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MAGNETIC HELICITY INJECTION DURING THE FORMATION OF AN INTERMEDIATE FILAMENT

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ABSTRACT

A necessary condition for the formation of a filament is magnetic helicity. In the present paper we seek the origin of magnetic helicity of intermediate filaments. We observed the formation of a sinistral filament at the boundary of a decaying active region using full-disk H_α images obtained from Big Bear Solar Observatory. We have measured the rate of helicity injection during the formation of the filament using full-disk 96 minute-cadence magnetograms taken by SOHO MDI. As a result we found that 1) no significant helicity was injected around the region (polarity inversion line; PIL) of filament formation and 2) negative helicity was injected in the decaying active region. The negative sign of the injected helicity was opposite to that of the filament helicity. On the other hand, at earlier times when the associated active region emerged and grew, positive helicity was intensively injected. Our results suggest that the magnetic helicity of the intermediate filament may have originated from the helicity accumulated during the period of the growth of its associated active region.

Key words : Sun: Magnetic helicity—Sun: Filament formation—Sun: Photospheric magnetic fields

I. INTRODUCTION

A filament always forms above a polarity inversion line (PIL) of the photospheric magnetic field (Bobcock & Bobcock 1955). Distinct motions in the photospheric region of filament formation are shearing (Chae et al. 2001) and convergence (e.g., Martin 1990) between the magnetic flux patches of opposite signs. The convergence toward the PIL leads to magnetic flux cancellation (Martin et al. 1985; Chae 2000; Chae et al. 2001; Wood & Martens 2003), which is another distinct feature at the site of filament formation. In the neighborhood of a filament, chromospheric fibrils usually run parallel to the PIL. Coronal arcades overlying a filament are also a constituent of overall surrounding structure (Martin 1990; Satio & Tandberg-Hanssen 1973). A region showing these characteristics is known as a filament channel (Martin 1990; Gaizauskas et al. 1997; Gaizauskas 1998). All these necessary conditions for the formation of filaments have been well discussed (e.g., Martin 1998).

Magnetic helicity is another necessary condition for filament formation. Chromospheric fibrils running parallel to the PIL of a filament imply that the filament has a highly sheared structure. EUV images of quiescent and eruptive filaments often show helical magnetic structures within the filaments (e.g., Dere et al. 1999). Many models making use of a twisted flux rope have also been suggested to explain the filament structure (Kuperus & Raadu 1974; Priest et al. 1989; Priest 1990; Rust & Kumar 1994; Low & Hundhausen 1995). The existence of handedness property (chirality) (Martin et al. 1994; Pevtsov et al. 2003) is another manifestation of the helicity requirement for the filament formation. There exists an one-to-one correspondence between filament chirality and magnetic helicity in filaments. Positive (negative) magnetic helicity is necessary for a sinistral (dextral) filament (Rust & Martin 1994; Mackay et al. 1997; Aulanier & Demoulin 1998; Rust 1999; Chae 2000).

Where does the magnetic helicity of a filament come from? This question is closely related to the formation of magnetic structures of a filament. Theoretical models have used either surface motion or subsurface motions to explain the magnetic structure, implying either surface origin or subsurface origin of the magnetic helicity of filaments, respectively.

Several models of filament formation have adopted photospheric shear flows, which support surface origin of filament helicity. van Ballegooijen & Martens (1989) and Kuperus (1996) used surface shear motions which is parallel to the PIL. The other model proposed by Zirker et al. (1997) used the shear motions of differential rotation and supergranulation. Such shear motions do not necessarily need to be parallel to the PIL.

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Martens & Zwaan (2001) applied the shear motions of differential rotation which operates on a pair of bipoles obeying the Hale's law and Joy's law. All these models included surface motions to form the helical structure of filaments.

On the other hand, filament formation models supporting subsurface origin of filament helicity have also been suggested. In some of these models, the filament helicity is provided by subphotospheric flows such as subphotospheric differential rotation (van Ballegooijen & Martens 1990; Rust & Kumar 1994; Priest et al. 1996). The other models initially take into account non-potential magnetic bipoles assuming the emergence of pre-twisted magnetic bipoles, and their MHD evolutions lead to the filament formation (Mackay & van Ballegooijen 2001, 2005; Mackay & Gaizauskas 2003). Like this, both the explicit and implicit inclusions of subsurface origin of the filament helicity have been suggested. In spite of these theoretical efforts of both surface and subsurface origin of filament helicity, still we are lack of observational evidence for the origin of filament helicity.

A quiescent filament is an interesting structure in the viewpoint that it forms and grows in the quiet region which appears a barren place to supply them with sufficient magnetic helicity (Welsch & Longcope 2003). What is the origin of quiescent filaments? Why do quiescent filaments show a distinctive hemispheric preference? Recently, Jeong & Chae (2007) suggested that the magnetic helicity of a quiescent filament may originate from the remnant helicity of its associated active region, based on their finding that magnetic helicity in active regions is mainly injected during the period of active region emergence, and the helicity injection after then is insufficient.

In the present study, we aim to examine a possibility that the magnetic helicity of a quiescent filament may originate from the remnant helicity of an associated active region. To scrutinize the possible process of helicity transfer from the associated active region to the region of filament formation, we choose an intermediate filament which resides at the boundary between a decaying active region and a surrounding region of quiet sun. It also constitutes a class between active region filaments and quiescent filaments. Since substantially more quiescent filaments are formed on neutral lines between bipolar regions than on those inside bipolar regions (Tang 1987), our selection of this intermediate filament leads us to understanding the majority of quiescent filaments.

Our approach is to compare the sign of filament helicity with the sign of injected helicity just below the coronal region of filament formation. We trace the target filament while it forms and grows. This paper is organized as follows. In section II, we describe the data and method to determine the sign of the observed filament and the measured helicity. In section III, we present our result of helicity sign comparison. After discussing about our result in section IV, we present the conclusion in section V.

II. DATA AND METHOD

Intermediate filaments form between weak unipolar background field regions and active region complexes (Engvold 1998). The target filament that we selected was an intermediate filament which was located at a boundary between a decaying active region complex (AR10386 and AR10389) and the surrounding unipolar quiet region. This active region complex represents the decay phase of the active region AR 10386 that was observed in the previous solar rotation. Figure 1, a full disk H_α image and a magnetogram, show that the selected filament is an intermediate filament.

We observed the formation of this intermediate filament using a time series of H_α full disk images taken at Big Bear Solar Observatory (BBSO). The region of interest was traced from 19 June 2003 to 24 June 2003, for about 5 days. The BBSO observed the Sun for about 8 hours per day. The observed data set has 30 minute cadence. The field of view that we selected for helicity measurement was $401'' \times 551''$.

We measured the rate of helicity injection through photospheric area just below the region of filament formation using MDI full disk magnetograms taken by SOHO MDI with a 96 minute cadence. The rate dH/dt is determined by the LCT method initially described by Chae et al. (2001). The helicity injection rate is determined by three physical quantities: the normal component of photospheric magnetic field, the apparent horizontal velocity of photospheric field line footpoint (Demoulin & Berger 2003), and the vector potential for the normal component of photospheric magnetic field. The only data required to calculate these three quantities is just a time series of line-of-sight magnetograms. We obtained the accumulated helicity in the corona by integrating the helicity injection rate over the observing period. The specific application of this method was the same as the one of Jeong and Chae (2007) except the choice of the angular distance of the central position of the measurement area from the solar disk center. While we traced the region of interest, the angular distance was less than 0.6 of the angular radius of the disk to reduce the projection effect.

III. RESULTS

It appeared that filament channel already existed before we started our measurement. It may have formed when it was on the back side of the solar disk. On May 29 when the region of our interest was located at the west limb, fibrils did not run parallel to the polarity inversion line at the region of our interest. On June 18 when the region of interest showed up again at the east limb, fibrils ran parallel to the polarity inversion line and a few small filaments existed there.

Figure 2 shows the evolution of filament formation

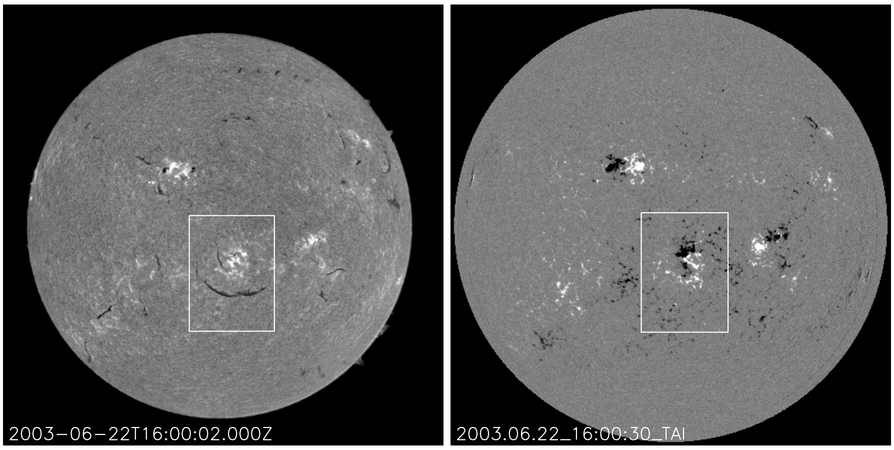

Fig. 1.— Full disk H_α image and magnetogram. The white boxes indicate the selected area for helicity measurement.

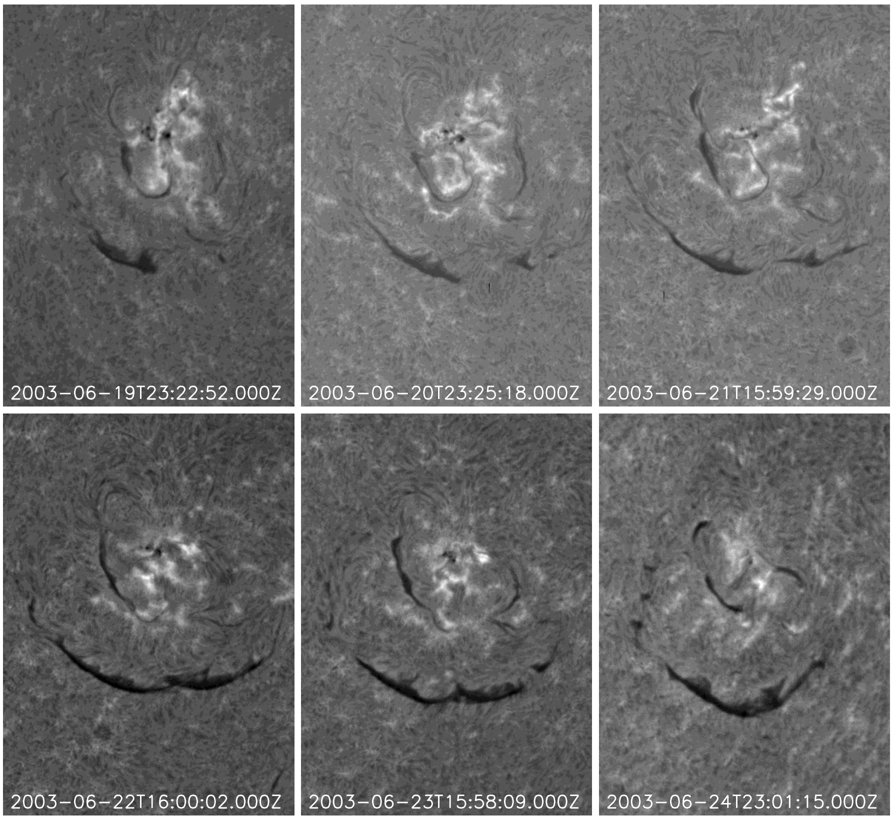

Fig. 2.— Evolution of the target filament which shows sinistral chirality (positive helicity).

seen in H_α. The sign of filament helicity is determined from the barb configuration of the filament. During the formation process, the sign of filament helicity kept positive. On June 21 two filaments grew more and both of them show a structure of positive helicity (sinistral chirality). On June 22 two sinistral filaments grew rapidly. On June 23 two sinistral filaments are about to be connected. On June 24 two sinistral filaments are connected to each other, and made a single long sinistral filament.

Figure 3 shows the magnetic helicity injection in its associated active region. For about 5 days negative magnetic helicity was steadily injected, and as a result -1.9×10^{42} Mx^2 of magnetic helicity was accumulated. Meanwhile, magnetic flux of 1.1×10^{22} Mx was lost. From the magnetograms we see that a significant amount of magnetic flux was canceled within the as-

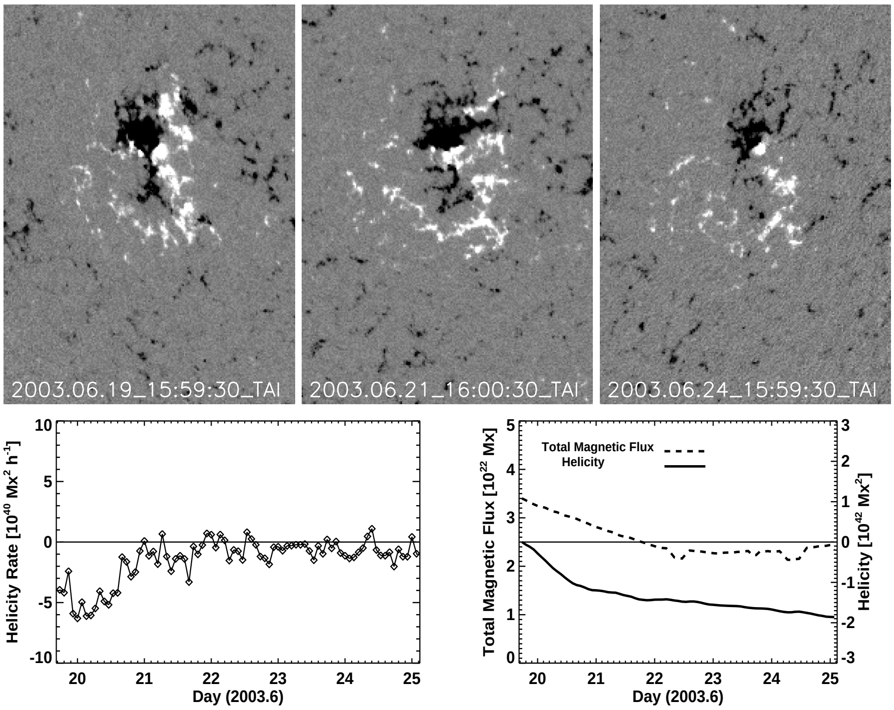

Fig. 3.— Magnetogram showing magnetic flux cancelation and plots representing negative helicity injection with magnetic flux decrease.

sociated active region. The amount of flux cancelation within the region of filament formation contributed a small fraction of that. It is clear from Figure 3 that the sign of injected helicity through photosphere was negative. Negative helicity was injected through the selected region containing both the decaying active region and the lower subregion of filament formation. We need to check the helicity contribution from each of both the decaying active region and the region of filament formation.

Figure 4 shows that there was insignificant and negative helicity injection within the subregion of filament formation, and the negative helicity injection came mainly through the decaying active region. For about 5 days the amount of helicity injected through the selected subregion of photosphere was -2.9×10^{41} Mx^2 while the amount of magnetic flux decrease was about 1.3×10^{21} Mx. The lower right plot shows that helicity injection around the region of filament formation is insignificant.

IV. DISCUSSION

We have sought an evidence for the supply of magnetic helicity while an intermediate filament formed at the boundary between a unipolar quiet region and a decaying active region. In order to study the helicity supply during the filament formation, we have measured helicity injection from below the photosphere in the area of the polarity inversion line (PIL) and its surroundings. The sign of measured helicity injection was compared with the sign of filament helicity which was inferred from the observed filament chirality.

As a result we found that while the filament formed, the helicity of proper sign was supplied neither through the decaying active region nor through the region of filament formation near the PIL. The sign of injected helicity was opposite to the helicity sign of the newly formed filament. The sign of the filament helicity indicated by the H_α barb structure was positive, but the injected helicity sign from below the photosphere during filament formation was negative. Filament helicity kept positive despite the steady injection of negative helicity. How can we understand such an inconsistency? Where did the positive helicity of the filament come from?

We propose the helicity of the filament would be the remnant of the helicity accumulated during the growing phase of its associated active region. Jeong & Chae (2007) measured magnetic helicity of AR 10365 which is the same active region observed in growing phase. They found that positive helicity injection was significant while the active region grew. So we conjecture that a part of this positive helicity may have gone to the filament of our interest.

We surmise that magnetic helicity injection would have been insignificant during the filament channel formation, too, as was during the filament formation. A filament channel, characterized by the alignment of fib-

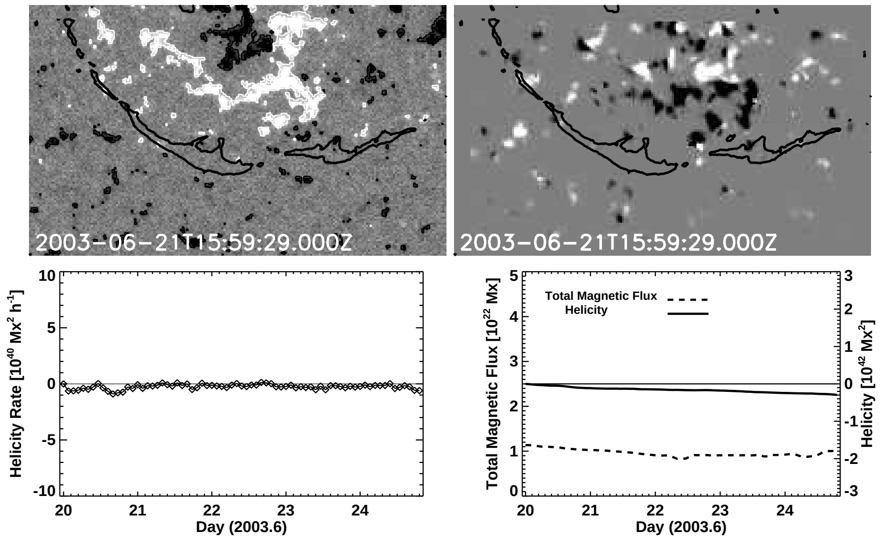

Fig. 4.— Distribution of magnetic flux (*upper left*) and helicity flux (*upper right*) at the region of filament formation together with plots representing insignificant helicity injection with more or less constant magnetic flux variation during the filament formation.

rils running parallel to the PIL, is considered to be the magnetic environment of filaments. In our study the filament channel seems to have developed at the back side of the solar disk. The filament channel was not developed until the active region was located at the west limb in its growing phase, but was there when the active region was at the east limb in its next disk passage when the active region decayed. According to Jeong & Chae (2007), while the active region passed the region of solar disk center in its growing phase, magnetic helicity injection was very significant. After that, it decreased to almost zero when the active region was located at the west limb. So we think helicity injection may also have been insignificant while the active region was located at the back side of the solar disk, and the positive helicity of the filament channel may also have originated from the remnant helicity of the associated active region.

Even though we have not directly measured the helicity injection while the filament channel formed, previous studies supports our conjecture above that the helicity of a filament channel would also come from the coronal structure of its associated active region not directly from below the photosphere while it formed. Gaizauskas et al. (1997) presented that a filament channel formed at the boundary of an active region while the active region emerged in a previously quiet region. Since an emerging active region carries its magnetic helicity (Leka et al. 1996; Jeong & Chae 2007) and at the boundary where the filament formed, helicity injection is negligible (Welsch & Longcope 2003), helicity of filament channel may be provided from the emerging active region, which is consistent with our finding. Soon after the observation by Gaizauskas et al (1997), studies using a force-free field model to account for this specific channel formation were done (Mackay et al. 1997; Mackay et al. 1998). The models suggest that the formation of the filament channel is due to the emerging activity complex in a sheared state. Later on, Gaizauskas et al. (2001) reported another observation of filament channel evolution that large-scale swirled patterns of chromospheric fibrils were still detectable in the migrating flux to form a filament channel after the source active regions of negative helicity had disappeared. So, preexisting coronal helicity of associated active regions seems to be used as a helicity source of filament channels.

Our suggestion is also consistent with a recent outcome after a series of previous efforts on the origin of hemispheric preference in chirality (helicity) of filaments. van Ballegooijen et al. (1998) developed a model of magnetic flux transport which includes the surface effects of differential rotation, meridional flows, and magnetic diffusion in helicity transfer, and applied the model to an initially potential magnetic field. Their model predicted that in each hemisphere the number of dextral and sinistral channels are approximately equal, which is different from current observations. Mackay et al. (2000) added a magnetofrictional relaxation method to the model of van Ballegooijen, which produces nonlinar force-free coronal fields. They also suggested that the effects of surface flows acting on an initial potential field are not sufficient to make a filament or a filament channel of required skew (helicity) within a proper time. Later on, Mackay & Gaizauskas (2003) added initial helicity to the simulation of Mackay et al. (2000) so that the helicity of adjacent active regions is supplied to the region of filament formation. They found that the inclusion of initial helicity results in sufficiently strong and large fields to account for the existence and length of an observed filament within the allotted time. Recently, Mackay & van Ballegooijen (2005), who studied the interaction of two magnetic bipoles, suggested that the dominant hemispheric pattern may be attributed to the dominant ranges of helicities and bipole tilt angles of the interacting active regions.

It seems that not all filaments take their helicity from the preexisting coronal helicity. According to Chae et al. (2001), sufficient negative helicity was provided from below the photosphere to make a dextral filament inside an active region. This case appears different from the case of our study. However, an important difference we need to note is that the filament was an active region filament while the one in the present study is an intermediate filament. The formation of an active region filament seems to be tightly coupled with the evolution of the active region. The active region studied by Chae et al. (2001) may have undergone a development with a significant injection of negative helicity and this kind of development may have directly contributed to the formation of the active region filament. On the other hand, the formation of the intermediate filament we studied may have taken place after the major development of its associated active region, leading to the time lag between the helicity injection through the active region and the formation of the filament.

V. CONCLUSION

The helicity of the intermediate filament we studied was not supplied directly from below the photosphere during the filament formation, and may have not during the filament channel formation either. Alternatively, we conjecture that the helicity of the filament may have originated from the remnant coronal helicity accumulated during the growing period of the associated active region. Our result on the helicity origin of the intermediate filament would also shed light on understanding the helicity origin of quiescent filaments, since intermediate filaments and quiescent filaments are similar in that both kinds are found in between two magnetic flux systems unlike active region filaments (Tang 1987). It may be worthwhile to examine whether helicity injection directly from the photosphere is insignificant during the formation of quiescent filaments as is in the case of intermediate filaments.

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