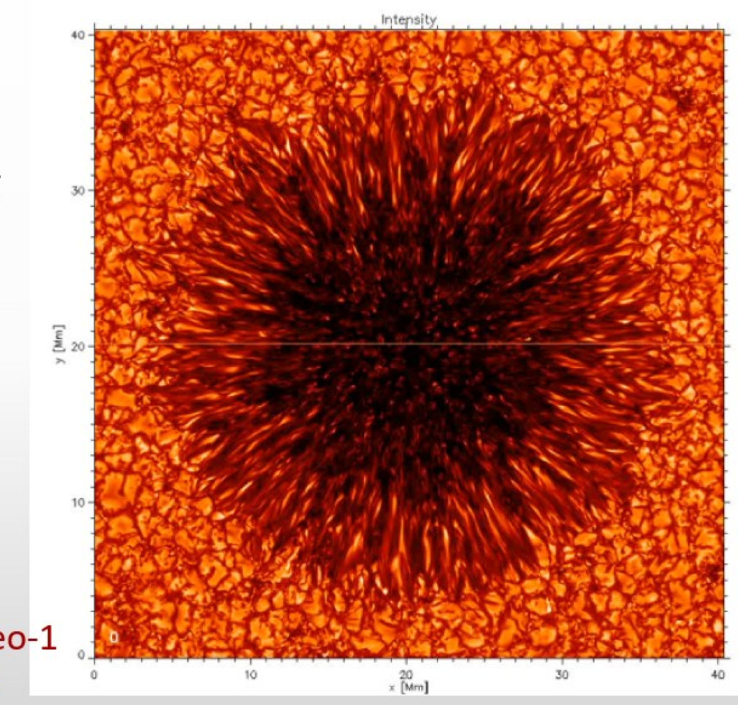
Continuation of M. Rempel's simulations (2012, ApJ, 750, 62) by Markus Schmassmann on Piz Daint (CH) super-computer under the SOLARNET Transnational Access Programme.

Parameters:
Top boundary: α = 2 (forced inclination)
Box size: 49.152 x 49.152 x 6.144 Mm^3
Grid spacing: 32 x 32 x 16 km^3 ("pixel size")
Grid cells: 1536 x 1536 x 384
Available at the 18 s cadence:
101 time steps = 30 min solar time

- Horizontal slices at τ = 1
- Vertical cuts across the spot's centre

$(T, \rho, v_{x,y,z}, B_{x,y,z}, I_{out})\ (t)$ Video-1

The inner penumbra is almost missing in the set.



7 Analysis of the 101 horizontal slices at τ = 1 using feature tracking

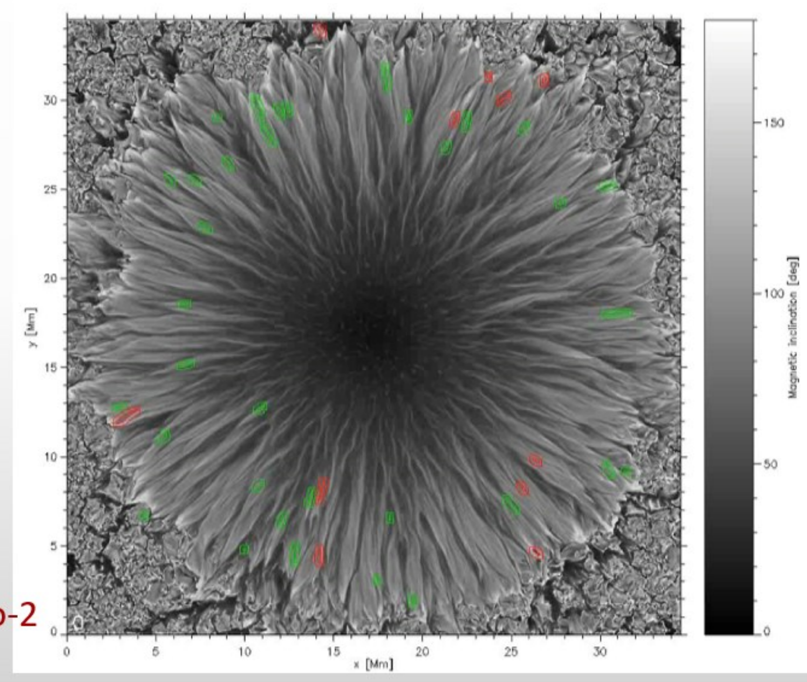
226 INW and 107 OUT PGs detected under the following conditions:

- vertical upflow > 1.5 km/s and I_{out} > 0.45 I_{ph} (segmentation parameters)
- tracked PGs have no split and no merge events
- min. lifetime = 180 s, min. size = 9 pix, max. horizontal speed = 4 km/s
- min. travel distance = 5 pix (160 km)

Mean γ(PG) in a segmented PG; mean γ(surr.) in its surroundings created by the *dilate* operator (~0.5") → Classes -1: γ(PG) < γ(surr.); 1: γ(PG) > γ(surr.)

Occurrence in individual frames:
INW: 47 % class -1, 53 % class 1
OUT: 63 % class -1, 37 % class 1

Video-2



8 Magnetic inclination in simulated PGs and surrounding field

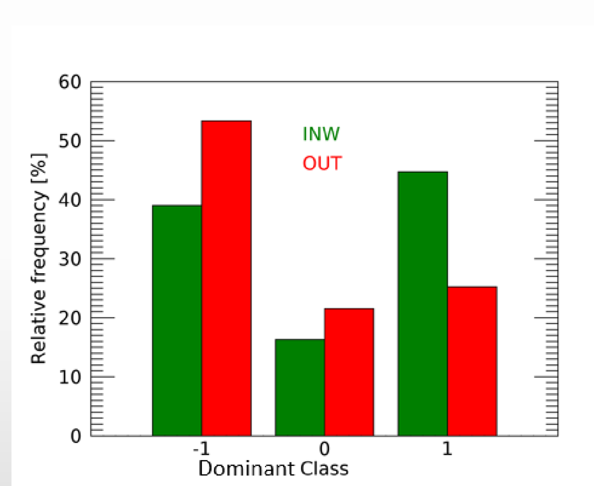
In many cases, the class (−1, 1) changes during the life of a PG. Time-averaged class $c = (p - n)/(p + n)$

Dominant class definition:
−1 for $-1.0 < c < -0.5$
0 for $-0.5 < c < 0.5$
1 for $0.5 < c < 1.0$
result →

Compared to observational results, there is not much difference between the INW classes 1 and −1. This is because the class 1 INW PGs that appear in the inner penumbra are almost missing in the simulations.

The statistics is consistent with that of observations.

- **γ(PG) > γ(surr.)** – Dominant class 1 is the most frequent case (45%) for simulated **INW** PGs
- **γ(PG) < γ(surr.)** – Dominant class −1 is the most frequent case (53%) for simulated **OUT** PGs



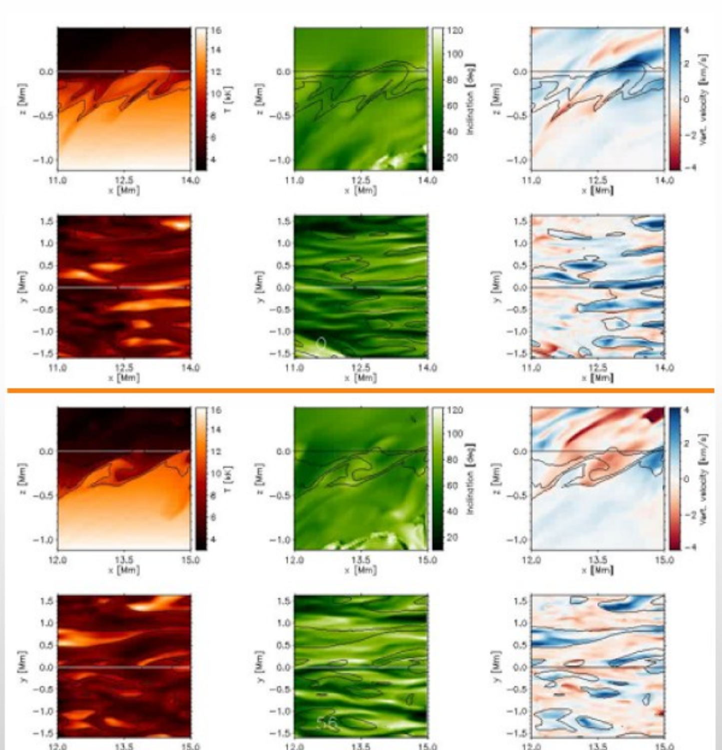
9 Analysis of the vertical cuts evolution: 11 cases of PGs

The turbulence introduces random disturbances in the dynamics of upflows and the magnetic field vector.

Apparent horizontal motion and field inclinations at the visible surface:

- 6 PGs of 11 have the expected relation (INW class 1, OUT class −1)
- *2 PGs change from INW to static or OUT, the class changes from 1 to −1*
- 3 PGs have the opposite relation (INW class −1, OUT class 1) – specific conditions (near the outer penumbral border, combination of low and high inclinations)

Examples:
Top – two close INW and OUT PGs, Video-3
Bottom – INW PG changing to OUT, Video-4

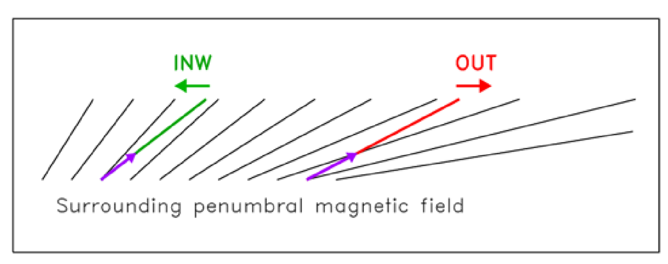


10 Conclusions

The simplified scenario

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

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



- The simulations show that the difference of magnetic inclinations inside and outside PGs and the direction of motion may change during the PG lifetime.
- The difference of inclinations inside and outside PGs at the visible surface affects their direction of apparent motion but this relation is disturbed by the turbulent character of magnetoconvective motions in the surface layers.

Online videos: https://indico.ict.inaf.it/event/2553/contributions/19545/

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