Subsurface flows associated with non-Joy oriented active regions: a case study

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Abstract.
Non-Joy oriented active regions (ARs) are a challenge for solar magnetic field modelers. Although significant deviations from Joy's law are relatively rare for simple bipolar ARs, understanding the causes of their particularity could be critical for the big picture of the solar dynamo. We explore the possibility of the sub-surface local dynamics being responsible for the significant rotation of these ARs. We apply the ring-diagram technique, a local helioseismology method, to infer the flows under and surrounding a non-Joy oriented AR and present the results of a case study in this paper.

1. Introduction

The solar magnetic cycle is generally explained using magneto-hydrodynamic dynamo theory. Hence, understanding the mechanisms of the solar dynamo, in particular the formation an emergence of active regions, is key to understanding the big picture of the Sun's behavior in order to ultimately forecast its activity. One of the characteristics of emerging active regions is the tilt of their orientation (Joy's law, [1]), caused by the Coriolis force, with the leading polarity appearing closer to the equator. Although statistically active regions follow this pattern [2], there are cases of clear deviation, where the leading polarity stays closer to the pole. Our purpose is to research the possibility of the local dynamics surrounding the non-Joy oriented active regions being responsible for their unusual tilt. The ultimate goal is to get enough statistics by obtaining the flows under the solar surface from local helioseismology methods of a large set of non-Joy oriented ARs. In this paper, we present the results of applying ring-diagram analysis to a single anti-Joy law active region (NOAA 11073), but expect to extend the work to a significant sample of them, as well as to a similarly large set of regularly-oriented active regions, using the same technique in the near future.

NOAA 11073 is a well isolated active region that emerged in the Northern hemisphere around May 28th 2010. Its leading negative polarity is farther away from the equator than the trailing negative one. This situation persists for the four days (May 30-June 2) that we follow the active region as it crosses the solar central meridian (see Fig 1). Its location and isolation make it a perfect case for analysis.

2. Analysis method

The ring-diagram technique [3], one of the local helioseismology techniques, uses medium/high-degree waves propagating in localized areas of the Sun to obtain an averaged horizontal velocity vector for that particular region. The input data for our analysis are high-resolution Dopplergrams from the Helioseismic and Magnetic Imager (HMI, [4]) on board the Solar Dynamics Observatory. In the typical analysis, a particular area (patch) of the Sun is tracked and remapped into a data cube, and the analysis of the corresponding 3-D power spectrum of solar oscillations renders an average horizontal velocity vector for the area at different depths. By analyzing a mosaic of these patches, it is possible to infer 3-D velocity map in the depth range where the waves propagate.

We applied the ring-diagram analysis technique to 1664 minute series of HMI data, using a resolution of about 1.5 Mm (0.75 Mm/pixel) at the center of the disk. From each reprojected data cube, a 3-D power spectrum was obtained. The power spectrum is then fitted to a profile that includes the perturbation in the spatial frequencies due to the horizontal velocity fields [5]. Finally, the mode-dependent velocities from the fitting go through an inversion process to get the depth dependence of the flows.

To study the flows around active region NOAA 11073 we divide the surrounding area into 25 patches. Each area of $8^\circ \times 8^\circ$ is apodized into a 7.5° circular area before calculating the 3-D power spectrum. A horizontal velocity vector at several depths is obtained from the analysis of each single patch. The combination of the results from the 25 areas give a low resolution map of flows surrounding the active region from the surface to approximately 6-7 Mm depth for each analyzed day (see Fig 1).

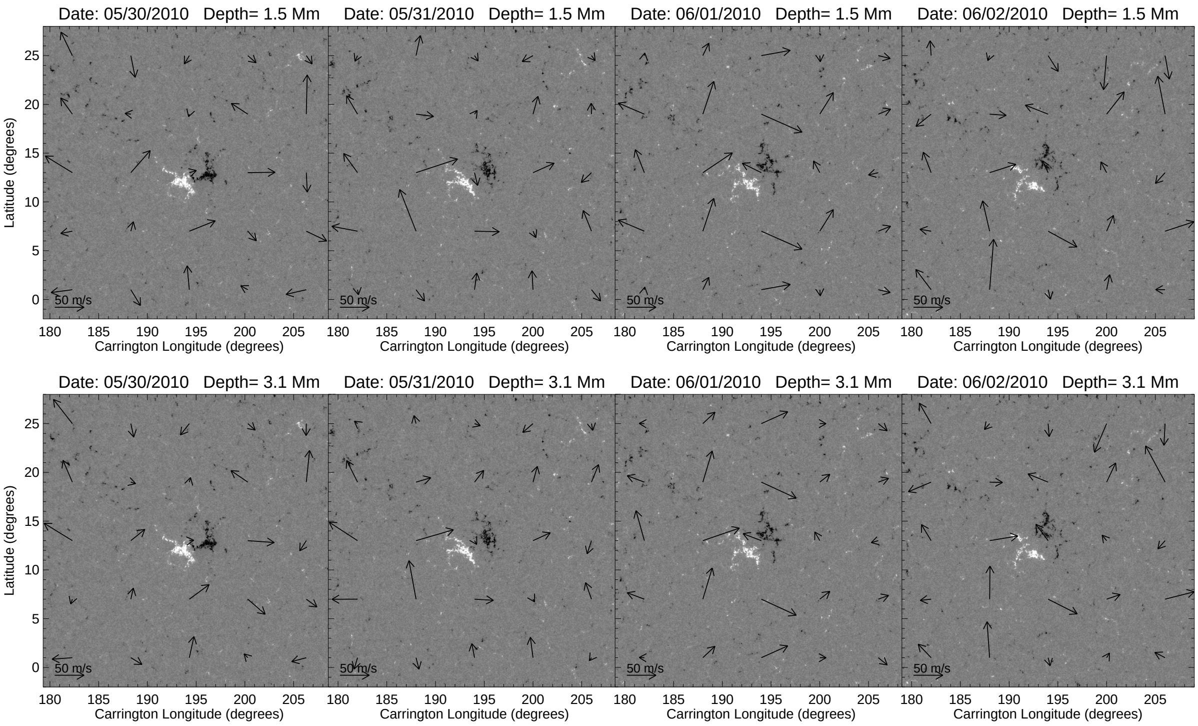

Figure 1. Subsurface flows surrounding AR NOAA 11073 at 1.5 Mm (top) and 3.1 Mm under the solar surface for four consecutive days as it crosses the solar central meridian.

We applied ring-diagram analysis as described to the 25 patches surrounding active region NOAA 11073 and obtained the horizontal subsurface flows for four consecutive days. In order to remove large scale flows, such as meridional circulation and rotation residuals, as well as contributions to the flows from projection effects, we subtract the average of three quiet solar areas located at exactly the same position as each of the individual analyzed patches on May 15-17. Figure 1 shows the results for the four days for two particular depths, 1.5 Mm and 3.1 Mm from the solar surface.

3. Results

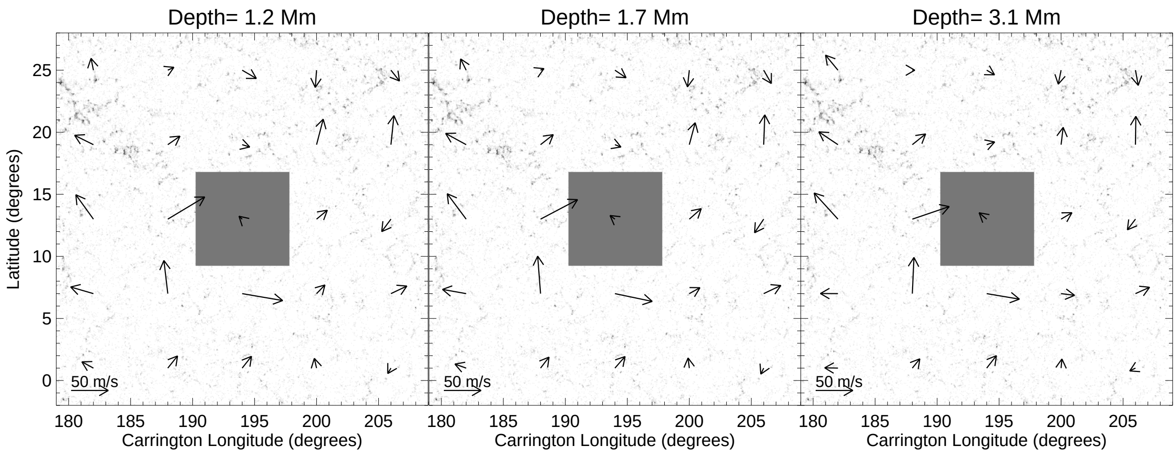

Figure 2. Temporal average of the subsurface flows surrounding active region NOAA 11073. The magnetic field background is the absolute value of the average for the four consecutive days. The central patch has been set to zero to show how quiet the contiguous analyzed regions are.

Temporal averages of the flows surrounding active region NOAA 11073 are presented in Fig. 2 for three different depths. Since we expect the subsurface macrodynamics to be relatively stable, we averaged the results from the four consecutive days of the analysis. The flows are superimposed on the absolute value of magnetic field averaged over the four continuous days from HMI magnetograms. The magnetic field from the central patch has been removed to emphasize how quiet the surrounding studied areas are.

From the horizontal velocity field an estimate of the vertical velocity can be calculated by assuming mass conservation [6]. Vertical vorticity (curl of horizontal flows) and associated helicity gives a sense of the curl of the material motions. The vertical vorticity is presented in Figure 3 for the 8° patches surrounding the active region. Figure 4 shows the vorticity of the synoptic map including the area of active region NOAA 11073 (approximate 13° latitude) from flows calculated using a lower resolution ring-diagram analysis of the full solar surface from NISP/Global Oscillations Network Group data. The vorticity is counter-clockwise (cyclonic) in both cases where the active region is located, which is what one might expect for an anti-Joy region, that is, flows that will drive the leading polarity away from the equator. However, previous work using large areas show a slight positive vorticity seems to be prevalent close to active regions in the Northern hemisphere [7]; whether AR NOAA 11073 have an excessive amount of positive vorticity compared to other regions of its size and strength needs to be determined by using this more targeted method to study a large data set of active regions.

4. Summary

With this single case analysis we have showed the potential of the ring-diagram analysis applied to HMI Dopplergrams for investigating the local dynamics around and below non-Joy orientated active regions. The effects of the magnetic field on helioseismology inferences are still a subject

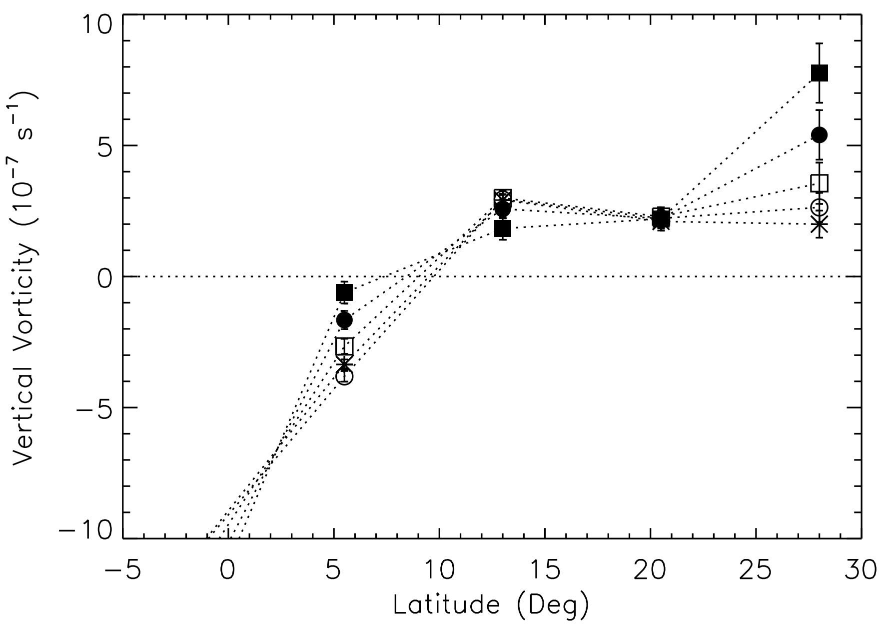

Figure 3. Calculated vertical vorticity for the areas surrounding AR NOAA 11073 using the 8° patches. There is positive (cyclonic) component close to the 13° latitude where AR NOAA 11073 is located.

of research. The power spectrum of solar oscillations is expected to be affected by the presence of magnetic field, making the interpretation of the fitted velocity parameters difficult. To avoid this, we have focus our analysis on the macrodynamics observed in the quieter areas surrounding the active region.

This particular case analysis shows counter-clockwise flows in the subsurface layers surrounding the active region, which may be responsible for driving the leading polarity away from the solar equator. However, statistics from the analysis of many such active regions are required to conclude whether the subsurface flows are responsible for the unusual orientation of these active regions. Customization of the method, such as a thorough determination of the trade-off parameter of the flows inversion (depth localization vs. error) need to be reviewed when more cases are added to the study. The subsurface flows associated with our case analysis (NOAA 11073) show the characteristic curl that would be expected to explain the leading polarity to be driven away from the equator. However we need to demonstrate that this is different for normally orientated active regions by analyzing with the same method a significant number of Joy oriented AR's as a control set.

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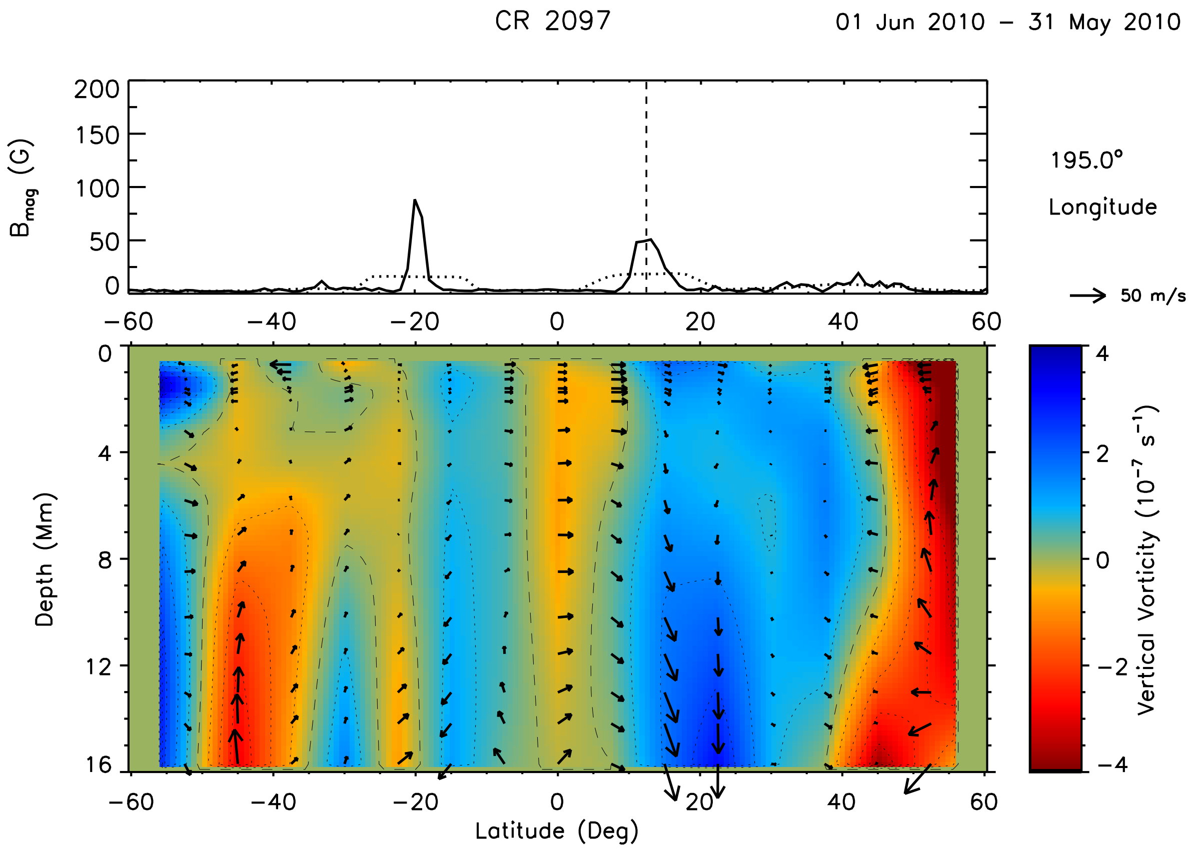

Figure 4. Calculated vertical vorticity for the areas surrounding AR NOAA 11073 using a low resolution ring-diagram analysis. A large area of the Sun at different depths is presented here, but there is clear positive (cyclonic) component close to the 13° latitude where AR NOAA 11073 is located.

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