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SPATIAL DISTRIBUTION OF MAGNETIC RECONNECTION IN THE 2006 DECEMBER 13 SOLAR FLARE AS OBSERVED BY *HINODE*

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ABSTRACT

A massive two-ribbon flare and its source magnetic field region were well captured by the Solar Optical Telescope (SOT) on board *Hinode* in the Ca II H spectral line and by the Spectro-Polarimeter of SOT, respectively. Using the high-resolution *Hinode* data sets, we compare the spatial distribution of the local magnetic reconnection rate and the energy release rate along the ribbons with that of G-band kernels that serve as a proxy for the primary energy release. The G-band kernels spatially coincide with the maximum of both modeled quantities, which gives strong support for the reconnection model. We also investigate the magnitude scaling correlation between the ribbon separation speed V_r and magnetic field strength B_n at four 2 minute time bins around the maximum phase of the flare. It is found that V_r is weakly and negatively correlated with B_n. An empirical relation of $V_r \propto B_n^{-0.15}$ is obtained at the flare peak time with an correlation coefficient ~ -0.33. The correlation is weaker at other time bins.

Subject headings: Sun: activity — Sun: flares — Sun: magnetic fields

1. INTRODUCTION

Separating flare ribbons are regarded as the most solid evidence for the standard magnetic reconnection scenario (known as the CHSKP model; Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976) and serve as the mapping of the coronal magnetic reconnection onto the visible surface. Under the principle of magnetic flux conservation, Forbes & Priest (1984) supplemented the CSHKP model for a quantitative estimate of the coronal magnetic reconnection rate in the reconnecting current sheet (RCS) from observable quantities, i.e., $\varphi_{\rm rec} = \int V_r B_n dl = \partial/\partial t \int B_n da$, where V_r is the ribbon separation velocity, B_n is the normal component of the local magnetic field strength measured in the ribbon location, dl is the length along the ribbons, and da is the newly brightened area swept by the ribbons. In particular, $E = V_r B_n$ is the electric field at the reconnecting X-point and is often used as a local magnetic reconnection rate. In the meanwhile, the magnetic energy release rate derived from Poynting vector theorem is proportional to $V_r B_n^2$ under the common assumption that B_c/B_n and A_c are constant during the flare (Isobe et al. 2002), where B_c is the strength of coronal field line coming into the X-point and A_c is the area of the RCS. Since then, as a test of the model, temporal and spatial correlations of these modeled quantities with observed flare nonthermal emissions (e.g., hard X-rays, microwaves) have been investigated in many studies and are found to be good in most cases of temporal comparison (e.g., Qiu et al. 2004; Asai et al. 2004; Jing et al. 2005; Lee et al. 2006; Miklenic et al. 2007).

On the other hand, the spatial distribution of these quantities as a function of ribbon position is a hard issue involving the complexity of the coronal magnetic field. A theoretical framework of the CSHKP model deals only with a two-dimensional (2D) configuration with a translational symmetry along the reconnecting X-line (the third dimension). From an observational point of view, however, almost all spatial properties of the ribbon motion and magnetic structure addressed in recent works apparently lack such translational symmetry (e.g., Fletcher et al. 2004; Grigis & Benz 2005; Temmer et al. 2007). For instance, the inhomogeneity of the magnetic field and the energy release rate along the flare ribbons was addressed first by Asai et al. (2002) and recently by Temmer et al. (2007). Both of them found that the magnitude difference is up to a factor of 3 in the case of the magnetic field and about 2 orders for the energy release rate along the ribbons. The ribbon sections with the strongest magnetic field strength and energy release rate spatially coincide with the site of hard X-ray (HXR) footpoint sources that serve as a proxy for the primary energy release. Jing et al. (2007) extended the work by measuring the intensity distribution of a ribbon-like HXR source that has been rarely observed before. In their result, the HXR evolved from footpoint to ribbon-like sources and the spatial correlation between the HXR intensity and the electric field decreased.

Previously, these quantitative studies face the problem that the strong magnetic fields cannot be measured reliably due to the Zeeman saturation effect. With the launch of the *Hinode* spacecraft (formerly known as *Solar-B*; Kosugi et al. 2007), flares have been observed at unprecedented spatial resolution, and the magnetic field strength of source regions, especially in the strong magnetic regions, has been measured with higher accuracy as the Zeeman saturation effect is significantly reduced. In this Letter, we revisit the issue of the spatial distribution of the modeled quantities along the ribbons during a massive flare of 2006 December 13, with the *Hinode* data sets and with our new techniques of image processing. We also study the V_r-B_n relationship during the flare, which could not be accurately done previously.

2. DATA SETS AND IMAGING PROCESSING

The 4B/X3.4 flare we discuss in this Letter occurred in active region NOAA 10930 on 2006 December 13 and was captured by the Solar Optical Telescope (SOT; Tsuneta et al. 2007) on board *Hinode*. The Broadband Filter Imager (BFI) of SOT obtained data in the Ca II H spectral line (397 nm) and the G band (430 nm) with a 2 minute cadence and a pixel size of 0.108″. The Spectro-Polarimeter (SP) of SOT obtained Stokes profiles (I, Q, U, and V) of two magnetically sensitive Fe lines

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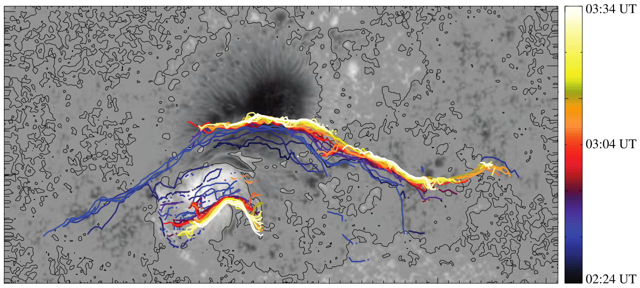

FIG. 1.—The detected outer edges of the flare. The background image is a *Hinode* line-of-sight magnetogram. The field of view is 216″ × 108″.

at 630.15 nm and 630.25 nm. The line-of-sight magnetogram was determined from Stokes *I* and *V* profiles using the center-of-gravity method. Compared with previous line-of-sight magnetogram data, *Hinode* magnetogram data have advantages in higher spatial resolution and more accurate field strength measurements without a saturation effect.

We need to trace multiple locations within a ribbon as it moves out. Once these points are located at each time, the velocity V_r can be derived as a function of time and/or distance along the ribbon. For this purpose, we have developed a method involving the Sobel edge detection algorithm, the Otsu thresholding algorithm (Otsu 1979), and some morphology processing techniques (Qu et al. 2004) to extract the outer edges of the ribbons. In particular, we first apply the Sobel edge detector to the Ca II H images to enhance the edges. Then we apply Otsu thresholding algorithm to automatically find the threshold that can separate the edges from the background with the maximum between-class variance. The edges determined so far include both outer edges and inner edges of the ribbons; only the former is of interest in this study. Therefore, we scan each pair of edges along the direction perpendicular to the magnetic polarity inversion lines (PILs). An edge is defined as being an outer edge if it has a longer distance to the PILs compared with its counterpart. Finally, we use morphology closing to eliminate small gaps between feature regions. Figure 1 shows the outer edges of the ribbons detected with our method, superposed on a *Hinode* line-of-sight magnetogram.

3. RESULTS

The top panel of Figure 2 is a Ca II H line image taken at the time of the flare maximum, 02:28 UT. The middle panel shows the co-aligned line-of-sight magnetogram overlaid with the magnetic PILs (*black curves*). The alignment between the SOT–Ca II and SOT-SP images is performed by manually aligning the spots and network structures. The blue and yellow lines show the outer edges of the ribbons obtained at 02:28 UT and 02:30 UT, respectively. Curves j_1 (running from 0 to 150) and j_2 (running from 0 to 50) are the indexes of the multiple points that are evenly spaced along two edges. The dotted boxes are drawn to mark the field of view of the G-band images presented in the bottom three panels.

As mentioned in § 1, the 2D reconnection model (Forbes & Priest 1984) predicts that the magnetic reconnection rate is given by V_rB_n and the energy release rate is proportional to $V_rB_n^2$. We note that ribbons in this case are moving rather non-uniformly and the motion in the weak magnetic field seems to be more complex. It implies a complex magnetic configuration in the weak magnetic field regions that may not be explained with the simple 2D reconnection model. Therefore, this study

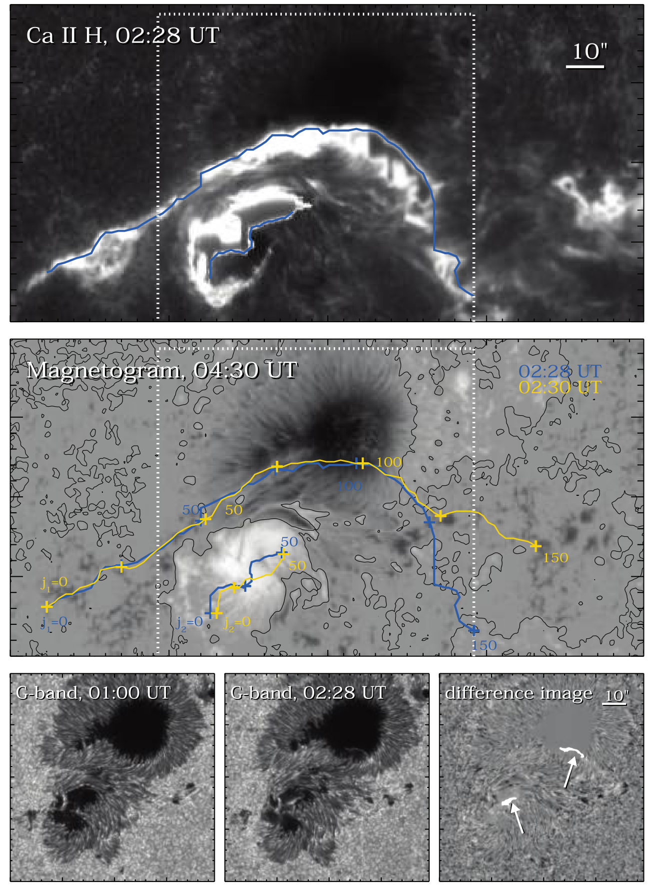

FIG. 2.—*Top:* Snapshot of the X3.4 flare observed by *Hinode* in the Ca II H line. *Middle: Hinode* line-of-sight magnetogram. *Bottom:* From left to right, *Hinode* G-band images taken before and after the flare and their difference image. The symbol-connected lines show locations of outer edges of ribbons. The dotted boxes show the field of view of the G-band images presented in the bottom three panels. The G-band kernels enhanced in white are indicated by the arrows.

focuses only on the parts of the ribbons on the strong magnetic field (j_1 = 50–115 and j_2 = 0–50). Determination of B_n is straightforward—we can just read from the co-registered magnetogram, but it is hard to determine the velocity distribution along the ribbon since we have no obvious tracers within the ribbon. To simplify the calculation, we use the index j as the motion tracer, measure the displacements of points, and divide them by the time interval. We then apply the cosine of the relative angle to the magnetic PILs to finally take only the velocity components perpendicular to the PILs as V_r. The accuracy of the velocity derived in this way is limited by our assumption that the points along the outer edge can be properly traced by their relative locations along the edge. This assumption may not be valid in general but should not seriously affect the velocity presented in this study because of the nature of current observation. We estimate the uncertainty by manually tracking several noticeable features taken as reference points and comparing them with the result derived in this way. The uncertainty is estimated to be less than 20%.

We need to compare the magnetic reconnection rate V_rB_n and energy release rate $V_rB_n^2$ with the energy deposition as observed with HXR for agreement. However, the HXR observation of this event at this time is not available. In this case, we take G-band kernels seen in the G-band difference image instead, because these kernels are also attributed to nonthermal flare emis-

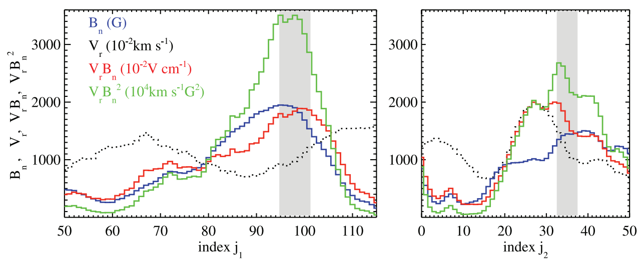

FIG. 3.—The spatial distribution of B_n (*blue*), V_r (*gray dots*), V_rB_n (*red*), and $V_rB_n^2$ (*green*) along the index $j_1 = 50$–115 (*left panel*) and $j_2 = 0$–50 (*right panel*). The gray bars indicate the locations of two G-band kernels in accordance with j_1 and j_2.

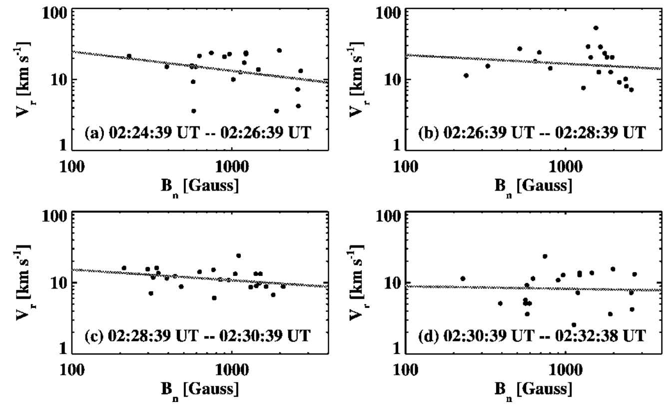

FIG. 4.—Scatter plots of V_r vs. B_n in a logarithmic scale for four time intervals (*a*)–(*d*). V_r and B_n refer to the average value of small ribbon sections at four time intervals. The solid line is a fit to the data points in the form of (*a*) $V_r = 85.1 \times B_n^{-0.27}$, (*b*) $V_r = 38.9 \times B_n^{-0.12}$, (*c*) $V_r = 30.2 \times B_n^{-0.15}$, and (*d*) $V_r = 10.5 \times B_n^{-0.03}$. The correlation coefficients, from (*a*) to (*d*), are -0.29, -0.16, -0.33 and -0.04, respectively.

sions (Xu et al. 2004). The left two panels in the bottom of Figure 2 are two G-band images taken before and during the flare. In their difference image (*rightmost*), two ribbon kernels at either side of PILs are enhanced in white and indicated by the arrows.

In Figure 3 we plot the intensity profiles of B_n, V_r, V_rB_n, and $V_rB_n^2$ along the coordinate indexes j_1 and j_2 for two ribbons. The G-band kernels within two ribbons appear in the confined regions that are marked by the gray bars. We note that both B_n and V_r show a certain degree of inhomogeneity along the ribbons. As a result, V_rB_n and $V_rB_n^2$ are not uniform along the ribbons. The peaks of B_n, V_rB_n, and $V_rB_n^2$ spatially coincide with the sites of G-band kernels. Such a spatial correlation supports the conventional idea that magnetic reconnection can be, while occurring everywhere along the X-line, locally enhanced in the regions with strong field strength. The average V_rB_n of ~20 V cm^{-1} within the G-band kernel regions is larger, by a factor of approximately 2.5, than that in the regions outside the G-band kernels. In previous studies, the values of V_rB_n are mostly in the range of 0.2–5 V cm^{-1}, up to ~40 V cm^{-1} in the case of the exetremely dramatic flare on 2003 October 29 (Jing et al. 2005).

Both V_r and B_n are contributing factors in deriving the magnetic reconnection rate and energy release rate. We further investigate the V_r-B_n relationship. Since the actual length and morphology of the ribbon keep varying with time as the ribbon evolves, we only choose four 2 minute time intervals (*a*–*d*) from 02:24 UT to 02:32 UT around the peak time of the flare, divide the outer edges into many small sections (~15 for the northern ribbon and ~10 for the southern ribbon), and trace them individually. Then we calculated the average velocity and average field strength of each corresponding section. Figure 4 shows the scatter plots of V_r versus B_n in a logarithmic scale for four time intervals. It is notable that V_r is weakly and negatively correlated with B_n. The correlation coefficients, from panels *a* to *d*, are -0.29, -0.16, -0.33 and -0.04, respectively. The solid line is a fit to the data points in the form of (*a*) $V_r = 85.1 \times B_n^{-0.27}$, (*b*) $V_r = 38.9 \times B_n^{-0.12}$, (*c*) $V_r = 29.3 \times B_n^{-0.15}$, and (*d*) $V_r = 10.5 \times B_n^{-0.03}$.

4. SUMMARY

The standard magnetic reconnection model allows a quantitative estimate of the magnetic reconnection rate and the magnetic energy release rate from flare observation. Since the observation of the locally confined G-band kernels is another proxy for the primary energy release, comparison of these quantities with G-band kernels in space can serve as a test of the model. With the high-resolution *Hinode* data set and our new techniques of image processing, we revisited the issue of spatial distribution of the magnetic field B_n and two modeled quantities, V_rB_n and $V_rB_n^2$. The former is equivalent to the coronal electric field (a simplified magnetic reconnection rate), while the latter is a proxy for the energy release rate under the assumption that B_c/B_n and A_c do not vary with time.

It is found that there is a certain degree of inhomogeneity in these quantities along the ribbons, indicating the inhomogeneity in the coronal magnetic reconnection. We can see a good agreement between the sites of G-band kernels and the strongest magnetic field regions. The average B_n within the G-band kernel regions is ~2 times larger than that in the nonkernel regions, which comparable with the previous observation by Asai et al. (2002). In the presence of such a magnetic field inhomogeneity along the ribbons, the maximum reconnection rate and the maximum energy release rate appear in G-band kernel regions as well.

The average V_rB_n found in G-band kernel regions, ~20 V cm^{-1}, is larger than the typical range of 0.2–5 V cm^{-1} reported in previous studies of flares that were not accompanied by the G-band emissions but less than ~40 V cm^{-1} derived in the 2003 October 29 flare. The 2003 October 29 flare is also known as the first white-light flare observed in the near-infrared (NIR) continuum at 1560 nm, the deepest photospheric layer. As Xu et al. (2004) pointed out, a "back-warming" mechanism may be responsible for the enhanced NIR emission. Although the G band is not directly heated by precipitating electrons, the back-warming process depends on the energy carried by nonthermal electrons. So the G-band emission is considered as an indirect diagnosis of nonthermal electrons. It is thus conceivable that V_rB_n derived from the local flare observations indeed provides a clue to the initial energy of electrons obtained in the acceleration process during the magnetic reconnection in the RCS. We further presume that a few tens of electric field strength in V cm^{-1} might be a crucial threshold to generate the white-light part of a flare.

We also examined the V_r-B_n relationship on the relatively strong magnetic field ($B_n > 200$ G) and found a weak, negative correlation between the quantities. An empirical relation of $V_r \propto B_n^{-0.15}$ at the flare peak time was found in this case. Our empirical relation accordingly suggests that the magnetic reconnection rate and the energy release rate are proportional to $B_n^{0.85}$ and $B_n^{1.85}$, respectively. For instance, spatial variation of field strength by a factor of 2 may lead to a contrast by a factor of ∼1.8 in the magnetic reconnection rate and ∼3.6 in the energy release rate. It explains why the high energy release regions (e.g., HXR sources, G-band kernels) tend to be concentrated in local strong field regions.

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