SIDE MAGNETIC RECONNECTIONS INDUCED BY CORONAL MASS EJECTIONS: OBSERVATIONS AND SIMULATIONS

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Received 2009 September 25; accepted 2010 May 24; published 2010 June 29

ABSTRACT

Over the last few years coronagraphic and spectroscopic observations have demonstrated that small-scale eruptions, such as “jets,” “narrow coronal mass ejections (CMEs),” “mini CMEs,” “streamer puffs,” “streamer detachments,” and others, occur ubiquitously on the Sun. Nevertheless, the origin of small-scale eruptive events and how these are interrelated with larger scale CMEs have been poorly investigated so far. In this work, we study a series of small-scale side eruptions that occurred during and after a large-scale CME. Observations show that a CME can be associated not only with a single reconnection process, leading to the large-scale phenomenon, but also with many other side reconnections occurring at different locations and times around the main flux rope, possibly induced by the CME expansion in the surrounding corona. White light and EUV observations of a slow CME acquired by the *SOHO*/LASCO and *SOHO*/UVCS instruments are analyzed here to characterize the locations of side reconnections induced by the CME. The magnetic reconnection rate M has been estimated from the UVCS data from the ratio between the inflows and outflows observed around the reconnection region, and from the LASCO data from the observed aperture angles between the slow mode shocks (SMSs) associated with the reconnection. It turns out that $M \simeq 0.05$ at the heliocentric distance of $1.8 R_{\odot}$, while between ~ 2.5 and $5.5 R_{\odot}$, M values progressively decrease with time/altitude from $M \sim 1$ down to $M \sim 0.3$. Such large values of M are theoretically acceptable only if flux pile-up reconnection is envisaged. The observed occurrence of multiple reconnections associated with a CME is verified by numerical simulations of an eruption occurring within multiple helmet streamers. The simulations confirm that small side reconnections are a consequence of CME expansion against the surrounding coronal streamers. The simulated and observed evolution of aperture angles between the SMSs are in good agreement as well. These results demonstrate the effect of the global coronal magnetic field in the occurrence of small-scale eruptions due to lateral reconnection in a preceding CME event.

Key words: magnetic reconnection – magnetohydrodynamics (MHD) – Sun: corona – Sun: coronal mass ejections (CMEs) – Sun: magnetic topology – Sun: UV radiation

Online-only material: color figures

1. INTRODUCTION

There is general agreement that the energy driving coronal mass ejections (CMEs) must originate in the magnetic field of the Sun (see review by Forbes 2000). The majority of recent work on CME initiation favors “storage-and-release” models (Klimchuk 2001), where the occurrence of a CME is related to the gradual storage of free magnetic energy in a quasi-static evolution, followed by a loss of equilibrium or instability that occurs because of the excess of accumulated shear or twist. There are essentially two pre-eruption configurations invoked in the storage of this free energy: sheared arcades, i.e., coronal arcades whose footpoints undergo a shearing motion in the direction perpendicular to the arcade plane (see, e.g., Antiochos et al. 1999); or the formation of magnetic flux ropes, i.e., twisted/sigmoidal structures of helical magnetic fields, anchored at both ends in the photosphere (see, e.g., Rust & Kumar 1996; MacTaggart & Hood 2009). Observational data analysis suggested many different candidates for triggering the release of the stored energy (i.e., the final occurrence of the CME), such as: the proximity of a CME site to coronal holes (Bravo et al. 1999), magnetic shear (Mikić & Linker 1994), filament helicity (Martin 2003), X-ray sigmoids (Rust & Kumar 1996; Sterling & Hudson 1997), and magnetic flux

emergence (Feynman & Martin 1995). In agreement with these different candidates, various CME models have been formulated, invoking different scenarios for the storage and release of magnetic energy that eventually lead to CMEs. Several excellent papers are available in the literature that give a thorough review on the different CME initiation theories and models (Klimchuk 2001; Low 2001; Forbes et al. 2006; Roussev & Sokolov 2006; Mikić & Lee 2006). In general, even if it has also been proposed that reconnection might not be necessary to initiate a CME, and that impulsive CMEs may be possible even without explosive reconnection (e.g., Sturrock et al. 2001; Rachmeler et al. 2009), there is wide consensus that, at least for stronger events also associated with X-class flares and radio bursts, magnetic reconnection plays a fundamental role in the energy release associated with the initial loss of equilibrium at the eruptive phase. In the minutes following the start of the eruption, the CME bubble expands in the surrounding corona, likely interacting and reconnecting with other favorably oriented magnetic structures located along their path, such as coronal streamers and rays. Many previous works demonstrated that large- and small-scale eruptive events are quite often interrelated, possibly by cause–effect relationships (for a review on this subject, see van Driel-Gesztelyi et al. 2008): during their expansion a CME may reconnect not

only with surrounding smaller-scale bipoles, leading to the observed large-scale EUV dimmings (see Attrill et al. 2007; Mandrini et al. 2007), but also with field lines left open by a previous CME and/or with nearby streamers, generating type III and N radio bursts (see e.g., Goff et al. 2007; Gilbert et al. 2001). Nevertheless, the occurrence of magnetic reconnection between a CME and nearby structures is not the only available condition to induce secondary eruptions. Coronal streamers are known to result from the dynamical equilibrium between plasma expansion and magnetic confinement, but, despite their overall long-term stability, this equilibrium is not necessarily stable: streamers themselves can produce small-scale eruptions. As it has been recently demonstrated, coronal streamers are intrinsically unstable below their cusp, where compact ejective flares occurring in the outer flank of the streamer base can produce many homologous small-scale eruptions traveling out along the streamer and leaving it largely intact (Bemporad et al. 2005; Moore & Sterling 2007). But coronal streamers are also unstable above their cusps, where reconnections may spontaneously occur (Chen et al. 2009) and one or more plasmoids may form (Bárta et al. 2008), as also anticipated by the detection of propagating blobs, “in & out pairs,” and “streamer detachments” (see, e.g., Wang & Sheeley 2006; Sheeley & Wang 2007).

All these results indicate that during a solar eruption, the expanding CME bubble may interact *directly* with the surrounding coronal structures (e.g., coronal streamers or open field lines) via magnetic reconnection, or *indirectly* by inducing disturbances which lead the unstable coronal streamers out of equilibrium. In both cases, the final result is the generation of one or more secondary side eruptions during and/or after the CME propagation. In principle, these interactions of CMEs with the surrounding ambient corona could play an important role not only in their subsequent evolution, but, maybe, also in their triggering. In the so-called magnetic breakout model (Antiochos et al. 1999), reconnection occurring in the arcades overlying a sheared filament transfers their magnetic flux to side arcades, finally triggering the eruption. In a similar way, if a flux rope is suspended by the magnetic field into an unstable equilibrium, it is possible that a small-scale eruption occurring near the flux rope leads to its final destabilization. For instance, the occurrence of a small-scale side eruption could partially remove the system of closed field lines globally trapping the flux rope, reducing the magnetic tension above it and triggering the eruption. Hence, in principle, the possibility that a small-scale phenomenon *triggers* a larger scale one cannot be excluded.

In this work, we focus on small-scale eruptions related to the occurrence of a large-scale CME. In the first part of this work, we report on the detection of secondary eruptions induced in the surrounding corona by a CME that occurred on 2005 December (Section 2). In particular, in the first part of this work, a general description of the white light coronal appearance and of the coronal magnetic field configuration as derived with a potential field source surface (PFSS) extrapolation is given (Section 2.1); the *SOHO*/UVCS and *SOHO*/LASCO data are used to characterize the reconnection processes occurring between the CME flanks and nearby streamers (Section 2.2) and those induced by the expanding CME in the streamer (Section 2.3) itself. Then, in the second part of this work, we show that similar eruptions can be obtained in numerical simulations of CME initiation by allowing magnetic reconnection in the ambient corona where the CME expands (Section 3). Our results are then summarized in the concluding section (Section 4).

2. OBSERVATIONS OF SIDE RECONNECTIONS

2.1. White Light and Soft X-ray Data

Full-disk soft X-ray images acquired by the *GOES*/SXI instrument⁴ show that in the first days of 2005 December a complex system of active regions (ARs) transits on the disk dragged by the solar rotation, crossing the west limb between December 9 and 11 (see Figure 1, top panels). The corresponding coronal streamer configuration above the west limb (on 2005 December 10) is clearly shown by the white light images obtained from the LASCO/C2⁵ coronagraph (the middle panels of Figure 1) in the range between 2 and 6 $R_{\odot}$. In particular, Figure 1 (panel (a)) shows two coronal streamers located almost symmetrically about the equator at latitudes of $\sim 40^{\circ}\text{N}$ and $\sim 40^{\circ}\text{S}$ (hereafter, northward and southward streamers—NS and SS—respectively), while a much more complex configuration is present in the equatorial band ($\pm 20^{\circ}$) where many small and thin radial structures are visible.

It is really important to start discussing how the white light appearance of the ambient corona can be interpreted in terms of the pre-CME coronal magnetic field configuration. This can be achieved by looking at the photospheric magnetic fields and the coronal fields extrapolated with the standard PFSS approximation. In particular, Figure 2 shows that, despite the observed complexity in the soft X-ray emission, the overall average photospheric magnetic field in the solar surface sector crossing the plane of the sky can be simply characterized as a pair of opposite polarity regions located in the equatorial band crossed by an inverse “S-shaped” neutral line (NL; see Figure 2, left panel). The NL is oriented mainly in the meridional direction close to the equator and in the parallel direction at two intermediate latitude regions. Hence, moving along a meridian from the north to the south pole, the NL is crossed three times: one time at the equator and two more times around the latitudes of $\sim 40^{\circ}\text{N}$ and $\sim 40^{\circ}\text{S}$. This peculiar orientation of the inverse “S-shaped” photospheric NL results in an ESA–polar magnetic configuration (i.e., three bipoles) along the meridional direction, with two large-scale, “soft” ($B \sim 10^2$ G) bipoles centered at intermediate latitudes of $\sim 40^{\circ}\text{N}$ and $\sim 40^{\circ}\text{S}$ and a smaller scale, “hard” ($B \lesssim 1.3 \times 10^3$ G) bipole centered at the equator. Accordingly, the extrapolated PFSS coronal field lines show two almost symmetric systems of extended arcades parallel to the plane of the sky (associated with the two large-scale mid-latitude bipoles), and a more compact system of closed field lines around the equator (associated with the smaller scale equatorial bipole—see Figure 2, right panel). A comparison with the white light images leads to the conclusion that the two systems of extended arcades approximate the field in the symmetric NS and SS well, while the more compact system is associated with the thin radial equatorial structures.

On 2005 December 10, starting on $\sim 19:00$ UT, a CME appears at the west limb in the LASCO/C2 field of view (FOV). LASCO/C2 difference images and wavelet enhanced images show a complex of opening nested loops followed by the superposition of many filamentary patterns probably linked to the loop footpoints down in the lower corona (Figure 1, panels (b) and (c)). The CME start time, as extrapolated from the

⁴ The Solar X-ray Imager aboard the *GOES* satellite is a Wolter Type I grazing incidence telescope measuring the broadband soft X-rays in the spectral region between 6 and 60 Å at a 1 minute cadence with a 512×512 intensified CCD; see Lemen et al. (2004).

⁵ The Large Angle & Spectrometric COronagraph; see Brueckner et al. (1995).

Figure 1. Top row: a sequence of *GOES*/*SXI* images showing the Active Region (AR) complex located around the equator and dragged across the disk by solar rotation in the days before the events reported here. The top right frame shows that, before the December 11 eruption, this AR complex was crossing the west solar limb. Middle row: the white light solar corona (west limb) as seen by the *LASCO*/*C2* coronagraph in standard (panels (a) and (f)) and running difference (panels (b)–(e)) images; panel (a): coronal configuration before the event; panel (b): CME propagation; panel (c): northwest streamer detachment; panel (d): secondary ejection after the CME; panel (e): southwest streamer detachment; panel (f): coronal configuration after the events; observation times are indicated in each panel. The solid white line corresponds to the position of the UVCS slit field of view, while the dashed line shows the radial toward the slit center at a latitude of 35° S; UVCS observations started and ended roughly at the times corresponding to panels (a) and (c), respectively. Bottom row: same as middle row, with wavelet enhanced *LASCO*/*C2* images.

LASCO height–time curves, is around 18:36 UT. This very slow CME ($\sim 130 \text{ km s}^{-1}$ around $4 R_\odot$) expanded at a latitude of about $\sim 15^\circ$ SW with an angular width of $\sim 70^\circ$: the CME, probably originating from the equatorial compact system of closed field lines, propagates in between the NS and SS, with its flanks close to the streamer axes. The white light images acquired later on show that the CME propagation is accompanied and followed by many other interesting events occurring on smaller scales with respect to the CME size. First, a streamer detachment occurs in

the NS: starting from about 03:00 UT on December 11 a concave Y-shaped feature propagates along the streamer axis (Figure 1, panels (b) and (c)). In the following hours, a secondary unstructured ejection occurs northward of the SS boundaries around $\sim 12:00$ UT (Figure 1, panel (d)), arising from a region formed in between the southward expanding CME flank and the SS boundary and propagating mainly parallel to the CME flank. Finally, a second streamer detachment also occurs along the SS: starting from $\sim 17:00$ UT, an X-point forms in between the two

Figure 2. Left: a map of photospheric magnetic fields observed during the transit of the AR complex across the solar disk (Carrington Rotation 2037). The vertical solid lines represent the east (left) and west (right) limbs on December 10, when the eruption started ($\approx 18:36$ UT); the dashed curved line shows the position of the neutral line, while different colors represent the magnetic field intensity from $+10^3$ G (white) to -10^3 G (black), with contour steps of 200 G. Blue arrows represent the position of the two dipoles associated with the northward and southward streamers and of the equatorial dipole associated with the CME source region. Right: pre-eruption coronal magnetic fields extrapolated (PFSS approximation) above the west limb from the photospheric fields shown in the left panel. The two systems of closed field lines are centered almost symmetrically with respect to the equator, hence in good agreement with the position of the northward and southward streamers shown by white light images (Figure 1, panel (a)).

(A color version of this figure is available in the online journal.)

radial features approaching each other, the northward one being aligned with the CME southward flank. The X-point stretches in two Y-shaped features, one propagating outward along the streamer and the other rooted on the Sun, while a current sheet (CS) develops in between (Figure 1, panel (e)). About 12 hr later, the pre-CME coronal configuration is mainly recovered (two streamers at intermediate latitudes) but the equatorial region is less bright in white light, which is likely because of the density decrease in the region where the CME occurred (Figure 1, panel (f)). We anticipate here that in the remainder of the paper we will not discuss the possible processes causing the release of the main CME, but rather concentrate on the secondary eruptive events associated with it and described above.

Taking into account the pre-CME photospheric and coronal magnetic field configurations (Figure 2), the evolution described above can be interpreted as qualitatively shown in the two-dimensional cartoon of Figure 3. A flux rope, initially embedded above the AR complex by the closed field lines around the equatorial region (Figure 3, panel (a)), is ejected and expands in between the northward and southward streamers (Figure 3, panel (b) and Figure 1, panel (b)). The CME expansion compresses and destabilizes the NS inducing a magnetic reconnection along its CS (Figure 3, panel (b)). The reconnection occurs below the LASCO/C2 occulter and results in the observed NS detachment (“Y”-point in Figure 3, panel (c)), which propagates outward, mainly coinciding with the CME (see also Figure 1, panel (c)). In the following hours, as the CME expansion proceeds, the southward CME flank interacts with the SS boundaries, leading to a series of reconnections occurring at altitudes increasing with time. One of these reconnections (Figure 3, panel (c)) results in the observed secondary eruption (Figure 1, panel (d)) which propagates outward parallel to the SS axis (Figure 3, panels (d)–(f)). The further expansion of the CME southward flank also destabilizes the SS, eventually inducing further reconnection (Figure 3, panel (f)) along its CS, which results in the observed SS detachment (“Y”-point in Figure 3, panels (g) and (h); see also Figure 1, panel (e)). At the end of this se-

quence of events, the initial configuration with two streamers located almost symmetrically with respect to the equator is recovered (Figure 3, panel (i) and Figure 1, panel (f)). Hence, the CME is accompanied and followed by many secondary events (ejections and streamer detachments), which are interpreted here as a consequence of side reconnections induced in the surrounding corona by the CME expansion, as described in Figure 3. This interpretation could be questionable, because it is based only on coronagraphic data acquired above $\sim 2 R_{\odot}$, hence two of the three inferred magnetic reconnections (Figure 3, panels (b) and (c)) that occurred below the LASCO occulter are not directly observed in white light. Fortunately, the slit of the *SOHO*/UVCS spectrometer, being centered below this altitude, directly observed one of these reconnections (Figure 3, panels (d) and (e)): in the next section, we describe how the UVCS data strongly support the above interpretation.

Please note that the illustrations in Figure 3 give only a very simplified two-dimensional picture: Figure 2 (left panel) shows that the three dipoles are distributed over the photosphere with different relative tilt angles. As a consequence, groups of closed loops associated with the three dipoles (Figure 2, right panel) have different orientations in three dimensions: loops associated with the two streamer dipoles are mainly aligned with the plane of the sky (hence are seen “face-on”), while those associated with the equatorial dipole bridge over the east limb (being seen approximately “edge-on”). Nevertheless, for the sake of simplicity, all the three dipoles have been plotted in Figure 3 as parallel, i.e., all aligned along the meridional direction. This means that in reality all the magnetic reconnection processes described above will not occur in two dimensions (i.e., over a meridional plane, as qualitatively shown in Figure 3), but in three dimensions (i.e., in the coronal volume located above the AR complex and the streamer bases).

Before concluding this section, we point out that the NS detachment has already been studied by Wang & Sheeley (2006): the authors found from LASCO images that this streamer is slowly expanding in the days before December 11 and concluded that this expansion (possibly driven by photospheric

Figure 3. Illustration showing the interaction between the expanding CME and the southwest streamer: positive and negative polarities are shown as light and dark gray areas, respectively; shaded regions represent coronal altitudes located below the LASCO/C2 occulter (gray), while the solid straight line represents the UVCS field of view. The illustration mimics the white light evolution (Figure 1, panels (a)–(f)); dimensions are not to scale. As the CME expands (panel (a)), magnetic reconnections (represented by “X” symbols) are induced along the CS of the northward streamer (panel (b)) and later on between the CME flank and the southward streamer (panel (c)). These reconnections proceed toward higher levels leading to the NS detachment (“Y”-point in panel (c)) and to the secondary eruption (“Y”-point in panel (e)). The propagation of the secondary eruption close to the SS axis leads to the streamer pinching by magnetic reconnection along its CS (panel (f)) and to the subsequent formation of the two “Y-shaped” features (panel (g)) and the final release of a streamer detachment (“Y”-point in panel (h)). Finally, the initial configuration is mainly recovered (panel (i)).

flux emergence) progressively leads the streamer to a non-equilibrium configuration and induces magnetic reconnection along the streamer CS finally resulting in the observed detachment. However, looking at LASCO movies, it is evident that the CME and the streamer detachment occur together: hence, it is likely that, at the end of the expansion described by Wang & Sheeley (2006), the occurrence of the CME at the side of the streamer accelerates this process, helping the reconnection inside the streamer and destabilizing the overall magnetic configuration.

2.2. Side Reconnection Observed in EUV Data

The UVCS instrument FOV was located in a good position to observe the December 10 CME: as shown in Figure 1 (panels (a)–(c)), the FOV was centered at a latitude of 35°S in the west limb and an altitude of $1.8 R_\odot$. At this position, the FOV covered approximately a latitude interval between 4°N and 67°S , while the CME and the SS was centered around 10°S and 40°S , respectively: hence, the UVCS FOV was favorably located to observe not only the CME, but also the evolution of the SS. The UVCS observations covered (with a time resolution of 2 minutes) an ~ 23 hr time interval starting on December 10, 08:29 UT (Figure 1, panel (a)), hence ~ 10 hr before the estimated CME start time, and ending on December 11, 07:33 UT (Figure 1, panel (c)). The selected spectral intervals included the $\text{O VI } \lambda\lambda 1032\text{--}1037 \text{ \AA}$ doublet lines, the $\text{H Lyman-}\beta \lambda 1025 \text{ \AA}$ and $\text{Lyman-}\gamma \lambda 973 \text{ \AA}$ lines, and the $\text{Si XII } \lambda 520 \text{ \AA}$, $[\text{Al XI}] \lambda 550 \text{ \AA}$ second order lines. Line intensities have been

estimated by integrating each spectral line over the observed profile and subtracting the average background; in order to increase the signal-to-noise ratio, line profiles have been averaged over 10 exposures (temporal resolution of ~ 20 minutes) and two spatial bins (spatial resolution of $\sim 6 \times 10^4 \text{ km}$).

The resulting $\text{O VI } \lambda 1032 \text{ \AA}$ and $\text{Si XII } \lambda 520 \text{ \AA}$ line intensity evolution are shown in Figure 4 (top left and right panels, respectively) at different latitudes and different times. At the beginning of the UVCS observations, the SS was centered approximately at a latitude of $\sim 40^\circ\text{S}$, hence 5° or $\sim 10^5 \text{ km}$ from the slit center. Figure 4 (top panels) shows that the main UV emission is associated with the SS and that apparently there are no significant variations of the line intensity during the CME. In order to highlight minor intensity variations (larger than the statistical uncertainties) we show in Figure 4 (bottom panels) the $\text{O VI } \lambda 1032$ and $\text{Si XII } \lambda 520$ line intensity evolution after subtracting from each bin along the slit its intensity averaged over the whole observation interval (~ 23 hr). Both bottom panels in Figure 4 show a much more complex pattern: it is possible to recognize, in particular in the O VI map, the transit of the CME front and void, while the identification of the CME core is more uncertain. Interestingly, these panels show that, during the CME propagation, two approaching features are also visible close to the streamer core: two branches, initially at a relative distance of $\sim 3.6 \times 10^5 \text{ km}$, start approaching each other ~ 5 hr after the UVCS observations start. The two branches, both moving toward an intermediate latitude, coalesce in ~ 11 hr on December 11, 00:30 UT, as we inferred by defining the “coalescence time” as the time the O VI emission peaks at the

coalescence latitude. In particular, the observed coalescence occurs at a latitude of $\sim 35^\circ\text{S}$, hence between the CME (centered at 15°S) and the SS (centered around 40°S —see also Figure 1, middle panels).

In order to explain the association between the LASCO and UVCS features better, Figure 5 shows the LASCO height–time curves relative to the CME front (top left panel) and the CME southward flank (bottom left panel): these plots have been obtained by cutting vertical slices from the LASCO/C2 data at different times and at constant latitudes of 15°S (top) and 35°S (bottom), i.e., at the latitudes where the O VI intensity map from the UVCS data shows the transit of the CME front and the two coalescing features, respectively (see Figure 4, bottom panels). Below the LASCO/C2 occulter projected altitudes, data points in Figure 5 show the times and heliocentric distances where the CME front and the two coalescing features are observed in the UVCS data (diamond and triangle symbols, respectively). A comparison between the UVCS data points and the LASCO height–time curves not only shows a good correspondence between the CME front in the LASCO and UVCS data, but also demonstrates that the coalescence observed in the UVCS data is clearly associated with the LASCO height–time curve for the CME flank. By also taking into account that the coalescence is observed in the UVCS data at an intermediate latitude between the CME and the SS latitudes, we interpret the coalescence observed in the O VI and Si XII intensity maps (Figure 4, bottom panels) as the signature of a magnetic reconnection, triggered by the CME expansion, that occurred between the southward CME flank and the boundaries of the SS. In this interpretation, the UVCS reconnection is also the same as shown in Figure 3 (panel (c)).

If this interpretation is correct, then the UVCS data can be used to estimate the physical parameters of coronal plasma in the reconnecting region. In particular, from the analysis of the O VI $\lambda 1032$, Si XII $\lambda 520$, and [Al XI] $\lambda 550$ line intensity evolution observed at the reconnection region, Bemporad et al. (2008) concluded that during the driven reconnection process, density and temperature increase respectively by $\sim 20\%$ and $\sim 30\%$ and that, possibly because of the weakness of the coronal magnetic field (< 1 G) at the heliocentric distance of $1.8 R_\odot$, these changes can be ascribed almost entirely to the adiabatic compression driven by the CME expansion, while only a small fraction of plasma heating is really due to the conversion of magnetic energy into thermal energy via reconnection.⁶ Further parameters on the observed side magnetic reconnection can be derived from the UVCS and LASCO data: in particular, a fundamental parameter in the formulation of realistic CME models is the inflow magnetic reconnection rate M_1 , which is given by $M_1 = v_1/v_A \simeq v_1/v_2$, where v_1 and v_2 are the velocities at which the plasma flows toward and is ejected from the reconnection region, respectively, while $v_A = B/\sqrt{\mu\rho}$ is the local Alfvén velocity for a plasma characterized by a magnetic field B and a mass density ρ . Despite the theoretical importance of M_1 , there are very few estimates of this parameter in the corona. Given the “coalescence time” ($\simeq 11$ hr), the inflow speed v_1 can be easily determined from the observed displacement with time along the UVCS slit of the two coalescing EUV features ($\simeq 2 \times 10^5$ km); it turns out that $v_1 \simeq 5$ km s $^{-1}$. The outflow speed can be approximately estimated from the LASCO height–time curve for the CME flank (Figure 5, bottom left

panel): from this curve we estimate that $v_2 \simeq 90$ km s $^{-1}$. Note that by assuming a local number density $n = 7.2 \times 10^{12}$ m $^{-3}$ as derived by Bemporad et al. (2008), it turns out that, in order to have $v_A \simeq 90$ km s $^{-1} = v_2$, as required by the reconnection theory, we expect a local magnetic field $B = v_2 \sqrt{\mu\rho} \simeq 0.11$ G; this value is in good agreement with our previous conclusion that the plasma heating provided by magnetic reconnection is negligible, hence $B < 1$ G (see Bemporad et al. 2008). The above values for the inflow and outflow velocities give a magnetic reconnection rate $M_1 \simeq 0.05$: this value will be discussed and compared in our conclusions with the reconnection rates estimated from the LASCO data and derived from magnetohydrodynamic (MHD) simulations (Section 4).

2.3. Side Reconnection Observed in WL Data

In the hours after the CME, the LASCO/C2 images show the propagation of a plasma blob along the axis of the SS: as mentioned before, we interpret this event as a streamer detachment that occurred because of magnetic reconnection driven at the streamer CS destabilized by the nearby occurrence of the secondary eruption and/or by the expanding CME flanks (see Figure 1, panels (d) and (e), and Figure 3, panels (f)–(h)). The event can be better visualized by the sequence of LASCO/C2 difference images of Figure 6 (panels (a)–(d), top) showing the progressive streamer pinching and stretching leading to the final ejection of a plasmoid from the streamer cusp. The possible corresponding evolution of magnetic field lines during the streamer detachment is tentatively shown by a sequence of illustrations in Figure 6 (panels (a)–(d), bottom): in particular, panels (c) and (d) of Figure 6 show the formation and propagation of the two “Y” and “inverse Y”-points and have to be directly compared with the configuration shown in the illustrations of Figure 3, panels (g) and (h), respectively.

From the white light evolution observed during the streamer detachment, it is possible to derive information on the magnetic reconnection occurring below the accelerating plasma blob. The magnetic field configuration at the reconnection site is shown in Figure 6 (panel (e)): according to the fast-reconnection model first proposed by Petschek (1967), the reconnection occurs in a “small” diffusion region (DR). The plasma flows toward the DR with an inflow velocity v_1 and, after the reconnection, is accelerated and ejected from the DR at an outflow velocity $v_2 > v_1$ with $v_2 \sim v_A$, as mentioned. Petschek (1967) also predicted a bifurcation of the CS into two pairs of slow-mode shocks (SMSs), which have been identified in solar flares (e.g., Tsuneta 1996) and reproduced in numerical simulations (e.g., Sato & Hayashi 1979). Hence, the SMSs separate the inflow and outflow plasma regions: across the SMS’s surface the plasma is compressed, heated, and accelerated (see Skender & Vršnak 2003; Vršnak & Skender 2005 for a complete 2.5-D solution of the jump equations across the SMSs). The angle between the two SMSs is 2ϕ , smaller than the angle 2ψ between the field lines of the reconnecting magnetic field B_1 (see Figure 6, panel (e)).

The main reconnection signature we expect to observe in white light coronagraphic images of the extended corona is the plasma compression occurring at the SMS crossing, while other effects related to the curvature of local magnetic fields will be hardly visible because after reconnection the compressed plasma is ejected with velocity v_2 , mainly parallel to the DR axis and is not traveling along the magnetic field lines. In this work, we interpreted the density jump, clearly visible in the LASCO/

⁶ See Bemporad et al. (2008) for the description of the UVCS data analysis relative to this peculiar event.

Figure 4. Top: the evolution of the O VI $\lambda 1032$ (left) and Si II $\lambda 520$ (right) intensities observed at different latitudes (i.e., along the UVCS slit; x-axis) and times (i.e., hours on December 10–11; y-axis). Bottom: same as top panels, but after the subtraction at each latitude of the line intensity averaged over the whole observation interval. The subtraction outlines the CME transit across the UVCS field of view and the side reconnection (converging features) induced by the CME; colors in both the bottom panels range from -2×10^9 (black) to $+2 \times 10^9$ phot cm $^{-2}$ s $^{-1}$ sr $^{-1}$ (white).

(A color version of this figure is available in the online journal.)

Figure 5. Left: h - t diagrams derived by extracting the LASCO/C2 white light intensity at different times along radials centered at latitudes of 15°S (i.e., the latitude of the CME front center in UVCS data) and 35°S (i.e., the latitude where the magnetic reconnection is observed in UVCS data; see Figure 4). Below the LASCO/C2 occulter altitudes, these plots also show the UVCS observation time coverage (solid line) and the transit times across the slit FOV of the CME front (top, diamond symbol) and of the magnetic reconnection (bottom, triangle symbol). Right: a LASCO/C2 image during the CME showing the position of the UVCS slit FOV (solid white line), the positions along the slit where the CME front and the magnetic reconnection have been detected (diamond and triangle symbols, respectively), and the radials used to build the h - t diagrams shown in the left panels (solid black lines).

(A color version of this figure is available in the online journal.)

C2 difference images (Figure 6, panel (f)), as the signature of the compression occurring at the two SMSs, and the angle between the two branches visible in these images has been interpreted as the 2ϕ angle between the pair of SMSs. It is also evident from LASCO difference images that the angle 2ϕ between the pair of SMSs located below the DR and those located above it are not the same. This was expected, because the white light structure shown in Figure 6 extends over a length of ~ 3 – $4 R_{\odot}$, hence physical parameters of plasma inflowing above or below

the DR and crossing the SMSs will be different, leading to different jump conditions across the SMSs and also to different 2ϕ angles between the SMSs. For this reason, we will make a distinction between the variables relative to the “up” and “down” part of the reconnecting CS, by using the “ u ” and “ d ” subscripts, respectively, for each variable, as shown in Figure 6 (panels (e) and (g)).

In the following, we describe how the LASCO/C2 difference images have been used to estimate the reconnection rate M_1 . If

Figure 6. Panels (a)–(d): a series of LASCO/C2 running difference images showing the coronal white light evolution during the SS detachment (top) and the corresponding supposed magnetic field configuration (bottom). The bottom illustrations also show the identified position of the “Y” and “inverse Y”-points (compare with Figure 3, panels (f)–(h)). Panel (e): the reconnection geometry leading to the observed streamer detachment; a distinction is made between the “up” (*u* subscript) and “down” (*d* subscript) variables. The plasma, flowing with velocity v_1 across the slow mode shocks (SMSs) and carrying a magnetic field B_1 , is accelerated by magnetic tension up to the velocity v_2 , leading to the formation of two outflow jets characterized by a weaker magnetic field B_2 . The aperture angle 2ϕ between the two SMSs (extending from the Diffusion Region—DR) is smaller than the magnetic field aperture angle 2ψ (adapted from Aurass et al. 2002). Panel (f): LASCO/C2 difference frame during the reconnection leading to the SS detachment. Panel (g): the corresponding position of the DR and the up ($2\phi_u$) and down ($2\phi_d$) aperture angles between the 2 SMSs. Panel (h): radials at different latitudes used to estimate the electron densities inside and outside of the reconnecting CS and the compression ratio x (see the text).

(A color version of this figure is available in the online journal.)

the DR has thickness δ and length Δ , the mass flux conservation of the reconnecting plasma implies that $\rho_1 v_1 \Delta = \rho_2 v_2 \delta$, where ρ_1 and ρ_2 are the mass densities of the in- and out-flowing plasmas, respectively. The DR sizes (δ, Δ) are related to the angle ϕ by $\tan \phi \approx \delta/\Delta$ (see, e.g., Vršnak & Skender 2005), hence the inflow reconnection rate M_1 can be roughly estimated as

$$M_1 = v_1/v_A \approx v_1/v_2 = \rho_2 \delta/\rho_1 \Delta \approx \tan \phi (\rho_2/\rho_1). \quad (1)$$

This implies that, given the compression ratio $x = \rho_2/\rho_1 > 1$, it is possible to estimate from the LASCO/C2 images the reconnection rate as $M_1 \approx x \tan \phi$. A similar technique has been already applied by Poletto et al. (2008) to infer the reconnection rates during a CME, but the authors assumed a first-order approximation $x \sim 1$.

The compression ratio x can be estimated from the LASCO pB (polarized brightness) images. In particular, the pB (usually normalized to the mean solar surface brightness $\bar{B}_\odot$) observed at each LASCO pixel at an heliocentric distance of observation

y is given by an integration along the line of sight (LOS; see, e.g., Cranmer et al. 1999):

$$pB(y) = \frac{\pi}{2} \sigma_T \bar{B}_\odot \times \int_{-\infty}^{+\infty} n_e(z) \left[\frac{(1-u)A(r) + uB(r)}{1-u/3} \right] \frac{y^2}{r^2} dz, \quad (2)$$

where σ_T is the cross section for the Thomson scattering by coronal electrons, $A(r)$ and $B(r)$ (defined by Altschuler & Perry 1972) are simple geometrical functions of the solid angle Ω subtended by the solar disk at the scattering point, $u = 0.58$ is the limb darkening coefficient in the visible wavelength of interest, and $n_e(z)$ is the unknown electron density at the position $z = \sqrt{r^2 - y^2}$ along the LOS. From the observed pB values at different altitudes y it is possible to derive a coronal electron density profile $n_e(r)$ by inverting the above integral. In order to perform this inversion we need an a priori expression for the dependence of n_e on latitude and longitude. This can be

Figure 7. Reconnection rate M_1 as a function of time estimated from LASCO/C2 images (see the text) during the SS detachment from the pair of SMSs located above (star symbols) and below (diamond symbols) the position of the DR.

done in several ways, from a simple spherical symmetric model (van de Hulst 1950) to an axisymmetric model, or to more complex models that take into account large-scale structures such as coronal streamers or polar plumes (e.g., Romoli et al. 1993; Strachan et al. 1993). In this work, we derived the electron density profile by assuming a simple spherical geometry.

On 2005 December 11, the LASCO/C2 coronagraph acquired one pB image at 21:03 UT (just before the frame shown in Figure 6, panel (f)): in order to derive an electron density profile inside and outside of the reconnecting CS, we extracted from the LASCO image three pB radial profiles, one centered at the reconnecting CS axis of symmetry ($46^\circ S$) and two profiles located at lower and higher latitude ($36^\circ S$ and $56^\circ S$, respectively), as shown in Figure 6 (panel (h)). For each of these profiles, we derived, with the technique described above, the electron density radial profiles inside ($46^\circ S$) and outside ($36^\circ S$ and $56^\circ S$) of the reconnecting CS, assumed to be representative of the average plasma densities ρ_2 and ρ_1 , respectively. From the derived $n_e(r)$ profiles we concluded that, within the measurement uncertainties (see Frazin et al. 2002 for a description of uncertainties in the LASCO/C2 pB measurements), the density compression ratio x is constant at different altitudes (i.e., along the reconnecting CS) and equal to $x = 1.9 \pm 0.7 \approx 2$.

Given the compression ratio x , the up and down reconnection rates M_{1u} and M_{1d} can be estimated as $M_{1u} \approx x \tan \phi_u$ and $M_{1d} \approx x \tan \phi_d$, respectively. The resulting M_{1u} and M_{1d} values obtained by measuring the angles ϕ_u and ϕ_d between the up and down SMSs (Figure 6, panel (g)) from successive LASCO/C2 difference images (i.e., at different times and altitudes) are shown in Figure 7. The M_1 evolution we derived is simply related to an observed progressive decrease in both the aperture angles ϕ_u and ϕ_d with time/altitude. Even if uncertainties in the M_1 values are quite large, this plot shows that during the SS detachment (1) the reconnection rate decreases from $M_1 \approx 1$ down to $M_1 \approx 0.3$ and (2) at any time/altitude the reconnection rate is systematically larger at the up pair of SMSs, where the plasma blob is ejected, and smaller at the down pair of SMSs. The systematic difference between the “up” and “down” reconnection rates suggests that the physical conditions of the reconnecting plasma are different, which is likely, given the different altitudes of the two regions.

Values derived above from LASCO data (Figure 7) are at least 2 orders of magnitude larger than the typical M_1 values

envisaged for the Petschek-type reconnection, and hence need to be better justified. Typical upper limit values for M_1 given by the fast Petschek reconnection model (Petschek 1967) range around $M_1 \sim 0.01$ – 0.001 , and values derived from the observed reconnection inflows during solar flares are in agreement with this range (see, e.g., Yokoyama et al. 2001). In particular, in the model originally proposed by Petschek (1967), the upper limit of M_1 is given by

$$M_1(\text{max}) = \frac{\pi}{8 \ln R} \quad (3)$$

where $R = Lv_A/\eta$ is the magnetic Reynolds number (or Lundquist number, a dimensionless parameter representing the ratio between the convective and the diffusive terms in the induction equation) and η ($\text{m}^2 \text{s}^{-1}$) is the magnetic diffusivity. Hence, in the original Petschek theory, M_1 is simply determined by R ; for plasma above a sunspot typically involved in flares, $T \sim 10^4 \text{ K}$, $n \sim 10^{20} \text{ m}^{-3}$, $L \sim 10^7 \text{ m}$, and $B \sim 10^3 \text{ G}$, hence $R \sim 2 \times 10^9$ (with the classical Spitzer diffusivity $\eta_c \sim 10^3 \text{ m}^2 \text{s}^{-1}$) and $M_1 \sim 0.01 \ll 1$. This formula led to reconnection rates much larger than those originally provided by the Sweet & Parker model (Sweet 1958; Parker 1957), where the reconnection rate is given by $M_1 = 1/\sqrt{S} \sim 2 \times 10^{-5}$, far too slow to explain solar flare observations.

Nevertheless, the above Petschek and Sweet & Parker models have been further developed in the following years. A generalization of the Petschek model was derived by Priest & Forbes (1986): the authors showed that, depending on the conditions of the flow on the inflow boundary, up to five different reconnection regimes may exist. In particular, for the flux pile-up regime (a family of solutions corresponding to slow-mode expansions) very large values (up to ~ 1) of the resulting reconnection rate are possible even for much smaller values of the local reconnection rate (see Priest & Forbes 1986). Ten years later, Litvinenko et al. (1996) demonstrated that the Priest & Forbes reconnection rate is limited by the gas pressure of the plasma in the CS (flux pile-up reconnection), so that the maximum allowed rate $M_1(\text{max})$ for Petschek reconnection is given by

$$M_1(\text{max}) \approx \frac{\pi \beta}{8 \ln R}, \quad (4)$$

(valid for $\beta \ll 1$) where $\beta = 2nk_B T/(B^2/2\mu_0)$ is the ratio between the thermal and the magnetic pressures. As a consequence, $M_1(\text{max})$ depends not only on R , but also on the value of the plasma β . Jardine & Allen (1998) demonstrated (by further developing the Jardine 1994 results) that the above formula is valid only in the assumption of two-dimensional reconnection (i.e., for zero-vorticity flows), while in the more general case of a three-dimensional reconnection (i.e., by including the effects of vorticity), much faster reconnection is allowed, even at high magnetic Reynolds numbers. In particular, the maximum allowed rate $M_1(\text{max})$ for Petschek reconnection is given by

$$M_1(\text{max}) = \frac{\pi \beta c}{8 \ln R}, \quad (5)$$

where the parameter $c \geq 1$ determines the scale of the perturbation in the direction perpendicular to the reconnection region (if $c = 1$, the two-dimensional case is recovered). Hence, Jardine & Allen (1998) concluded that the “steady-state flux pile-up reconnection can proceed at speeds up to the Alfvén speed in a highly conducting, low β plasma,” so that the maximum allowed reconnection rate can be up to

$M_1(\text{max}) \lesssim 1$. Moreover, Litvinenko & Craig (2000) have shown that optimized solutions for the flux pile-up reconnection model are locally equivalent to the Sweet & Parker current sheet, but “optimized flux pile-up models allow enhancements of the Sweet–Parker rate typically by factors of 1000.”

The above considerations show that values of M_1 plotted in Figure 7, theoretically too large for the two-dimensional reconnection models originally proposed by Sweet (1958), Parker (1957), and Petschek (1967), are allowed by further developments of these theories. Moreover, the flux pile-up regime is expected to form pairs of SMSs (similar to those described above for the Petschek model) and a much more elongated DR (more similar to that envisaged by the Sweet & Parker model; see Priest 1986): both these features are observed in LASCO/C2 images (Figure 6). The evolution shown in Figure 7 indicates a progressive transition from a faster reconnection associated with a white light large-scale structure qualitatively similar to that envisaged by the Petschek model, to a slower reconnection associated with a more elongated large-scale structure similar to that envisaged by the Sweet & Parker model. In the following section, we are going to investigate the following question: is it possible to reproduce by numerical simulations the occurrence of the observed secondary eruptions and the evolution of the aperture angles ϕ_u and ϕ_d observed in the white light between the SMSs?

3. SIMULATIONS OF SIDE RECONNECTIONS

In this section, we describe how the observed secondary eruptions described above have been reproduced by numerical simulations of the solar corona. The aim of these simulations is not only to demonstrate how a CME can produce these secondary eruptions, but also to discuss if and how the latter may have consequences on the CME initiation and on its subsequent evolution.

3.1. Description of the Numerical Model

The solar corona, the initial arcades, and the wind are modeled in the framework of ideal MHD where the equations are solved numerically in spherical geometry and assuming axisymmetry (2.5-D), over a 480×201 cell grid for $(r, \theta) \in [1 R_\odot, 30 R_\odot] \times [0, \pi]$. At the inner boundary the radial resolution at the solar surface is 1.5 Mm, while the angular resolution at the equator is 5.5 Mm. All the simulations discussed in this paper are performed with a modified version of the versatile advection code (VAC; Tóth 1996). The magnetic field is kept divergence-free by using an approach similar to Balsara & Spicer (1999), but instead of storing the magnetic field components B_r and B_θ on a staggered mesh, we use the vector potential component A_ϕ in the nodes. The MHD equations are solved in a frame corotating with the Sun where one solar rotation corresponds to a Carrington rotation of approximately 25 days, 9 hr, and 7 minutes, resulting in the inclusion of the centrifugal and Coriolis force. The other source terms in our model are related to the gravitational force, with an escape velocity of $6.18 \times 10^7 \text{ cm s}^{-1}$, and an additional heating/cooling term that mimics the effect of heat conduction and dissipation above the transition region to reproduce a realistic solar wind. For the latter, we use a functional form of the extra heating/cooling term Q closely resembling that of Groth et al. (2000), and later described in more detail by Manchester et al. (2004), namely

$$Q = \rho q_0 (T_0 - T) \exp \left[\frac{-(r - R_\odot)^2}{\sigma_0^2} \right], \quad (6)$$

where ρ is the plasma mass density and q_0 is the volumetric heating amplitude. The target temperature, T_0 , is $1.5 \times 10^6 \text{ K}$ from a certain critical angle $\theta_0(r)$ in the direction of the equator and $2.63 \times 10^6 \text{ K}$ in the direction of the poles. For $r < 7 R_\odot$, this critical angle is defined by $\sin^2(\theta_0) = \sin^2(17.5^\circ) + \cos^2(17.5^\circ)(r/R_\odot - 1)/8$. For $7 R_\odot < r < 30 R_\odot$, this becomes $\sin^2(\theta_0) = \sin^2(61.5^\circ) + \cos^2(61.5^\circ)(r/R_\odot - 7)/40$. The heating scale height σ_0 is 4.5 from the critical angle equatorward and it increases poleward as $\sigma_0 = 4.5[2 - \sin^2(\theta)/\sin^2(\theta_0)]$. The adiabatic index is $\gamma = 5/3$. The inclusion of this extra source term will create the bimodal structure of the solar wind. The same formulation of the heating/cooling term has been used repeatedly in previous studies of the CME initiation (e.g., van der Holst et al. 2007; Zuccarello et al. 2008; Soenen et al. 2009). The inner boundary of the simulation domain corresponds to the lower solar corona, where we have fixed the density to $\rho = 10^8 \text{ cm}^{-3}$, the temperature is $T = 1.5 \times 10^6 \text{ K}$, and the boundary angular velocity is set to zero in the corotating frame. The radial component of the magnetic field is kept constant, and all other values at the solar base and the outer boundary located at $30 R_\odot$ are extrapolated. The initial configuration of the magnetic field in this simulation is a superposition of a dipole and quadrupole potential field. The corresponding vector potential is given by

$$A_\phi = \frac{\sin \theta}{r^2} \left(B_1 + B_2 \frac{5 \cos 2\theta + 3}{4r^2} \right), \quad (7)$$

where B_1 and B_2 are constants (with values of -1.1 G and -2.2 G , respectively); the maximum strength of the magnetic field is $|B| = 11 \text{ G}$. The initial setup of the magnetic field consists of three arcades, enclosed by the global dipole field. The radial outflow of the solar wind (as shown in Figure 8) will stretch the three arcade structures outward and remove the overlying field, resulting in the triple streamer configuration shown in Figure 9.

The stationary solar corona obtained after time relaxation (Figure 9, left panel) is very similar to the configuration that was extrapolated on the plane of the sky from the observed photospheric fields shown in Figure 2 (right panel). In particular, the open field-line regions at the poles and the two groups of extended closed loops (associated with the NS and SS) are reproduced. The more confined system of loops at the equator corresponds to the extrapolated equatorial system of ARs.

3.2. Simulation Results

The system is driven on the inner boundary in order to obtain a CME that will then allow us to study its evolution over time. To produce a CME, we essentially want to energize the central streamer by stressing the magnetic field sufficiently. By applying shearing motions on a confined part of the inner boundary, the inner streamer is made unstable. Shearing of the magnetic footpoints is a popular and successfully applied technique to obtain CME liftoff in numerical simulations (e.g., Linker & Mikić 1995; Antiochos et al. 1999; Jacobs et al. 2006; van der Holst et al. 2009; Soenen et al. 2009).

The azimuthal velocity v_ϕ we impose on the inner boundary can be expressed as

$$v_\phi = v_0(\lambda^2 - \Delta\Theta^2)^2 \sin \lambda \sin[\pi(t - t_0)/\Delta t], \quad (8)$$

where the shear flow start time is $t_0 = 0$, the solar latitude over which the shear is applied is denoted by λ , $\lambda = \pi/2 - \theta$ is in the range $|\lambda| < \Delta\Theta$, $\Delta\Theta = 0.5$, and $v_\phi = 0$ otherwise. The total

Figure 8. Contour plots of the radial velocity (left) and density (right) in the modeled stationary solar wind.
(A color version of this figure is available in the online journal.)

Figure 9. Left: the initial coronal configuration used in our simulations obtained by the potential superposition of a dipolar and a quadrupolar configuration. The purple and green colored field lines represent regions of open field lines and fast flow while the three streamers are colored in white. Right: the orientation of the magnetic field lines of the initial coronal configuration.

(A color version of this figure is available in the online journal.)

shear time, Δt , is 42 hr. The maximum shear flow is defined by the value of the amplitude, v_0 , and is 14 km s^{-1} . This value is substantially higher than what is observed on the Sun. However, the oversimplification of the magnetic configuration and the fact that there should be a compromise between observational constraints and computational requirements, makes this an acceptable value. This three streamer configuration will require less shear to erupt than a single streamer embedded in a simple dipolar field as there is less overlying field that needs to be removed for the eruption. The streamer will also require less shear to get disrupted than its corresponding potential field configuration since it is already partially open to begin with and will therefore start off with a larger magnetic energy (Linker & Mikić 1995).

3.2.1. Time Evolution

Figure 10 (top panels) shows the time evolution of the system in response to the applied shearing motions. The color code indicates the relative density, i.e., $\rho_r(t) \simeq [\rho(t) - \rho(0)] / \rho(0)$, while the white lines represent the magnetic field lines. The

leftmost top panel of Figure 10 shows the steady-state coronal configuration. An extra upward magnetic pressure force is built up due to the extra azimuthal magnetic field, B_ϕ , generated at the solar base in response to the applied shearing motions, eventually causing the central structure to expand outward. The plasmoid has expanded outward significantly after $t = 15 \text{ hr } 58 \text{ minutes}$ (Figure 10, second top panel). The expansion of the middle arcade moves the cusps of the side streamers toward the solar poles and compresses the plasma in the current sheets, as is demonstrated by the increase in relative density in these regions. Figure 10 (third top panel) shows how the central structure has continued to expand outward. As it rises outward, the plasma within the central streamer is accelerated into the solar wind, stretching and opening the field lines. Eventually, a current sheet is created underneath the expanding arcade, allowing the lower-lying loops to reconnect and, after $t = 22 \text{ hr } 7 \text{ minutes}$, the flux rope is ejected from the solar surface. Figure 10 (fourth top panel) shows how the CME has expanded outward even further and consists of a bright leading edge, a cavity, and a dense core embedded in this cavity. The

Figure 10. Top: snapshots showing the relative mass density and magnetic field lines at different times during our simulation. The leftmost panel shows the initial configuration. The second panel and third panel show how the relative density has evolved after $t = 15$ hr 58 minutes and $t = 19$ hr 40 minutes, clearly showing how the expanding CME is pinching the northern and southern streamers. The fourth panel shows the evolution after $t = 22$ hr 7 minutes where we can clearly see how induced lateral reconnection has detached the top parts of the two streamers. Bottom: snapshots showing the azimuthal current density and magnetic field lines at different times during our simulation. The left panel shows the current density at $t = 15$ hr 58 minutes. Later panels show how the reconnection region changes in altitude over time.

(A color version of this figure is available in the online journal.)

expansion of the central arcade has induced reconnection in the two adjacent streamers resulting in the detachment of the top of both streamers (at $\approx 4.5 R_{\odot}$). Because of the up–down symmetry in the simulation, these detachments occur simultaneously for both the NS and SS. Toward the end of the shear profile, the streamers reform and the original triple streamer configuration is recovered.

As can be seen in Figure 11, the maximum CME velocity in the simulation is approximately 360 km s^{-1} , making it a slow CME. The CME velocity is measured by tracing the center of the flux rope, i.e., the maximum vector potential, along the equatorial plane. The CME gets accelerated toward this speed after which it is simply carried away by the solar wind. The previously detached side streamers decelerate the main CME, slowing it down to a velocity below the solar wind speed.

When the distance between the expanding central streamer and the adjacent streamers is of the order of the grid resolution, reconnection will set in. The reconnection in these simulations is

a numerical effect due to the presence of numerical dissipation, which is necessary to stabilize the numerical scheme. An easy way to identify the regions where reconnection takes place is to look at the azimuthal current density: a high negative/positive azimuthal current density indicates the reconnection regions. The bottom panels in Figure 10 show the current density at different times during our simulations. The plasmoid that has started to form within the central streamer will continue to accelerate toward the local solar wind speed as the build up of pressure in the plasmoid overcomes the tension trying to restrain it. The outward expanding plasmoid pushes the adjacent NS and SS, inducing reconnection between them as shown in Figure 10 (first bottom panel). As the plasmoid continues to rise, it pushes ahead of it the upper parts of the NS and SS. The middle streamer propagates outward and the location of the reconnection with the side streamers moves to higher latitudes and heliocentric distances. The region of contact between the upper and lower parts of these streamers and the plasmoid

Figure 11. Velocity vs. height plot for the CME speed and the background solar wind speed (in the equatorial plane). The maximum CME velocity is approximately 360 km s^{-1} .

continues to be stretched out so that a larger reconnection region can be detected (Figure 10, second bottom panel). This process continues (Figure 10, third bottom panel) until the upper and lower parts of the two streamers are finally severed (Figure 10, fourth bottom panel).

Figure 12 compares the aperture angles from the simulations (θ_u and θ_d , left panel) with those measured from white light observations (ϕ_u and ϕ_d , right panel). In the early phase of the simulated CME expansion, θ_{up} and θ_{down} open up, while later on, as the breakout reconnection sets in at the bottom of the flux rope and the CME starts to detach, the aperture angles from simulations close down. Observed values qualitatively agree with simulations in the later evolution (even if from simulations $\theta_u > \theta_d$ at any time, while results from observations give $\phi_u < \phi_d$): this is likely related to the fact that aperture angles could not be measured from white light observations at earlier times, when the reconnection occurred below $2 R_\odot$.

In these ideal MHD simulations, the magnetic reconnection is only due to numerical dissipation. This numerical resistivity is non-uniform since it increases in regions where there is a strong gradient, e.g., in current sheets. Amari et al. (1999) showed that the role of resistivity (which is small in the solar corona) in triggering large-scale eruptive events such as CMEs might not be so crucial. Resistive MHD simulations, where the magnetic resistivity is larger than the numerical dissipation, will not quantitatively change the overall behavior of the CME and secondary eruption. The reconnection rate, on the other hand, will change with the inclusion of magnetic resistivity. The inflow velocity scales as $v_1 \approx \eta \delta / \mu_0$. Increasing the resistivity will therefore increase the reconnection rate causing the CME and secondary eruption to detach sooner. We plan to investigate all this in detail in a future paper so that we can compare the reconnection rates in the simulations with those estimated from the observations.

3.2.2. Secondary Eruptions

The symmetrical setup of the simulation with respect to the solar equator does not allow the reproduction of the secondary eruption as shown in Figure 1 (panels (d)–(e)), as it is an eruption occurring only at one side of the CME rather than two eruptions occurring symmetrically at both sides and at the

Figure 12. Up and down aperture angles between the SMSs as computed from our simulation (θ_u and θ_d , left) and those obtained from LASCO observations (ϕ_u and ϕ_d , right). See also Figure 6, panel (e), for a definition of ϕ_u and ϕ_d angles.

same time. With the axisymmetric setup of the simulation, we do not take into account that the observed magnetic field has a much more complex three-dimensional topology, as implied by the presence (1) of a tilt angle between the equatorial and the two streamer dipoles (Figure 2, left panel) and (2) of magnetic field asymmetries between the north and south hemispheres. The magnetic field in the simulation is up–down symmetric with respect to the equator, which is not exactly the case for the observed magnetic field. The 2.5-D setup of the simulation can however be used to demonstrate the concept of the secondary eruptions. The white light coronagraphic images show two streamers centered at approximate latitudes of 39°NW and 40°SW (18:00 UT) and a complex of smaller radial structures in between. The two streamers in our simulations are centered at a latitude of 35°NW and 35°SW . The complex of smaller radial structures is represented by a single streamer centered around the equator. The secondary eruption observed at one side of the CME will only be reproduced if a more complex structure is placed in between the two streamers or, alternatively, by unstabilizing one of the side streamers. We have opted for the latter and applied similar shearing motions on the central part of the SS. Results show that a secondary eruption, only in qualitative agreement with observations, can be reproduced. The central and NW streamers are pushed northward by the expanding SS; reconnection causes the tops of both streamers to eventually disconnect, while reconnection between the CME flank and the NW and central streamer causes a small secondary eruption that can be seen in Figure 13. The secondary eruption follows the disconnection of the streamer tops. This simulation shows that an erupting CME can induce reconnection and cause a secondary eruption in an adjacent streamer system.

4. SUMMARY AND CONCLUSIONS

In this work, we focused on the occurrence of secondary eruptions during and after a large-scale CME. The cause–effect relationship between these small-scale events and the main CME has been first deduced through the white light and EUV observations and then demonstrated by MHD simulations. The observed secondary eruptions are induced by the CME expansion in the surrounding corona, where side reconnections can be induced *directly* between the CME flank and the nearby streamer boundary (producing secondary eruptions) and/or *indirectly* along the streamer current sheet (inducing streamer detachments).

In the analysis of the white light data acquired by the *SOHO*/LASCO coronagraph relative to the induced streamer

Figure 13. Snapshot of the relative density and magnetic field lines showing the secondary eruption in the wake of the disconnected streamer top. (A color version of this figure is available in the online journal.)

detachment, we developed a new technique to derive the evolution of the inflow reconnection rate M_1 . The knowledge of this parameter is fundamental to the development of the magnetic reconnection theory: M_1 was first measured many years ago in a two-ribbon flare by Poletto & Kopp (1986) and there are many measurements of M_1 in the lower corona during solar flares in the literature, obtained with different techniques (see, e.g., Tsuneta 1996; Yokoyama et al. 2001; Qiu et al. 2002; Isobe et al. 2005; Nagashima & Yokoyama 2006). Nevertheless, there are very few measurements of M_1 in the higher corona during and after CMEs: Ko et al. (2003) and Lin et al. (2005) estimated M_1 in post-CME CSs by measuring the reconnection inflows and outflows from the DR, while more recently Poletto et al. (2008) estimated the evolution of M_1 below an expanding CME by measuring the angle ϕ between the SMSs. Values obtained by these authors range between $M_1 \sim 0.01$ and 0.23.

The technique used by Poletto et al. (2008) has been improved here, by removing the assumption made in that work that the density compression ratio x between the CS and the coronal plasmas is $x \simeq 1$. The new technique developed here allows an evaluation of the reconnection rate from white light images without measuring the inflow or outflow velocities, subject to large uncertainties. By simply measuring from the LASCO/C2 data acquired during a streamer detachment of the compression ratio x and the angle ϕ between the SMSs, we found that M_1 progressively decreases with time/altitude from $M_1 \simeq 1$ down to $M_1 \simeq 0.3$, for altitudes ranging between ~ 2.5 and $5.5 R_\odot$. As discussed above, these values (far too large for the original Petschek and Sweet & Parker reconnection theories) can be considered as theoretically acceptable by taking into account further developments of reconnection theory in the last decades (see Priest & Forbes 1986; Litvinenko et al. 1996; Jardine & Allen 1998). Hence, these observations (together with the results of Poletto et al. 2008) demonstrate that after a CME or a streamer detachment, the magnetic reconnection rate in the post-eruption

structures progressively slows down with time/altitude. This suggests that, as $M_1 \rightarrow 0$, the process will probably end up leaving in the post-eruption corona a more stable streamer-like structure aligned with the CME or the streamer detachment.

The reconnection rate M_1 has also been estimated here at lower altitude for another secondary eruption by making use of the *SOHO*/UVCS data, where the reconnection is observed as a couple of features approaching each other. This gave us the opportunity to estimate the coronal reconnection inflows and outflows, and hence the reconnection rate M_1 . A similar analysis has been performed, for instance, by Lin et al. (2005) to infer the reconnection rate in a post-CME CS from the UVCS data, where two approaching features were detected in the evolution of the H Lyman- α $\lambda 1216$ Å line intensity. As far as we know, results reported here represent the first estimates from the UVCS data of reconnection inflows associated with a CME-driven side reconnection; the inflow pattern (Figure 4) is very similar to what has been reported at lower altitude by Yokoyama et al. (2001, see Figure 4 in their paper). From the first analysis of these data, Bemporad et al. (2008) already concluded that, due to the weakness of coronal magnetic fields at the UVCS slit altitude ($0.8 R_\odot$ above the limb), the observed plasma heating during the reconnection can be almost entirely ascribed to the adiabatic compression due to the expanding CME. Here, the same data have been further analyzed in order to estimate the reconnection rate M_1 : from the ratio between the reconnection inflow and outflow velocities we found that, at $1.8 R_\odot$, $M_1 \simeq 0.05$. This value, much lower than those derived at higher altitude from the LASCO/C2 data and closer to what was observed in the lower corona by previous authors during flares, suggests that, moving down from ~ 2.5 to $1.8 R_\odot$ a further decrease of M_1 also occurs. Hence, M_1 possibly maximizes at an intermediate altitude between ~ 2.5 and $1.8 R_\odot$.

The simulations presented here started from an initial magnetic field configuration that mimics the field configuration extrapolated in the corona from photospheric fields using a PFSS approximation. The initial axisymmetric simulations were able to reproduce the observed streamer detachments. The expanding CME interacts with the adjacent streamers, inducing reconnection, and eventually detaches the streamers. Moreover, the simulated evolution with time of the aperture angles between the SMSs is in qualitative agreement with the evolution observed in white light images, at least for the later part of the evolution. These axisymmetric simulations did not manage to reproduce the observed secondary eruptions. However, when stressing the bottom streamer instead of the central structure, a secondary eruption was observed in our simulations. This clearly shows the need for a non-symmetrical setup to produce secondary eruptions. Moreover, we concluded from our simulations that the lateral reconnection seems to facilitate the CME release, because the system has to be sheared less than was required in previous simulations where no adjacent streamers were present. This suggests that the occurrence of side reconnections could play a fundamental role in the final CME release: this possibility will be investigated in much more detail in a future work.

A.B. is grateful to Dr. B. Vršnak, G. Poletto, and M. Jardine for very useful discussions on the magnetic reconnection process; the author acknowledges support from ASI/INAF contract I/035/05/0. *SOHO* is a mission of international cooperation between ESA and NASA. Numerical results were obtained in the framework of the projects GOA/2009-009 (K.U. Leuven), G.0304.07 (FWO-Vlaanderen),

3E090665 (FWO-Vlaanderen), and C 90347 (ESA Prodex 9). Financial support by the European Commission through the SOLAIRE Network (MTRN-CT-2006-035484) and support from the European Commission's Seventh Framework Programme (FP7/2007-2013) under the grant agreement No. 218816 (SOTERIA project, <http://www.soteria-space.eu>) is gratefully acknowledged. The numerical results were obtained on the HPC cluster VIC of K.U. Leuven.

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