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DETECTION OF A STEEP HEIGHT GRADIENT OF THE ROTATIONAL VELOCITY IN THE LOW PHOTOSPHERE OF THE SUN

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Abstract. We present a new method to measure the rotational height gradient in the solar photosphere. The method is inspired from differential interferometric techniques, it is applied to spectroscopic observations in the FeI 630.15 nm obtained at the solar telescope THEMIS equipped with an efficient adaptative optics system. At the center of the solar disk, we measured systematic retrograde shifts between images of the granulation pattern obtained at different line cords that are formed at different heights. The shift varies linearly with height. We interprete this as the signature of a steep decrease of the rotational velocity in the low photosphere.

Keywords: Techniques: high angular resolution - Techniques: spectroscopic - Sun: photosphere

1 Introduction

Rotational shear plays a major role in driving the stellar dynamo. For the Sun helioseismic observations have revealed two regions that show a strong height-gradient of the rotation rate, namely, the tachocline at the base of the convective zone and the near surface shear layer (NSSL). Heliosismic technics do not allow us to explore the photospheric layer. Previous spectroscopic observations by Livingston & Milkey (1972) failed to find any evidence of a depth gradient but more recently Cunnyngham et al. (2017) using 3 years of the Helioseismic and Magnetic Imager (HMI) data could measure a steep rotational shear of the latitudinal average of the rotational velocity in the upper photosphere. Here we show that the rotation profile in the photosphere may be probed by high resolution spectroscopic methods and we report the detection of a steep decrease of the rotational velocity in the low photosphere.

2 Observations and method

Our detection method relies on the measurements of systematic shifts between simultaneous images of the granulation taken at different altitudes. Systematic shifts may arise from two different effects, namely, a perspective effect in the radial direction when the images are taken away from the center of the solar disk or horizontal shifts that are induced by a height-gradient of large scale horizontal velocities projected on the plane of the sky. The perspective effect allowed us to measure the formation height of line-cord images with respect to the continuum layer, whereas at the center of the solar disk where the perspective effect vanishes we measured systematic retrograde shifts along the solar equator of the images formed higher up in the photosphere.

We used spectroscopic observations obtained at the solar telescope THEMIS dating from July, 18 to July 22, 2022, in the FeI 630.15 nm line. To measure the perspective shift we also used HINODE Solar Optical Telescope (SOT) spectropolarimetric (SP) data from the irradiance program, HOP79, performed on July 21, 2022. We defined 25 cords in the line profile from the continuum (level 25) to the line core (level 1). To measure a very small displacement between images in the continuum and in the line wings, we used the phase of their cross-spectrum. This method requires us to consider the power spectra of intensity fluctuations in images taken rigorously at the same time in the continuum and in the line. To extract statistical information we performed ensemble averages of the cross-spectra obtained at a large number of slit positions. Actually, 2D images are not

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needed as far as the spectrograph slit is oriented in the direction of the displacement. In practice, we used 1D power spectra of the intensity variations along the spectrograph slit and we summed over all the slit positions. A shift between the images gives rise to a linear phase term in their cross-spectrum, the slope of this linear phase term allows us to determine the shift between the images. The details are given in Faurobert et al. (2023). We stress here that this method allows us to measure shifts that much smaller than the resolution of the telescope.

3 Retrograde shift measured at the center of the solar disk along the equator

Figure 1 shows a schematic representation of the drag of the granular pattern at a height z by the rotational height-gradient. This gives rise to a shift Δx of the intensity distribution along the spectrograph slit if we align it with the equator.

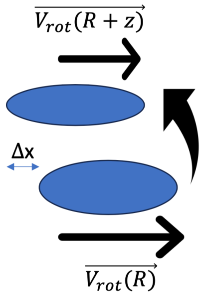

Fig. 1. Schematic representation of the drag of the upper layer at height z due to the rotational depth-gradient.

Figure 2 shows as an example, the cross-spectrum phase of images at line-cord 15 with images at the continuum level, when the slit is oriented along the north/south polar axis (left panel) and when its is oriented along the equator (right panel). In the last case we show the results obtained for three different observing days. No shift of the images is observed along the polar axis (the phase is noisy but remains close to 0), whereas we do observe a linear behavior of the cross-spectrum phase when the slit is along the equator. This allows us to measure the shift Δx, that it is negative meaning that the rotational velocity decreases with height. For the line cord shown here we get $\Delta x = -22.3 \pm 1.3$ km. In Faurobert et al. (2023) it is shown, using several line cords that Δx is proportional to the height z (obtained from the perspective effect) in the low photosphere.

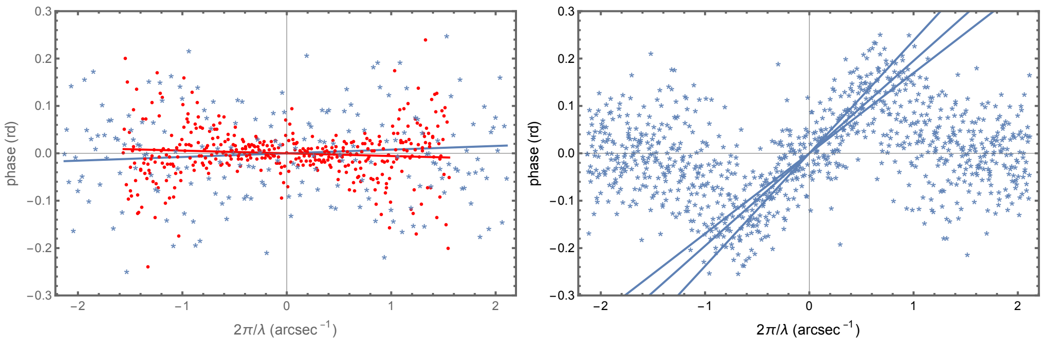

Fig. 2. Left: Phase of the cross-spectrum of images at cords 15 and 25 (continuum) with the slit along the polar axis. Blue symbols: from Themis data, red symbols: from Hinode data. **Right:** Phase of the cross-spectrum with the slit along the equator for three different observing days. The straight lines show linear fits at spatial frequencies smaller than 0.6 arcsec^{-1}.

References

Cunnyngham, I., Emilio, M., Kuhn, J., Scholl, I., & Bush, R. 2017, Phys. Rev. Lett., 118, 051102

Faurobert, M., Corbard, T., Gelly, B., Douet, R., & Laforgue, D. 2023, A&A, 676, L4

Livingston, W. & Milkey, R. 1972, Sol. Phys., 25, 267