MAGNETIC HELICITY PUMPING BY TWISTED FLUX TUBE EXPANSION

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ABSTRACT

Recent observations have shown that coronal magnetic fields in the northern (southern) hemisphere tend to have negative (positive) magnetic helicity. There has been controversy as to whether this hemispheric pattern is of surface or sub-surface origin. A number of studies have focused on clarifying the effect of the surface differential rotation on the change of magnetic helicity in the corona. Meanwhile, recent observational studies reported the existence of transient shear flows in active regions that can feed magnetic helicity to the corona at a much higher rate than the differential rotation does. Here we propose that such transient shear flows may be driven by the torque produced by either the axial or radial expansion of the coronal segment of a twisted flux tube that is rooted deeply below the surface. We have derived a simple relation between the coronal expansion parameter and the amount of helicity transferred via shear flows. To demonstrate our proposition, we have inspected Yohkoh soft X-ray images of NOAA 8668 in which strong shear flows were observed. As a result, we found that the expansion of magnetic fields really took place in the corona while transient shear flows were observed in the photosphere, and the amount of magnetic helicity change due to the transient shear flows is quantitatively consistent with the observed expansion of coronal magnetic fields. The transient shear flows hence may be understood as an observable manifestation of the pumping of magnetic helicity out of the interior portions of the field lines driven by the expansion of coronal parts as was originally proposed by Parker (1974).

Key words : sun: magnetic fields—sun: photosphere —sun: corona

I. INTRODUCTION

It is now observationally well-established that magnetic fields in the solar atmosphere are often strongly sheared or helically structured. Moreover, it has been found that there is a hemispheric preference to the sign of the magnetic helicity: negative, left-helical helicity in the northern hemisphere and positive, right-helical helicity in the southern hemisphere (e.g., Pevtsov et al. 1995, 2001). But it is still controversial as to how coronal magnetic fields attain such helicity. Some argue that the helicity is produced by shearing motion on the surface, while others argue that the helicity is brought from below along with the emerging flux.

Differential rotation is the best-known shearing flow on the solar surface. Since it is a steady shearing flow of large scale, it has been considered a potential source of magnetic helicity in the corona. van Ballegooijen (1999) showed, by numerical simulations, that an initially untwisted bipole, like an active region, evolves into an inverse S-shaped, left-helical flux rope in the northern hemisphere and an S-shaped right-helical flux rope in the southern hemisphere, being consistent with

the observed hemispheric dependence. DeVore (2000) first quantified the amount of magnetic helicity possibly accumulated by differential rotation. By performing numerical simulations to integrate the time-dependent rate of helicity injection, he found that after 2-4 solar rotation periods have elapsed, the helicity accumulated by differential rotation amounts to about 10% of the product of the bipole's squared flux and the cosine of twice its tilt angle. This result was fully confirmed by Démoulin et al. (2002a), who used a different method of numerical computation. Moreover, they found that the helicity accumulated over a very long time by differential rotation can not exceed 20% of the bipole's squared flux. This is because the rate of helicity injection reverses sign when the tilt angle exceeds 45°, because of the deformation of the flux distribution by differential rotation. This kind of reversal also explains why van Ballegooijen et al. (1998) failed to reproduce the observed hemispheric dependence of helicity at high latitudes where the polarity inversion lines are oriented east-west. As a cure for this defect, DeVore (2000) suggested that helicity of the correct sign produced during the early phase of an active region may be able to sustain the correct sign of helicity in the remnant fields in the high latitude of each hemisphere.

Is the helicity production by differential rotation ef-
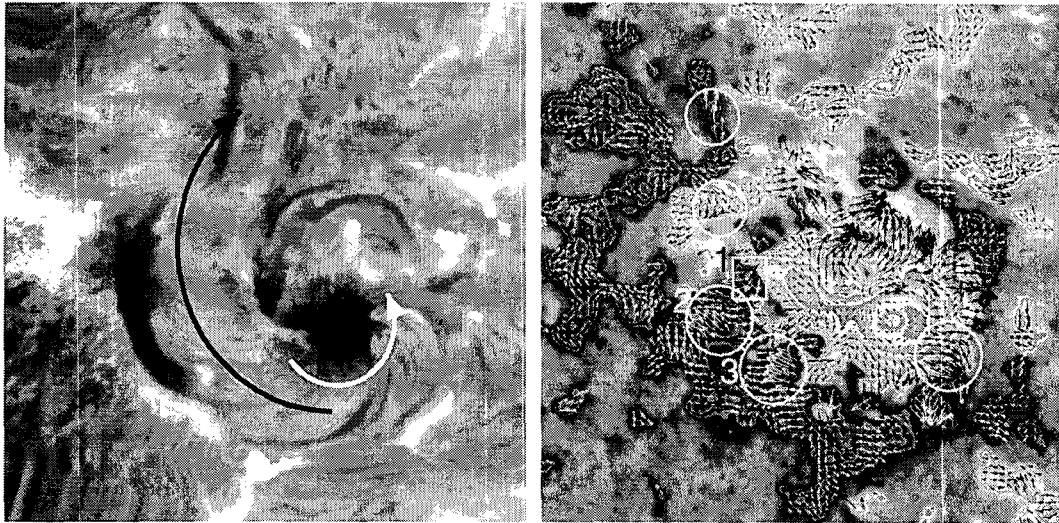

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Fig. 1.— Hα centerline image (*left*) and the photospheric velocity field superposed on a gray-scale map of the SOHO/MDI magnetogram (*right*) of AR 8668 taken 1999 August 17. Strong shearing motions are found inside the encircled areas, and they form a counter-clockwise rotational pattern in the positive flux area, and a clockwise rotational pattern in the negative flux area with respect to the center of the leading sunspot. Both the rotational pattern inject magnetic helicity of the same negative sign, whereas much more contribution came from the rotation of the positive sunspot having strong magnetic fields.

ficient enough to supply the helicity of the active regions and the helicity carried away by coronal mass ejections? DeVore (2000) found that the total amount of magnetic helicity supplied by differential rotation for one solar cycle is about 1×10^{46} Mx^2 and is comparable to that lost by coronal mass ejections for the same period. So he concluded that the shearing of bipolar regions by differential rotation contributes substantially to the sun's total magnetic helicity. On the other hand, Démoulin et al. (2002b) concluded that, contrary to DeVore (2000), differential rotation is not able to supply the magnetic helicity ejected from active regions. They carefully examined the long-term helicity balance during the lifetime of a specific active region AR 7978, and found that the helicity injected by differential rotation is too small, by at least a factor of 2.5, to explain the coronal helicity, and also too small, by at least a factor of 4, to explain the magnetic helicity carried away by coronal mass ejections. A similar conclusion was also reached by Green et al. (2002) who examined the helicity budget in another active region AR 8100. In the next section, we will support this conclusion by arguing that the net helicity contribution of differential rotation will be zero.

Other kinds of horizontal motion may inject magnetic helicity. Chae (2001) first attempted to measure the rate of helicity injection by determining both the flux distribution and the horizontal flow field from real data. He used time sequences of line-of-sight magnetograms taken by SOHO/MDI and determined the horizontal flow field, by applying the technique of local correlation tracking to magnetic features. Not surprisingly, the determined flow field fluctuated highly

in time and space. Nevertheless, the flow field sometimes displayed a spatially coherent pattern for hours, which can inject a non-vanishing amount of magnetic helicity. Chae et al. (2001) applied the same technique to active region AR 8668, and found a pattern of shear motion that fed a magnetic helicity of -3×10^{42} Mx^2 at a rate an order of magnitude higher than that by differential rotation. The flow pattern persisted for about 50 hours. The helicity injection by the transient shear flow was coincident with the formation of a prominence in the active region. Moon et al. (2002a) found that the occurrence of homologous flares in AR 8100 was associated with the magnetic helicity injected during the flaring time intervals by a transient shear flow. The transient flow has supplied magnetic helicity of 1×10^{42} Mx^2 in 7 hours. A strong transient shear flow was also observed in an emerging active region by Nindos & Zhang (2002). The flow persisted for about 40 hours, and injected magnetic helicity of -6×10^{42} Mx^2, which is the biggest among the reported amounts of magnetic helicity injected by transient shear flows.

All of these recent observational studies reveal transient shear flows that can inject magnetic helicity at a much higher rate than differential rotation does. What is the physical origin of transient shear flows? Are transient shear flows evidence for or against the sub-surface origin of magnetic helicity? The present paper is motivated to answer to these questions.
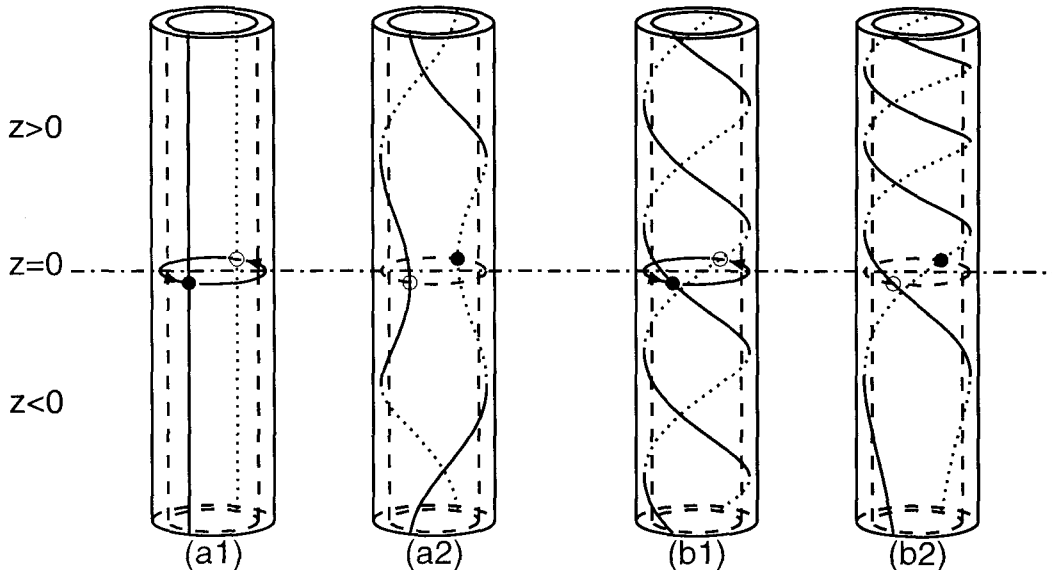
Fig. 2.— Two kinds of possible interpretations for the observed surface rotational motion. (a) Generation of helicity in an initially untwisted flux tube. (b) Transfer of helicity in a twisted flux tube.

II. HELICITY INJECTION BY TRANSIENT SHEAR FLOWS

Figure 1 presents an example of transient shear flows in AR 8668, as detected from the SOHO/MDI magnetograms by Chae et al. (2001). The localized shear flows in the encircled areas indicate that the leading sunspot of positive polarity rotated counter-clockwise with respect to its center, and the trailing negative flux regions rotated in the opposite sense. The rotation of this spot was clearly identified in TRACE white light images, too (Nightingale et al. 2001). The transient shear flows injected negative magnetic helicity to the corona.

In Figure 2, we introduce two flux tubes rooted below the surface to illustrate two pictures of possible interpretations of the helicity injection by the observed surface rotational motion. In the first case (a), the flux tube is initially untwisted. Then, the counter-clockwise rotation on the surface $z = 0$ twists the flux tube and injects negative magnetic helicity to the corona $z > 0$. At the same time, due to conservation of magnetic helicity, the motion injects the same amount of positive magnetic helicity to the sub-surface volume $z < 0$. In this case, the rotational motion can be regarded as the process of *generating* magnetic helicity. According to this picture, positive helicity would be prevalent in the interior of the northern hemisphere and the negative helicity, in the interior of the southern hemisphere as opposed to the observed hemispheric preference in the corona. In the other case (b), the flux tube is initially twisted. The counter-clockwise rotational motion on

the surface injects negative magnetic helicity to the corona. As a result, the absolute value of magnetic helicity in the corona increases, whereas it decreases in the sub-surface volume. The rotational motion can be regarded as a process that *transfers* magnetic helicity from the sub-surface to the corona.

Figure 2(a) captures the idea of helicity generation by differential rotation. It also helps to understand what may be wrong with this concept. As we have seen, although idealized simulations with differential rotation give a plausible global rate of helicity generation per solar cycle, application to well-observed active regions fails to yield either the helicity content inferred from force-free fits to the coronal loops or losses by coronal mass ejections. We suggest the problem is that the differential rotation shearing flow calculations do not account for conservation of magnetic helicity. For each twist due to surface shears, as in Figure 2a, two helical Alfvén waves propagate into the magnetic rope (Galloway et al. 2001). One wave becomes twist in the corona, but the other, of opposite chirality, tries to propagate into the interior. The upward propagating helical wave will be trapped in the coronal loop, but the downward propagating wave will not propagate far into the interior before reversing direction and returning to the surface, because in the interior the density is so high that the field lines are effectively tied. Its helicity will exactly cancel the helicity of opposite sign just injected into the corona. Therefore, we do not expect surface shear flows due to differential rotation to produce any net magnetic helicity. Besides, if the twist
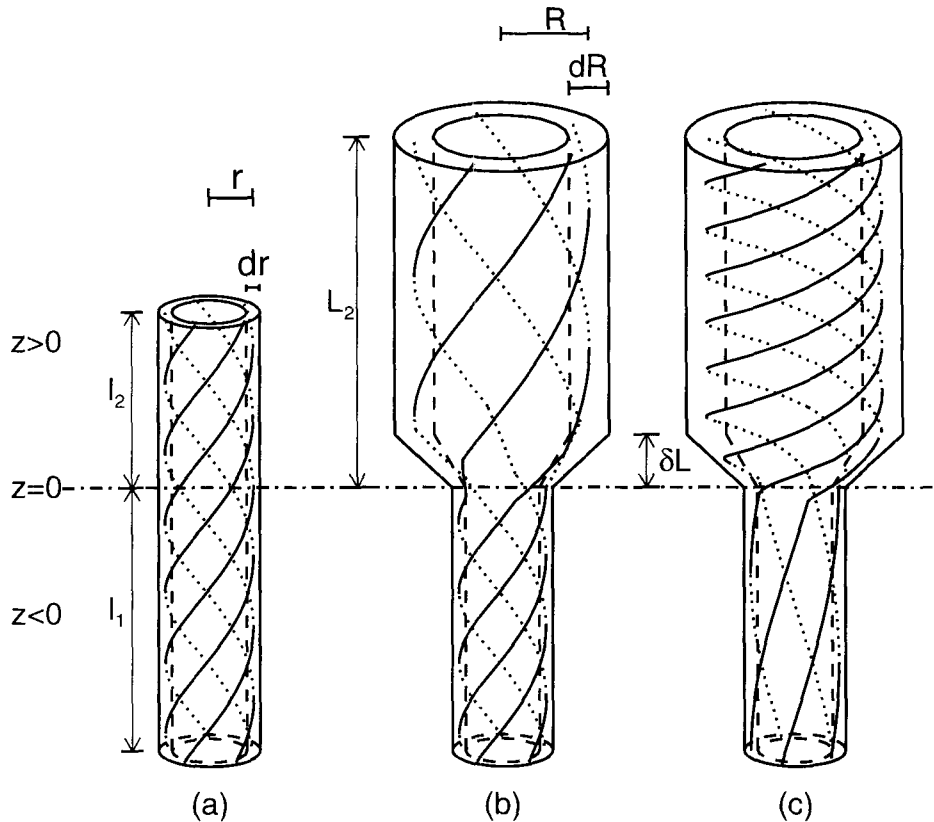
Fig. 3.— Helicity transfer by the expansion of the coronal segment of a twisted flux tube: (a) initial flux tube, (b) expansion conserving the helicity on each segment, and (c) expansion keeping the torque balanced between the two segments.

carried down by the waves were to collect in the photosphere, magnetograms would show positive chirality beneath negative helicity in the corona. Instead, active region observations show that the sign of the helicity in photospheric and coronal fields correlate strongly (Pevtsov et al. 1997).

The injection of helicity associated with the transient shear flows, as shown in Figure 1, is consistent with the second picture (b). The Hα image in the figure shows a counter-clockwise whorl of the sunspot penumbral and chromospheric fibrils and, an inverse S-shaped filament, supporting that the active region magnetic field was left-helically structured. The counter-clockwise rotation of the sunspot supplied more negative magnetic helicity, as in (b). In this picture, the torque driving the rotational motion is magnetic, and may have arisen from the dynamics of the twisted flux tube itself, rather than from the interaction with the field-free surroundings.

III. MAGNETIC HELICITY PUMPING BY TWISTED FLUX TUBE EXPANSION

We propose that the net magnetic torque in the surface, caused by the expansion of the coronal segment

of the twisted flux tube, drives the observed transient shear flows. The consequences of the expansion of the whole, or a part of, a twisted flux tube were first studied by Parker (1974). Based on the Parker's idea and the principle of helicity conservation, we describe the effect of expansion in driving rotational motion and the helicity transfer.

We consider the expansion of a flux tube initially uniformly twisted along the axis with axial field b_z and azimuthal field b_ϕ (see Figure 3a). The flux tube is divided into two segments: the sub-surface segment $z < 0$ and the second coronal segment $z > 0$. The axial flux of the annulus with radius r and thickness dr is given by $d\Phi = 2\pi b_z r\, dr$. The pitch (distance the line of force encircles the axis once) is given by $\lambda = 2\pi r b_z / b_\phi$ According to Priest (1999), the magnetic helicity of each segment is given by $dH_i = 2T_i \Phi\, d\Phi$ where T_i is the winding number of field lines in the i-th segment. Since T_i is equal to l_i / λ, it follows that $dH_i = 2l_i / \lambda \Phi\, d\Phi$. The field lines are tied to the boundary surfaces at the bottom $z = -l_1$ and at the top $z = l_2$, and hence the total helicity $dH_{\rm tot} = dH_1 + dH_2 = 2(l_1 + l_2)/\lambda \Phi\, d\Phi$ should be conserved during dynamical evolution.

We consider two extreme cases of expansion: one

that conserves magnetic helicity in each segment separately, the other that makes the net torque in the interface of the two segments vanish. The first case occurs when the coronal segment undergoes a sudden expansion either in the axial or radial directions (see Figure 3b). Considering this kind of expansion is helpful to understanding how the observed shear flows can be driven, even though it may not realistically represent the flux tube expansion in the solar corona. For simplicity, we assume the pitch in each segment is uniform along the axis. The expanded annulus now has length L_2, radius R, radial thickness dR, axial field B_z, azimuthal field B_ϕ, and pitch $\Lambda = 2\pi R B_z/B_\phi$. Note that the interface between the expanded segment and the unexpanded segment is so thin that its helicity is negligible. Then, from conservation of flux and helicity, it follows

$$b_z r\, dr = B_z R\, dR \tag{1}$$

$$\frac{l_2 b_\phi}{r b_z} = \frac{L_2 B_\phi}{R B_z}. \tag{2}$$

Note that this helicity-conserving expansion is far from dynamical equilibrium, since magnetic torque imbalance arises between the expanded and unexpanded segment. The net torque on the small interface volume between the two segments is then given by, (Longcope & Klapper 1997),

$$\tau_z = \frac{1}{4\pi} \oint (\mathbf{r} \times \mathbf{B})_z \mathbf{B} \cdot d\mathbf{S} \tag{3}$$

$$= \frac{1}{4\pi} R B_\phi\, d\Phi - \frac{1}{4\pi} r b_\phi\, d\Phi \tag{4}$$

$$= \frac{1}{4\pi} r b_\phi\, d\Phi \left(\frac{1}{\gamma} - 1\right) \tag{5}$$

where γ is the expansion factor given by

$$\gamma = \frac{L_2}{l_2} \frac{r}{R} \frac{dR}{dr}. \tag{6}$$

Suppose $dr/r = dR/R$. Then the axial expansion makes $\gamma > 1$. Then the torque τ in, for example, the right-handed twisted flux tube as in Figure 3 has a negative value, and drives a clockwise rotational motion on the interface, when viewed from the expanded segment. As a result, the expanded segment becomes more twisted whereas the unexpanded segment unwinds. This is equivalent to the transfer of magnetic helicity from the unexpanded segment (sub-surface volume) to the expanded segment (coronal volume). Note that clockwise rotation transfers helicity of positive sign into a coronal loop, irrespective of its magnetic polarity. The transfer of twist may eventually lead to an equilibrium configuration in which the torque balances. A similar process will occur in the case of a radial expansion, too, if $dR/R > dr/r$.

In the torque-balanced configuration, not only the pitch in the expanded segment, but also the pitch in

the unexpanded segment changes. The torque balance condition now reads

$$r\tilde{b}_\phi = R B_\phi, \tag{7}$$

where $\tilde{b}_\phi$ is the azimuthal field in the unexpanded segment in the new configuration. The condition of the total helicity conservation now reads

$$\frac{l_1 b_\phi}{r b_z} + \frac{l_2 b_\phi}{r b_z} = \frac{l_1 \tilde{b}_\phi}{r b_z} + \frac{L_2 B_\phi}{R B_z}. \tag{8}$$

The helicity of the expanded segment in the new configuration is now given by

$$d\tilde{H}_2 = \frac{L_2 B_\phi}{2\pi R B_z} \Phi\, d\Phi \tag{9}$$

$$= \gamma \frac{1 + l_2/l_1}{1 + \gamma l_2/l_1} dH_2 \tag{10}$$

$$= \frac{\gamma l_2/l_1}{1 + \gamma l_2/l_l} dH_{\text{tot}}, \tag{11}$$

which shows that the amount of the helicity pumped by the flux tube expansion depends on the expansion factor γ, the length ratio l_2/l_1, and the helicity budget dH_{tot}. It also follows $\tilde{b}_\phi = (1 + l_2/l_1)/(1 + \gamma l_2/l_1)b_\phi$.

In the case where the unexpanded segment is long enough or the expansion is mild, it follows $\tilde{b}_\phi \simeq b_\phi$ and $d\tilde{H}_2 = \gamma\, dH_2$. The unexpanded segment acts like a helicity reservoir. In the extreme case of expansion $\gamma l_2/l_1 \gg 1$, it follows that $\tilde{b}_\phi \simeq 0$ and $d\tilde{H}_2 \simeq dH_{\text{tot}}$. Most of the helicity initially stored in the unexpanded segment will be transferred to the expanded segment. In real situations, however, it may take finite time to reach the torque-balanced configuration. The time scale may be a few times the Alfvén crossing time of the length $l_1 + L_2$. If the flux tube dynamically would evolve on a shorter time scale, the flux tube could not reach the torque-balanced equilibrium at all. A consequence is that the amount of magnetic helicity pumped to the corona by the flux tube expansion would be less than $d\tilde{H}_2 - dH_2$.

IV. OBSERVATIONAL EVIDENCE

Figure 4 shows the observational evidence that the expansion of coronal magnetic fields took place in the active region on 1999 August 17 when transient shear flows were observed in the photosphere. The bright X-ray emitting structure has the shape of the so-called sigmoid. The important thing is that the structure expanded for about 5 hours after the flare while preserving its shape fairly well. It appears that the expansion process stopped eventually, as the images taken later than 20:00 UT of August 17 showed little indication of further expansion.

It appears that the brightening and expansion of the structure was physically related to the occurrence of
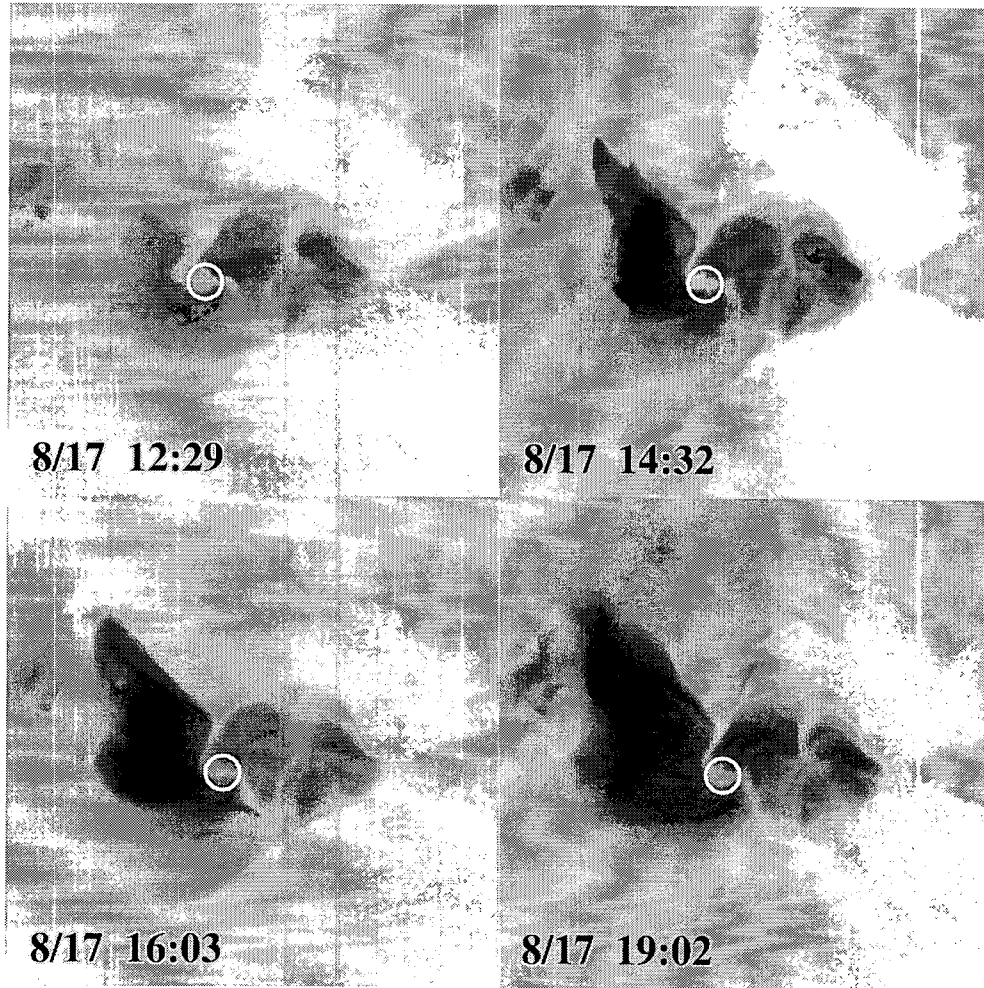
Fig. 4.— Yohkoh Soft X-ray images showing the expansion of coronal magnetic fields that proceeded in association with the C-class flares of 1999 August 17 in AR 8668. The open circle in each image marks the location of the biggest sunspot in the active region.

flares. Gibson et al. (2002) reported that two C-class flares took place on August 17 at 13:23 UT and 16:02 UT, respectively. It is not surprising that flares and the expansion of coronal magnetic fields are related, since flares are believed to occur as a result of substantial changes of local magnetic fields (magnetic reconnection), and local magnetic field changes may be related to large-scale field re-organization. Flares occurred on the former day (August 16), too, and we have noticed some indication of coronal magnetic expansion from Yohkoh X-ray images taken on that day, even if the observational indication is not so strong as that shown in Figure 4. Therefore, this finding that the expansion of coronal magnetic fields took place 16-17 August 1999 in close association with flares is a strong qualitative support that the transient shear flows observed during the same period may have been driven by the expansion of coronal magnetic fields.

Now we attempt to quantitatively relate the coronal expansion to the transient shear flows using our formulation of the helicity change. For simplicity, we assume that γ is constant over the radial distance from the axis, and the sub-surface segment is much longer than the coronal segment (namely $l_2/l_1 \ll 1$). Then it follows from equation (11),

$$\Delta H = (\gamma - 1)H_2. \tag{12}$$

Here ΔH is the change of magnetic helicity related to the shear flows, and H_2 is the initial amount of the magnetic helicity of the coronal magnetic fields.

It can be inferred, from the comparison of the images taken at 14:32 UT and 19:02 UT (Figure 4), that the size of the bright X-ray structure increased by a factor of about 2 as a result of the expansion. Relating this factor to γ depends on the specific internal structure of the sigmoid. So far there is no consensus on the magnetic structure of sigmoids. Some regarded a sigmoid as a single horizontal twisted flux tube (e.g., Gibson et

al. 2002). To us, however, it looks like an arcade of sheared loops, each of which may be identified with a twisted flux tube. With this picture, the expansion of the sigmoid as a whole may be interpreted as the axial expansion of all the twisted flux tubes by the same factor $L_2/l_2 = 2$. Thus from equation(6) and neglecting the lateral expansion, we have $\gamma = 2$.

The initial helicity of the coronal magnetic fields in the active region, H_2, was not measured directly. Instead, we make use of the finding of Démoulin et al. (2002a) and Green et al. (2002) that an active region with magnetic flux Φ usually has a helicity of $n\Phi^2$, with a typical value of $n = 0.2$. Figures 1 and 4 shows that both the shear flows and the sigmoid are confined to the narrow stripe along the polarity inversion line. This suggests that the magnetic flux Φ to be used for the estimation of H_2 may be significantly smaller than the active region flux Φ_{AR}. As a rough estimate, we choose the range $\Phi = 0.3 - 0.5\Phi_{AR} = 0.3 - 0.5 \times 10^{22}$ Mx using $\Phi_{AR} = 1 \times 10^{22}$ Mx (Chae et al. 2001). This leads to $H_2 = 2 - 5 \times 10^{42}$ Mx^2. Using the relation (12) and $\gamma = 2$, we obtain a predicted value $\Delta H = H_2 = 2 - 5 \times 10^{42}$ Mx^2. This value is comparable to the change of magnetic helicity 3×10^{42} Mx^2, measured by Chae et al. (2001). This comparison quantitatively supports the role of coronal expansion in pumping magnetic helicity out of the interior.

V. DISCUSSION

It has been proposed that photospheric transient shear flows, as recently observed in active regions, are driven by the net torque produced by the expansion of the coronal part of an initially twisted flux tube that is rooted deep below the surface. The helicity injection by the shear flows is interpreted as the process of transferring magnetic helicity from the interior to the corona. According to our interpretation, the magnetic helicity transferred by the transient shear flows originates from the interior. The idea of a sub-surface origin of coronal magnetic helicity has also been advocated by Berger & Ruzmaikin (2000), Rust (2001), Démoulin et al. (2002b) and others.

Parker (1974) first pointed out that when expansion occurs, the unexpanded portion unwinds and twists up the expanded portion. He illustrated this principle by considering an expansion of a force-free flux tube. Recently, Longcope & Welsch (2000) presented a dynamical model that connects a twisted subphotospheric flux tube to a force-free coronal field. They found that as the flux tube continues to emerge, the helicity of the coronal field increases owing to the rotation of the footpoints. This result is quite consistent with ours. Our analysis in the present paper is not for a detailed modeling, so it does not assume a force-free field. But it is illustrative and general enough for our purpose. Based on our analysis, we have obtained a new result that the expansion factor defined in Eq.(6) is closely related to the amplification factor of the coronal magnetic helicity

associated with the expansion, as shown in Eq.(11).

Our study together with the previous studies indicates that the expansion of the coronal magnetic field may be playing an essential role in pumping magnetic helicity from the interior. The Yohkoh satellite provided evidence that coronal loops overlying some active regions are continually expanding (Uchida et al. 1992). The importance of the active region loop expansion in helicity transfer was previously recognized by Rust & Kumar (1994). The extreme examples of coronal expansion may be eruptive prominences and coronal mass ejections. Helical structures have been best identified in eruptive prominences (Vrsnak et al. 1993; Karlický & Šimberová 2002) and coronal mass ejections (Chen et al. 1997; Wood et al. 1999). The expansion may cause the rotational motions observed in eruptive prominences as proposed by Jockers (1978) based on Parker's idea. Perhaps pumping by the expansion of a flux rope may be able to provide the azimuthal (poloidal) flux, as required by Chen's flux rope model of coronal mass ejection (Chen 1996, 2001). The sudden magnetic shear increase observed in major flares (Wang et al. 1994) and the sudden variations of magnetic helicity change rate (Moon et al. 2002b) might be also attributed to the same process. Wang et al. (2002) found a sudden increase in the flux of the leading sunspot in a few active regions during X-class flares. They proposed the impulsive sunspot expansion as one of the possible explanations for their finding.

Our study may also explain why rotational motions are often observed in association with eruptive phenomena or expansion. Various kind of rotational motion have been frequently reported in sunspots (Nightingale et al. 2001), prominences (Pettit 1941; Liggett & Zirin 1984), macrospicules (Pike & Mason 1998), Hα surges (Canfield et al. 1996), flare sprays (Pike & Mason 2002) and loops (Chae et al. 2000). Moreover, our study predicts counterclockwise rotation shall be prevalent in magnetic structures having negative helicity, and clockwise rotation, in magnetic structures having positive helicity. It would be interesting to investigate whether a hemispheric preference exists in the rotational motion or not.

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