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FEATURES AND PROPERTIES OF CORONAL MASS EJECTION/FLARE CURRENT SHEETS

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ABSTRACT

Solar eruptions occur when magnetic energy is suddenly converted into heat and kinetic energy by magnetic reconnection in a current sheet (CS). It is often assumed that CSs are too thin to be observable because the electric resistivity η_e in CSs is taken to be very small. In this work, we show the implications for the CS thickness d estimated from observations of three eruptions by the UVCS and the LASCO experiments on *SOHO*. We infer the effective η_e causing the rapid reconnection, which predicts much faster reconnection in a thick CS than that caused by the classical and anomalous resistivities. We find that in these events CSs are observable and have extremely large values of d and η_e, implying that large-scale turbulence is operating within CSs. We also discuss the properties of the so-called hyperresistivity caused by the tearing mode and the relation to our results.

Subject headings: diffusion — Sun: flares — Sun: magnetic fields — turbulence

1. INTRODUCTION

Eruptive solar flares involve the formation of long current sheets (CSs) connecting coronal mass ejections (CMEs) to the associated flares (Ciaravella et al. 2002; Ko et al. 2003; Raymond et al. 2003; Webb et al. 2003; Sui et al. 2004; Lin et al. 2005; Bemporad et al. 2006). The formation of such CSs was predicted by the catastrophe model of solar eruptions (Lin & Forbes 2000) and has also been found in numerical experiments of CMEs using MHD codes (e.g., Linker et al. 2003). Such models and simulations reproduce observed features of solar eruptions, such as the dependence of motions of flare ribbons and loops on the rate of magnetic reconnection in CSs, flare-CME correlations, and rapidly expanding CME bubbles (Lin et al. 2004).

In addition, recent observations showed plasma flows continuously moving along CSs toward (McKenzie & Hudson 1999) and away from (Ko et al. 2003; Lin et al. 2005) the Sun, and they were recognized as the reconnection outflow in CSs. In those flows, many plasma blobs were identified (e.g., McKenzie & Hudson 1999; Ko et al. 2003; Lin et al. 2005). In the numerical experiments of Forbes & Malherbe (1991), Y. Fan (2005, private communication), and Riley et al. (2007), the repeated formation of a set of blobs that move both toward and away from the Sun occurred.

Although these numerical experiments were not performed to model any specific event, there is good general agreement in the formation of CSs and the formation and propagation of the blobs flowing along CSs. Riley et al. (2007) pointed out that the formation and evolution of the blob in CSs are strongly suggestive of the tearing mode instability (e.g., Furth et al. 1963) that plays an important role in diffusing the magnetic field and governing the scale of CSs (Strauss 1988; Drake et al. 2006). More investigations indicate that the diffusion caused by the tearing mode could be much faster or more efficient in a thick CS than that caused by the classical and anomalous resistivities (Strauss 1988; Bhattacharjee & Yuan 1995), and that a nonlinear effect and saturation of the mode further broadens CSs (Loureiro et al. 2005 and references therein). All of these imply that reconnecting CSs developed in the solar eruption could be thick enough to be observable in certain circumstances, instead of being a few meters thick as suggested by Wood & Neukirch (2005 and references therein).

We note that the plasma blobs may also result either from the nonuniform magnetic reconnection process in a complex plasma and magnetic field environment or from other types of reconnection (e.g., Priest & Forbes 2000, pp. 222–229). Here we follow Riley et al. (2007) and identify those blobs with a magnetic island due to the tearing mode. For three events, we work out the consequences of such an identification.

In § 2, we infer the CS thickness d for three events observed by the Ultraviolet Coronagraph Spectrometer (UVCS) and the Large Angle and Spectrometric Coronagraph (LASCO) experiments on the *Solar and Heliospheric Observatory* (*SOHO*). In § 3, the results obtained are used to estimate the effective electrical resistivity η_e in CSs. In § 4, we compare the resulting values of η_e with those evaluated under various circumstances and investigate the reasonableness of these values. Finally, § 5 gives a discussion and summary of this work.

2. OBSERVATIONS AND RESULTS

Although the high electrical conductivity and force-free environment in the corona makes it difficult to observe CSs and magnetic reconnection processes directly, more and more direct evidence of them has accumulated during the last decade. Combining the knowledge that we have collected so far allows us to look into more details of reconnecting CSs. Below we analyze a set of data for three eruptions, of which different aspects were studied previously by Ciaravella et al. (2002), Ko et al. (2003), and Lin et al. (2005).

2.1. *The 2002 January 8–10 Event*

This eruption started with the rapid expansion of a magnetic arcade over an active region and then developed a CME and a long thin CS with successively growing loop systems beneath it (Ko et al. 2003). The information about d can be deduced directly from UVCS observations. When the CS was observed, the UVCS slit was located at polar angle (PA) of 78° and a heliocentric height of 1.53 $R_\odot$. Within a narrow region with $\Delta\mathrm{PA} = 7.2°$ (the FWHM of the emission intensity distribution along the UVCS slit; see Figs. 12*k* and 12*l* of Ko et al. 2003),

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strong emission was observed from highly ionized ions (such as [Fe XVIII] λ974 and [Ca XIV] λ943) that imply high temperatures of (3–6) × 10^6 K and are rarely seen in the quiet corona at this heights. Taking the size of this region as d, we find $d = 1.3 \times 10^5$ km. Because of projection effects and the possible complex morphology of the CS, this value for d is considered as the upper limit, $d_{\max}$.

2.2. *The 2003 November 18–19 Event*

This event was well observed over the east limb by several instruments both on the ground and in space, including UVCS, LASCO, and the EUV Imaging Telescope (Lin et al. 2005). It commenced with sudden and severe stretching of a closed magnetic structure in the low corona. The two legs of the stretched structure soon started moving toward one another, approaching the region where a reconnecting CS is presumed to lie. This region appeared as a dark gap in the Lyα images of the UVCS slit, and its width decreased with time, which was ascribed to the reconnection inflow near the CS (see Figs. 5 and 11*a* of Lin et al. 2005).

Figure 1 plots the gap width against time, from which we deduced four values of the reconnection inflow speed, v_i, at different times: 58.6, 84.6, 29.3, and 8.42 km s^{-1}. These values differ from those deduced by Lin et al. (2005) because of improvements in measuring the gap width. The asymptotic behavior of the width-time curve suggests that the reconnection inflow stopped somewhere near the edges of the CS around 10:14 UT. Such a tendency implies that the observed width of the gap was about 6.8 × 10^4 km, which is for $d_{\max}$ instantaneously, but should not differ much from the natural d.

A dark gap seen in Lyα emission may also be broadened by projection. However, such broadening would imply a corresponding reduction in contrast. Since the intensity of Lyα emission linearly depends on both H I density and roughly the depth of the observed object in the line of sight, a dark CS appearing 10 times wider than its natural d will have only about 0.1 contrast. Fig. 11*a* of Lin et al. (2005) indicates that the Lyα gap was 2–4 times fainter than the adjacent emission. This brings the contrast to range from 0.5 to 0.75, which suggests that the projection effect is not significant for this event.

2.3. *The 1998 March 23 Event*

On 1998 March 23, UVCS observed what appears to be a striking example of the CME-CS-arcade structure. The high-temperature emission of (6–8) × 10^6 K from the CS behind the CME (refer to Figs. 4 and 10 of Ciaravella et al. 2002) was observed by several instruments, including UVCS, the Coronal Diagnostic Spectrometer, and the Solar Ultraviolet Measurement of Emitted Radiation on *SOHO*, and the *Yohkoh* Soft X-Ray Telescope (SXT; e.g., Feldman et al. 1998; Innes et al. 2001; Ciaravella et al. 2002). The work of Ciaravella et al. (2002) was the first to demonstrate the existence of the long CS developed by the eruption, as predicted by the model of Lin & Forbes (2000).

The [Fe XVIII] emission from the CS can be easily identified from its intensity distribution along the UVCS slit, and the hot flare loops below the CS were also seen in the *Yohkoh* SXT images. According to Ciaravella et al. (2002), we obtain $d_{\max} = 10^5$ km.

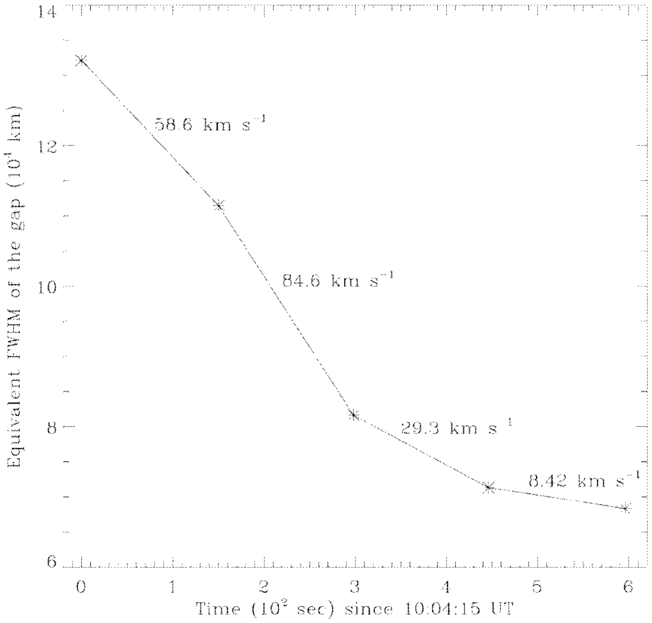

FIG. 1.—Variations of the Lyα gap width vs. time and the corresponding speeds of the reconnection inflow, v_i, near the current sheet (see also Figs. 5 and 11*a* of Lin et al. 2005).

3. ELECTRICAL RESISTIVITY OF CURRENT SHEETS

Knowing d and the reconnection inflow speed v_i near CSs helps further deduce the electrical resistivity, η_e. According to the standard theory of magnetic reconnection, the magnetic field is continuously dissipated through CSs at the rate same as magnetic flux is brought into CSs. This leads to (e.g., see Priest & Forbes 2000, p. 120)

$$v_i = \frac{\eta}{l}, \quad \eta = \frac{\eta_e}{\mu_0}, \tag{1}$$

where v_i is in units of m s^{-1}, η is the magnetic diffusivity in units of m^2 s^{-1}, $l = d/2$ is the half-thickness of the CS in meters, η_e is in ohms m, and $\mu_0 = 4\pi \times 10^{-7}$ H m^{-1}.

We note that the terms "diffusion," "dissipation," and "CS" used here have more general meanings than those used traditionally. They refer to any process that causes magnetic diffusion and any region where such diffusion occurs (see Lin & Forbes 2000), respectively. In this sense, each parameter in equation (1) should be considered effective and average, and equation (1) is applied to dynamical processes in the present work although it was originally deduced for steady state reconnection (e.g., Priest & Forbes 2000). This issue will be further discussed later.

Figure 1 gives $v_i = 8.4$ km s^{-1} for the 2003 November 18 event, Ko et al. (2003) deduced $v_i = 10$ km s^{-1} for the 2002 January 8 event, and Ciaravella et al. (2002) also obtained $v_i = 10$ km s^{-1} for the 1998 March 23 event by assuming $M_A = 0.1$. Combining these values with those for d obtained earlier, equation (1) brings the values of η_e to around 5 × 10^5 ohms m, which are considered as the upper limit.

4. REASONABLENESS OF LARGE d AND η_e VALUES

For comparison, the classical resistivity in the quiet corona, $\eta_c = 4\pi \times 10^2 T^{-3/2}$ m^2 s^{-1}, and the anomalous resistivity, $\eta_a = 6.4\pi \times 10^6 n_e^{-1/2}$ m^2 s^{-1}, as the result of interactions between electrons and the low-frequency ion-acoustic turbulence are evaluated as well. Here T is the plasma temperature and n_e is the density in m^{-3}, and the turbulence energy is 1% of the thermal energy (e.g., Priest 1982, pp. 80–81). Values of T and n_e are taken from Ciaravella et al. (2002), Innes et al.

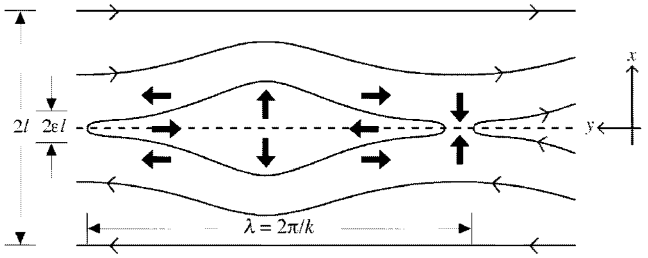

FIG. 2.—Interior structure of the current sheet in which the tearing mode instability develops. Thick arrows show plasma flow, and thin arrows are for magnetic field lines. (Courtesy of E. R. Priest.)

(2001), and Ko et al. (2003) and vary from 5 × 10^6 to 10^7 K and 4 × 10^{12} to 6 × 10^{13} m^{-3}, respectively. We thus find η_c of (0.4–1.1) × 10^{-7} and η_a of 2.6–10.0 ohms m, respectively.

We notice that η_e is significantly greater than both η_c and η_a and ever much bigger than those assumed for solar flares (e.g., Miyagoshi & Yokoyama 2004). We understand that both d and η_e obtained so far are just the upper limit. To reach a more meaningful conclusion, the corresponding lower limits need to be figured out. Works of Forbes & Malherbe (1991), Y. Fan (2005, private communication), and Riley et al. (2007) suggest an approach to this purpose by relating the plasma blobs flowing along a CS to magnetic islands due to tearing mode turbulence.

When the tearing mode turbulence develops (Fig. 2) with the growth rate slower than the hydromagnetic rate but faster than the resistive diffusion rate, its wavenumber k is related to l such that $S^{-1/4} < kl < 1$ (e.g., see Furth et al. 1963), where $S = \tau_d/\tau_\mathrm{A}$ is the Lundquist number of the CS, and $\tau_\mathrm{A} = l/V_\mathrm{A}$ and $\tau_d = l^2/\eta$ are the times at which the Alfvén wave and the resistive diffusion traverse the CS, respectively. Here, V_A is the local Alfvén speed near the CS.

If the plasma in the CS has sufficiently high conductivity such that both S and $S^{1/4}$ are large compared to unity, magnetic dissipation or reconnection will be confined to a very thin CS and the tearing mode develops with very long wavelengths (e.g., Furth et al. 1963; Priest & Forbes 2000). In this case, $kl \ll 1$ holds so that the turbulence could grow at the rate between $1/\tau_d$ (the resistive diffusion rate) and $1/\tau_\mathrm{A}$ (the hydromagnetic rate). For the events studied here, however, M_A (S) varies from 10^{-3} (10^3) to 10^{-1} (10) (e.g., Yokoyama et al. 2001; Ko et al. 2003; Lin et al. 2005). So although $S = \tau_d/\tau_\mathrm{A} \gg 1$ did hold for these events, $S^{1/4} \gg 1$ did not. Therefore, kl possesses a finite lower limit, and the dissipation as the result of the tearing mode could well progress in broadened CSs.

After going through simple algebra, we find from $kl > S^{-1/4}$

$$l_\mathrm{min} = k^{-1}S^{-1/4} = M_\mathrm{A}^{1/4}\frac{\lambda}{2\pi}, \qquad (2)$$

where $M_\mathrm{A} = v_i/V_\mathrm{A}$ is the rate of magnetic reconnection and is related to S in the way of $M_\mathrm{A} = S^{-1}$ by using equation (1); $\lambda = 2\pi/k$ is the turbulence wavelength (see Fig. 2) and is identified with the distance of two successive plasma blobs flowing along the CS (see Ko et al. 2003; Lin et al. 2005). Therefore, equation (2) relates l_min to M_A and λ in a simple and straightforward fashion.

Plasma blobs were observed to move in CSs in both events of 2002 January 8 (see Figs. 7 and 18 of Ko et al. 2003) and 2003 November 18 (see Fig. 3 and the associated movies of Lin et al. 2005 and Fig. 1 of Riley et al. 2007). But no blob was observed in the 1998 March 23 event. Figure 3 plots the heights of the five blobs, which were well recognized, against time for the first event. The smallest distance of two successive blobs is 3.1 × 10^5 km. There could be smaller distances present below the edge of the occulting disk of the coronagraph, but this might be the best we can obtain for the time being. We use this value for λ in equation (2). Ko et al. (2003) found that M_A ranged from 0.015 to 0.03. Substituting these values into equation (2) gives $l_\mathrm{min} = 1.7 \times 10^4$ km, and then $d_\mathrm{min} = 3.4 \times 10^4$ km.

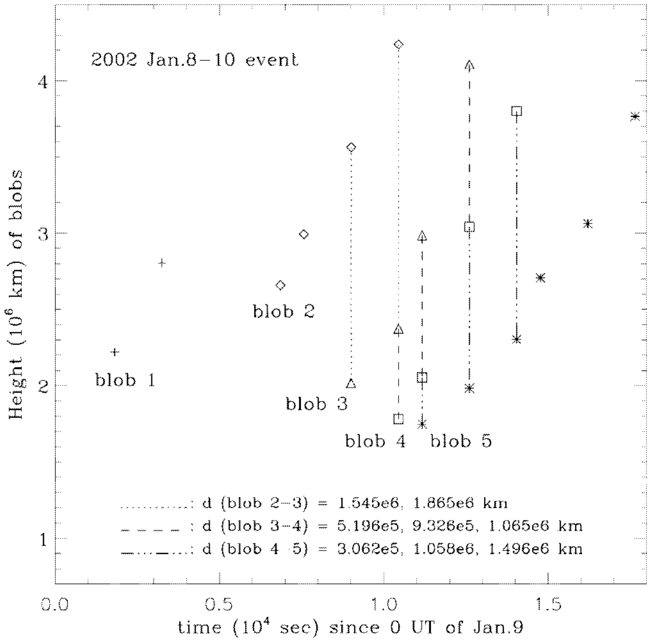

FIG. 3.—Heights of five well-recognized blobs in the 2002 January 8 event vs. time. The corresponding distances of two successive blobs are also indicated.

For the 2003 November event, the plasma blobs were observed more than 6 hr after the Lyα dark gap (see Fig. 5 of Lin et al. 2005). The value of λ is found to be 9.1 × 10^5 km, and M_A ranges from 0.008 to 0.18 according to the results from the improved measurements (see Fig. 1). Substituting these results into equation (2) gives $l_\mathrm{min} = 4.3 \times 10^4$ km and $d_\mathrm{min} = 8.6 \times 10^4$ km. This value is slightly larger than that deduced from the Lyα gap, which apparently constitutes an inconsistency such that $d_\mathrm{min} > d_\mathrm{max}$.

Significant broadening of the CS during the course of the eruption may account for this inconsistency because the blobs were observed about 6 hr later than the Lyα gap. We suggest that the tearing mode is responsible for the broadening (Strauss 1988; Drake et al. 2006). This is consistent with the plasma blobs being the tearing mode magnetic islands. This inconsistency might be resolved when the observations from the *Solar Terrestrial Relations Observatory* and *Solar-B* become available.

We list the above results for d and η_e in Table 1 and noticed that η_e is around 12–13 and 4–5 orders of magnitude larger than η_c and η_a, respectively. This suggests that even the role

TABLE 1
PARAMETERS FOR CURRENT SHEETS IN VARIOUS EVENTS

Event	d (10^4 km)	v_i (km s^{-1})	η_e (10^5 ohms m)	D_e (10^{20} ohms m^3)
2002 Jan 8	3.4–13.0	∼10.0	2.2–8.2	0.6–34.0
2003 Nov 18	6.8–8.6	∼8.4	3.6–4.5	4.1–8.4
1998 Mar 23	<10.0	∼10.0	<6.3	<16

of the conventional anomalous resistivity in governing the process in the CME/flare CSs is quite limited and that the tearing mode turbulence should account for such high values of η_e.

5. DISCUSSION AND CONCLUSIONS

Overall, for three eruptive events, we have deduced $d_{\max}$ from observations and estimated $d_{\min}$ by combining observations and properties of the tearing mode in the reconnecting CS, and also by more direct investigations of the Lyα gap. The range of η_e for each event was estimated according to equation (1). This may be the first measurement of both d and η_e for solar eruptions in progress since the reconnection theory was applied to solar flares six decades ago (see Priest & Forbes 2000, p. 359). The results in Table 1 show that the CME/flare CS could be as thick as 10^4 km. This implies that some models of the particle acceleration in the CS (e.g., see Wood & Neukirch 2005 and references therein) need to be modified because d in these models is only tens of meters.

The values of η_e that we deduced for three individual events are similar in magnitude, and are all incredibly large compared to those deduced from theories of classical and anomalous resistivities, and even to those usually assumed for solar flares. This result apparently suggests a very efficient diffusion process occurring in the reconnecting CS. But such an unusual result is also quite probably due to using equation (1) to relate η to other parameters for CSs, which may be valid only for the diffusion caused by the classical or conventional anomalous resistivities, although a justification in the effective and average sense might partly account for the result.

The diffusion process taking place in the tearing CS (see Fig. 2) may not be governed by classical and anomalous resistivities at all. Instead, theories on plasma turbulence indicate that the turbulence in the tearing CS can cause a much higher resistivity than other processes, which is known as the hyperresistivity D (Strauss 1988; Bhattacharjee & Yuan 1995), and produce a broadening CS (Strauss 1988; Drake et al. 2006). Strauss (1988) found that

$$v_i = \frac{D}{l^3} \tag{3}$$

compared to equation (1), where D is in units of m^4 s^{-1}. Corresponding to η_e given in equation (1), we calculate $D_e = \mu_0 D$ for each of the three events according to equation (3). We still call D_e the hyperresistivity, and now it is in units of ohms m^3.

The value of D_e deduced for each event is listed in the last column of Table 1 as well. This is the first such investigation for real events to our knowledge, so there is no example present that allows us to perform any comparison. But Strauss (1988) found that the diffusion caused by D_e could be 10^9 times that by η_a. Detailed studies on properties of equation (3) and D_e are surely necessary in the future, and the results of this work also pose a serious challenge to the existing reconnection theories that cannot rigorously handle the situations in which the size of the reconnection region is rapidly evolving.

Finally, we note that the linear theory of the tearing mode was utilized to relate $l_{\min}$ to λ and that values of λ used here are for those blobs that are easily recognized in LASCO images. There may be many small islands in the CS below the instrument resolution, and the nonlinear effects may serve to increase the island separation above the actual island tearing wavelength. For example, small islands could merge into bigger ones as they are ejected along the CS (e.g., Ambrosiano et al. 1988); or tearing could be sporadic, creating single short-wavelength islands one at a time, with a large time separation between two islands. This is analogous to plasmoid ejection in a magnetospheric substorm (e.g., see Murata et al. 1995). Furthermore, the island wavelength expected from tearing in a turbulent CS, as discussed in § 5, could be very different from that of the linear tearing mode in a laminar CS. Thus, more detailed investigations are needed.

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