MAGNETIC HELICITY TRANSPORTED BY FLUX EMERGENCE AND SHUFFLING MOTIONS IN SOLAR ACTIVE REGION NOAA 10930

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ABSTRACT

We present a new methodology which can determine magnetic helicity transport by the passage of helically magnetic field lines from the sub-photosphere and the shuffling motions of footpoints of preexisting coronal field lines separately. It is well known that only the velocity component, which is perpendicular to the magnetic field \( \mathbf{v} \), has contributed to the helicity accumulation. Here, we demonstrate that \( \mathbf{v}_{\perp B} \) can be deduced from a horizontal motion and vector magnetograms under a simple relation of \( \mathbf{v}_{\perp} = \mathbf{v}_{\parallel} + (\mathbf{v}_{\perp}/B_{\parallel})B_{\perp} \), as suggested by Démoulin & Berger. Then after dividing \( \mathbf{v}_{\perp B} \) into two components, as one is tangential and the other is normal to the solar surface, we can determine both terms of helicity transport. Active region (AR) NOAA 10930 is analyzed as an example during its solar disk center passage by using data obtained by the Spectropolarimeter and the Narrowband Filter Imager of Solar Optical Telescope on board Hinode. We find that in our calculation the helicity injection by flux emergence and shuffling motions have the same sign. During the period we studied, the main contribution of helicity accumulation comes from the flux emergence effect, while the dynamic transient evolution comes from the shuffling motions effect. Our observational results further indicate that for this AR the apparent rotational motion in the following sunspot is the real shuffling motions on the solar surface.

Key words: Sun: activity – Sun: photosphere – Sun: surface magnetism

1. INTRODUCTION

It is widely believed that eruptions in the solar atmosphere, such as flare, filament eruption, and coronal mass ejection (CME), are the intermittent liberation of non-potential magnetic energy stored in the coronal magnetic field. Magnetic helicity is a quantitative measure of twists, kinks, and interlinkages of magnetic field lines (Berger & Field 1984) and is a useful and important parameter to indicate the topology and non-potentiality of a magnetic field system. Moreover, it is conserved in a closed volume as well as in an open volume in the absence of boundary flows (Berger & Field 1984). Since the solar corona is an open volume with the photosphere as a boundary with normal flux, the magnetic helicity can be transported from the sub-photosphere into the corona through the boundary of the photosphere by the emergence of helical flux and shuffling motions (Berger & Field 1984). According to Berger (1999), the transport rates of relative helicity, \( \dot{H} \), due to both processes are given by

\[
\dot{H}_n = \oint 2(B \cdot A)\nu_{\perp} dS
\]

\[
\dot{H}_t = -\oint 2(v \cdot A)B_{\parallel} dS,
\]

where subscripts “\( n \)” and “\( t \)” represent the normal and tangential components, respectively. Chae (2001) has observationally determined \( \dot{H}_t \) by considering the horizontal motions \( \mathbf{v}_t \), which is deduced from a time series of line-of-sight magnetograms with the local correlation tracking (LCT) method (November & Simon 1988) as the shuffling motions \( \mathbf{v}_s \), and found that shuffling motions on the photosphere can provide enough magnetic helicity for the CMEs, which was confirmed by a series of subsequent studies (Nindos & Zhang 2002; Moon et al. 2002a, 2002b; Nindos et al. 2003). It has also been proven that in some active regions (ARs) magnetic helicity transported by rotational motion is comparable with that deduced from the LCT method (Zhang et al. 2008a; Min & Chae 2009). However, Démoulin & Berger (2003) have demonstrated that the horizontal motions \( \mathbf{v}_t \) include both components \( \mathbf{v}_n \) and \( \mathbf{v}_t \) with the relation \( \mathbf{v}_t = \mathbf{v}_n - (\mathbf{v}_n / B_{\parallel})B_{\perp} \). Therefore, helicity injection calculated this way not only includes the contribution of shuffling motions but also the emerging fluxes.

The emergence of twisted fluxes and shuffling motions are the popular triggers for solar eruptions and the common mechanism for magnetic helicity accumulation both in theoretical and observational works (Leka et al. 1996; Grigoryev & Ermakova 2002; Fan & Gibson 2004). Emergence naturally carries magnetic flux, as well as helicity, through the photosphere if the emerging fluxes have magnetic helicity. Shuffling motions generate magnetic shear and then supply helicity and free energy into the coronal field. But even now, we only know a little bit about how and to what extent both processes contribute to the helicity accumulation.

It is worth noting that the presence of the magnitude of flow along the field lines has no bearing on the temporal evolution of the magnetic field (as described by the ideal MHD induction equation) and also has no contribution to the helicity accumulation. So, we should consider only the motion that is perpendicular to the magnetic field in the estimation of helicity accumulation. Démoulin & Berger (2003) have pointed out that there are two ways to get the normal velocity by which we can separately calculate the magnetic helicity transport by flux emergence and shuffling motions. First, since the magnetic field and velocity field are not mutually independent, we can deduce the normal velocity from known conditions under some assumptions. Second, if the AR is located around the center of the solar disk, we can use the Doppler velocity as the normal velocity. Advantages and disadvantages of both methods were discussed by many authors (Démoulin & Berger 2003; Pariat et al. 2005). So far, only the first method has been tried. Kusano et al. (2002) have deduced \( \nu_n \) and \( \nu_t \), which only include components perpendicular to the magnetic field by using the
observations of \( \mathbf{B} \) and \( \mu_t \) on the photosphere together with the induction equation. They found that both processes have equal contributions to the helicity injection and have supplied magnetic helicity of opposite signs in AR NOAA 8210. Welsch et al. (2004) have introduced two methods to get the normal velocity. One is to deduce \( \mathbf{v}_n \) and \( \mathbf{v}_t \) under an assumption of \( \mathbf{v} \cdot \mathbf{B} = 0 \) and by a simple relation of \( \mathbf{v}_t = \mu_t + (\mathbf{v}_n/B_n)\mathbf{B} \). The other is to solve the same equations as Kusano et al. (2002) with a different technique. Using the high spatial resolution vector magnetogram obtained by Helioseismic and Magnetic Imager (HMI) on board Solar Dynamics Observatory (SDO), Liu et al. calculated the velocity vector by the differential affine velocity estimator (DAVE) method, which models image motion with either the continuity equation or the convection equation (depending on a switch). And then they found that the helicity flux from the shuffling term is dominant, while that from the emergence term is small (Y. Liu et al. 2011, private communication). Based on a simple relation \( \mathbf{v}_t = \mu_t + (\mathbf{v}_n/B_n)\mathbf{B} \) (Démoulin & Berger 2003), we find that the component of velocity that is perpendicular to the magnetic field can be deduced from the vector magnetograms and the horizontal motions (see details in Section 3). After projecting this velocity into tangential and normal components of the photosphere, we can separately deduce the magnetic helicity transport by shuffling motions and flux emergence. We apply our new method to an isolated AR NOAA 10930. In order to decrease the ambiguities, we only study the day that the AR passed through the solar meridian. This paper is organized as follows. Section 2 presents the description of the observations. The method of how to get the plasma velocity that is perpendicular to the magnetic field and data reduction are presented in Section 3. In Section 4, we provide the observational results. Summary and discussion are presented in Section 5.

2. OBSERVATIONS

Figure 1 shows the morphological evolution of AR NOAA 10930 from December 8 to 13. It has a mature and stable leading sunspot, and a small and rapidly changing following sunspot. The temporal evolution of the sunspot area (a thick (thin) line for the leading (following) sunspot) and tilt angle is also shown in Figure 1. In order to distinguish opposite polarities in \( \delta \) sunspot, only pixels whose intensity is weaker than 45% of the quiet sun are included in the area estimation. The tilt angle is measured as an angle between the connection of two polarities and the south direction. From Figure 1, we see that the leading sunspot was stable during its solar disk passage. The morphology of the following sunspot changed very rapidly according to emergence, cancellation, and merging, whereas its area changed little until December 9. After that, there was a significant emergence. It slowed down very quickly at the beginning of December 10. Around 12:00 UT on December 10, the flux emergence reoccurred. Associated with the emergence, the following sunspot rotated counterclockwise around its center and moved rapidly eastward, resulting in an increase in magnetic complexity. These growing processes continued till a X3.4 flare occurred on December 13.

AR NOAA 10930 passed through the solar meridian on 2006 December 11, with the location changing from W4S6 to E7S6. Meanwhile, the following sunspot area increased from \( 4.9 \times 10^{7} \text{ km}^2 \) to \( 8.7 \times 10^{7} \text{ km}^2 \), with a 35% total area increase during its solar disk passage. The variations of the tilt angle due to the eastward motion of the following sunspot changed from \( 10^\circ \) to \( 32^\circ \), with a 50% total increase in the tilt angle. The rotational speed of the following sunspot increased up to \( 8^\circ \text{h}^{-1} \) on December 11. It maintained this speed till a X3.4 flare occurred on December 13. And then the rotational speed slowed down to \( 3^\circ \text{h}^{-1} \) (Min & Chae 2009). All the observational evidence shows that December 11 was an important day for the AR evolution.

3. METHOD AND DATA REDUCTION

3.1. Deduction of Plasma Velocity Perpendicular to the Magnetic Field

First, we give a simple description of the relation between different velocities that are used in the present work. From observations, we can get the horizontal motions \( \mu_t \) of the magnetic features by the LCT method, which we indicate by the purple arrow in Figure 2(a). Shuffling motions of plasma on the solar surface \( \mathbf{v}_n \) can be deduced from \( \mu_t \) by \( \mathbf{v}_n = \mu_t + (\mathbf{v}_n/B_n)\mathbf{B} \). The normal velocity of plasma \( \mathbf{v}_n \) can be obtained in several ways as noted in the previous section. Both \( \mathbf{v}_t \) and \( \mathbf{v}_n \) are outlined by red arrows in Figure 2(a). Their combined vector is the real motion of plasma \( \mathbf{v} \), which is represented by the black arrow in Figure 2(a). With reference to the direction of the magnetic field, as shown by the thick black arrow in Figure 2(a), \( \mathbf{v} \) can be divided into two components, one is parallel to the magnetic field \( \mathbf{v}_\parallel \) and the other is perpendicular to the magnetic field \( \mathbf{v}_\perp \). We use an automated ambiguity-resolution code based on the minimum energy algorithm (Leka et al. 2009) to resolve the ambiguity of magnetograms. The noise level is estimated from the blue arrows. Since \( \mathbf{v}_\parallel \) has no contribution to the magnetic helicity accumulation, we neglect it in the present work. Then, we get the normal velocity and shuffling motions of the plasma by dividing \( \mathbf{v}_\perp \) into two components, one is tangential to the solar surface \( \mathbf{v}_\perp^{\parallel} \) and the other is normal to the solar surface \( \mathbf{v}_\perp^{\perp} \), as shown by green arrows in Figure 2(a). According to the vector relations depicted in Figure 2(a), we get

\[
\mathbf{v}_\perp = \mathbf{v}_t - (\mathbf{v}_n \cdot \mathbf{b})\mathbf{b},
\]

where \( \mathbf{b} \) is the direction vector of the magnetic field. That means \( \mathbf{v}_\perp \) can be deduced from \( \mathbf{v}_n \) and \( \mathbf{B} \).

3.2. Data Reduction

The Spectropolarimeter (SP) of the Solar Optical Telescope (SOT) on board the Hinode measures spectral profiles of full Stokes parameters of two Fe I lines at 630.15 and 630.25 nm and a nearby continuum with 21.5 mA spectral resolution (Kosugi et al. 2007; Suematsu et al. 2008; Ichimoto et al. 2008). On 2006 December 11, SP observed AR NOAA 10930 under a fast map mode with the spatial resolution of 0.32 and obtained six sets of Stokes \( I, Q, U \), and \( V \). Vector magnetograms are derived from the inversion of the full Stokes profiles based on the assumption of the Milne–Eddington (ME) atmosphere model. We use an automated ambiguity-resolution code based on the minimum energy algorithm (Leka et al. 2009) to resolve the 180° ambiguity of magnetograms. The noise level is estimated by selecting one quiet region within the SP map to calculate the 1σ standard deviation of the average value of field strengths. In order to avoid ambiguity, we only analyze those pixels with \( B_s \) and \( B_t \) greater than the above deviation. Figure 2(b) shows a vector magnetogram on 11:10 UT. It shows that the arrows in the leading sunspot are almost radial except in the southwest part, as well as the white thick curve and labeled as A. In this region, the magnetic field is obviously left handed. Meanwhile, the following sunspot is also left handed, which corresponds to
the negative helicity for AR located in the southern hemisphere. There is a so called “magnetic channel” (Wang et al. 2008) structure along the neutral line. The magnetic field here is highly sheared, as indicated by arrows parallel to the neutral line.

The horizontal motions $\mu_t$ were calculated by two-minute longitudinal magnetograms taken by the Narrowband Filter Imager (NFI) of SOT (Tsuneta et al. 2008) by the LCT method, and is shown in Figure 2(c). Our result shows similar organized motions, such as an inward motion in the inner-penumbra and outward motion in the outer-penumbra of the leading sunspot, and a counterclockwise rotational motion and an eastward motion of the following sunspot, which are consistent with Min & Chae (2009). Furthermore, horizontal motions in region A show clockwise rotation, which correspond to a positive helicity injection.

Figure 2(d) shows $v_{\perp t}$, which was deduced from $\mu_t$ and $B$. In this map, for the leading sunspot, the inward motion in the inner-penumbra remains, while the outward motion in the outer-penumbra disappears. Meanwhile, in the following sunspot, the counterclockwise rotational motion remains, while the eastward motion disappears. It means that the horizontal motion, which was deduced by the LCT method, does include two components.
One is the shuffling motion, which is the real horizontal motion of the plasma on the photosphere in a more or less vertical magnetic field. It will drag the magnetic field associated with the plasma and remains in the $v_{\perp t}$ map. The other results from the flux emergence or submergence in the nearly horizontal magnetic configuration and footpoints of tubes move along the magnetic field. This motion will disappear from the $v_{\perp t}$ map. As in our example, the outward motion in the outer-penumbra in the leading sunspot and the eastward motion along the neutral line disappear from the $v_{\perp t}$ map, which are motions resulting from the emergence since the sunspot is going through its growing phase. Meanwhile, the inward motion in the inner-penumbra of the leading sunspot and the counterclockwise rotation in the following sunspot, which remain in the $v_{\perp t}$ map, are the shuffling motions of the plasma. Furthermore, in this map, the clockwise rotation in region A is more outstanding than that in the $\mu_t$ map.

The normal velocity, $v_{\perp n}$, is shown in Figure 2(e), where the white tone represents an upward motion and the black one represents a downward motion. It shows that the sunspot is dominated by an upward motion. But at the boundary of the penumbra and photosphere, the upward and downward motions are mixed, which presents a complex distribution of normal velocity. As a comparison, the Doppler map, which is calculated from the spectral line core fits to the Fe I 630.15 nm line profile at each spatial position, is shown in Figure 2(f). The pixel resolution of the $v_{\perp n}$ map is much lower than that of the Doppler map because it was deduced from the $\mu_t$ map. So, more small features can be identified in the Doppler map. However, roughly speaking, both maps are consistent. Especially, there are some downward motions along the neutral line. Comparing Figures 2(e) and (f) to 2(b), we find that these downflow areas spatially correspond to the magnetic channel.

4. RESULTS

From Zhang et al. (2008b) and Park et al. (2010), we know the magnetic helicity injection in AR NOAA 10930 is predominantly negative throughout the period of its disk passage. Park et al. (2010) found that there are three time periods
over which the magnetic helicity injection is mainly positive for more than nine hours. The day we studied in the present work is within the second period of the positive helicity injection.

Figure 2(g) shows the distribution of \(-2(v \cdot A_n)B_n dS + 2(B \cdot A_p)v dS\) on 11:10 UT, which is a sum of the local contribution by flux emergence and shuffling motions. It shows that the helicity injection in following the sunspot is predominantly negative, which is consistent with the left-handed twisted magnetic field and counterclockwise rotation of the sunspot. However, in the leading sunspot, both negative and positive helicity injection occurred. It is clearly seen that the positive helicity injection occurred in two separate regions. One is along the neutral line. The other is region A.

The distribution of helicity injection by flux emergence and shuffling motions in Figures 2(h) and (i) demonstrate the origin of positive helicity injection. From both panels, we see that the positive helicity injection along the neutral line comes from \(H_n\), while the other positive injection comes from \(H_t\) in region A. The complex evolution properties along the neutral line was studied by several authors (Wang et al. 2008; Park et al. 2010) and was conjectured as a result of the emergence of a positive helicity system. In region A, the positive injection of the helicity in the \(H_t\) map is consistent with the clockwise rotation of the sunspot. While in the \(H_n\) map, the negative helicity injection is consistent with the left-handed twist of the magnetic field.

The temporal evolution of \(H\) on December 11 was shown in Figure 3. Triangles indicate the contribution of flux emergence, stars represent the shuffling motions, and diamonds indicate their sum. The top panel shows that the flux emergence and shuffling motions contribute almost the same sign of magnetic helicity during the whole period. The helicity injected by the flux emergence is almost negative, which is consistent with the dominated left-handed twist of the magnetic field for the southern hemisphere AR. On the other hand, helicity injected by a shuffling motion varies from time to time. It is negative until 12:00 UT and then becomes positive. The dynamical transient variation of \(H\) is consistent with \(H_t\), while the variation of \(H_n\) is a little bit stable. The variation tendency derived by us is almost the same as that by Park et al. (2010), although the exact value was not equal because of the differences of data type, observational time, and calculation method.

The middle and bottom panels show the temporal evolution of \(H_t\) and \(H_t\) for the following and leading sunspot, respectively. For the following sunspot, the helicity injections by the shuffling motion and flux emergence are always negative, and the helicity accumulation caused by both effects are \(-178 \times 10^{40} M x^2\) and \(-164 \times 10^{40} M x^2\), respectively. For the leading sunspot, the helicity injections caused by both effects are negative at first, and then associated with the flux emergence along the neutral line and the clockwise motion in region A, which changes its sign from negative to positive. The helicity accumulation by the shuffling motion and flux emergence are \(248 \times 10^{40} M x^2\) and \(46 \times 10^{40} M x^2\), respectively. Here it is worth noting that the magnetic helicity accumulation in this active region is negative. Also the period that we studied includes a positive helicity transport phase (Park et al. 2010), even though as a whole the magnetic helicity accumulation in this active region is \(-48 \times 10^{40} M x^2\). Our results show that the helicity accumulation mainly results from the following sunspot, but the dynamic variation mainly results from the leading sunspot. And also, even though the magnetic flux of the following sunspot is much smaller than that of the leading sunspot, it contributes the most helicity accumulation because of the predominance of the negative helicity injection to the solar corona in this AR. Moreover the active region was located in the southern hemisphere and showed the left-handed (negative) helicity, violating the so-called hemispheric rule. So, the characteristics of helicity evolution of the region may be specific to that category of ARs, which should be studied by further observations.

5. SUMMARY AND DISCUSSION

By fully using the observational data, we have developed a new methodology by which we can estimate the magnetic helicity injection by flux emergence and shuffling motions separately. The key point of the methodology is that we deduce the component of plasma velocity, which is perpendicular to the magnetic field, by observational data only. It provides us with a useful tool to study the contribution of flux emergence and shuffling motion in energy storage and eruption initiation,
especially after the launch of SDO. The derivation of the helicity injection is demonstrated for AR NOAA 10930. The observational properties of this AR during the period of our study are a stable mature leading sunspot and a fast emerging and rapidly rotating following sunspot. Some important conclusions are as follows.

1. The sign of the helicity fluxes from flux emergence and shuffling motions are the same. The temporal variations of \( \dot{H}_n \) is relatively stable, while \( \dot{H}_t \) changes rapidly. The variation tendency of \( \dot{H} \) is consistent with \( \dot{H}_t \), implying that flux emergence provided the continuous accumulation of the helicity, which may play a key role in helicity or energy storage, while the shuffling motions added some dynamic change of the helicity injection, which may play a key role in eruption initiation.

2. For the following sunspot, the helicity injection from flux emergence and shuffling motion are all negative. The helicity flux from flux emergence is relatively stable compared with that from shuffling motions.

3. For the leading sunspot, helicity injection changes its sign from negative to positive for both effects, which is conjectured associated with the emergence of a magnetic flux, which contains opposite helicity and a clockwise rotation in southwest of the sunspot.

Usually, the rotational motion and the twisted magnetic field in the sunspot occur simultaneously. We want to know whether the observed rotation of sunspots represents the emergence of the twisted magnetic flux tube or the rotational shuffling motion twists of the magnetic flux tube. When the rotational motion represents the emergence of a twisted flux rope, one can expect that the motion results from the emergence along the magnetic field. However, in AR 10930, we find that the rotational motion remains in the \( v_{\perp t} \) map. So, we conjecture that the rotational motion in AR NOAA 10930 is the real shuffling motion, although more observational evidence will be necessary for the final conclusion to the question stated above.

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REFERENCES

Berger, M. A. 1999, in Magnetic Helicity in Space and Laboratory Plasmas, ed. M. R. Brown, R. C. Canfield, & A. A. Pevtsov (Geophys. Monogr. 111; Washington, DC: AGU), 1
Berger, M. A., & Field, G. B. 1984, J. Fluid Mech., 147, 133
Chae, J. Y. 2001, ApJ, 560, L95
Démoulin, P., & Berger, M. A. 2003, Sol. Phys., 215, 203
Fan, Y. H., & Gibson, S. E. 2004, ApJ, 609, 1123
Grigoryev, V. M., & Ermakova, L. V. 2002, Sol. Phys., 207, 309
Ichimoto, K., Lites, B., Elmore, D., et al. 2008, Sol. Phys., 249, 233
Kosugi, T., Matsuzaki, K., Sakao, T., et al. 2007, Sol. Phys., 243, 3
Kusano, L., Maehashi, T., Yokoyama, T., & Sakurai, T. 2002, ApJ, 577, 501
Leka, K. D., Canfield, R. C., & McClymont, A. N. 1996, ApJ, 462, 547
Leka, K. D., Graham, B., Crouch, A. D., et al. 2009, Sol. Phys., 260, 83
Min, S. Y., & Chae, J. Y. 2009, Sol. Phys., 258, 203
Moon, Y. J., Chae, J. Y., Choe, G. S., et al. 2002a, ApJ, 574, 1066
Moon, Y. J., Chae, J. Y., Wang, H. M., Choe, G. S., & Park, Y. D. 2002b, ApJ, 580, 528
Nindos, A., & Zhang, H. Q. 2002, ApJ, 573, L133
Nindos, A., Zhang, J., & Zhang, H. Q. 2003, ApJ, 594, 1033
November, L. J., & Simon, G. W. 1988, ApJ, 333, 427
Paraj, E., Démoulin, P., & Berger, M. A. 2005, A&A, 439, 1191
Park, S. H., Chae, J. C., Jing, J., Tan, C. Y., & Wang, H. M. 2010, ApJ, 720, 1102
Saematsu, Y., Tsuneta, S., Ichimoto, K., et al. 2008, Sol. Phys., 249, 197
Tsuneta, S., Ichimoto, K., Katsukawa, Y., et al. 2008, Sol. Phys., 249, 167
Wang, H. M., Jing, J., Tan, C. Y., Wiegelmann, T., & Kabo, M. 2008, ApJ, 687, 658
Welsch, B. T., Fisher, G. H., Abbett, W. P., & Regnier, S. 2004, ApJ, 610, 1148
Zhang, Y., Liu, J. H., & Zhang, H. Q. 2008a, Sol. Phys., 247, 39
Zhang, Y., Yan, Y. H., & Tan, B. L. 2008b, ApJ, 682, L133