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Research Paper

Detecting a New Type of Stokes *V* Profiles Observed by Hinode in a Sunspot

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Abstract. Realizing upflows and downflows in sunspot penumbrae are important for understanding the process of heat transport there. Doppler effect signatures on Stokes spectra are the best diagnostic tools to find the flow field in a sunspot. A part of a mature sunspot including of umbrae and penumbrae is observationally examined to find photospheric dynamics. We analyze spectro-polarimetric observations of photospheric Fe I lines with the Solar Optical Telescope aboard Hinode to find signatures of Doppler velocities on the Stokes V profiles. Stokes V profiles characterized by humps on both blue and red lobes with the same magnetic polarity as the sunspot umbrae were detected in both umbrae and penumbrae. These types of profiles have not been previously reported. Pixels whose Stokes V profiles show humps on, at least, either blue or red lobe are ubiquitous: 42.1% show both humps; 36.8% (3.7%) show only blue (red) hump. Umbra shows profiles having both blue and red humps. Investigating the Stokes V profiles characterized by humps implies that all types of these profiles are the same entity with different hump amplitudes. This means that both blue and red humps alter the Stokes V profiles either as explicit humps or as tail extension of the lobes. The magnetic fields of these *hidden* structures have to be weak and almost vertical. This implies that two humps cannot belong to a single-2nd-component. Bidirectional flows propagating along vertical magnetic fields as the result of redirection of outflows along the vertical magnetic field, after a magnetic reconnection, gives a possible mechanism producing adjacent upflows and downflows. Blue and red humps can be the Doppler effect signatures of these upflows and downflows, respectively.

Keywords: Sun: Sunspots, Fine-Structures

1 Introduction

A sunspot consists of an umbra which is dark due to partially preventing convection by relatively vertical and strong magnetic fields, and a brighter penumbra with filamentary structure created, probably, by photospheric convection in the presence of inclined strong magnetic fields. In order to obtain the flow fields in penumbrae and to understand its relation to the filamentary structure of penumbrae, magnetic and thermal structure of penumbrae have been studied by many authors (for reviews, see [1–3]). Observations suggest that the penumbral magnetic fields consist of two different components [4,5]: a relatively vertical and

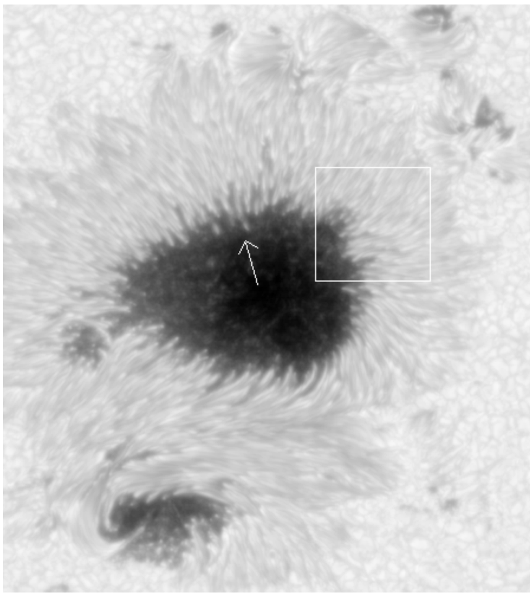

Figure 1: Map of continuum intensity. The white box (15×15 arcsec^2,) indicates the region of interest. The arrow points to the disc center.

strong background field and a weaker and more horizontal field where the known Evershed flow takes place (see *e.g.*, [6–8]).

Upflows as well as downflows is important for understanding the process of heat transport in penumbrae. Spectro-polarimetric (SP) observations of penumbrae provide evidences for sources and sinks of the Evershed flow at the inner and outer ends of penumbral filaments [9–11]. On the other hand, some observations imply that there are elongated upflows in the center of the filaments with surrounding downflows as evidences for overturning convection in the penumbral filaments [12,13].

Both chromosphere and photosphere of sunspot penumbrae is known to have dynamic and small scale structures [11,14] (see also reviews in [15,16]). Katsukawa & Jur*čá*k [17] identified newly small downflow patches in penumbrae with the same magnetic polarity as the spot, which are different from flows associated with the Evershed flows. It is therefore of vital importance to pay more attention to penumbral observation to recognize accurately flow and magnetic fields.

In this paper, we analyze the data set of the SP observations of photospheric spectral lines in a sunspot close to the disc center. We present newly multi-component Stokes V profiles of neutral iron lines at 630 nm showing co-existing small scale down- and up-flows at the same resolution element with the same magnetic polarity as the spot.

2 Data Set

We study SP observations of the active region NOAA 10930 taken by the Solar Optical Telescope (SOT, [18,19]) onboard the Hinode satellite [20]. The width of the spectrograph slit and the step of the slit are equivalent to 0.16 and 0.15 arcsec, respectively. The wavelength sampling is 2.15 pm. The SP recorded full Stokes spectra of the two Fe I lines at 6301.5 and 6302.5 Å were observed on 11 December 2006 from 13:10 to 16:05 UT, when the spot was located at the heliocentric angle of 5°, very close to the disc center. The data are calibrated with standard routines available under the Solar SoftWare (SSW). The calibration of wavelength was performed using the line center of an average quiet Sun profile. The Stokes profiles were normalized to the continuum intensity at the solar disc center (I_{sdc}). The continuum image of the observed sunspot is shown in Figure 1. A field of 15 × 15 arcsec^2, corresponding to 98 × 97 pixels, was selected for the current study (white box in Figure 1). In order to find regions that show large Doppler velocities in the photosphere, probably in deep layers, the observed Stokes V profiles are investigated.

3 Results

3.1 Abnormal Stokes *V* profiles

According to Ichimoto et al. [11] and Katsukawa & Jurčák [17] we construct far blue- and red-wing magnetograms using Stokes V signals of the 6301.5 Å line to find pixels with strong signals. These magnetograms have been used to identify Doppler shifts of Stokes V profiles [21,22]. Figure 2 shows both blue- and red-wing magnetograms at −215 (middle panel) and +215 mÅ (right panel) from line center. The polarization of the magnetic field of the selected region (and the biggest sunspot, see Figure 1) is downward and negative. Therefore, the blue lobes of regularly expected Stokes V profiles are negative. In the sunspot penumbra, small patches having enhancements of Stokes V signals on either wing are commonly observed, as shown in the middle and right panels in Figure 2.

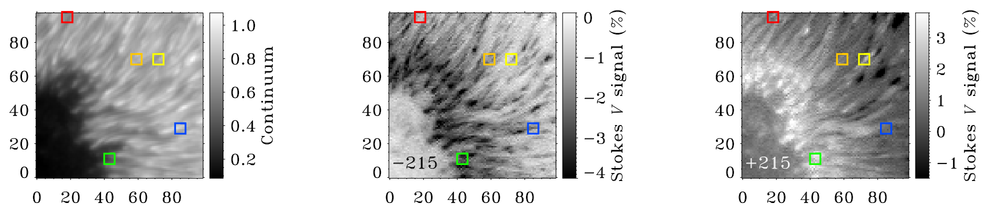

Figure 2: Maps of continuum intensities (left), blue wing magnetogram (Stokes V signals at −215 mÅ from the line center, middle), and red wing magnetogram (Stokes V signals at +215 mÅ from the line center, right) reconstructed from the SP data using the Fe I 6301.5 Å line. The (centers of) square symbols mark example pixels showing Stokes V profiles with signal enhancements whose profiles are plotted in Figure 3.

Different types of patchy enhancements are visible in the far-wing magnetograms:

1) Negative patchy enhancements on the red wing of the Stokes V visible as darkest patches in the right panel in Figure 2. The negative Stokes V signals on the red wing are produced by a strongly red-shifted Stokes V profile with the polarity opposite to the major polarity of the sunspot (*e.g.*, [23]). These patches are attributed to downflows of the Evershed flows along magnetic field lines returning into the photosphere mainly observed near the boundary of the penumbra when the spot was located near the disk center [9,11,21,24]. Similar negative patches are also seen even in the middle of the penumbra by Sainz Dalda & Bellot Rubio [25], who suggested that these can be associated with the sea-serpent field lines in the mid-penumbra.

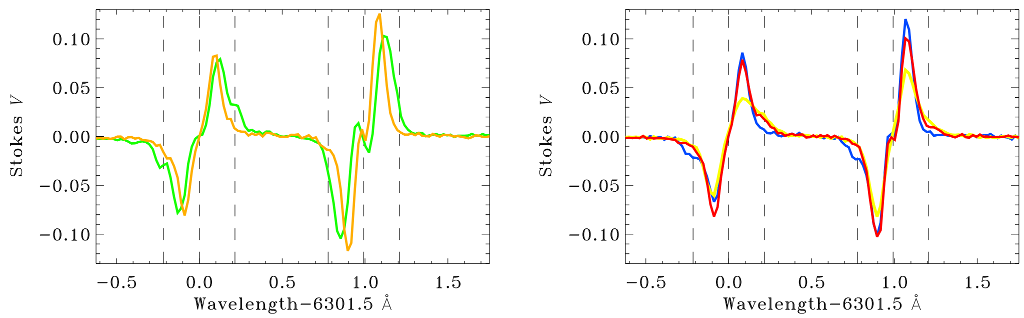

Figure 3: Examples of Stokes V profiles with enhanced negative Stokes V signals on only blue wing (right panel, blue), of those with enhanced positive Stokes V signals on only red wing (right panel, red and yellow), and those with enhanced Stokes V signals on both blue and red wing with the same polarity as the main component (left panel, green and orange). The vertical dashed lines show the line cores and the wavelength offsets of ± 215 mÅ from 6301.5 and 6302.5 Å, which are used to make the maps of Stokes V signals in Figure 2. The positions of the sampled profiles are marked by the corresponding colored square symbols on the inset continuum maps and also displayed in Figure 2.

2) Negative enhancement on the blue wing (darker patches in the middle panel in Figure 2) and positive enhancement on the red wing (brighter patches in the right panel in Figure 2) are commonly visible in the sunspot penumbra. These enhanced Stokes V signals on both blue and red wing can be caused by either temperature or magnetic field broadening which are expected to influence both the red and blue wings equally. But the asymmetric profiles suggest that the main cause of the enhancements is Doppler blue- or red-shifts of Stokes V. Some of these types of Stokes V profiles show hump on the blue wing (blue hump) with the same polarity as the spot. An example is shown in the right panel in Figure 3 (blue profile). The blue-shifted Stokes V profiles were studied by Rimmele & Marino [10] and Ichimoto et al. [11], and it was found that they correspond to bright penumbral grains. Profiles having enhancements of Stokes V signals on the red wing with the same magnetic polarity as the spot were recognized by Katsukawa & Jurčák [17] for the first time. Hump on the red wing (red hump) with the same polarity as the spot is a characteristic of some of these types of Stokes V profiles. Examples of Stokes V profiles with red lobe broadening or having red hump are shown in the right panel in Figure 3 (yellow and red, respectively). Katsukawa & Jurčák [17] reported that these patches are smaller than 0.5 arcsec and less frequent than the patches with the negative enhancements.

3) The profiles, which have not been realized before, have enhancements of Stokes V signals on both blue and red wing characterized by extra blue and red humps with the same magnetic polarity as the spot. In the left panel in Figure 3, two examples of this type of Stokes V profiles observed inside the studied region (near to the umbra: green; at the mid-penumbra: orange) were shown.

Figures 4 to 8 display the selected Stokes V profiles showed in Figure 3 along with their eight near neighbors. The newly identified Stokes V profiles having humps on both blue and red wings with the same polarity as spot (green and orange in Figure 3) along with their eight near neighbors are shown in Figures 4 and 5, respectively. One of those appears

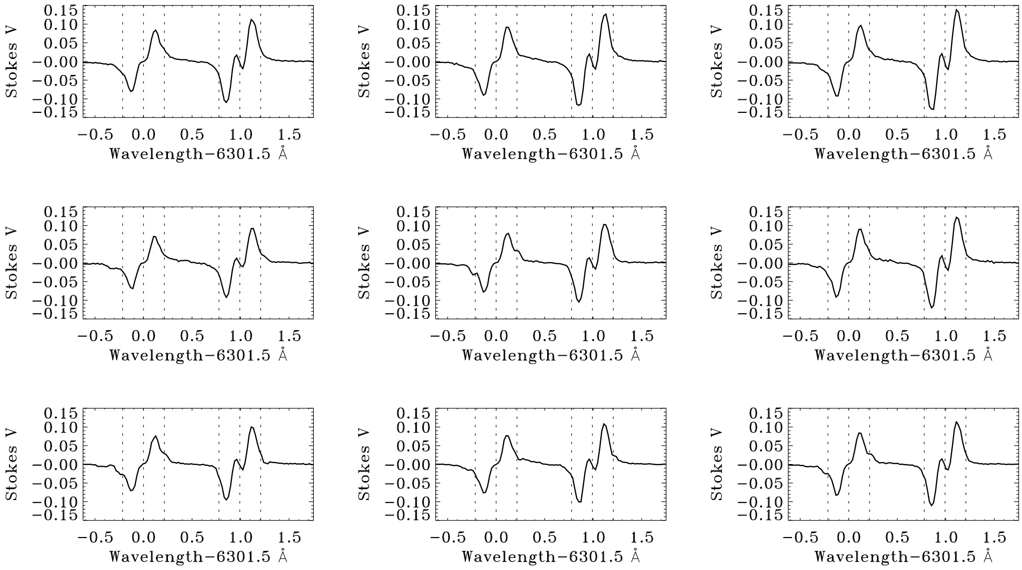

Figure 4: Stokes V profile (center panel) having both blue and red humps in the 6301.5 Å line shown in Figure 3 (green) along with its eight near neighbors. The vertical dashed lines show the line cores and the wavelength offsets of ±215 mÅ from 6301.5 and 6302.5 Å. The position of the profile in center panel is marked by the green square symbol on the 2D maps displayed in Figure 2.

near the umbra and adjacent a penumbral grain (Figure 4) and the other one locates at mid-penumbra (Figure 5). The humps are better visible in the 6301.5 Å line and especially on the blue wing. Some of their neighbors show humps on both blue and red lobes. In some neighbors the blue hump is visible and the red hump is hidden causing the red lobe be more skewed to the longer wavelength (*e.g.*, middle-left and upper-left panels in Figures 4 and 5, respectively). In some cases, the hump is visible in the 6302.5 Å line (*e.g.*, lower-middle and middle-right panels in Figure 4 and 5, respectively). These profiles are not necessarily recognizable in the blue- or red-wing magnetograms (Figure 2) as individually dark/bright patchy structures (see also Figure 11).

The Stokes V profiles showing a only blue hump with the same polarity as spot (blue in Figure 3) along with their eight neighbors are shown in Figure 6. A hump is visible in both 6301.5 and 6302.5 Å lines. However, we found profiles having a hump only on the blue wing of the 6301.5 Å line, although the blue lobe of the 6302.5 Å line is broadened and skewed to the shorter wavelengths. Some of their neighbors (lower-right panel in Figure 6) show humps on both blue and red lobes of the 6301.5 Å line. But in most neighbors the red lobe of the 6301.5 Å line is more or less skewed to the longer wavelengths, as seen in some cases in Figure 5 (*e.g.*, lower-right panel).

The sample Stokes V profile showing only a red hump with the same polarity as spot (red in Figure 3) or having a broadened red lobe (yellow in Figure 3) along with their eight neighbors are shown in Figures 7 and 8, respectively. In some cases in Figure 7, the red hump is not visible in the 6302.5 Å lines; instead a broadened red lobe is seen (*e.g.*, lower-left panel in Figure 7). Some of their neighbors (lower-left panel in Figure 6) show humps on both blue and red lobes of the 6301.5 Å line. But in some neighbors the blue lobe of the

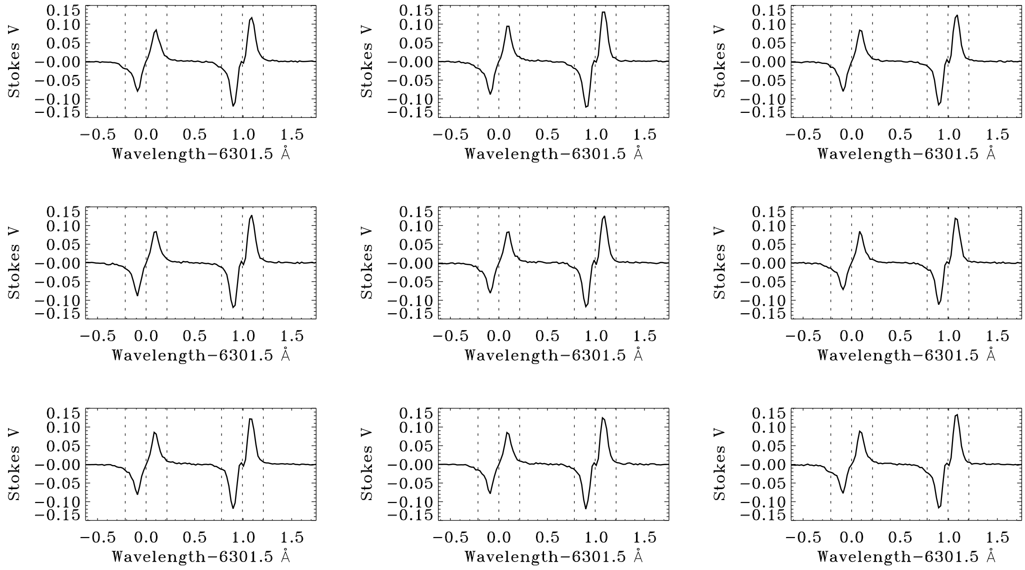

Figure 5: Same as Figure 4 but for the profile (center panel) characterized by both blue and red humps in the 6301.5 Å line plotted in Figure 3 (orange). Its position is marked by the orange square symbol on the 2D maps displayed in Figure 2.

6301.5 Å line is more or less skewed to the shorter wavelengths (*e.g.*, lower-center panel), as in some cases shown in Figures 5 and 6. This is remarkable that all bright patchy structures in the red-wing magnetogram (right panel in Figure 2) do not necessarily sample pixels with red humps (see also Figure 11).

It seems that the selected profile shown in the center panel in Figure 8 with a broadened red lobe is the same as a profile characterized by a red hump as the profile shown in the center panel in Figure 7: the small amplitude of the Stokes V of the main component makes the red hump appears as the broadening of the red lobe. In some cases, the blue hump is clearly visible in the 6301.5 Å line (middle-right panel in Figure 8) and the 6302.5 Å line (upper-right panel in Figure 8). The broadening of the red lobe of the 6302.5 Å line is a noticeable feature of these profiles.

3.2 Correlation of Stokes *V* signals at far wings

We introduce a simple identification method to find the Stokes V profiles having an extra hump on the red and/or blue lobes (like the examples given in Figures 4 to 8). An extra hump on the far red- or blue-lobe of Stokes V profile causes a change in its curvature. So, by calculating the 2nd derivative of the Stokes V profile the wavelength position (*hump position*) where the sign of the 2nd derivative (curvature) changes can be examined. Then, the profiles showing an extra hump can be recognized. Then, we can obtain the blue- or red-hump positions as well as the Stokes V signals at hump positions (*hump amplitudes*). Also, we know the spatial locations of abnormal Stokes V profiles inside the studied region.

We plot Stokes V signals at far red wings versus those at far blue wings for different abnormal Stokes V profiles (having humps) at 215, 280 and 323 mÅ away from the line core of the 6301.5 Å line (Figure 9): for most of the profiles far enough from the line core,

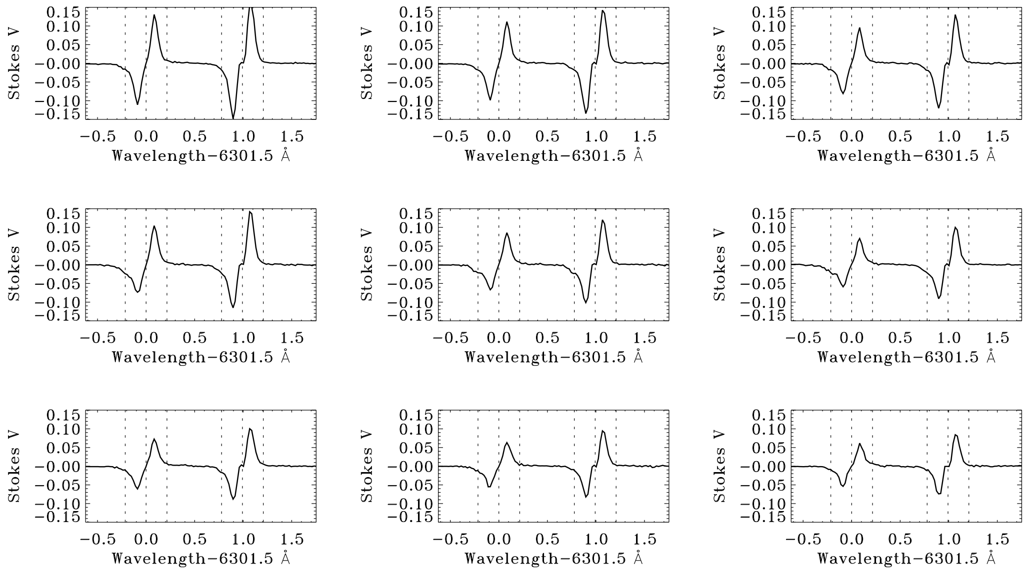

Figure 6: Same as Figure 4 but for the characterized profile (center panel) having only blue hump plotted in Figure 3 (blue). Its position is marked by the blue square symbol on the 2D maps displayed in Figure 2.

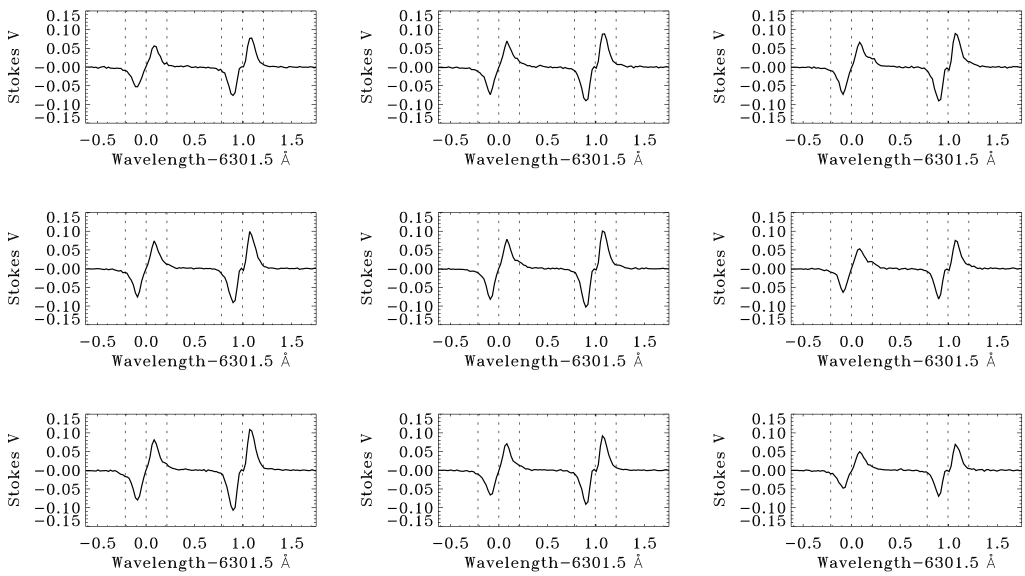

Figure 7: Same as Figure 4 but for the characterized profile (center panel) having only red hump plotted in Figure 3 (red). Its position is marked by the red square symbol on the 2D maps displayed in Figure 2.

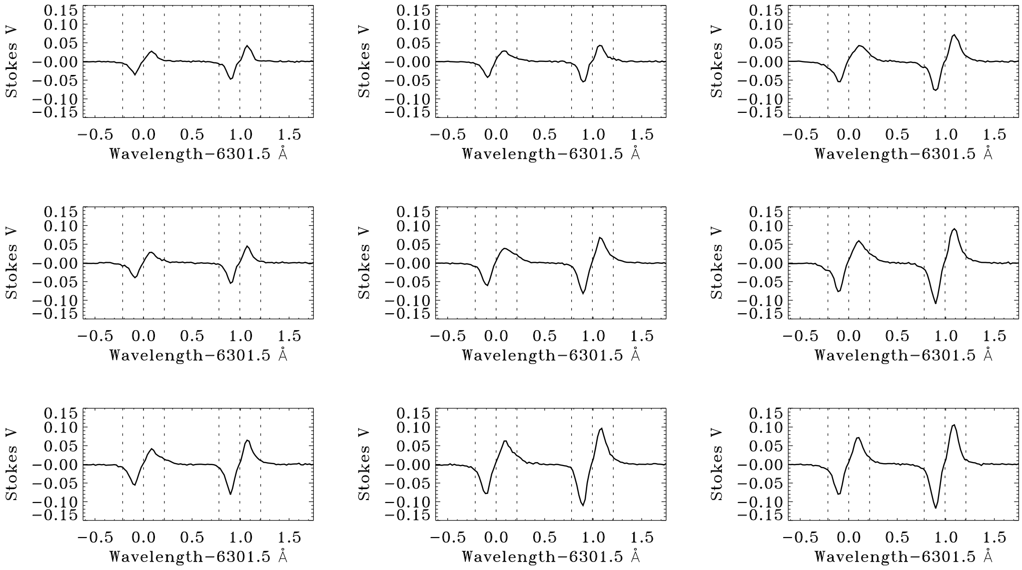

Figure 8: Same as Figure 4 but for the characterized profile (center panel) having a broadened red lobe plotted in Figure 3 (yellow). Its position is marked by the yellow square symbol on the 2D maps displayed in Figure 2.

irrespective humps are seen in blue and/or red lobes, Stokes V signals at blue wings are larger than those at red wings (upper panels and lower-left panel in Figure 9). However, this inference is not valid for hump amplitudes of the profiles having both blue and red humps: blue hump amplitude is not necessarily larger than red hump amplitude (see lower-right panel in Figure 9).

3.3 Broadening the lobes of abnormal Stokes *V* profiles

For a more investigation, we compare the tails extension of the blue- and red-lobes of the Stokes V profiles showing hump on either lobes of the Stokes V profiles. We define the *tail extension* of either lobe of a Stokes V profile as the total wavelength points that lay between Stokes V amplitude and 17% of it towards declining. In addition, the *tail extension excess* is defined as the subtraction of blue tail extension and red tail extension. The left panel in Figure 10 shows the histograms of the tail extension excesses for Stokes V profiles having only blue or red hump. Stokes V profiles showing blue humps have, in average, positive tail extension excesses. This means that their blue tail extension is longer than their red tail extension. However, red hump cannot necessarily extend the tail of the red lobe of the Stokes V profile with respect to the blue lobe. This implies that these types of profiles have smoothed blue hump causing extended blue tail which is slightly, in average, longer than the red tail extension.

The histogram of the tail extension excesses for Stokes V profiles having both blue and red hump is shown in the right panel in Figure 10 (solid line): in average, blue tail extension is longer than the red one. Stokes V profiles showing blue humps have also, in average, positive tail extension excesses (solid line in the left panel in Figure 10). Moreover, Stokes V profiles that do not show any hump (right panel in Figure 10; gray dashed line) show, in

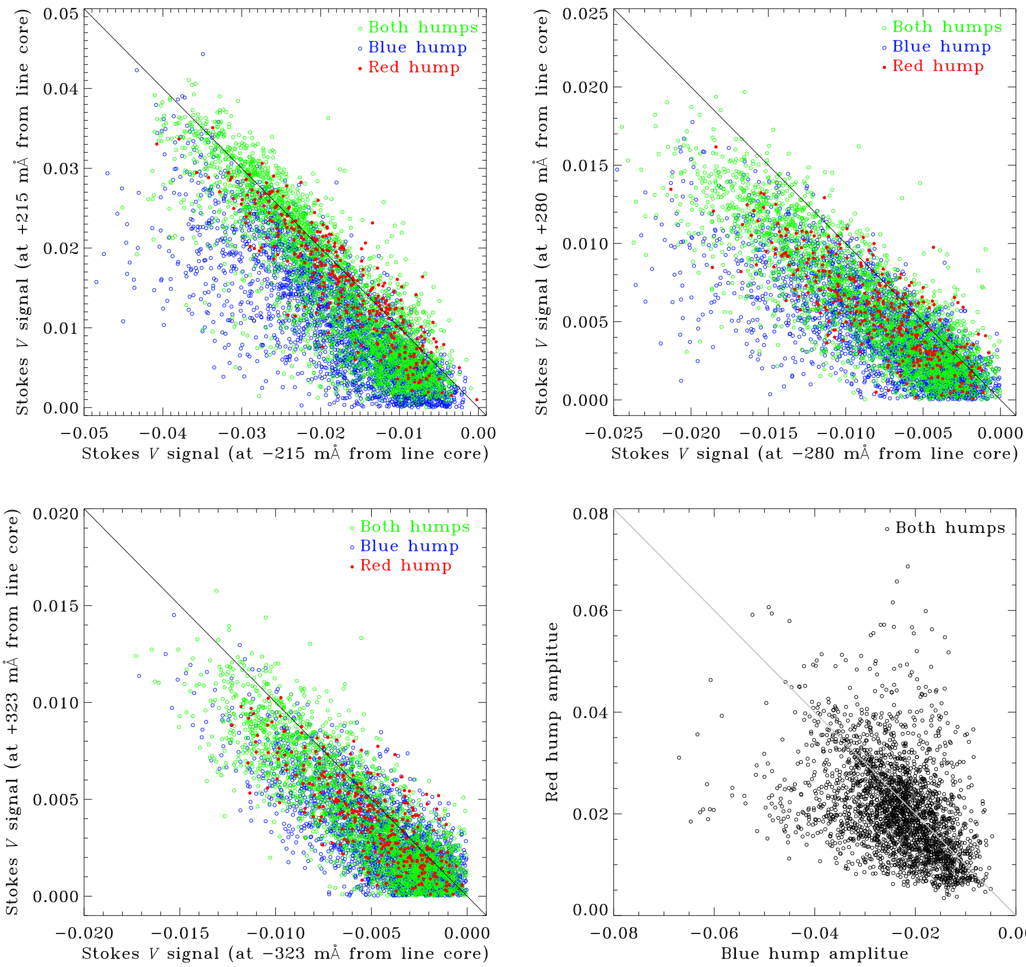

Figure 9: Upper panels and lower-left panel: scatter plots of Stokes V signals at far red wing versus those at far blue wing for different abnormal Stokes V profiles: profiles having both blue and red humps (green circles), only blue (blue circles) or red (red circles) hump. Lower-right panel: scatter plot of hump amplitudes for profiles having both blue and red humps.

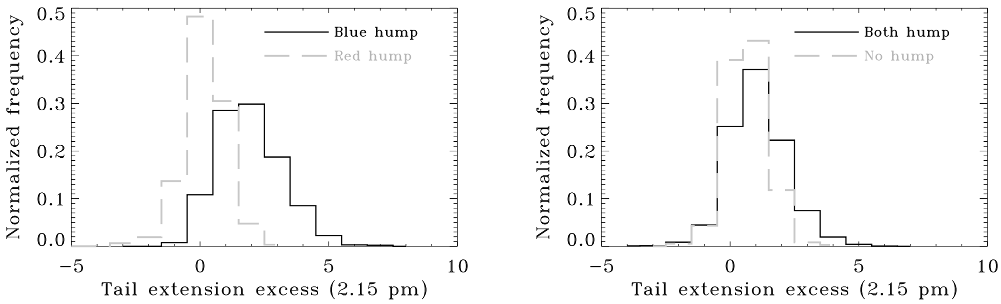

Figure 10: Histograms of tail extension excess. Left panel: Stokes V profiles having only blue (solid line) or red (gray dashed line) hump. Right panel: Stokes V profiles having both blue and red hump (solid line), and Stokes V profiles do not show any hump (gray dashed line). Tail extension excess is positive if the blue tail extension is longer than the red tail extension.

average, a positive tail extension excess.

3.4 Spatial distribution of abnormal Stokes *V* profiles

The spatial locations of abnormal Stokes V profiles inside the studied region are demonstrated in the left panel in Figure 11 along with the continuum map (right panel) to have a better comparison. Comparing the left and right panels in Figure 11, we can see profiles showing blue hump (36.8%) locate on bright filaments. The umbra and dark diffused backgrounds between bright filaments are the locations of profiles having both blue and red humps (42.1%). Profiles showing only the red hump are fewer (3.7%) and scattered inside the penumbra.

4 Summary and Discussion

Using the Hinode SP data, we detected Stokes V profiles characterized by humps on both blue and red lobes that have the same magnetic polarity as the sunspot umbra. Such Stokes V profiles seen in both umbrae and penumbrae have not been previously reported. The Stokes profiles having humps on either blue or red wing of the Stokes V profiles [17] show enhancements on the other lobe (Figures 4 to 8). At their adjacent we find Stokes V profiles characterized by both blue and red humps (Figures 4 to 8).

Hamedivafa [26] studied a single umbral dot whose Stokes V profiles showed humps. By assuming humps are the effects of blending spectral lines and considering a single-component model, he retrieved atmospheric stratifications of the umbral dot by eliminating the blending lines: the umbral dot is recognized as a small bright structure with a more vertical and twisted magnetic field with respect to its surroundings.

As shown in Figure 9, enhancements in Stokes V signals at far blue wing are, in most cases, stronger than those at far red wing for abnormal profiles showing blue and/or red hump. This is not as a result of blue-shifting of the main component. Figure 10 that show histograms of tail extension excess for abnormal Stokes V profiles confirms this finding: the blue tail extension is longer than the red one. This indicates that the red hump, if shows an individual downflow, is smoothed by an overlay upflow producing the blue hump. Both

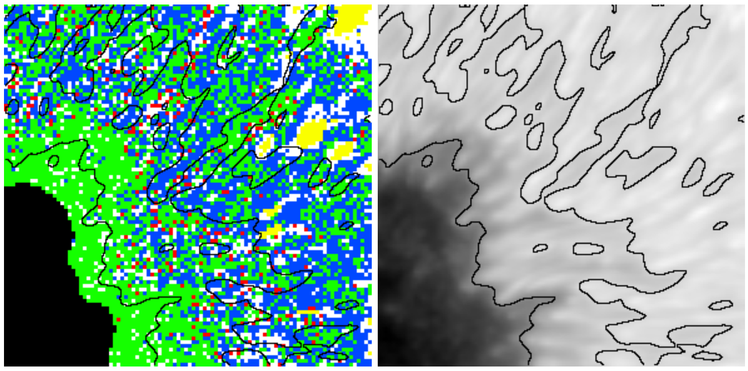

Figure 11: Left panel, colors blue, red and green: positions of Stokes V profiles having only blue hump, red hump, and both blue and red humps, respectively. White pixels are the locations of Stokes V profiles that do not show any well-defined humps. Patches marked by yellow color show positions of profiles having hump on the red lobe with opposite magnetic polarity of the spot (which are not the subject of this study). The part of the umbra with continuum intensities less than $0.17\mathrm{I_{sdc}}$ is excluded (black area in left panel) because Stokes V profiles are noisy there. Right panel: continuum image. Black contours help to find and compare positions in both panels.

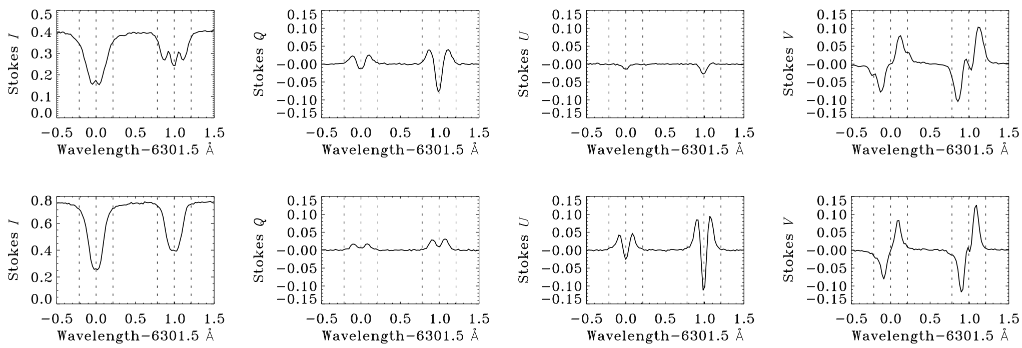

Figure 12: Full Stokes spectra for the two sampled pixels having both blue and red humps marked by green (upper panels) and orange (lower panels) squares in Figure 3. The vertical dashed lines show the line cores and the wavelength offsets of ±215 mÅ from 6301.5 and 6302.5 Å.

assumed downflow and upflow have the same magnetic polarity as the umbra. There is also a noteworthy point: since the distance between blue and red humps is large (estimated about 20 wavelength points equivalent to 430 mÅ; see Figures 4 to 8) these humps cannot be produced by a magnetized atmosphere as a single-2nd-component. Because the magnetic field strength in this atmosphere has to be as strong as 4500 gausses.

Since both linear polarization signals associated to the humps at far wings are weak (see Figure 12; also see Figures 2c and 2d in [17]) and humps amplitudes are small (lower-right panel in Figure 9) the magnetic fields of these *hidden* upflow/downflow structures have to be weak and almost vertical. All of these findings as well as this fact that we can find different types of abnormal Stokes V profiles having humps, in neighboring each other in the penumbrae, imply that all types of these profiles are the same entity with different hump amplitudes.

Magnetic reconnection between horizontal and vertical magnetic fields in a penumbra has been studied by Sakai & Smith [27] and Magara [28] using a numerical simulation. They verified bidirectional flows propagate along vertical magnetic fields as the result of redirection of outflows along the vertical magnetic field. This simulation gives a possible mechanism of the very adjacent upflows and downflows (in the same resolution elements) producing blue and red humps or enhancements of Stokes V signals on blue and red wings, respectively.

Figure 11 shows the spatial distribution of pixels whose Stokes V profiles show humps on, at least, either blue or red lobes. This implies that these abnormal Stokes V profiles are really normal and common in Hinode spectro-polarimetric observations in sunspots. The humps wavelength positions and their amplitudes are important parameters which are studied in another paper [29].

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Authors' Contributions

The author contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all aspects of this work.

Data Availability

No data available.

Conflicts of Interest

The author declares that there is no conflict of interest.

Ethical Considerations

The author has diligently addressed ethical concerns, such as informed consent, plagiarism, data fabrication, misconduct, falsification, double publication, redundancy, submission, and other related matters.

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