A HIGH-SPEED ERUPTING-PROMINENCE CME: A BRIDGE BETWEEN TYPES

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Abstract. Several studies have indicated that there may be two distinct types of coronal mass ejections (CMEs); a high-velocity bright energetic type associated with flares, and a smaller slower less impressive type associated with erupting prominences. How valid is this distinction? We analyze a CME combining attributes of both types, a high-velocity bright CME associated with an erupting prominence. A study of this event and several others allows us to argue that the apparent differences separating the two types may be an observational effect. Our results are consistent with a single CME process for both flare-associated and filament-associated CMEs. This process consists of three stages. The initial stage is brought about by the emergence of new magnetic flux, which interacts with the pre-existing magnetic configuration and results in a slow rise of the magnetic structure, which later becomes the CME. The second stage is a fast reconnection phase with flaring and a sudden increase of the rise velocity of the magnetic structure. It also includes a rapidly increasing CME acceleration followed by a rapidly falling acceleration. The third stage or CME propagation stage shows only slow changes in the acceleration and finally the velocity becomes constant. LASCO observes only the third stage. The differences found between observed flare-associated and prominence-associated CME velocity behavior appear to be primarily due to the relative heights in the corona at which the erupting structures form.

1. Introduction

It has long been established that CMEs occur in association with both active-region solar flares and with erupting quiescent filaments. (Filaments are also called prominences when viewed on the solar limb against the plane of the sky. We use the terms prominence and filament interchangeably). Some studies have stressed the similarity between CMEs from these two sources (Feynman and Martin, 1995; Švestka, 2001), particularly the form of the spatial structures. Others have drawn attention to differences in the behavior of these CMEs within the corona. One of the most interesting differences, first pointed out by MacQueen and Fisher (1983), is the contrast of the behavior of the CME velocities within the corona. CMEs associated primarily with active-region solar flares typically have constant or decreasing velocities in the corona, whereas quiescent filament-associated CMEs show constant acceleration as they pass through the corona (Sheeley *et al.*, 1999; Andrews and Howard, 2001; Moon *et al.*, 2002).

The topic of the division of CMEs into types has been the subject of many papers in the last few years. The definition of the types varies somewhat from

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paper to paper. In their review Andrews and Howard (2001) describe the two types of events as follows: 'Type A (accelerating) events produce curved (positions of the CME front as a function of time) plots that often indicate a constant acceleration. These events are usually associated with pre-existing helmet streamers, and are often associated with prominence eruptions or filament disappearances. The Type C (constant speed) events show a constant speed. These events are usually brighter, larger and faster than Type A events and may be associated with X-ray flares. While the two types of events can be distinguished in other ways, the height – time plots are a simple and unambiguous way to make this distinction.' We adopt their recommendation and use the height – time plots to distinguish between the two types of events.

It has also been reported that the CMEs associated primarily with filaments have systematically lower velocities than those associated with active regions (Webb, 1998; Delannee, Delaboudinière, and Lamy, 2000; Moon *et al.*, 2002). In this paper we discuss a counter example and explore its implications for understanding CMEs. We describe a clearly observed filament-associated Type A event in which the CME reaches an extremely high velocity within the corona, i.e. $v > 1500\ \mathrm{km\ s^{-1}}$.

The separation of active-region events and prominence-associated events is not a trivial task. Observations of active regions and prominences can be described in much the same terms. On the one hand, active regions in which flares occur often contain filaments. On the other, eruptions of filaments not associated with active regions are sometimes accompanied by flaring (Dodson and Hedeman, 1970). Nevertheless, studies of the Sun and solar activity have long distinguished two classes of prominences: active-region prominences (ARP) and quiescent prominences (QP). Both types of prominences overlie neutral lines in the magnetic field. ARPs are the short filaments that form low within the chromosphere above the strong localized magnetic fields of active regions (Rompolt, 1990). In contrast, QPs form in weak field regions, are relatively long and remain stable for a long time. The CME we describe in detail below is clearly associated with an erupting QP.

2. CME of 12 September 2000

On 12 September 2000, a long quiescent filament erupted and was observed by a variety of space-based and ground-based instruments. A CME occurred and an intense two-ribbon flare was seen in extreme ultraviolet by the EIT (Extreme Ultraviolet Imaging Telescope) instrument on the SOHO spacecraft. The energy release process in the flare has been studied by Vršnak *et al.* (2003a, b), H. Wang *et al.* (2003). Here we study the event in the context of CME types.

The data used in this study are from the catalog of CMEs seen by SOHO LASCO (Large Angle and Spectrometric COronagraph) C2 and C3 coronagraphs, and the corresponding SOHO/EIT images. The C2 and C3 coronagraphs cover the range of coronal distances from 1.5 to 30 solar radii. We use the full-disk EIT images as seen in the Fe XII line at 195 Å. This line forms in the lower corona and is common at a temperature of 1.5 million degrees K. In addition, we use the NOAA/Space Environment Center data for energetic particle fluxes and the National Geophysical Data Center reports for Hα flares, X-ray flares, prominence activity and active-region areas.

The 5 panels of Figure 1(a) and 1(b) show a time history of the event as seen by SOHO. The top panel shows the Sun before any activity took place in the region of interest. The 23-degree long quiescent filament, seen as a dark band in the 195 Å data, is lying above a magnetic neutral line. The LASCO (C2) image taken at nearly the same time shows a coronal streamer near the position at which the CME will take place. The filament began to rise slowly at about 10:00 UT and became unstable at 11:30 UT $\pm$ 10 min. This eruption was observed from the ground as a 'disparition brusque', sudden disappearance. In panel two (11:24 UT) the rising filament seems to show some helical structure (see also Vršnak *et al.*, 2003a, b). The C2 observation is unchanged. In panel 3 (11:48 UT) the plane-of-the-sky projection of the rapidly rising prominence material has reached the solar limb and there are EIT flare brightenings along the edges of the channel in which the filament had lain. The CME is seen in the corona in the C2 frame at 12:06 UT, establishing that the filament eruption and the CME are parts of the same event. Panel 4 ($\approx$ 12:30 UT) shows the CME well beyond the C2 occulting disk and the 195 Å flare saturating the EIT detector. The C2 image is quite clearly compatible with the expected three dimensional shape of the CME, i.e., a loop-like end to a tunnel-like shape. This is in agreement with a large angular extent of CMEs (Hirshberg, 1968) in the direction parallel to the two-ribbon flare and a smaller angular extent in the direction perpendicular to the flare ribbon. The 5th panel shows the two-ribbon flare in 195 Å. The two legs are connected by bright arches formed by the reconnection of the magnetic field loops below the erupting CME (see, for example, Forbes, 2000). The 195 Å flare continued to be very bright as the ribbons moved apart for at least 6 hours. The CME is now far beyond the C3 occulting disk edge as shown in the figure and the energetic proton event has begun as evidenced by the bright spots scattered across the image. These are caused by particles at 1 AU interacting with the detection elements of the EIT instrument, see also Figure 2. The ejected prominence material is seen within the CME as bright strands.

The usual source of data for Hα optical flares used in CME studies is the reports of the National Geophysical Data Center. Five observatories reported an optical manifestation of the impressive event seen in EIT 195 Å. The reported intensities varied from SF (Faint Subflare) to 2N (medium-sized and normal brightness). Thus the Hα flare was not outstanding. The observatory notes report it as a two-ribbon flare in which the brightness follows the filament disappearance in the same place. The flare onset is listed as about the time that the prominence began its rapid rise.

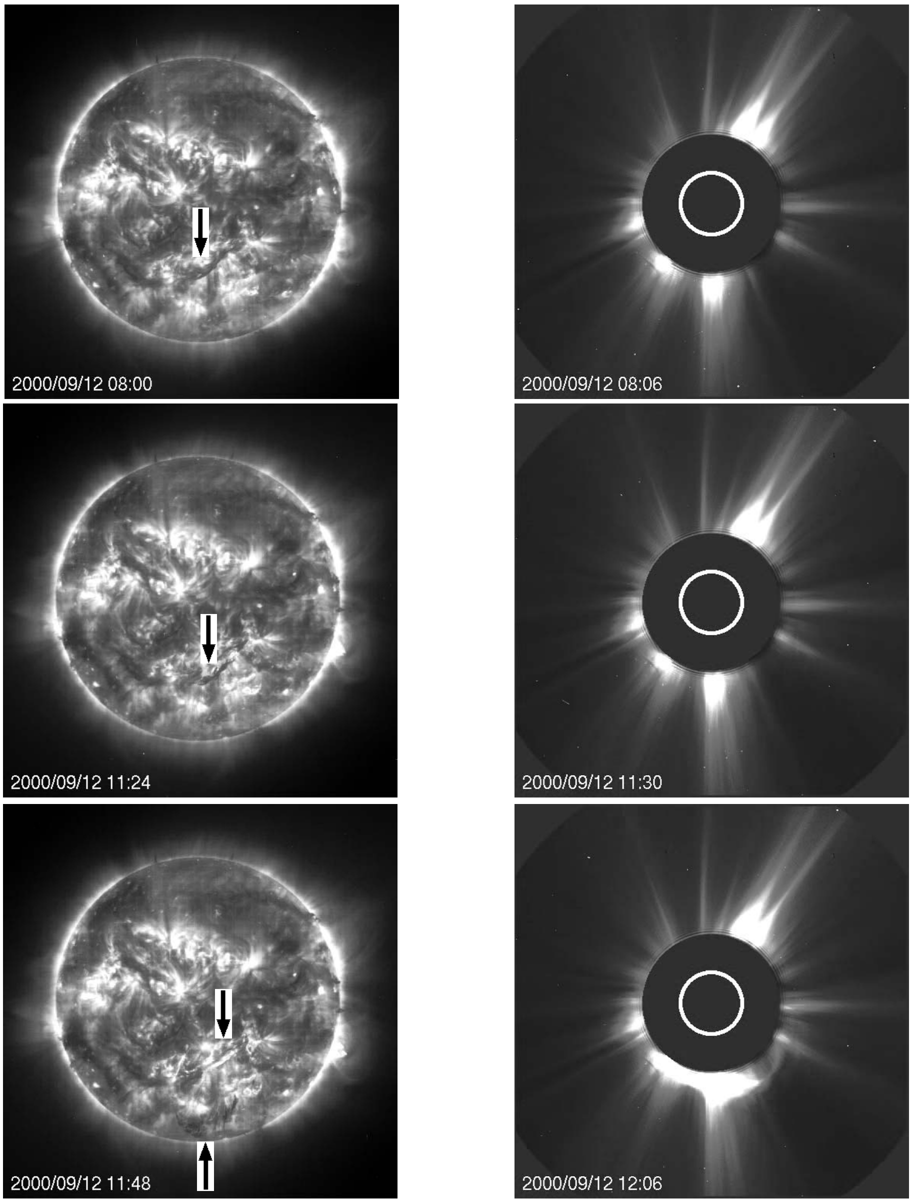

Figure 1. a. Snapshots of the September 12, 2000 event. The three panels in the *left* column show EIT 195 Å images. The *arrows* indicate structures discussed specifically in the text. The images on the *right* are from LASCO C2. The time of the observation is given at the lower left of each image.

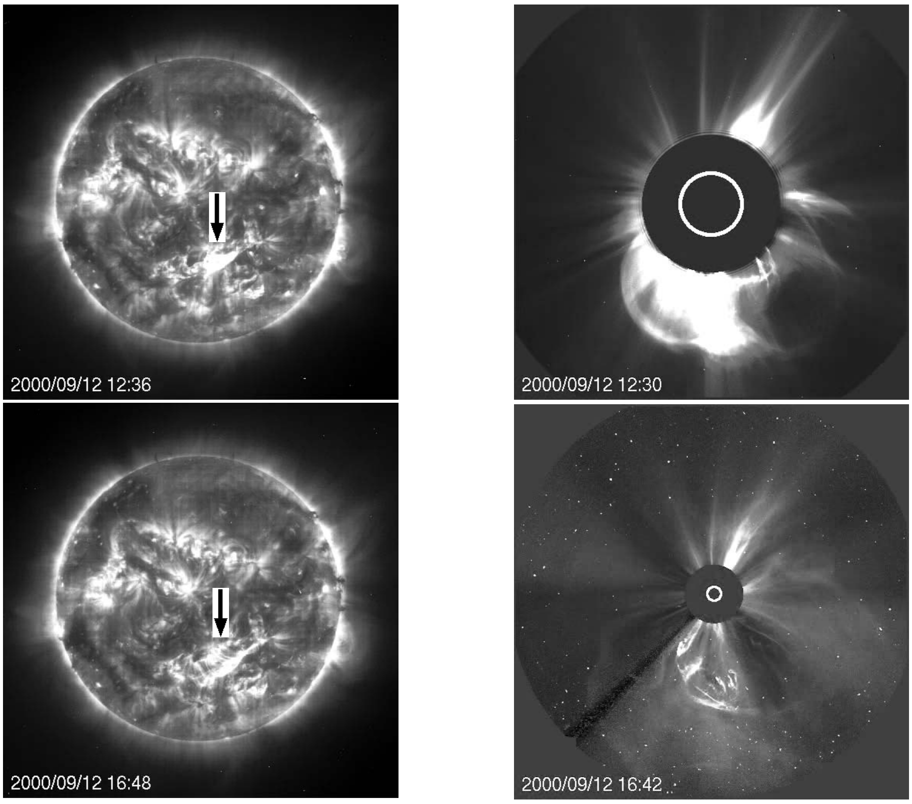

Figure 1. b. Continuation of snapshots of the September 12, 2000 event. The two panels in the *left* column show EIT 195 Å images. The first image on the *right* is from LASCO C2 and the second image is from LASCO C3.

The event was also accompanied by a soft X-ray flare, but its onset time could not be accurately determined because it was obscured by the decay phase of an earlier flare as shown in the bottom panel of Figure 2.

The velocity of the CME in the corona exhibits a constant acceleration (Figure 3), thus establishing it to be a Type A event. As is typical of Type A events, it is associated with a prominence eruption. However, in many ways it did not conform to the usual description of a Type A event. It was a very large bright CME and attained a velocity of over 1800 km s^{-1} before it left the LASCO field of view. Velocities this large are very rare. In addition, unlike reported Type A events it was accompanied by a long duration (LDE) X-ray flare and a proton event (Figure 2). Hence this event combined attributes reported for Type A and Type C events, calling into question the dichotomy between these two types.

Because this CME challenges the current classification scheme, it is important to investigate its origin more closely. The events that took place on the solar surface were almost a textbook example of a picture that has been developed to describe

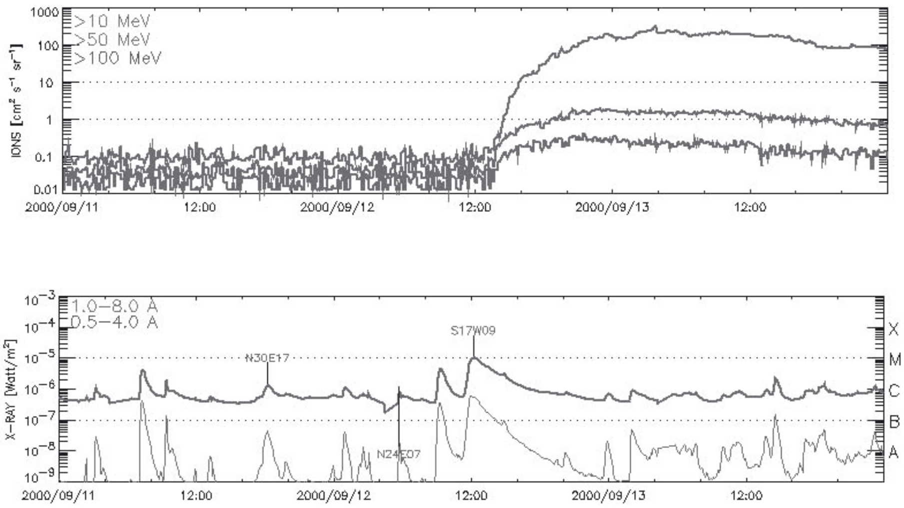

Figure 2. GOES data from September 11-13, 2000. The *top panel* gives the GOES counting rate indicating the Solar Energetic Particle Event, which accompanied the September 12, 2000 CME. The *upper line* is the $>$ 10 MeV counting rate, the lowest curve the $>$ 100 MeV rate. The *lower panel* shows the X-ray flux showing the M-class flare.

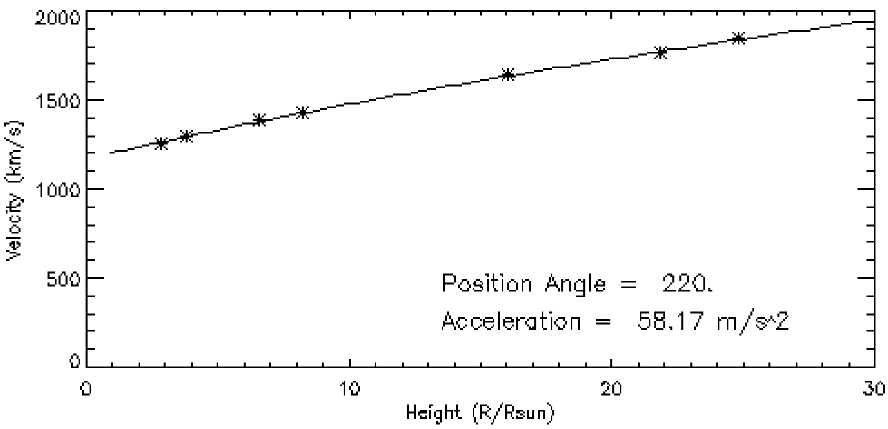

Figure 3. The best-fit constant acceleration CME velocity – height data from LASCO for the September 12, 2000 event. Velocities this high are rare.

observations of quiescent prominence eruption (QP-CME). Feynman and Martin (1995) found that the destabilization of quiescent filaments and the initiation of CMEs are strongly associated with the emergence of new magnetic flux in the vicinity of the filament (see also Wang and Sheeley, 1999). Feynman and Martin reported a very strong relationship between QP eruptions and newly emerging magnetic flux in the vicinity of the filament. Of 22 filaments that erupted, substantial flux began to emerge 1 to 4 days before the eruption in 17 cases. Conversely only

5 of 31 filaments erupted if no substantial new flux emerged in the vicinity. These results are in agreement with the 12 September 2000 CME studied here. The daily full-disk data in the *Solar-Geophysical Data* issued by NOAA for the day before the event (11 September) showed a quiescent prominence with no nearby sunspots. On the day of the event (12 September) no less than three nearby newly growing sunspot groups were reported (region 9162 at S35 W23, region 9163 at S19 W05, and region 1964 at S13 W01). Another group appeared the day after the destabilization and may also have begun its growth on 12 September. Apparently this remarkably large widespread and rapid emergence of magnetic flux destabilized the filament and caused this very-high-velocity CME.

3. CME Types for High-Velocity Events

The descriptions of Type A events and Type C events often include a comment to the effect that Type C events tend to be brighter, larger and faster than Type A events. In order to test this for the fastest CMEs we used the LASCO catalogue to survey all the CMEs from 1998 to 2001 and identified 38 events for which the velocity was > 1500 km s^{-1}. In 23 cases the sources of these events could be determined. Of these, 11 CMEs (48%) showed acceleration in the corona and 12 (52%) showed either a constant speed or a deceleration. Thus, although very fast events are rare, they are as likely to be Type A events as Type C events.

This result can be easily reconciled with the finding by Moon *et al.* (2002) that the median velocity of flare-associated CMEs was larger than the median velocity of filament-associated events. In that study CMEs such as that of 12 September 2000, which were associated with both flares and eruptive filaments were excluded from the data set. However, filament eruption events accompanied by two-ribbon flares are generally more energetic than filament eruptions without flares. The systematic exclusion of the most energetic filament eruptions may have contributed to the low mean velocity found by Moon *et al.* (2002).

4. Discussion

Although we have shown here that the division of CMEs into two distinct types of velocity profile in the corona (accelerating or constant) does not correspond to the division between CMEs associated with erupting prominences and with flares, the fact that there are two different coronal velocity profiles persists. In this section we make a suggestion for further study as to how these two velocity profiles arise. The suggestion involves a three-stage CME process, much like that suggested by Zhang *et al.* (2001) based on their study of three limb CMEs.

In the picture we will describe, we assume, with Hundhausen (1988), that all CMEs involve neutral lines in the coronal magnetic field. Magnetic neutral lines capable of containing prominences occur in active regions as well as in the larger-scale magnetic fields supporting QP.

We also assign an important role to flux emergence typically starting days or hours before the CME eruption. For erupting QP's, the role of newly erupting flux that can interact with the magnetic field configuration containing the QP was demonstrated by Feynman and Martin (1995). For QP's the flux does not need to emerge in the filament channel. The new flux need only to be oriented so that it is able to reconnect with the magnetic fields involved with the stability of the QP.

The role of newly erupting flux in active-region-associated CMEs has not been studied as extensively. However, it is well known that new flux emerges frequently within complex active regions. In addition, more distant new regions may also be involved. A case in point may be the (ongoing at the time of this writing) CME and Solar Energetic Particle events of October 2003. On 28 October 2003 there was a large and complex magnetic region containing many sunspots (region 10486) in the southern hemisphere near central meridian. An X17 flare took place in the region, a CME was launched and a Solar Energetic Particle (SEP) event took place. The halo CME left the Sun with a velocity 2125 km s^{-1}. This was the first of a series of flare/CME/SEP events that occurred over the next few days. Series like this are typical of the major proton events that threaten damage to spacecraft systems (Feynman and Gabriel, 2000; Feynman, Ruzmaikin, and Berdichevsky, 2002).

The release of this CME was preceded by a most remarkable flux emergence event (see Figure 4). At approximately the same longitude as the southern hemisphere region 10486 (86) flux began to emerge rapidly in a previous magnetically quiet area in the northern hemisphere that contained monopolar low-intensity fields and no sunspots. The first sighting of the new flux and sunspots occurred on 26 October at 14:28 UT (See Figure 4). The region grew rapidly and became a major active region (10488). When region 88 began to emerge there were no obvious coronal structures connecting it with 86 but the 88 flux soon began to interact with the 86 flux and a connecting structure could be seen in the EIT 195 Å fourteen hours after the emergence began. The connections between the two magnetic regions changed over the next 31 hr, they moved from place to place and sometimes the connections were temporarily cut. Multiple connections could be seen just before the X17 flare occurred and the CME took place. The connections seemed to be severed at the time of the CME but reformed later. It thus appears probable that flux emerging in other sunspot groups can also influence CME initiation.

4.1. The three-stage CME process

The 12 September 2000 QP CME described in this paper is a very clear example of a 3 stage CME process. The relative timing of the steps must be kept in mind.

A newly emerging activity region (9162) was first reported near the filament on 12 September at 00:45 UT. There was no obvious immediate response of the filament. About 9 hr later the filament underwent an initial first stage destabilization

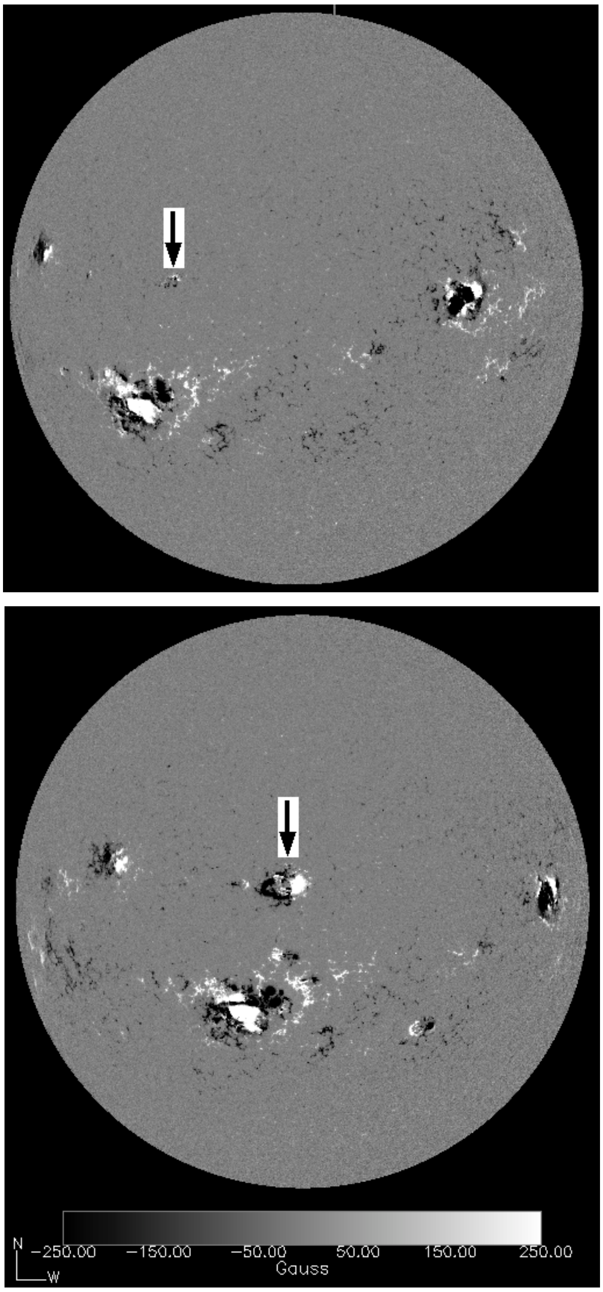

Figure 4. Newly emerging flux of October, 2003. The *arrow* in the *top panel* shows the first sighting of flux associated with sunspot region 10488 in the northern solar hemisphere on October 26, 2003. The *arrow* in the *lower panel* shows sunspot region 10488 two days later on October 28. See text for discussion of the interaction observed between the flux from 10488 and the flux from sunspot region 10486 which is at about the same solar longitude but in the southern hemisphere.

in which it became active and began to rise slowly. This first destabilization was probably caused by the interaction of the new fields with the existing coronal fields.

About one and a half hours after it began its slow rise, it further destabilized. The time of this second stage destabilization, about 11:30, was determined from a marked increase in the rise velocity. It was accompanied by the appearance of helical structure seen in the EIT image. The slow rise clearly preceding the fast acceleration stage and the appearance of helical structures is a typical sequence of events for destabilizing prominences (Rompolt, 1990; Vršnak, Ruždjak, and Rombolt, 1991). At the same time as the onset of this second and major destabilization, the X-ray (Figure 2), Hα and EIT flares began. This time also corresponds to the CME 'onset time' that would be found by extrapolating the velocity data to the solar surface (Figure 3). The timing of the second destabilization and the flares in various spectral lines appeared to be simultaneous (Vršnak *et al.*, 2003; Gopalswamy *et al.*, 2003). This second destabilization is believed to mark the onset of major magnetic field reconnection below the coronal structure that becomes the CME. The flares in various spectral lines are believed to be caused by coronal particles accelerated by the reconnection (Fletcher, 2002).

The third stage is the propagation of the CME in the corona as seen in coronagraphs.

Our description also agrees in general with the three-stage CME concept suggested by Zhang *et al.* (2001) based on their study of three limb CMEs.

The 28 October 2003 active-region-flare-associated event can also be described in terms of this three-stage picture. In the first stage the newly emerging flux interacted with the old flux and caused some re-organization of the magnetic fields in the corona. The process continued until the structure became unstable, probably because conditions for fast reconnection had been fulfilled. At this point the second stage began as the flare and CME destabilization take place. Again the third stage was the coronal propagation phase as seen by LASCO.

4.2. Height in Corona

When this three-stage picture is combined with the observation of the velocity profile of an extremely fast ($v > 2000$ km s^{-1}) limb-flare-associated CME (Gallagher, Lawrence, and Dennis, 2003) a new interpretation of the QP and ARP CME dichotomy presents itself.

Gallagher, Lawrence, and Dennis (2003) combined observations of a 21 April 2002 limb event from TRACE, UVCS and LASCO to obtain a velocity profile throughout the solar atmosphere. The first TRACE observations showed the CME front about 20 Mm above the limb of the Sun. (One solar radius equals 700 Mm). Since the source region was believed to be just behind the limb, this height gave only a very rough estimate of the height in the corona. The stage 1 slow rise was already underway.

The stage-two sudden velocity increase began when the apparent height of the CME was at about 60 Mm. In the next 10 minutes the acceleration observed by TRACE rapidly increased to about 1500 m s^{-2}. The acceleration then decreased gradually.

In the third stage, when first observed by LASCO, the acceleration given by Gallagher, Lawrence, and Dennis (2003) was down to about 300 m s^{-2}. At the time of the next LASCO image, the earliest time the velocity could be determined from LASCO data alone, Gallagher, Lawrence, and Dennis (2003) show almost constant velocity. In the CDAW LASCO catalogue the constant velocity fit is 2408 km s^{-1} and the constant acceleration best fit to the data is 17 m s^{-2}, both of which agree well with Gallagher, Lawrence, and Dennis (2003).

Assuming that the general form of velocity and acceleration vs. height curve that Gallagher, Lawrence, and Dennis (2003) found (i.e., a rapid increase in acceleration followed by a slower decrease until acceleration disappears and the velocity becomes constant) is the normal form, then the Type A and Type C dichotomy suggests that the Type A events are being observed at an earlier stage in the development then the Type C events. Since Type A events are most frequently reported to be associated with erupting prominence events and type C events with flares, this hypothesis would only be tenable if we systematically observed an earlier stage of the CME velocity profile for erupting prominence events than for flare events.

Studies of quiescent prominences and active-region prominences indicate this is the case. In a comparative study of QPs and ARPs, Rompolt (1990) showed that generally QPs form much higher in the solar atmosphere than ARPs. The average coronal height at which ARPs form is 10 Mm and that of QPs is 50 Mm. Both filament types begin the destabilization with a slow rise, which is followed by a rapid rise, so both show the first two stages of the eruption process described above. However, not only do the ARPs form lower in the corona but the sequence of events develops more rapidly in ARPs (Rompolt, 1990). This indicates that the reconnection onset occurs lower in the corona in the complex strong fields associated with active regions. In contrast, during the first slowly rising stage of the QP evolution the prominences are often visible in $H\alpha$ above the limb of the Sun and sometimes form huge arches. The maximum height at which a QP was observed to be stable was 235 Mm (Rompolt, 1990). The CMEs become visible in the LASCO coronagraphs when they reach a height of 1.5 solar radii, i.e., 1000 Mm. Thus LASCO is seeing only the later stages of the velocity and acceleration curve of CMEs, and the stage is systematically later for the ARPs than for the QPs. Thus the QPs will be more likely to show some residual acceleration.

5. Summary

We suggest that both active-region- and quiescent-prominence-associated CMEs take place in three stages:

Stage 1. Slow rise of the magnetic field configuration that either contains a prominence or is capable of containing a prominence. Stage 1 can continue for several hours. This slow rise is apparently caused by an interaction (slow or small scale reconnection?) of the magnetic fields of the pre-CME configuration with the newly emerging magnetic fields. These fields may have begun to appear as much as a day or more earlier.

Stage 2. Fast reconnection, flaring and the sudden increase of CME velocity. The acceleration profile of the CME changes rapidly as this stage progresses. In the observed cases this stage takes of the order of tens of minutes.

Stage 3. Gradually decreasing acceleration leading to constant velocity. LASCO observes only stage 3 CMEs. These CMES are classified as Type A if observed earlier in stage 3 and Type C if observed later in stage 3.

Erupting quiescent prominences tend to be Type A because prominences form higher in the corona and also rise higher before the onset of rapid reconnection. They are therefore being observed by LASCO relatively early in stage 3. Active-region events begin lower in the corona and develop more rapidly. They are therefore observed at a later stage of development, i.e., the constant velocity stage. Very-high-velocity CMEs ($v > 1500$ km s^{-1}) are as likely to be Type A as Type C.

Further studies are required to determine the extent to which this description is valid for all CMEs.

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