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PHOTOSPHERIC MOTIONS AND CORONAL MASS EJECTION PRODUCTIVITY

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ABSTRACT

Shearing motions have been frequently used in MHD simulations of coronal mass ejection (CME) initiation but have hardly been reported from observations of CME-producing regions. In this Letter, we investigate whether the bulk of magnetic helicity carried away from the Sun by CMEs comes from helicity injected to the corona by such motions or by emerging magnetic flux. We use photospheric magnetic field observations of NOAA Active Region 9165, which is an ideal candidate for such study because (1) it is the site of both new flux emergence and intense horizontal shearing flows; (2) it shows rapid development and rapid decay, and for a few days it is the site of violent activity; (3) the horizontal motions occur when it is close to disk center, thus minimizing the errors involved in the relevant computations; and (4) observations of a magnetic cloud associated with one of the CMEs linked to the active region are available. The computed helicity change due to horizontal shearing motions is probably the largest ever reported; it amounts to about the total helicity that the active region's differential rotation would have injected within three solar rotations. But the CMEs linked to the active region remove at least a factor of 4–64 more helicity than the helicity injected by horizontal shearing motions. Consequently, the main source of the helicity carried away by the CMEs is the new magnetic flux that emerges twisted from the convective zone. Our study implies that shearing motions, even when they are strong, have little effect in the process of buildup of magnetic free energy that leads to the initiation of CMEs.

Subject headings: solar-terrestrial relations — Sun: activity — Sun: coronal mass ejections (CMEs) — Sun: magnetic fields

1. INTRODUCTION

The magnetic field carried away by the coronal mass ejections (CMEs) is twisted. CME activity is considered as a valve through which the Sun gets rid of excess magnetic helicity (e.g., van Driel-Gesztelyi et al. 1999). The relative magnetic helicity (hereafter referred to as helicity) of a field $\boldsymbol{B}$ within the entire coronal volume V with respect to the helicity of a reference field $\boldsymbol{B}_p$ having the same distribution of vertical magnetic flux on the surface S surrounding V is defined as $H = \int_V \boldsymbol{A} \cdot \boldsymbol{B}\, dV - \int_V \boldsymbol{A}_p \cdot \boldsymbol{B}_p\, dV$. Being a potential field is a convenient choice for $\boldsymbol{B}_p$. The quantity $\boldsymbol{A}_p$ is the corresponding vector potential satisfying $\boldsymbol{\nabla} \cdot \boldsymbol{A}_p = 0$ and being horizontal on S. Then the term $\int_V \boldsymbol{A}_p \cdot \boldsymbol{B}_p\, dV$ vanishes (Berger 1988). Helicity is a quantitative measure of the chiral properties of the structures observed in the solar atmosphere. In a closed volume, it is a fairly well conserved quantity. In an open volume like the solar atmosphere, however, helicity can change because of the emergence of new twisted field lines that cross the photospheric surface S (e.g., Leka et al. 1996) and/or by horizontal motions on the photospheric surface. Such motions may come from differential rotation and/or from photospheric shearing flows. According to Berger (1999), the rate of helicity change dH/dt due to horizontal motions is

$$\frac{dH}{dt} = -2 \oint (\boldsymbol{v} \cdot \boldsymbol{A}_p) B_n\, dS, \qquad (1)$$

where B_n is the vertical component of the magnetic field on the photosphere and $\boldsymbol{v}$ the photospheric horizontal velocity.

The question we address in this Letter is whether the magnetic helicity carried away from the Sun by CMEs comes mainly from helicity injected to the corona by photospheric horizontal shearing motions (other than differential rotation) or by emerging magnetic flux. This is an important issue because the answer may provide clues about the mechanism for the buildup of magnetic free energy that may lead to CMEs. Previous studies (Green et al. 2001; Démoulin et al. 2002) focus on the contribution of differential rotation to the helicity budget of active regions. Démoulin et al. (2002) found that differential rotation cannot provide the required helicity to the field ejected to interplanetary space. The active region they studied showed no horizontal shearing motions; therefore, they concluded that the needed helicity could be transferred to the corona by flux emergence. Our target, NOAA Active Region 9165, is the site of new flux emergence; it also shows intense shearing motions that inject much higher amounts of helicity to the corona than the amounts of helicity injected by differential rotation. Therefore, all possible mechanisms for the injection of helicity are present, and our attention is shifted to the comparison between the efficiency of these mechanisms and the helicity carried away by the CMEs originating from the active region.

2. OBSERVATIONS AND DATA ANALYSIS

In AR 9165 we compute the rate of helicity changes due to horizontal photospheric motions (see eq. [1]) using high-cadence magnetograms obtained with the Michelson Doppler Imager (MDI) on board the *Solar and Heliospheric Observatory*. Our MDI database consists of both "high-resolution" magnetograms and "full-disk" (FD) magnetograms obtained during 2000 September 14–17 with 1 minute cadence. We also used 96 minute cadence MDI magnetograms taken between September 14 and 21 for the study of the overall evolution of the active region. Photospheric vector magnetograms for September 15 and 16 were obtained by the Huairou Solar Observing Station (HSOS) magnetograph.

For all high-cadence MDI images, we remove solar rotation (our reference time is the time when AR 9165 passes through the central meridian, i.e., September 16, 01:06 UT), and we

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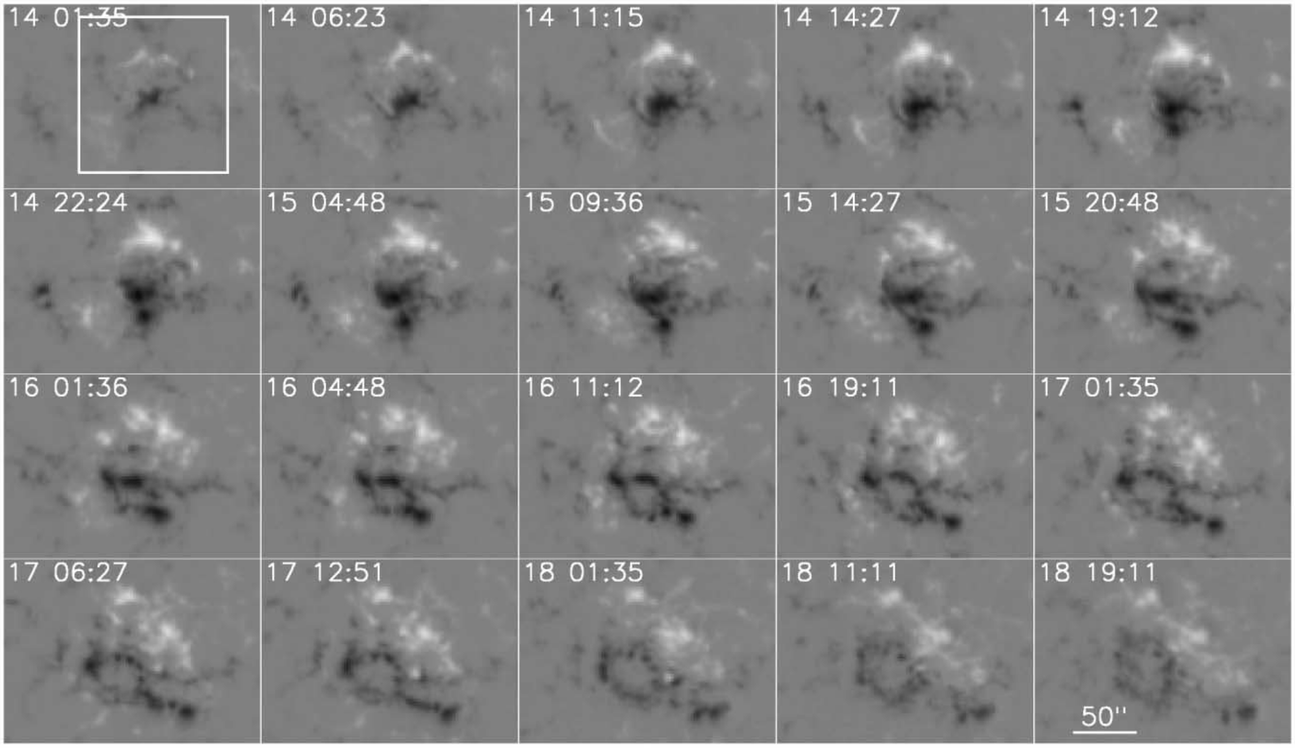

FIG. 1.—Selected MDI images that show the evolution of AR 9165 from 2000 September 14 to 18. The white frame marks the area that appears in Fig. 2.

compute the rate of helicity change dH/dt due to horizontal motions using the method described by Chae et al. (2001). For the B_n calculation, we assume that the photospheric magnetic field is vertical: therefore, B_n can be derived from the longitudinal field. The value of $\boldsymbol{A}_p$ is computed using the properties of Fourier transforms (see Chae 2001). The velocities $\boldsymbol{v}$ associated with the photospheric horizontal motions are computed using the local correlation tracking technique (November & Simon 1988). Two parameters are critical to the accuracy of this technique: the FWHM w of the apodizing function and the time interval between a pair of images, ΔT. After several tests, we choose $w = 7''.5$ and $\Delta T = 15$ minutes. This combination yields the smallest number of velocity vectors measured with maximum cross-correlation smaller than 0.85 and the smallest number of velocity vectors with absolute values higher than 1 km s^{-1} (following Nindos & Zirin 1998, such velocities are rejected).

3. RESULTS

The evolution of AR 9165 is presented in Figure 1. Positive flux emerges at the northern part of the active region, and predominantly negative flux emerges at the southern part of the active region. During September 14, its northern part shows a predominantly clockwise motion, while the southern part shows a counterclockwise motion. From September 15, some of the northeastern part of the active region starts moving northward, northeastward. The decay of the active region starts already on September 16 and can be seen until September 22, when it reaches the western limb. When AR 9165 returned on the next rotation, it contained no sunspots.

Figure 2 shows the horizontal velocity field and the corresponding distribution of $G = -2\boldsymbol{v}\cdot\boldsymbol{A}_p B_n$ at four specific times. The maximum of the absolute value of the derived velocities is 0.7 km s^{-1} and occurs around September 14 (23:45 UT) to September 15 (03:00 UT). The velocity fields in Figure 2 show clearly the large-scale systematic flow patterns that characterize the active region during its development and early decay phase. During the development phase, the large velocities are associated with the counterclockwise motion of the active region's southern part; they are confined close to the neutral lines and correspond to (1) large-scale twisting and shearing motions and (2) "converging" motions. Because of converging motions, negative flux elements collide with positive ones, and cancellation occurs. On September 16, shearing motions are still present (although weaker than earlier), but the converging motion and an overall radially expanding motion are more prominent. The value of G is predominantly negative, and as expected, the maxima of the spatial distribution of G correlate well with the regions that show intense shearing and twisting motions. Therefore, these motions feed negative helicity into the corona. Note that according to soft X-ray telescope images, the active region's magnetic field emerged having left-handed chirality.

The temporal variation of the rate of helicity changes due to horizontal motions appears in Figure 3*b*. We have determined dH/dt every 15 minutes for the time intervals that high-cadence MDI images are available by integrating G over the area shown in Figure 2. In Figure 3*c*, we show the accumulated change of helicity $\Delta H(t)$ calculated from the measured dH/dt as a function of time. The temporal variation of dH/dt shows that during the active region development the rate of helicity change is negative; i.e., horizontal motions contribute to the increase of the (absolute) value of the coronal magnetic field helicity. Initially, dH/dt is small, but it reaches its absolute maximum value within about 30 hr. Then dH/dt decreases, reaching gradually its September 14 00:00 levels and finally changing sign. In addition to these large-timescale trends in the variability of dH/dt, irregular fluctuations with periods of 45–120 minutes are also present. Somewhat similar dH/dt fluctuations have been de-

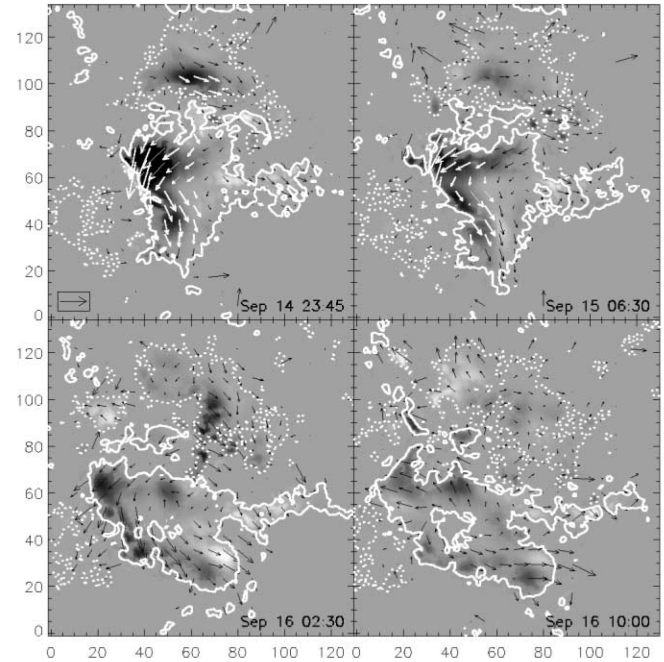

FIG. 2.—Horizontal velocity vectors and the corresponding gray-scale maps of $G = -2\boldsymbol{v}\cdot\boldsymbol{A}_p B_n$ at four specific times. The length of the arrow inside the small rectangle at the lower left corner of the top left image measures velocity of 0.5 km s^{-1}. The solid and dotted contours represent longitudinal magnetic field strengths of −200 and 200 G, respectively. The axis labels denote arcseconds on the solar photosphere.

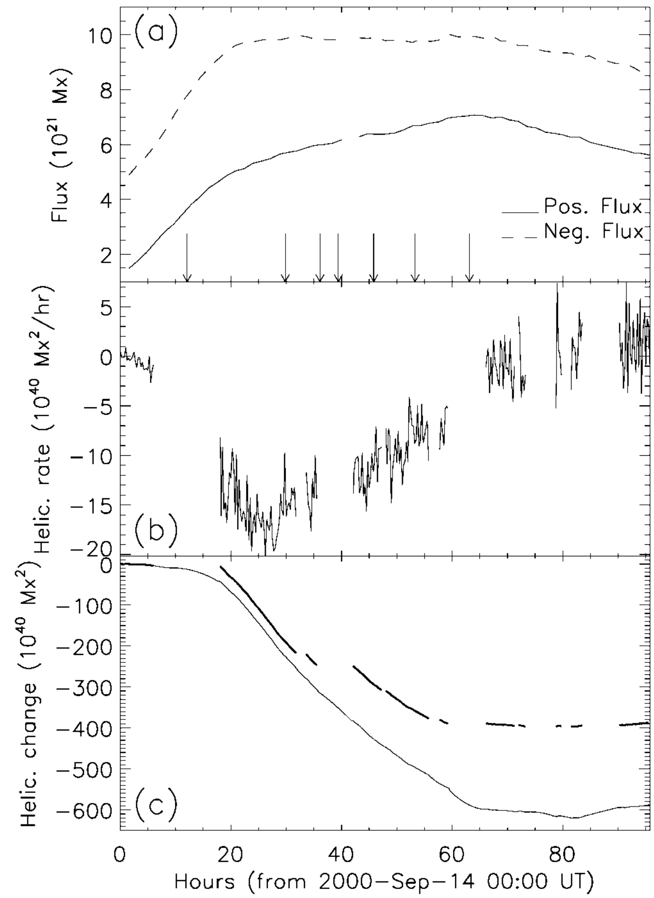

FIG. 3.—(*a*) Time profile of the active region's longitudinal magnetic field flux derived from FD MDI images. The arrows indicate the time of the first appearance in the LASCO images of seven CMEs originating from AR 9165 (another CME linked to AR 9165 occurred on September 19 but is not represented here). (*b*) Time profile of the rate of helicity injected by horizontal motions. (*c*) Time profile of the accumulated change of helicity $\Delta H(t)$ calculated from the measured dH/dt (*thick line*) and the estimated $\Delta H(t)$ if a spline interpolation is used for the determination of the missing dH/dt values (*thin line*).

tected by Chae (2001). Of course, the time variability of ΔH is mostly due to the large-timescale trends of the dH/dt variability. There are time intervals when no dH/dt measurements are available owing to the lack of high-cadence MDI data. Using spline interpolation, we estimate these missing dH/dt values, and the resulting ΔH curve is presented in Figure 3*c* with the thin line.

All CMEs linked to AR 9165 are associated with flare events (their sources are identified in EUV Imaging Telescope images; their first appearance in the Large Angle and Spectrometric Coronagraph [LASCO] images is indicated by the arrows in Fig. 3). The helicity carried away by CMEs cannot be directly computed; Démoulin et al. (2002) assumed that each CME ejected from the active region they studied produced a magnetic cloud (MC). Then one assumes that the helicity carried away by each CME is equal to the helicity in the corresponding MC. The magnetic helicity per unit of length in a MC can be computed if we know the axial magnetic field B_0 and the radius R of the cloud's flux rope (DeVore 2000). These parameters can be calculated using a force-free magnetic field model (Lepping, Burlaga, & Jones 1990).

A MC was observed by the *Wind* spacecraft on September 18. AR 9165 was the source of all four halo CMEs detected by LASCO during September 14–17. Statistical studies show that more than 90% of the CMEs associated with MCs are halo events (Gopalswamy et al. 2000). Thus, we are confident that the September 18 MC is associated with a CME linked to AR 9165. The best-fit model of Lepping et al. (1990) for the September 18 MC yields $B_0 = 46.6$ nT and $R = 0.2$ AU.[3] To calculate the total helicity in the MC, we need the length l of the cloud's flux tube. Since the true l cannot be obtained observationally, we assume that the MC is expanding in a self-similar manner and $l \sim 1$ AU. Then the resulting MC's helicity is -6.35×10^{43} Mx^2. However, the above B_0- and R-values come from a model fit that has been judged to be poor. If we use the average values of B_0 and R resulting from the model fits to all MCs observed in the year 2000, we get $B_0 = 23.7$ nT and $R = 0.16$ AU, and the corresponding MC's helicity is -7.7×10^{42} Mx^2.

4. DISCUSSION

The MDI measurements suffer from saturation at fields above about 1.5–2 kG. We find that for $|B| > 500$ G, the MDI fields are lower than the HSOS fields by a factor of 1.6–1.7. When we apply this correction to the MDI data and do all helicity computations again, we find that the resulting values of dH/dt are higher than the values derived in § 3 by a factor of about 1.1–1.4, and for the maximum accumulated helicity due to horizontal motions (just before dH/dt changes sign) we get $\Delta H = -8 \times 10^{42}$ Mx^2. This is an extreme upper limit because HSOS magnetograph overestimates strong fields (Bao et al. 2000). The other possible sources of error are introduced by the computed B_n and $\boldsymbol{v}$ away from disk center. However, their influence to our results is small because the largest amount of

[3] See http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_pub1p.html.

the computed helicity changes comes from horizontal motions that occur when the active region is close to disk center. Using the HSOS transverse field images, we find that the simple B_n model used in the calculations overestimates dH/dt by about 5%–7% on September 15 and underestimates dH/dt by 3% on September 16. Following Chae et al. (2001), we find that the fake motions introduced by errors in $\boldsymbol{v}$ are very localized and do not affect our results more than $\pm 5\%$. The uncertainties involved in the total helicity carried away by the CMEs originated from AR 9165 are larger because (1) we do not know if any CMEs originated from the active region when it was on the far side of the Sun, (2) we do not know how many CMEs become MCs, and (3) the length l of the cloud's flux tube is essentially unknown.

Our computations show that horizontal motions cannot produce enough helicity to provide the helicity ejected into the interplanetary medium, even if we consider only the accumulated change of helicity until the time $\Delta H(t)$ changes sign. In such case, if we assume that the active region produced no CMEs when it was on the far side of the Sun and that all eight CMEs linked to AR 9165 become MCs, then the ejected helicity is a factor of 8–64 higher than the helicity injected by horizontal motions. If we assume that only the halo CMEs become MCs, then the helicity ejected from the observed halo CMEs is only a factor of 4–32 higher than the helicity injected by horizontal motions. We note that the maximum total helicity accumulated by horizontal motions within 80 hr is only roughly equal to the helicity of one "average year 2000 MC CME," while the helicity ejected by each individual CME in AR 9165 is probably larger. In order to match the helicity produced by horizontal motions and the helicity carried away by the eight CMEs, the September 18 MC's flux tube length should be 0.015–0.12 AU, i.e., much smaller than the $l = 0.5$ AU used by DeVore (2000). Alternatively, using the mean helicity injection rate due to horizontal motions that occur from September 14 (00:00 UT) until the time dH/dt changes sign (it is -1.1×10^{41} Mx^2 hr^{-1} after the application of the MDI strong field correction factors), we find that 23–192 days would be needed for the accumulation of the helicity carried away by the eight CMEs.

We have also computed the temporal variation of dH/dt due to differential rotation for September 14–21. Without correcting MDI data for possible saturation effects, the resulting maximum dH/dt is -6.6×10^{39} Mx^2 hr^{-1} and the total helicity change is $\Delta H_{\rm rot} = -6 \times 10^{41}$ Mx^2. The value of $\Delta H_{\rm rot}$ is a factor of 10 smaller than the maximum ΔH owing to the other horizontal motions (see Fig. 3*c*). Using the September 14–21 mean helicity injection rate due to differential rotation, we find that the maximum helicity accumulated by the shearing flows amounts to about the total helicity that the active region's differential rotation would have injected within three solar rotations. Overall, our computed helicity change due to horizontal shearing motions is probably the largest ever reported (Chae 2001 and Chae et al. 2001 report maximum $|\Delta H| = 10^{40}$ and 2.9×10^{42} Mx^2). However, it cannot account for the helicity carried away by the CMEs linked to the active region.

5. CONCLUSION

All mechanisms that change helicity are present in the CME-productive AR 9165. Strong shearing motions feed negative helicity into the corona, which is of the same sign as the active region's helicity. The rate of helicity injection by shearing motions reaches its absolute maximum value within about 30 hr, then decreases gradually and finally changes sign. Despite the presence of unusually strong shearing flows, the CMEs remove at least a factor of 4–64 more helicity than the helicity injected by horizontal shearing motions. Therefore, the main source of the helicity carried away by the CMEs is the new magnetic flux that emerges twisted from the convective zone.

Shearing motions have been widely used in MHD simulations of CME initiation but have hardly been reported from previous observations of CME-producing regions, possibly owing to the lack of high-quality, high-cadence magnetograms (some CMEs originate in coronal helmet streamers that often swell several days before the eruption; such swelling often is attributed to shearing of the magnetic footpoints, but the emergence of new flux also could produce the same effect). In the framework of the "storage and release" paradigm for the initiation of CMEs, our conclusion implies that the slow buildup of magnetic free energy that eventually leads to CMEs cannot be done by footpoint shearing motions.

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