UNRESOLVED MIXED POLARITY MAGNETIC FIELDS AT FLUX CANCELLATION SITE IN SOLAR PHOTOSPHERE AT 0′3 SPATIAL RESOLUTION

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ABSTRACT

This is a follow-up investigation of a magnetic flux cancellation event at a polarity inversion line (PIL) on the Sun observed with the spectropolarimeter on board Hinode. Anomalous circular polarization (Stokes V) profiles are observed in the photosphere along the PIL at the cancellation sites. Kubo et al. previously reported that the theoretically expected horizontal fields between the canceling opposite-polarity magnetic elements in this event are not detected at granular scales. We show that the observed anomalous Stokes V profiles are reproduced successfully by adding the nearly symmetric Stokes V profiles observed at pixels immediately adjacent to the PIL. This result suggests that these observed anomalous Stokes V profiles are not indications of a flux removal process, but are the result of either a mixture of unresolved, opposite-polarity magnetic elements or the unresolved width of the PIL, at an estimated resolution element of about 0′3. The hitherto undetected flux removal process accounting for the larger-scale disappearance of magnetic flux during the observing period is likely to also fall below resolution.

Key words: line: profiles – Sun: magnetic fields – Sun: photosphere – techniques: polarimetric

1. INTRODUCTION

We address the mutual disappearance of opposite-polarity magnetic elements from the solar photosphere following their apparent “collisions,” as observed in line-of-sight (LOS) magnetograms. This phenomenon is called “magnetic flux cancellation” (Martin et al. 1985). The study of magnetic flux cancellation is important for understanding the nature of the flux removal process from the solar surface layers. Kubo et al. (2010) investigated five flux cancellation events at granular scales in which the horizontal magnetic fields between the canceling opposite-polarity magnetic elements were detected in only one event that takes place in a small emerging flux region. This finding is interesting since almost all theoretical scenarios proposed to explain photospheric flux cancellation expect an increase in the horizontal magnetic field between the canceling opposite-polarity magnetic elements (e.g., Zwaan 1987). Magnetic reconnection in the photosphere or around the temperature minimum region has been proposed to explain the formation of the horizontal magnetic field (Litvinenko 1999; Takeuchi & Shibata 2001; Ryutova et al. 2003). Such horizontal magnetic fields have been observed in some events (Chae et al. 2004; Kubo & Shimizu 2007; Iida et al. 2010). Prior to the work of Kubo et al. (2010), only one flux cancellation event without a detection of horizontal magnetic field was reported (Bellot Rubio & Beck 2005). The increase in horizontal magnetic field expected theoretically has not been commonly observed at least in flux cancellation events at granular scales (Kubo et al. 2010). The Solar Optical Telescope (SOT; Tsuneta et al. 2008) on board Hinode (Kosugi et al. 2007) has shown that these small-scale flux cancellation events at granular scales may be observed everywhere on the solar surface which clearly makes this phenomenon key to understanding the removal of photospheric magnetic flux. Kubo et al. (2010) suggested that flux cancellations with and without detectable horizontal fields are physically distinct processes. They also cautioned that the SOT observations of flux removal events at granular scales without the appearance of the horizontal fields may not be spatially resolved. This caution is based only on the null detection of linear polarization signals representing horizontal magnetic fields. However, circular polarization signals (Stokes V) are also detected at the polarity inversion line (PIL) in these events. In the present paper, we investigate the observational implications of the observed Stokes V profiles for the spatially unresolved flux removal process.

The Doppler velocity at the flux cancellation site is an important parameter that may discriminate between an emerging U-loop model or a submerging Ω-loop model (see Figure 2 in Zwaan 1987). The zero-crossing wavelength of the Stokes V profile is sometimes used to derive a Doppler velocity of the magnetized atmosphere. However, the Stokes V profiles observed along the PIL often take asymmetric or multi-lobed forms (e.g., Sigwarth 2001). It is difficult to determine the zero-crossing wavelength of such anomalous Stokes V profiles. There are two processes commonly invoked to explain anomalous Stokes V profile: (1) a coupling of gradients in velocity and magnetic field along the LOS (e.g., Illing et al. 1975; Auer & Heasley 1978; Sanchez Almeida & Lites 1992; Solanki & Montavon 1993), or (2) the superposition of two or more magnetic components of both polarities with relative Doppler shifts within a resolution element (e.g., Grigorjev & Katz 1972; Golovko 1974; Sanchez Almeida & Lites 1992). A correct interpretation of the anomalous Stokes V profiles is essential for interpreting the magnetic field structures in the neighborhood of the PIL between the canceling magnetic elements.

2. OBSERVATIONS

We investigate circular polarization (Stokes V) profiles at the PIL formed by canceling opposite-polarity magnetic elements just outside an active region NOAA 10944 on 2007 March 2. The SOT spectropolarimeter (SP; Lites et al. 2013) provides the Stokes profiles with a 0′15 slit width and a 0′16 pixel sampling along the slit. The Stokes profiles were measured with an integration time of 4.8 s at each slit position. The calibration
of the Stokes profiles was done with a standard procedure (Lites & Ichimoto 2013).

The total circular polarization ($C_{\text{tot}}$) is estimated as follows:

$$C_{\text{tot}} = \frac{\int_{\lambda_0-4.32 \text{pm}}^{\lambda_0+4.32 \text{pm}} V(\lambda) \, d\lambda}{I_c \int_{\lambda_0-21.6 \text{pm}}^{\lambda_0+21.6 \text{pm}} d\lambda}.$$  

The center of the Fe i 630.25 nm line ($\lambda_0$) is defined in each pixel as the center of gravity of the Stokes $I$ profile. The local continuum intensity ($I_c$) is defined as the average of the Stokes $I$ profile from $\lambda_0 + 43.2 \text{ pm}$ to $\lambda_0 + 64.8 \text{ pm}$. Figure 1 shows a map of the total circular polarization for our target cancellation event. The opposite-polarity magnetic elements independently appear in the quiet area outside the moat region and then approach each other. The cancellation activity of these magnetic elements is observed during a 10 minute period after the map of Figure 1, but the linear polarization signal does not increase near the PIL during the cancellation. The temporal evolution and detailed properties of this cancellation event were described as “region A” in Kubo et al. (2010).

Doppler shifts are derived from both $\lambda_0$ of the Stokes $I$ profile and the zero-crossing wavelength of the Stokes $V$ profile. A reference wavelength to the Doppler shift is the average of $\lambda_0$ of Stokes $I$ profiles in the quiet area, and the same value is used as the reference wavelength for the zero-crossing wavelength of Stokes $V$ profiles. The zero-crossing wavelength is derived by the linear fit to successive four wavelength points crossing the zero.

3. RESULTS

A highly asymmetric, strongly redshifted Stokes $V$ profile in the Fe i 630.25 nm line is observed at the PIL, as shown in Figure 2(d). If we interpret the shift of the zero-crossing wavelength as being caused by a Doppler velocity, it would be 3.3 km s$^{-1}$, which is much higher than the Doppler velocity of the Stokes $I$ profile ($-0.6 \text{ km s}^{-1}$). The three-lobed shape is more clearly seen in the Stokes $V$ profile of Fe i 630.15 nm (Figure 3(a)), and one of two zero-crossing wavelength positions is more redshifted for the Fe i 630.25 nm line. Hereafter, we try to explain such a strange Stokes $V$ profile by mixing profiles of the canceling magnetic elements. The Stokes $V$ profile at the PIL ($V_{\text{PIL}}^{\text{syn}}$) is synthesized as follows:

$$V_{\text{PIL}}^{\text{syn}} = A \times V_{\text{obs}} + B \times V_{\text{obs}}^{-},$$  

where $V_{\text{obs}}$ and $V_{\text{obs}}^{-}$ are the Stokes $V$ profiles observed at the pixels next to the PIL on the positive-polarity side and on the negative-polarity side, respectively (Figures 2(e) and 2(f)). Note that nearly symmetric Stokes $V$ profiles are observed at the pixels next to the PIL. The positive constant values of $A$ and $B$ are determined to minimize the difference between the observed Stokes $V$ profile and the synthesized profile at the PIL inside a wavelength range of $\pm 43.1 \text{ pm}$ from the averaged center of the Fe i 630.25 nm line. The values calculated from this fit are $A = 0.42$ and $B = 0.52$. The synthesized Stokes $V$ profile is shown by the diamond symbols in Figure 2(d), and it looks very similar to the observed one. Most of the local dips and peaks in the Stokes $V$ profile at the PIL are successfully demonstrated in spite of such a simple summation of the observed Stokes $V$ profiles. Beck (2008) performed a similar addition of opposite-polarity Stokes $V$ profiles to reproduce multi-lobed Stokes $V$ profiles like those within sunspot penumbrae. He stressed the importance of relative Doppler shifts between the opposite-polarity elements. In the present work, we infer a relative Doppler velocity of 1.3 km s$^{-1}$ between the pixels next to the PIL, but we find a relative difference of $-0.3 \text{ km s}^{-1}$ for the corresponding Stokes $I$ profiles. The different spectral extents of the Stokes $V$ lobes in the positive- and negative-polarity magnetic elements also help in the generation of an anomalous Stokes $V$ profile at the PIL. The different spectral extents originate from the difference in the field strength of the canceling opposite-polarity magnetic patches. Figure 3(a) shows that the reproduction of the Stokes $V$ profile in the Fe i 630.15 nm line is as good as that of the Fe i 630.25 nm line with similar values for $A$ and $B$ ($A = 0.39$ and $B = 0.52$).

Similar results are obtained at the neighboring pixel along the PIL, as shown in Figures 4(d)–(f). A three-lobed profile is observed at the PIL, which is produced by the sum of the observed profiles at the pixels next to the PIL. In this case, the coefficients $A$ and $B$ are 0.52 and 0.54 for the Stokes $V$ profile in the Fe i 630.25 nm line, respectively. These values are similar to those of the previous case. The value of $A$ is 0.49 and $B$ is 0.61 for the Fe i 630.15 nm line. The different coefficients between the two Fe i lines may be caused by the height gradient of the
Figure 2. Panels (a)–(c) show the observed Stokes $I$ profiles of the Fe $i$ 630.25 nm line at pixels represented by black, white, and gray crosses in panel (b) of Figure 1, respectively. These profiles are normalized by the continuum intensity averaged over the quiet area. The solid lines in panels (d)–(f) are observed Stokes $V$ normalized by the continuum intensity at the pixels same as their left panels. The diamond symbols in panel (d) show the profile synthesized from the observed profiles in panels (e) and (f). The vertical dotted line represents the averaged position of the line centers over the map. The vertical dash-dotted line represents a line center for the Stokes $I$ profile and a zero-crossing wavelength for the Stokes $V$ profile.

Figure 3. Panel (a) is same as panel (d) of Figure 2, but for the Stokes $V$ profile of the Fe $i$ 630.15 nm line. Panel (b) is same as panel (a), but for the pixel represented by the black triangles in panel (b) of Figure 1.
magnetic field structures at the pixel of PIL or at the neighboring pixels.

4. DISCUSSION

Highly asymmetric or three-lobed Stokes $V$ profiles are observed at the PIL between the canceling magnetic elements. Such anomalous Stokes $V$ profiles at the PIL are successfully produced by the sum of the Stokes $V$ profiles observed at the pixels next to the PIL. This could serve to warn of over-interpreting Stokes profiles observed at the PIL. For example, the Doppler velocity derived from the zero-crossing wavelength of the Stokes $V$ profile is not necessarily reliable. The mixture of opposite-polarity Stokes $V$ profiles with a relative Doppler shift causes the anomalous Stokes $V$ profiles at the PIL formed by canceling opposite-polarity magnetic elements like those observed in the penumbra (Beck 2008). The large relative Doppler shift is not observed in the Stokes $I$ profiles, but is observed in the Stokes $V$ profiles at the pixels next to the PIL.

The combination of opposite-polarity Stokes $V$ profiles could originate from the presence of unresolved opposite-polarity magnetic elements or the unresolved boundary between the opposite-polarity patches. We cannot investigate the mixture of magnetic fields within the pixel because we analyze Stokes profiles in a single pixel of 0.16 width which is about half of a diffraction limit of a 50 cm diameter telescope at 630.25 nm. The diffraction-limited performance of the telescope with a Strehl ratio of about 0.8 was confirmed with images taken by the Broadband Filter Imager of SOT (Suematsu et al. 2008; Wedemeyer-Böhm 2008). The rms contrast of the continuum intensity is 8.1% in our data set, which is similar to the rms contrast (8.5%) of a synthetic image from the MHD simulation that was degraded by a point-spread function of the SOT/SP without the defocus in Danilovic et al. (2008). This means that our observations are performed under the almost best focus condition and the size of a resolution element is about 0.32. Although it is difficult to clearly distinguish the mixture of unresolved opposite-polarity elements from the unresolved boundary between the opposite-polarity magnetic patches, our result may support the later case because we can reproduce the Stokes $V$ profiles at the PIL using a fraction of the neighboring profiles, i.e., there are no indications of other magnetic elements in the area.
Magnetic flux disappears in this flux cancellation event during our observing period (Kubo et al. 2010). Therefore, it is expected that a magnetic flux removal process is actually operative in this event. However, our results suggest that the Stokes $V$ profile arising from the flux removal process is not yet detected, at least in the event studied herein. The mixture of the opposite-polarity magnetic elements to be canceled is limited within a local area around the PIL since nearly symmetric profiles are observed at the pixels next to the PIL. One possibility of a lack of the Stokes $V$ profile arising from the flux removal process is that the spatial resolution of the SOT/SP ($\sim 200$ km) is still insufficient to detect the removal process of photospheric magnetic flux (Kubo et al. 2010). Whether it is possible to observe the horizontal fields expected in the flux-removal process of the event studied depends on both observational resolution as well as the actual MHD nature of this process. The latter is worthy of theoretical investigation but lies outside the scope of the paper. For the present there is much to learn from Stokes-polarimetric analysis of photospheric events involving the interaction of flux elements of opposite magnetic polarities such as presented in our paper and elsewhere (e.g., Rezaei et al. 2007).

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