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NON-COPLANAR MAGNETIC RECONNECTION AS A MAGNETIC TWIST ORIGIN

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ABSTRACT

Recent studies show the importance of understanding three-dimensional magnetic reconnection on the solar surface. For this purpose, I consider non-coplanar magnetic reconnection, a simple case of three-dimensional reconnection driven by a collision of two straight flux tubes which are not on the same plane initially. The relative angle θ between the two tubes characterizes such reconnection, and can be regarded as a measure of magnetic shear. The observable characteristics of non-coplanar reconnection are compared between the two cases of small and large angles. An important feature of the non-coplanar reconnection is that magnetic twist can be produced via the re-ordering of field lines. This is a consequence of the conversion of mutual helicity into self helicities by reconnection. It is shown that the principle of energy conservation when combined with the production of magnetic twist puts a low limit on the relative angle between two flux tubes for reconnection to occur. I provide several observations supporting the magnetic twist generation by reconnection, and discuss its physical implications for the origin of magnetic twist on the solar surface and the problem of coronal heating.

Key words : MHD – Sun : Magnetic Fields

I. INTRODUCTION

Observations indicate that magnetic reconnection ubiquitously occurs on the Sun as a result of interaction of two or more magnetic loops. Interacting flare loops seen in X-rays (Hanaoka 1996, 1997; Nishio et al. 1997) may be an example of this kind of reconnection occurring in active regions. On the other hand, transition region explosive events seen in ultraviolet emission lines may represent small-scale reconnection due to loop interactions in the quiet Sun, as evidenced by their close association with photospheric flux cancellation (Chae et al. 1998a).

Traditionally, the magnetic reconnection due to loop interactions has been studied in the two-dimensional space, as in the emerging flux model by Heyvaerts, Priest, and Rust (1977) and the converging flux model by Priest, Parnell, and Martin (1994). Even though these kinds of two-dimensional reconnection models have contributed to our understanding on the reconnection process on the Sun, they are limited by not being able to be compared directly with observations. Real magnetic geometries of interacting loops may be much different from those proposed in two-dimensional models as indicated by Aschwanden et al. (1999)'s examination of flare loop geometries. This kind of difficulty of two-dimensional reconnection has been the primary reason why many three-dimensional reconnection models have been developed. On the other hand, three-dimensional magnetic reconnection may have physical characteristics which are never expected in two-dimensional magnetic reconnection, and some of which are only beginning to be explored. Therefore, three-dimensional magnetic reconnection may be more than a simple geometric generalization of two-dimensional magnetic reconnection.

In the present paper, I investigate a few physical characteristics which are uniquely attributed to three-dimensional magnetic reconnection, by considering only a local region of reconnection due to the collision of two loops (see Figure 1). The local portions of loops can be considered as straight flux tubes which are not located on the same plane. We will show that 1) this kind of reconnection due to the collision of non-coplanar loops is characterized by the relative angle of the two loops at the reconnection point, and 2) it may lead to production of magnetic twist in reconnected loops. Note that the present investigation is mostly based on geometrical consideration of reconnection with the aid of energy and helicity conservation principles. I do not attempt to solve specific magnetohydrodynamic equations in the present work.

II. NON-COPLANAR MAGNETIC RECONNECTION

(a) Geometry

The purpose of the present paper is not to establish a realistic model, but to get insights on a few physical characteristics and observational consequences of three-dimensional reconnection. So I will concentrate on a magnetic configuration which is simple, but enlightening enough. Figure 1 illustrates a collision of two loops

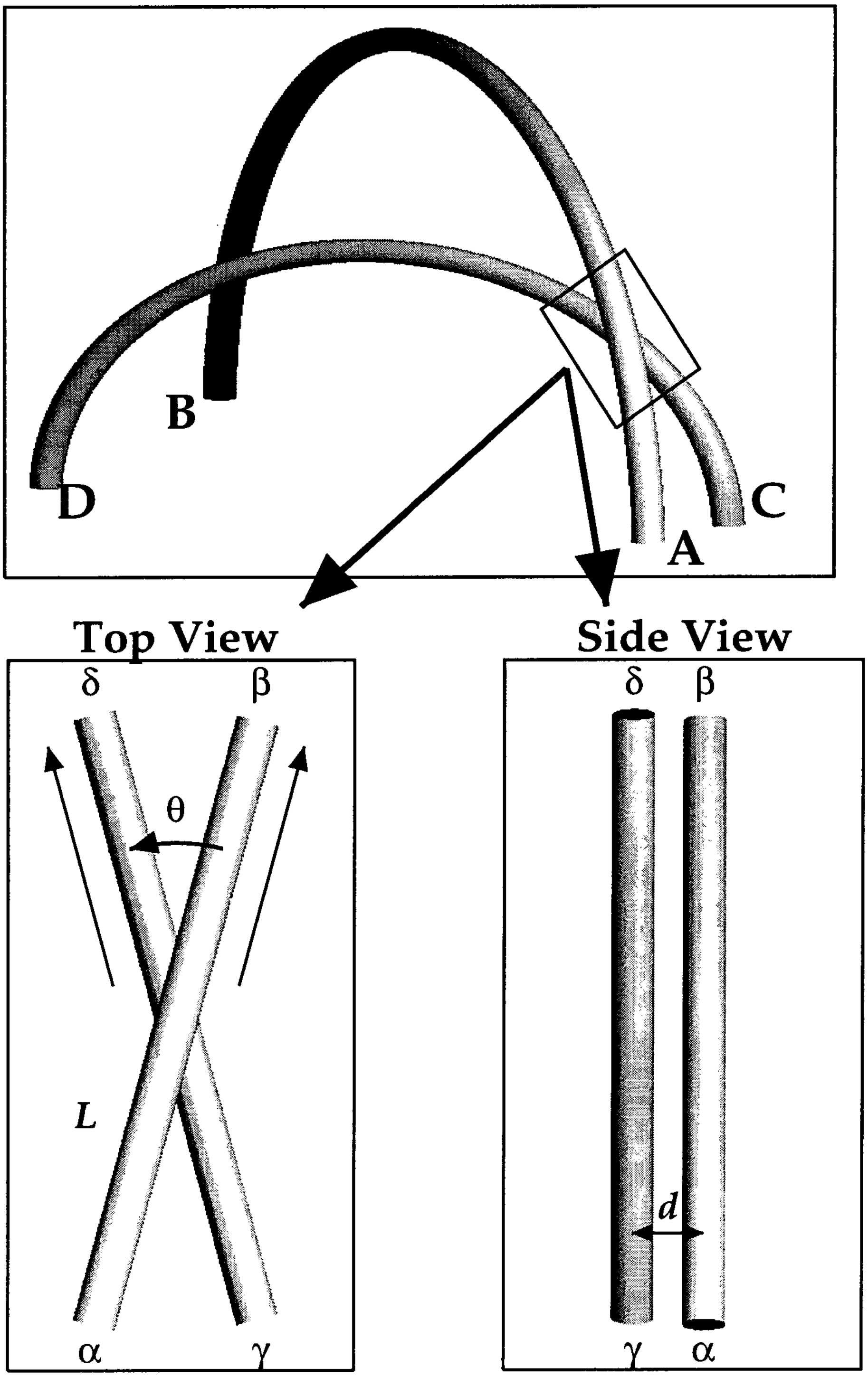


Fig. 1.— A three-dimensional magnetic reconnection geometry and its simplified model geometry.

l_{AB} and l_{CD}, which results in magnetic reconnection and, as a result, forms the two new loops l_{AD} and l_{CB}. All the loops have the same amount of magnetic flux Φ, the constant cross-sectional area A and, hence, the constant axial field strength B. The pre-reconnection loops l_{AB} and l_{CD} are untwisted, having no axial currents. But we will see later that the post-reconnection loops can be twisted as a result of reconnection. The footpoints are rooted at the photosphere, so they are insensitive to magnetic reconnection occurring in a high level. Therefore, the loops are effectively tied to the footpoints during magnetic reconnection. This line-tying condition implies no transport of magnetic energy and magnetic helicity across the photospheric boundary. To make the magnetic configuration even simpler, the two loops are assumed to have equal lengths L and negligible curvatures, and to collide with each other at the middle point, making a relative angle θ. Under these simplifications, the pre-reconnection loops l_{AB} and l_{CD} are modeled as the straight flux tubes $l_{\alpha\beta}$ and $l_{\gamma\delta}$, and the post-reconnection loops l_{AD} and l_{CB}, as $l_{\alpha\delta}$ and $l_{\gamma\beta}$. Note that the relative angle θ is measured counterclockwise from the overlying flux tube to the underlying flux tube. We define θ so as to ensure $-\pi<\theta\leq\pi$. It will be shown later that the negative (positive) value of θ means the negative (positive) value of the mutual helicity of the two flux tubes.

Reconnection starts when the distance d between the two colliding flux tubes becomes comparable to the loop diameter. If we consider the case of very small diameter-to-length ratio of the flux tubes, the reconnection geometry is mostly specified by only the two parameters L and θ. It is also easy to show that the relative angle and length of the post-reconnection flux tubes are given by $\theta_{\rm new} = 0$ and $L_{\rm new} = L\cos(\theta/2)$, respectively. They are smaller than the corresponding pre-reconnection values, which simply means that magnetic energy is released by reconnection.

Note that with the non-zero value of d, there are only two cases in which the two flux tubes $l_{\alpha\beta}$ and $l_{\gamma\delta}$ can be located on the same plane: $\theta=0$ or $\theta=\pi$. The case $\theta=\pi$ is the only situation where the reconnection could occur as a result of the collision of two coplanar loops. All kinds of two-dimensional magnetic reconnection models can be categorized into this very special case. In the three-dimensional space, it is more likely that two flux tubes are not on the same plane, so three-dimensional magnetic reconnection can be considered to be non-coplanar in general.

The speed of the outflow in non-coplanar reconnection is approximately given by

$$v_{\rm out} = \frac{B\sin(|\theta|/2)}{\sqrt{4\pi\rho_{\rm c}}} \qquad (1)$$

where $\rho_{\rm c}$ is the density inside the neutral current sheet. Note that the factor $\sin(|\theta|/2)$ has been introduced to account for the fact that only the anti-parallel field components are directly involved in the energetics and dynamics of magnetic reconnection. In the case of $\theta = \pi$, the outflow speed is reduced to the conventional value, $B/\sqrt{4\pi\rho_{\rm c}}$.

The maximum amount of magnetic energy which can be released into other forms is estimated to be

$$\Delta E = 2\,(1-\cos(\theta/2))\,LA\frac{B^2}{8\pi}. \qquad (2)$$

As expected, the formula says that large angle reconnection releases more energy than small angle reconnection. Since the angle determines the available energy in the magnetic system, it can be considered as a measure of magnetic shear in the system.

(b) Two Extreme Cases

Figure 2 compares the two extreme cases of non-coplanar magnetic reconnection: 1) a large $|\theta|$ case and 2) a small $|\theta|$ case. The non-coplanar reconnection with a large value of $|\theta|$ which is close to π, is qualitatively similar to two-dimensional reconnection occurring from the collision of two loops on the same plane. In this case, the reconnection outflow is well-collimated in the direction of the initial loops. Thus it looks like bi-directional jets. Because of the well-collimated nature of the outflow, there is a good chance of spatial separation of upflow stream and downflow stream in a large angle reconnection event, depending on the line of sight. For example, an observer with the line of sight 2 sees only the blue stream whereas another with the line of sight 4 sees only the red stream. On the other hand, an observer with the line of sight 1 is likely to see both the blue and the red streams if the observation is done using an optically thin emission line. Another important consequence of this kind of large inclination reconnection is that there is a chance to observe flux cancellation at the photospheric level. If the downward magnetic tension in the lower reconnected loop overcomes the magnetic buoyancy, the loop can retract from the surface, resulting in observed flux cancellation at the photospheric level.

Transition region explosive events observed on the quiet Sun may represent events of non-coplanar reconnection with large relative angles in several ways. First of all, they are characterized by the line profiles which indicate bi-directional jets. Second, spatial separation of upflow and downflow streams are observed (Innes et al. 1997). Finally, the majority of explosive events occur in association with magnetic flux cancellation at the photospheric level (Chae et al. 1998a).

The characteristics which are uniquely attributed three dimensional reconnection are manifest in the case of small $|\theta|$. Interestingly, small angle reconnection can be driven even by the interaction of two loops having the same polarity footpoints at the photospheric level. Therefore, unlike large angle reconnection, it does not necessarily accompany photospheric flux cancellation. The reconnection outflow is not well-collimated because of the large span angle. Thus the reconnection outflow

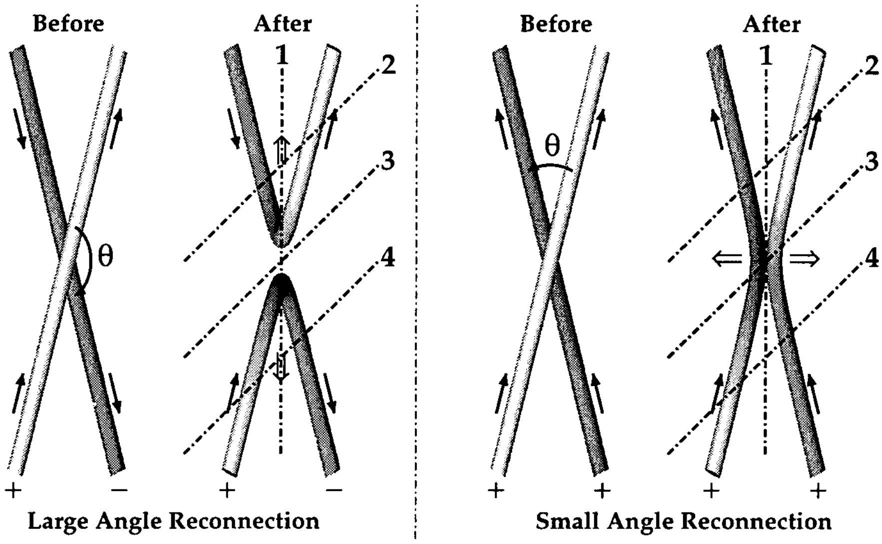


Fig. 2.— Two extreme cases of non-coplanar magnetic reconnection.

may not be able to develop into visible jet structures. Only the early phase of the outflow could be detected from spectrograph observations. But, as illustrated in Figure 2, it would be nearly impossible to to observe the spatial separation of the blue and red streams.

A variety of transient brightening events on the Sun which do not accompany obvious jet-like high velocity motions may represent events of non-coplanar reconnection with small relative angles. A particular example may be blinkers, quiet Sun transient brightening events at transition region temperatures discovered by SOHO/CDS (Harrison 1997; Harrison et al. 1999). CDS blinkers are different from explosive events in that they do not display obvious high velocity motions. However, the recent study by Chae et al. (2000a) strongly suggests that there may be a continuous transition of spectral characteristics from explosive events to small and short-lived brightening events which seem to make up blinkers. The determining factor may be magnetic geometry or the relative angle between colliding flux tubes. Blinkers may be a result of many reconnection events with small relative angles, whereas explosive events result from large angle reconnection.

(c) Magnetic Twist Generation

Magnetic reconnection due to collisions of non--coplanar flux tubes can produce magnetic twist through the re-ordering of the field lines. Figure 3 graphically illustrates this mechanism. In this simplified picture, the loops are assumed to consist of many strands in a given plane. A series of the inner pairs of field strands successively collide and reconnect. This process leads to the reversing of the order of the field lines. As a result, the reconnected loop becomes twisted by the amount of about half-turn or π in angle. Initially magnetic twist would be concentrated near the reconnection point, but it should soon propagate to the two footpoints of the flux tubes at the local Alfvén speed. The bi-directional propagation of magnetic twist is expected to accompany rotational motions at each half of a reconnected flux tube, which is a kind of torsional Alfvén wave. Note that the direction of the rotational motion at one part should be opposite to that at the other part for untwisting or twist propagation to occur. The specific direction depends on the direction of field lines and the sign of twist. For example, in the case of small angle reconnection presented in Figure 3, the upper part would display left-handed rotating motion, with the right side displaying blue-shifted motion, and the left side, red-shifted motion, whereas the lower part, right-handed rotating motion.

If field lines are tied at the footpoints, the magnetic twist will be soon uniformly distributed all over the loops. The strength of the uniform azimuthal field component is estimated to be

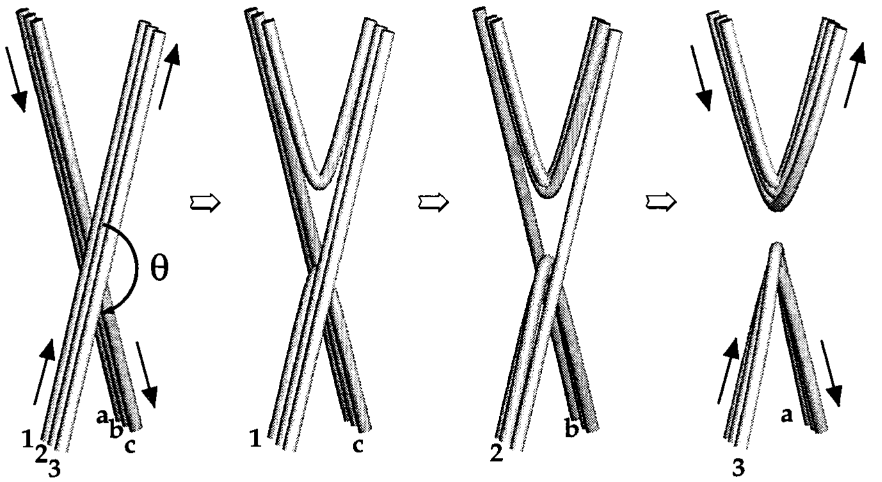
$$B_\phi = \phi \frac{R}{L_{\rm new}} B \tag{3}$$

where ϕ, R and $L_{\rm new}$ are the twist angle radius and length of the new flux tubes, respectively. The corresponding magnetic energy is

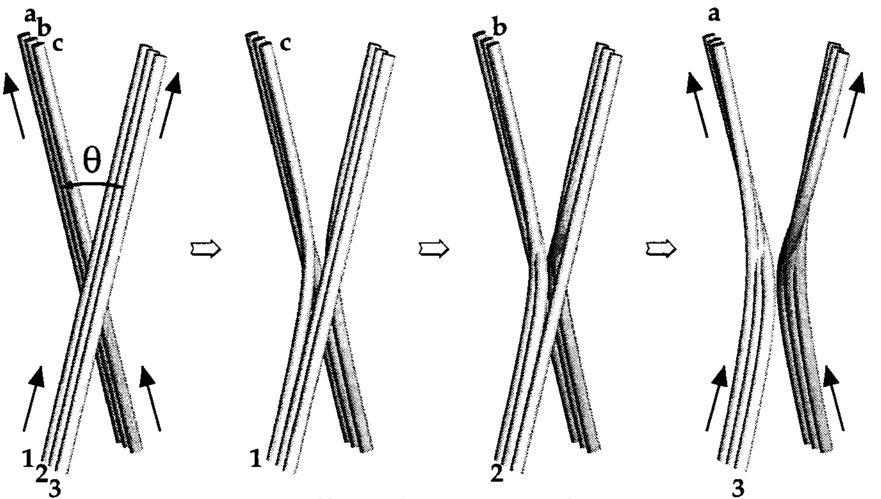
$$E_{\rm twist} = 2 L_{\rm new} A \frac{B_\phi^2}{8\pi}. \tag{4}$$

This energy must come from, and, therefore, should be less than the total amount of the released magnetic energy given by Equation 2. This requirement leads to a necessary condition for magnetic reconnection to occur,

$$\frac{E_{\rm twist}}{\Delta E} = \frac{\phi^2 (R/L)^2}{\cos\frac{\theta}{2}(1-\cos\frac{\theta}{2})} < 1 \tag{5}$$



Large Angle Reconnection



Small Angle Reconnection

Fig. 3.— Illustrations of magnetic twist generation due to reconnection.

with the use of $L_{\rm new} = L\cos\theta/2$.

Figure 4 presents $E_{\rm twist}/\Delta E$ as a function of θ in several cases of R/L. Specifically in the case of $R/L = 0.05$, the figure shows that $|\theta|$ should be greater than 26° and less than 177° for reconnection to occur. The upper limit of the angle may not be physically meaningful since its existence is mostly due to the too simplified geometry which always leads to the zero length of the reconnected tube in the case of $|\theta| = \pi$. The low limit, however, should be considered physically meaningful, which implies that the collision of two loops with a too small angle does not lead to the reconnection. The figure also shows that the reconnection between two loops with a smaller value of R/L is preferred in that it has the smaller value of the low limit.

Another interesting thing seen from Figure 4 is that in the case of small angle reconnection a large portion of the magnetic energy released from reconnection goes to magnetic twist energy. Since magnetic twist energy is uniformly distributed over the loops, the final consequence of reconnection may be the global heating of the loops via the dissipation of magnetic twist energy. This is contrasted to the case of large angle reconnection in which case most of the released energy should be converted to energy other than magnetic twist energy, like kinetic energy and thermal energy. So, the heating would be more or less local in nature in the case of large angle reconnection.

(d) Magnetic Reconnection and Helicity Conservation

In this section, I will show that the magnetic twist generation by reconnection is a natural consequence of magnetic helicity conservation. The discussion in this

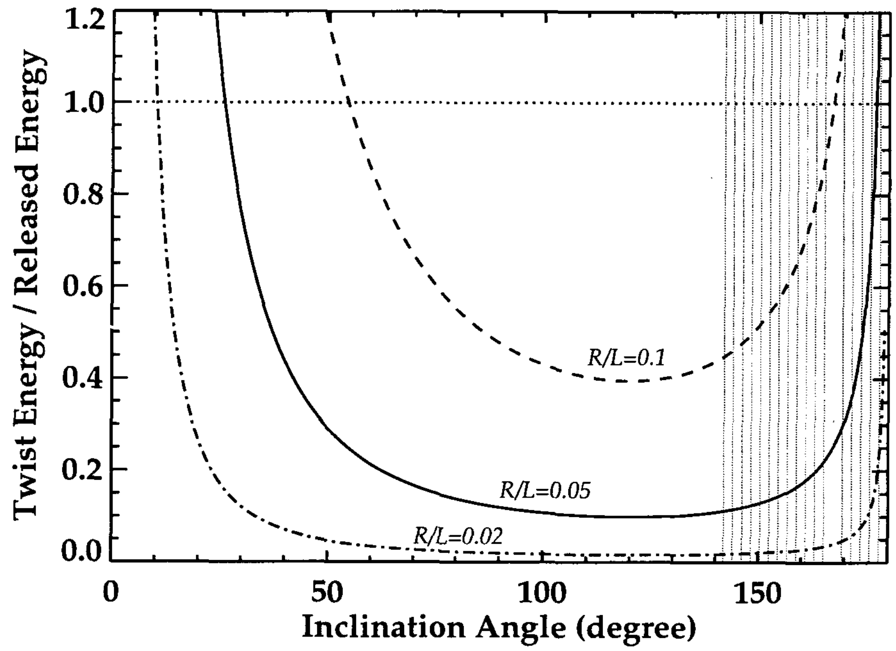


Fig. 4.— The ratio of magnetic twist energy to the total released energy. The increase in the hatched regime may not be physically meaningful because it is a consequence of the too simplified geometry.

section is mostly based on the nice introduction to solar magnetic helicity by Berger (1999). Magnetic helicity is normally defined by the volume integral of the scalar product of magnetic field and its vector potential, and is interpreted as the sum of linking over all pairs of field lines. There are two kinds of helicities: self helicities and mutual helicities. Mutual helicities measure the linking of field lines between two different flux tubes, and self helicities do the same within the same tube. Self helicities can be decomposed into a term measuring the twist of field lines about a central axis, plus a term measuring the writhe of the axis. According to Berger (1999), the self helicity of a twisted loop is

$$H_s = \frac{\Theta}{2\pi}\Phi^2 \tag{6}$$

where Θ and Φ are the twist angle and the flux of the loop, respectively. On the other hand, the mutual helicity of two loops is given by

$$H_m = \frac{\theta_{Pn} - \theta_{Pp} + \theta_{Np} - \theta_{Nn}}{\pi}\Phi_{PN}\Phi_{pn} \tag{7}$$

where the subscripts P and N denote the positive and negative footpoints of the overlying loop, and p and n do the same things of the underlying loop. The angle, for example, θ_{Pn}, is the angle of the position vector $\mathbf{r}_{Pn}$ measured counterclockwise with respect to a reference direction, i.e., the west-east direction.

A very useful property of helicity is that the total helicity is well conserved in many cases. In a closed volume in which magnetic fluxes never pass through the surface, the total helicity is conserved even in the presence of magnetic energy dissipation, if reconnection or dissipation process occurs over a time which is much shorter than a dissipation time scale determined by the system size and the magnetic diffusivity. This condition is satisfactorily achieved in the Sun. Meanwhile, the helicity of a subvolume which is open may change by the motion of magnetic fluxes on the surface. However, in the absence of the motion at the photosphere, i.e. in the case of line-tied coronal loops, the total helicity of the open volume is conserved, too. Therefore, any change in the mutual helicity results in the corresponding change in the self helicity.

Applying Eqn. 7 to the two idealized symmetric pre-reconnection flux tubes which are depicted in Figure 1 results in

$$H_{\rm m} = \begin{cases} -\Phi^2 & : \; -\pi < \theta < 0 \\ 0 & : \; \theta = 0 \\ \Phi^2 & : \; \pi > \theta > 0 \\ 0 & : \; \theta = \pi \end{cases} \tag{8}$$

in each case of θ. On the other hand, the mutual helicity of the post-reconnection flux tubes turns out zero. Therefore, the change in the mutual helicity is given by $\Delta H_{\rm m} = -H_{\rm m}$, and the helicity conservation requires that the change in self helicities $\Delta H_{\rm s}$ should be equal to $-\Delta H_{\rm m}$ or $H_{\rm m}$. Therefore, in the case of $\theta > 0$ ($\theta < 0$), each of the two reconnected loops should be twisted with the angle of π in the right-handed (left-handed) direction. This characteristic is exactly what has been inferred from Figure 3 based on geometrical consideration.

III. OBSERVATIONS

In this section I present a few observations which may support the picture of magnetic twist generation by reconnection.

(a) Magnetic Twist in a Transient Prominence

Figure 5 shows a huge prominence observed at 16:07 UT on 1997 August 26 by SOHO/EIT using the He II 304 Å filter. This prominence appears to be transient since it is not visible at the limb in other He II images taken several hours before and after this image. The comparison of this He II prominence with Hα data taken at 16:07 UT was made by Wang et al. (1998). Now I examine the time evolution of this prominence during the period 14:40 to 15:45 UT, which is before the time of the He II observation shown in Figure 5, based on the BBSO full disk Hα movie. The contrast of the prominence in Hα data at this period was barely enough (1%) to show the evolution of the prominence. The prominence as seen in Hα was under outward expansion. Interestingly I found a motion which diverges outward from a surface point which is located below the middle of the prominence. This kind of motion is expected when two loops reconnect near the surface, and form a new larger loop, and, therefore, could be considered to be evidence for the reconnection origin of this huge transient prominence.

The transient prominence appear to be twisted. The field lines inside the prominence can be traced based on its filamentary linear structures. A possible field line configuration is illustrated in Figure 5 (b) and its top view is given in Figure 5 (c). The model field lines are twisted in the left-hand direction. Note that the determination of the direction of twist is not without ambiguity because it is hard to discriminate between overlying and underlying field lines. The left-handed twist has been chosen simply because it prevails in the northern hemisphere (e.g. Martin 1998). Despite the ambiguity of the sense of direction, it is very appealing that the appearance of the observed prominence may be explained by introducing a magnetic twist of half turn or π in angle. Therefore, this peculiar transient prominence appears to be consistent with the picture of magnetic twist generation due to reconnection.

(b) Rotational Motions of Dynamic Loops

Figure 6 shows active loops observed by SOHO/SUMER on 1996 May 6 in He I Lyβ. By analyzing this data set, Chae et al. (2000b) showed that active region loops can be categorized into either stationary or dynamic loops, depending on the values of Doppler shifts and non-thermal broadenings determined from the line profiles. The figure shows a dynamic loop which is more or less vertical. An important finding is that the loop displays high velocity shear as seen from the adjacent redshift and blueshift patterns along the loop. This kind of velocity shear is likely to represent rotational motion around the loop axis. The rotational motion in turn implies the existence of magnetic twist to keep the motion. The rotational motion seems to be closely related to the small flare as seen from the Yohkoh/SXT data. The X-ray intensity distribution shows two peaks. The right intensity peak coincides with the Lyβ intensity peak and, possibly, near the footpoint of the dynamic loop displaying the rotational motion. The close association of the rotational motion and the small flare may be compatible with the picture of the generation and propagation of magnetic twist as a result of magnetic reconnection.

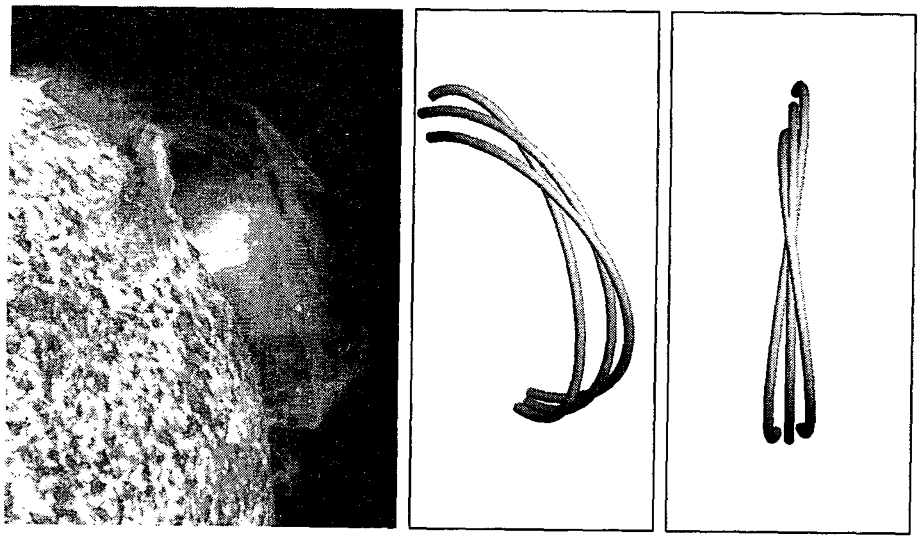
(c) Shear Increase after Strong Flares

Wang et al. (1994) reported that magnetic shear, defined as the angular difference between the measured transverse field and calculated potential field, increases after all of the five X-class solar flares they examined. Moreover, they demonstrated that the shear increase is impulsive, with time scales of several minutes. This kind of behavior is hard to explain in terms of magnetic reconnection as in two-ribbon type flares, since such reconnection would lead to the relaxation of magnetic system which should be consistent with the decrease of magnetic shear at the photospheric level. However, it is possible to explain the observation if reconnection due to the collision of two non-coplanar loops occurring at the very low height near to the photosphere is responsible for the observed flares. As already discussed, the non-coplanar reconnection could generate magnetic twist not only in the overlying reconnected loops, but also in the underlying reconnected loops, naturally explaining the observed increase of photospheric shear angle after flares.

IV.. DISCUSSION

(a) Mutual Helicity as a Source of Magnetic Twist

The generation of magnetic twist as a result of magnetic reconnection is a physical consequence of the total helicity conservation. We have considered the reconnection caused by the interaction of two loops which do not have self helicities initially, but have a mutual helicity due to the non-coplanarity of the two loops. The reconnection of the non-coplanar loops leads to the decrease of the mutual helicity, and the increase of the self helicities which means the generation of magnetic twist in the reconnected loops. I have illustrated that the conversion of mutual helicity into self helicities occurs during reconnection via the re-ordering of field lines. I have showed that the twist generation puts an low limit on the relative angles between two flux tubes



(a) Prominence (b) Field line model (c) Top view

Fig. 5.— Magnetic twist seen in a transient prominence. The prominence image was taken by SOHO/EIT using the He II 304 Å filter at 16:07 UT on 1997 August 26.

for reconnection to occur.

The possibility of twist generation due to magnetic reconnection was first suggested by Wright (1987) under the context of magnetospheric physics, and was supported by Song and Lysak (1989). A recent review of the studies on the role of magnetic helicity in magnetospheric physics has been given by Wright (1999). In the study of the Sun, however, little attention has been given to three-dimensional reconnection as a possible mechanism of twist generation. In fact, there has been increasing evidence for ubiquitous reconnection all over the solar surface, and lots of helical structures and rotating motions. Therefore, twist generation by reconnection seems to be very important in the study of the Sun, too.

It should be noted that the conversion of mutual helicity into self helicities is only one of the many possible ways of the helicity transfer and conversion associated with magnetic reconnection. For example, the idea of transfer of magnetic twist has been often considered to explain observations of flare loop structures (Pevtsov et al. 1996; Canfield and Reardon 1998). The transfer of twist might be closely related to the transfer of electric current as proposed by Melrose (1997). Magnetic reconnection can covert the twist into the mutual helicity, too, as suggested by Kuijpers (1997) for a prominence model. These ideas are assuming the existence of initial twists whereas the idea I considered assumes the existence of initial mutual helicities. Therefore, the question of which kind of helicity conversion is more important in the solar atmosphere may be closely related to that of how much portion of the total helicity in the solar atmosphere is contributed by each kind of helicity. There have been many attempts to quantify the self helicity in the solar atmosphere, but the amount of the mutual helicity has rarely been studied, even if a recent study of chirality of solar features (Martin 1998) strongly suggests that mutual helicities may be abundant on the solar surface.

(b) Origin of Magnetic Twist on the Solar Surface

The fact that mutual helicities and self helicities are convertible may be important in understanding the origin of magnetic twist observed on the solar surface. The mutual helicities have been often neglected in previous works. When the mutual helicities are neglected, there are two possibilities for the origin of magnetic twist on the solar surface: 1) twisting and braiding motions at the photospheric footpoints and 2) the emergence of twisted loops from the convection zone. So far, there has been no strong observational evidence for the first kind of motions. On the other hand, the second kind of motion has often observed. Thus there has been a trend to believe that magnetic twist is of sub-photospheric origin. If this is true, the question to be answered next is how magnetic twist is generated below the photosphere.

To find a possible source of twist in the convection zone, Longcope et al. (1998) studied the evolution of rising thin flux tubes in differential rotation and turbulent convective motions. They found that the most successful is the so-called Σ-effect whereby twist arises from the deformation of the tube's axis by turbulence. From the helicity conservation point of view, the accumulative effect of turbulence in this study is the gen-

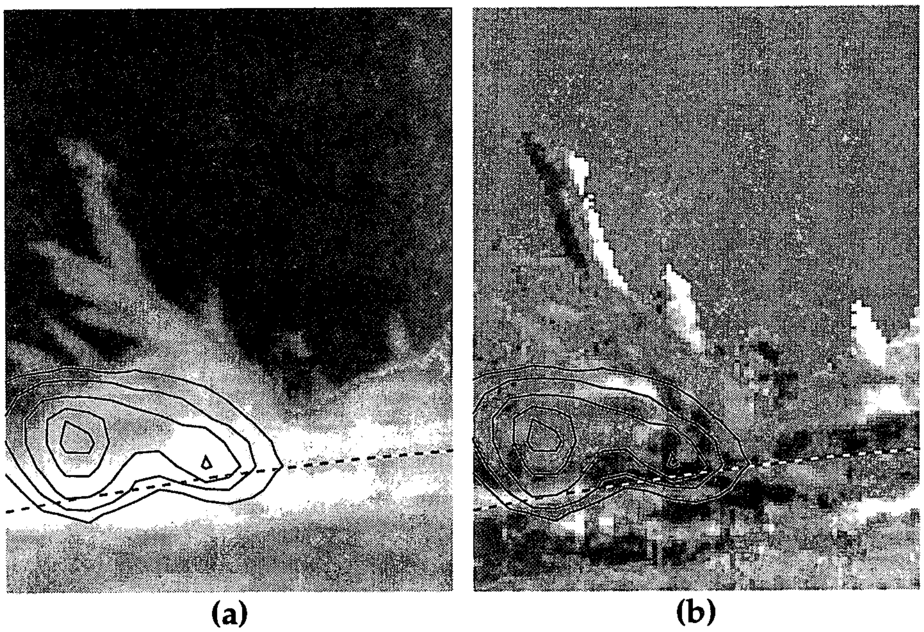


Fig. 6.— Active regions loops observed by SOHO/SUMER in H I Lyβ during the 20 minute period from 13:40 to 14:00 UT on 1996 May 6. (a) Intensity map. The east solar limb is specified by the arc. The north is at the right. The field of view is 100″ x 120″. The contours represent the Yohkoh/SXT AlMg intensity distribution. (b) Doppler shift map. The white and black represents 30 km s^{-1} (red-shifted) and -30 km s^{-1} (blue-shifted) levels of the Doppler shift measured with respect to the quiet area on the disk.

eration of non-zero twist from the initial zero self helicity, which is accompanied by the generation of opposite sense of non-zero writhe with the same amount as the twist. Therefore, the total self helicity, the sum of twist and writhe, should be zero. This means there is no transfer between self and mutual helicities which is possible only when the field line connectivities are preserved. It is, however, doubtful that this condition could be fulfilled in the highly turbulent convective medium.

On the other hand, van Ballegooijen (1999) attributed the origin of the magnetic twist to the effects of systematic flows (solar differential rotation) and random flows (granulation and supergranulation) acting on active-region magnetic fields after they emerge through the photosphere. The essential ingredient of his model is the introduction of photospheric diffusion which describes the effect of the random footpoint motions and the magnetic flux cancellation at the photospheric level. He found that an initially untwisted bipole evolves and leads to the formation of a left-helical flux rope in the North hemisphere and a right-helical flux rope in the South, in agreement with the observed hemispheric dependence of magnetic twist in quiescent filaments. From the helicity conservation point of view, this model is incorporating two kinds of important physical processes: 1) the production of mutual helicities by solar differential rotation, and 2) the conversion of mutual helicities into self helicities via magnetic flux cancellation. Since magnetic flux cancellation is considered to be a kind of magnetic reconnection, his model is consistent with our finding that reconnection is a good way of helicity conversion, and a possible source of magnetic twist.

It is still not resolved observationally whether the observed weak hemispheric pattern of magnetic twist in active regions is of subsurface origin or due to differential rotation on the solar surface, even if it is now accepted that magnetic fluxes are often twisted when it first emerges through the photosphere. The ambiguity mostly comes from the fact that active regions of all ages have been sampled to study the hemispheric pattern of magnetic twist. Studies based on more careful sampling would be required to resolve this important issue.

(c) Implications for Coronal Heating

Since a mutual helicity can be converted into self helicities through magnetic reconnection, magnetic reconnection is a way of producing small-scale current sheets (often called tangential discontinuities) in magnetic fields. The presence of tangential discontinuities is the essence of the so-called nanoflares (e.g., Parker 1983a, 1983b, 1988) which might be important in coronal heating. Parker attributes the existence of such tangential discontinuities to the shuffling and intermixing of the footpoints by photospheric convection. However, these motions have not been observationally confirmed, possibly because the difficulty of resolving individual flux tubes. The reconnection of magnetic loops might be a possible alternative to the photospheric motions for producing tangential continuities in the magnetic fields. Since that magnetic flux cancellation is very often observed both in active regions and in the quiet Sun, I think the magnetic twist produced by flux cancellation may be potentially important in coronal heating.

The non-coplanar reconnection may also be related to the idea of Alfvén wave heating, since the creation of magnetic twist during reconnection is accompanied by the generation and propagation of torsional Alfvén waves. It should be, however, noted that this does not support the traditional idea of heating by Alfvén waves generated by convective flows in the photosphere and below, since this kind of wave is generated in the upper atmosphere by reconnection. Measurements of spectral broadenings of lines formed at the chromosphere and transition region (Chae, Schühle, and Lemaire 1998) indicate that there are at least two difficulties in explaining the coronal heating in terms of Alfvén waves generated in the photosphere and below, if the broadenings are due to Alfvén waves. One is that the Alfvén wave flux in the chromosphere as inferred from the spectral line broadenings is much smaller than that in the transition region. The other is that the waves should have very short periods, smaller than a few seconds. It is not certain that photospheric convection can produce Alfvén waves which have enough power in such short periods. On the other hand, the waves generated by reconnection are impulsive and may have enough power in short periods. Once created, the waves would be trapped in the coronal portions of the loops until they are eventually dissipated as heat. The dissipation of Alfvén waves may be accompanied by the dissipation of small-scale current sheets implied by the magnetic twist. So it would be difficult to make a clear distinction between wave heating and nanoflare heating.

V. CONCLUDING REMARKS

I have examined a few physical characteristics of magnetic reconnection driven by the collision of two loops which are not on the same plane initially. The relative angle between the two initial loops characterizes the reconnection. Large inclination reconnection is similar to the traditional two-dimensional reconnection whereas small inclination reconnection shows many characteristics which are not expected in two-dimensional reconnection. An important characteristic of non-coplanar reconnection is that it produces magnetic twist in post-reconnection loops via re-ordering the field lines. The amount of twist introduced by reconnection has been estimated to be about π radian. This kind of magnetic twist generation can be understood in terms of the conversion of the mutual helicity into self helicities which is a consequence of the helicity conservation. The helicity conservation together with the energy requirement puts a low limit on the relative angle between two colliding flux tubes for reconnection to occur. I have discussed the implications of the magnetic twist generation by reconnection in understanding the origin of magnetic twist on the solar surface and the coronal heating mechanism(s).

The present study provides a few guidelines for future observational and theoretical studies. First of all, it would be important to uniquely determine the changes in the self and mutual helicities during reconnection processes in flares and filaments using high tempo-spatial resolution observations like TRACE observations. This kind of work will be helpful in evaluating the importance of each kind of helicity transfer associated with reconnection. To understand the origin of magnetic twist, it would be necessary to measure the mutual helicities in each solar hemisphere. It is also required to determine the dependence of magnetic twists in active regions on their ages. In the theoretical aspect, it appears worthwhile to investigate the characteristics of non-coplanar reconnection and twist generation by relaxing the simplifying assumptions I adopted. For example, the model I used in the present work is implicitly assuming that flux tubes are surrounded by field-free plasma. This assumption best holds at the photosphere and low chromosphere where the plasma beta is very high. In the high chromosphere and corona, the formulation needs to be modified to incorporate the low beta plasma condition which makes it hard to keep flux tubes surrounded by field-free plasma. Another issue to be investigated is how to explain twists with many turns. The present model predicts half-turn twist which sometimes appears to be insufficient for observed twists. Models of multiple-reconnection which produces a single twisted structure might be promising. Finally, the effort of establishing a realistic model of non-coplanar reconnection should be made for the comparison with observations.

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