Rotational shear in the low solar photosphere

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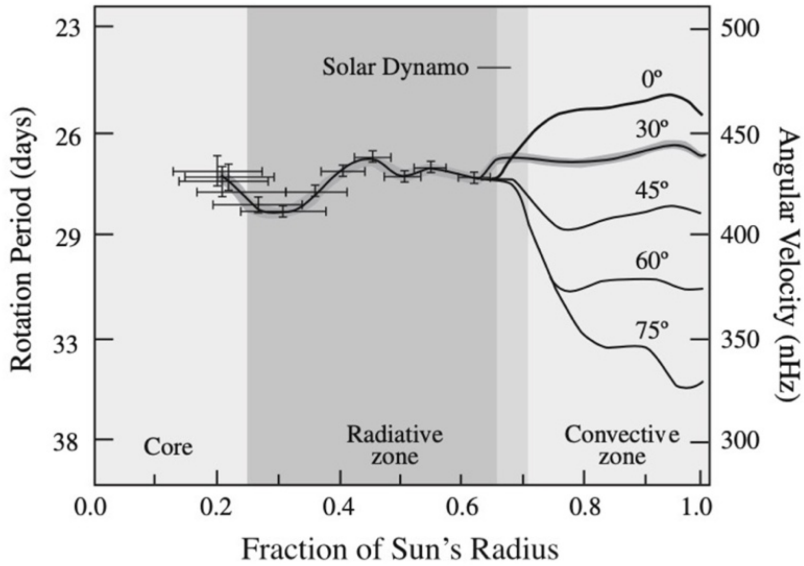
Radial differential rotation is an important physical ingredient in stellar dynamo theory. In the case of the Sun heliosismology techniques revealed the existence of a near surface shear layer. It was shown recently that the rotation velocity gradient is not uniform in this layer but increases steeply near the surface.
We report the detection of a rotation velocity depth-gradient in the low photosphere that is not accessible by heliosismology techniques. The detection is based on the measurement of a systematic East-West shift between images of the solar granulation at different depths in the FeI 630.15 nm observed at the center of the solar disk. We also measure the height-difference between the images from their perspective shift when they are observed away from the disk center. Both THEMIS and HINODE/SOT data are used for the height-difference measurement and give similar results.
At the center of the solar disk, we measure a systematic retrograde shift of the photospheric granular structures on the East/West axis and no shift in the Nord/South direction. The retrograde shift increases linearly with height. We interprete these findings as the signature of a steep decrease of the angular velocity in the low photosphere.

Context

- The convective envelope of the Sun shows differential rotation in latitude and radial shear in 2 zones: the Tachocline and the Near Surface Shear Layer (NSSL)

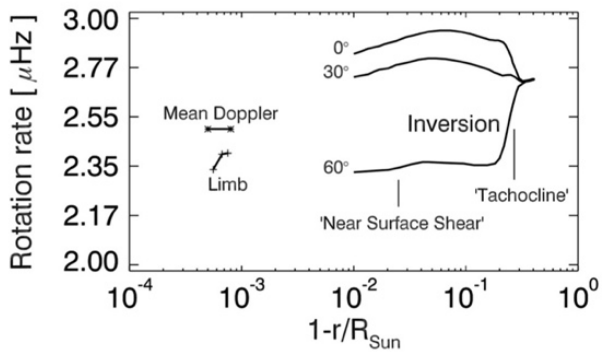


In the photosphere

70's : Active regions (sunspots) rotate faster than the quiet sun plasma.

1972: Livingston & Harvey found no evidence of rotational shear in the photosphere (from Doppler measurements in several lines).

2017: Cunnyngham et al. from 3.5 years of HMI data, measured a steep radial decrease of the latitudinal average of the angular velocity in the upper photosphere.



Cunnymgham *et al.*, PRL 2017

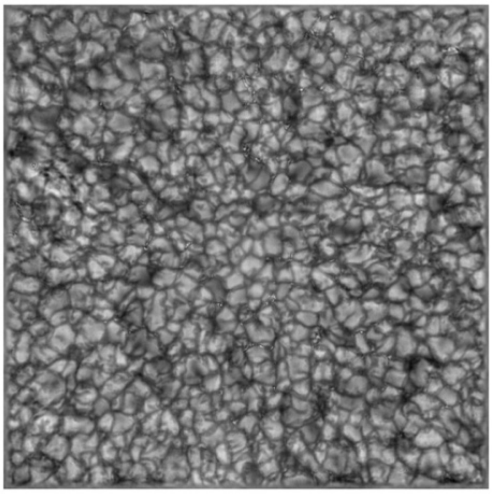
This work

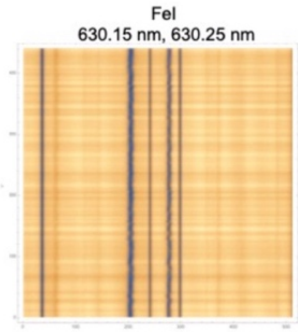
- New observations and data analysis

The method relies on the detection of small shifts between images of the granulation at different heights in the photosphere

The Method

Spectroscopic observations with high angular resolution at Themis (Tenerife)

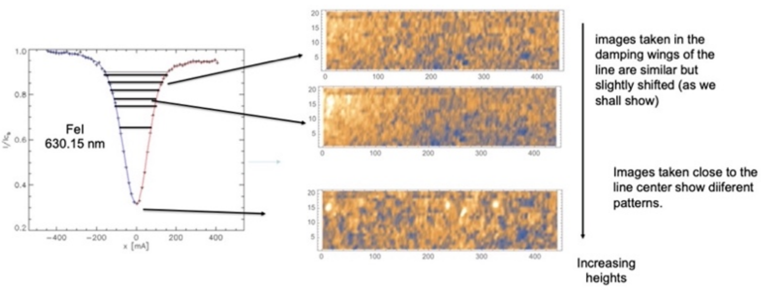




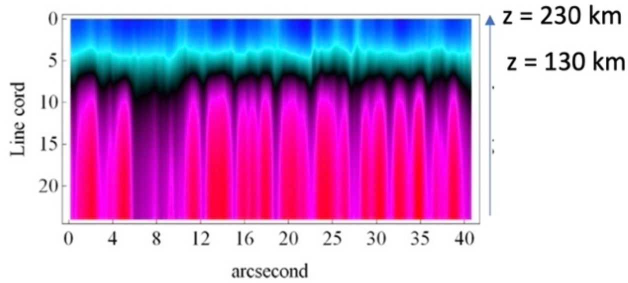
Example of spectrum for one slit position at disk center

We select the best images from a contrast criteria

Images formed at different line-cord widths allow us to scan the granulation pattern at various depths.



Vertical cut of the granulation
(from Hinode data)
We observe coherent structures at different depths



Faurobert et al. A&A 2012

Measurement of small shifts between images

We compute the cross-spectrum of the images

- <> ensemble average on a large number of granular structures. Only systematic effects remain.

Intensities along the slit

Line-wing Continuum

$$I_i(x) \sim I_c(x-\delta)$$

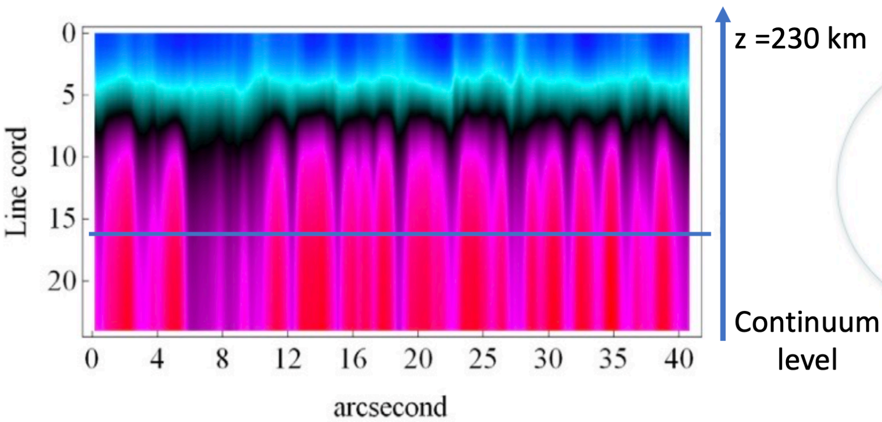
Cross-spectrum of the images

$$\widehat{Q}_{ci}(u) = <\widehat{I_c}(u)\widehat{I_i^*}(u)>$$
$$\sim <|\widehat{I_c}(u)|^2> e^{-2i\pi\delta u}$$

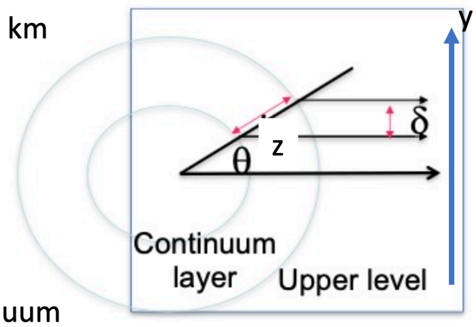
The cross-spectrum is linear with *u*,
The slope is proportionnal to the shift δ
Allows us to measure very small shifts

The perspective effect (seen out of disk center)

Vertical cut of the granulation from images at different line cords (From Hinode data)



Schematic representation of the perspective shift for images at two line-cords taken out of the disk center



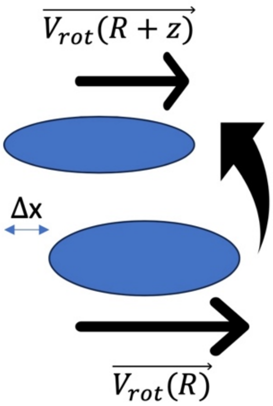
$\Delta y = \delta = z \sin\theta$

Equatorward shifts due to a height-gradient of the rotational velocity

$$\Delta x = \Delta V_{rot}\,\tau$$

Coherence time of the granular pattern

$$\Delta x = z\,\frac{dV_{rot}}{dz}\,\tau$$



Measurements

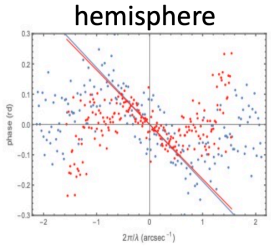
Perspective shift measured at positions long the central meridian with the slit along N/S direction

Shift due to rotational shear measured at the equtor with the slit E/W

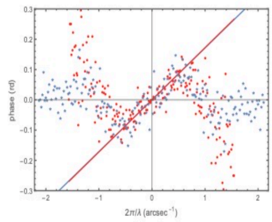
Measurement of the perspective shift

- **The cross-spectrum phase** shows a linear behavior for spatial frequencies smaller than 0.6 arcsec^{-1} (spatial scales larger than 1.7 arcsec),
- Opposite slopes in the northern and southern hemispheres.
- Here the altitude difference between the 2 images (line cords 16 and 25) is
- z = 21.6 +/- 0.9 km

Northern hemisphere



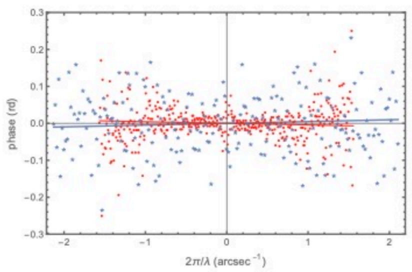
Southern hemisphere



At cos ϑ = 0.74, North (Left), south (right)
Blue: from Themis data, **Red: from Hinode/SOT data**

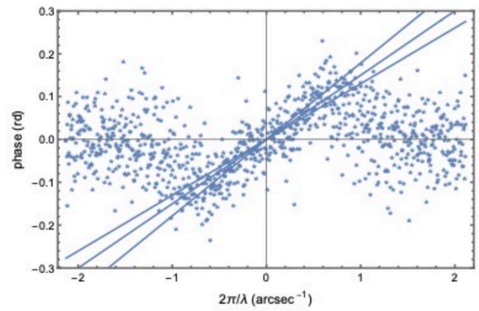
Retrograde longitudinal shifts at the equator

- At the center of the solar disk, the perspective effect vanishes (the cross-spectrum phase is 0).



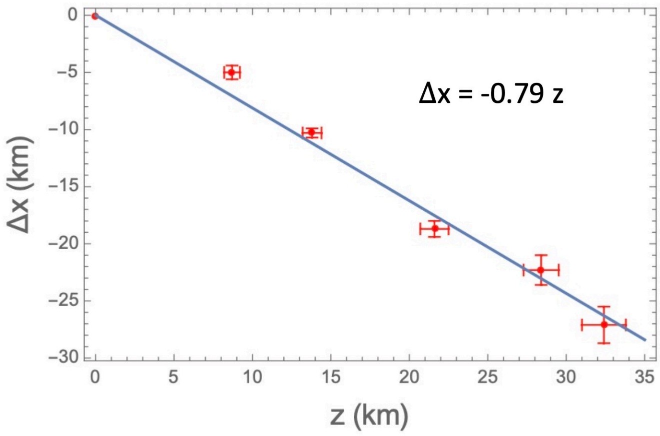
Scans at the equator with the ***slit along the north/south direction***

Scans at the equator with ***the spectrograph slit along the east/west direction***



Cross-spectrum phase for three different scans performed on July 19, 20 and 22, 2022
Shows a ***negative shift of -18.7 +/- 0.7 km*** of the structures seen at z= 21 km above the reference level (line cord 16).

Height-dependence of the equatorward shift



- We observe a linear variation of the retrograde shift with z, in agreement with

$$\Delta x = z \frac{dV_{rot}}{dz} \tau$$

- This gives

$$\frac{dV_{rot}}{dz}\tau \sim -0.79$$

Estimate of the coherence time of the granulation:
- $\tau \sim 440\ s$ (Title *et al.* 1988)

$$\frac{dv_{rot}}{dz} \sim -1.8\ 10^{-3}\ (s^{-1})$$

$$\boxed{\frac{\Omega(R+z)}{\Omega(R)} = (1 - \alpha z)\ with\ \alpha \sim 9\ 10^{-4}\ (km^{-1})}$$

$$\Delta\Omega \sim -0.23\ \mu rd/s\ on\ \Delta z = 100\ km$$

Measured in a thin layer of 30 km in the low photosphere

Conclusion

- Our estimate of the rotational gradient is steeper than the value obtained in the upper photosphere by Cunningham et al. but they measured a latitudinal average on effective heights.
- Our estimate depends on the coherence time of the granulation.
- What are the causes and consequences of this rotational shear?
- The determination of the $\Omega(\vartheta)$ variations might be affected by the rotational depth gradient if measurements at different latitudes are also at different heights.

- More in Faurobert *et al.* A&A 676, L4 (2023)