INITIATION AND DEVELOPMENT OF TWO CORONAL MASS EJECTIONS

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ABSTRACT

We analyze the initiation and development of coronal mass ejections (CMEs) launched on 2001 May 15 and 2001 May 25. Both CMEs show clearly recognizable three-part structure already at low heights during the initial gradual rise in the pre-eruptive phase. This provides measurements of relative kinematics of the three-part structure from the very beginning of the eruption up to the post-acceleration phase. In both CMEs the frontal rim starts accelerating some 10-20 min before the prominence. However, the acceleration maximum of the prominence and the frontal rim was synchronized. CMEs attained the maximum acceleration of ≈ 350 m s⁻² and ≈ 250 m s⁻², at the leading edge heliocentric distance \( R = 2.4 \) and \( R = 2.1 \) solar radii, respectively. In both cases the acceleration time profile of the frontal rim was broader than that of the prominence, although the peak values were similar. The CMEs attained velocities in excess of 1000 km s⁻¹, showing a weak deceleration at large heights. The leading edge of CME starts decelerating before the prominence in both cases, indicating that the deceleration is caused by the aerodynamic drag force.

Key words: Sun: coronal mass ejections, MHD.

1. INTRODUCTION

Coronal mass ejections (CMEs) are large-scale solar phenomena during which \( 10^{11} - 10^{13} \) kg of atmospheric magnetoplasm is launched into interplanetary space at speeds ranging from several tens km s⁻¹, up to 2000 km s⁻¹. CMEs often show a three-part structure: the bright frontal rim, the cavity, and the prominence (Hundhausen 1987). Observations of CMEs show several evolutionary phases (Vršnak 1998). The eruption is preceded by a gradual rising motion usually revealed by prominence growth at velocities in the order of 1 to 10 km s⁻¹. This phase can be described as a quasi-stationary evolution of the pre-eruptive structure through a sequence of equilibrium states. The acceleration phase most often starts by an exponential-like development after the height of the structure becomes comparable with the footpoint separation. The acceleration maximum is usually attained within a distance of several solar radii (Vršnak 2001). At large heights the velocity becomes roughly constant (Hundhausen 1987). A weak deceleration/acceleration caused by the aerodynamic drag force tends to adjust CME velocities to the solar wind speed (Gopalswamy et al. 2001).

CMEs are often associated with eruptive prominences (EPs), which rises a question on the causal relationship:
- are EPs driving the entire flux rope/arcade eruption,
- are EP and the frontal rim of CME two parts of a common magnetic structure that erupts as an entity,
- is it the eruption of the overlying arcade that releases the prominence lift-off,
- is it the cavity formation responsible for the CME launch,
- can the flows created by the magnetic reconnection in the associated flares push CME,
- is it the reconnection between a sheared arcade and neighboring flux systems that triggers the CME,
- is it the reconnection above the arcade providing the eruption, etc.

In this paper we analyze details of the kinematics of the three-part structure in two fast limb CMEs, from the pre-acceleration phase till late phases of the eruption. The goal is to enlarge a relatively small set of such analyzes, which is essential in advancing our comprehension of the initiation of CMEs and the forces driving the eruption.

2. THE DATA SET

The instruments of the Mauna Loa Solar Observatory (MLSO): the Digital Prominence Monitor (DPM)¹ and the Chromospheric Helium-I

¹http://also.hao.ucar.edu/dpm.gif/archive.html


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Figure 1. Evolution of 2001 May 15 (left) and 2001 May 25 (right) CMEs: a) and d) EIT FeXII 195 Å difference images, showing the frontal rim, dark cavity, and the prominence; The region of interest is shown with enhanced contrast. b) and e) MK-IV images taken at 18:39 and 17:32 UT. c) and f) LASCO C2 images taken at 19:29 and 18:06 UT. The MK-IV field of view $R = 1.08-2.85$, partly overlaps with the EIT and LASCO C2 field of view.
10830 Å Imaging Photometer (CHIP)\textsuperscript{3} are used to track the eruptions in the inner corona. These data are complemented by the HeII 303.7 Å, FeX 171 Å, FeXII 195 Å, and FeXV 284.1 Å images gained by the Extreme-ultraviolet Imaging Telescope\textsuperscript{3} (EIT; Delaboudiniere et al. 1995) aboard Solar and Heliospheric Observatory (SOHO). As an additional information we used the imaging data from the \textit{Yohkoh} Soft X-Ray Telescope\textsuperscript{4} (SXT; Tsuneta et al. 1991) and GOES soft X-ray flux measurements\textsuperscript{5} (Donnelly and Unzicker 1974).

The white-light data obtained by the Large Angle Spectroscopic Coronagraph\textsuperscript{6} (LASCO; Brueckner et al. 1995) and MK-IV K-coronameter\textsuperscript{7} of MLSO are utilized to follow the eruption from the inner corona towards the interplanetary space. The LASCO C2 and C3 coronagraphs are designed to observe the solar corona from 1.7 to 6 and 3.7 to 32 \(r_\odot\), respectively. The MLSO MK-IV K-coronameter, the Mauna Loa Solar Observatory provides images in the range 1.08 - 2.85 \(r_\odot\). The enhanced spatial resolution yields a wider field of view which overlaps the LASCO C2 instrument. The high temporal resolution (3 minutes) allows a more detailed study of the inner corona than any other coronagraph.

In Fig. 1 we display EIT FeXII 195 Å difference images (top panels), MKIV images (middle panels), and LASCO C2 images (lower panels) of the 2001 May 15 and May 25 CMEs, showing the development and propagation of the frontal rim, the cavity, and the prominence.

3. GENERAL DESCRIPTION OF THE EVENTS

3.1. The CME of 2001 May 15

The CME 2001 May 15 took place at the position angle \(PA \approx 50^\circ\). It was associated with the eruptive prominence observed in Hα and HeI. In the late phases of the event EIT images expose a huge system of growing postflare loops, disclosing a long-duration, and probably large flare behind the limb in the active region NOAA 9461. The GOES soft X-ray data show only a very weak gradual X-ray event that had a decay phase lasting for about 7 hours. The CME also disrupted the magnetic structure of the active regions NOAA 9461/62, located southwards.

The eruption started by the appearance of an arch overlaying the prominence. It is first seen in the EIT difference image 17:12–17:00 UT at the height of 0.35\(r_\odot\), showing a gradual outward expansion. Between the leading edge of the CME and the prominence a dark cavity developed. The initial rise of the arch, which later on become the frontal rim of CME, was tracked in the EIT images. Its further kinematics was measured utilizing the MK-IV data, partly overlapping with the EIT field of view.

In MK-IV, C2, and C3 coronagraph images the CME exposes a clearly recognizable three-part structure. The frontal rim was nearly circular and consisted of two concentric elements. The prominence was characterized by helical fine structure threads. The entire structure maintained its integrity while propagating through the MK-IV, C2 and C3 fields of view.

3.2. The CME of 2001 May 25

The CME of 2001 May 25 was also associated with a huge prominence eruption which was observed as a quiescent prominence above the south-east limb a day before the eruption. The prominence was oriented in the north-south direction, having the height of approximately 0.08\(r_\odot\) above the limb. Around 17:00 UT, the prominence destabilized and began to expand.

A very faint arch developed above the prominence at 16:36 UT at \(PA \approx 110^\circ\), having the height of 0.57\(r_\odot\). It started to expand at \(\approx 16:45\) UT in the \(PA \approx 100^\circ\) direction. The direction of motion was gradually changing to \(PA = 95^\circ\) at 17:35 UT, as clearly seen in MK-IV movies. The event was recorded by LASCO C2 at 17:50 UT, at \(PA \approx 90^\circ\) having the width of 40°. Different EIT and C2 \(PA\)s indicate that the CME motion was non-radial. The appearance of the May 25 CME in MKIV, C2, and C3 images is similar, showing a clearly recognizable three-part structure. Like in the former CME, the prominence was characterized by helical fine structure threads.

Below the CME an arcade of loops developed about one hour after the filament eruption, again indicative of the flare behind the limb. However, the GOES data does not show any distinct increase of the soft X-ray flux. Since no active region appeared at the corresponding \(PA\) at the east limb in the following few days, one can conclude that if the CME was really accompanied by a flare it was a spotless flare.

4. KINEMATICS OF CMEs

The kinematics of the frontal edge of CME, the top of the cavity (lower edge of the bright frontal rim), and the top of the prominence is traced by measuring radial distances from the solar centre, \(r(t)\).

After the corresponding features in all relevant images were identified, the \(r(t)\) data measured by different instruments were joined for a given element, and smoothed. To get a more reliable smooth through the raw data we limited the smoothing intervals to specific phases of the eruption. In particular, we divided the eruptions in the pre-acceleration phase, the
Figure 2. The acceleration phase time profiles of the 2001 May 15 (left) and May 25 (right) CMEs: a) radial distances; b) velocities derived from the smoothed \( r(t) \) data; c) acceleration; d) the cavity thickness (note a different scale of the z-axis). The raw data in a) are depicted by crosses, squares, and circles, representing the frontal edge, the top of the cavity, and top of the prominence, respectively. The smoothed data are shown by thick-black, thin-gray, and thick-gray curves, respectively. In both events the time is elapsed at \( T_0 = 00:00 \) UT \( (t = T - T_0) \). In the left column \( t = 1020 \) min corresponds to \( T = 17:00 \) UT and in the right column \( t = 1000 \) min corresponds to \( T = 16:40 \) UT. In the inset of a) the complete sets of measurements are shown – the z-axis scale is the same as in d).
main acceleration phase, and the late phase. The procedure of smoothing was repeated several times, successively changing the number of steps and the smoothing interval to get an information on the accuracy of the results.

In Fig. 2a we display the raw data, $r(t)$, and smoothed curves, $\hat{r}$, covering a part of the gradual pre-eruption phase and the main acceleration phase for all three CME components of May 15 and May 25 CMEs (left and right, respectively). The complete set of measurements, covering the $R = r/r_\odot = 1 - 30$ range, is shown in the inset.

From the smoothed $\hat{r}(t)$ data we have evaluated the velocities $v(t)$ by taking two successive smoothed data points:

$$v(t_i^*) = \frac{\hat{r}(t_{i+1}) - \hat{r}(t_i)}{t_{i+1} - t_i}$$  \hspace{1cm} (1)

where $\hat{r}(t_i)$ is the height at time $t_i$ and $t_i^* = (t_{i+1} + t_i)/2$. In the following step we have estimated the acceleration by applying:

$$a(t_i^*) = \frac{v(t_{i+1}) - v(t_i)}{t_{i+1} - t_i}$$  \hspace{1cm} (2)

where $v(t_i)$ is the velocity at the instant $t_i$ and $t_i^* = (t_{i+1} + t_i)/2$.

The $v(t_i^*)$ profiles of three parts structure for both CMEs are shown in Fig. 2b, whereas the $a(t_i^*)$ are presented in Fig. 2c, for the May 15 and May 25 CMEs, respectively.

The main acceleration phase of CMEs started at approximately 18:00 UT (elapsed time $t = 1080$ min) in the May 15 event, and at 16:50 UT ($t = 1010$ min) in the May 25 event, and lasted for some 1.5 hours in both events. The initial stage of the main acceleration phase is characterized by an exponential-like growth, indicated by $v \propto \omega r$ phase (Vršnak 1998). In both events this phase lasted roughly for a half hour. The growth rate can be estimated to $\omega = 1 - 2 \times 10^{-3} \text{s}^{-1}$, being approximately the same for the leading edge and the prominence.

The May 15 CME attained acceleration maximum of $a_{max} \approx 350 \text{ m s}^{-2}$ at the heliocentric distance of $R = 2.4$ at around 18:30 UT ($t = 1110$ min). In the May 25 event $a_{max} = 250 \text{ m s}^{-2}$ was measured around 17:20 UT ($t = 1040$ min) when the leading edge was at $R = 2.1$. In both cases the leading edge and the prominence showed the almost same peak acceleration at approximately the same time. The acceleration dropped to $1/4$ of the maximum acceleration at $R \approx 6$ in both events.

In the upper corona the velocity of both CMEs became roughly constant. The frontal edges of the May 15 and May 25 CMEs attained velocities of about 1200 km s$^{-1}$ and 1050 km s$^{-1}$, respectively. This is significantly faster than the ambient solar wind, which Sheeley et al. (1997) found to be roughly 100-200 km s$^{-1}$ in C2 field of view and 200-300 km s$^{-1}$ farther out, on average asymptotically increasing towards $\approx 400$ km s$^{-1}$. Both CMEs were gradually decelerating in the C3 field of view. The frontal rim starts decelerating earlier than the prominence (see the insets in Fig. 2a).

In Fig. 2d we present the thickness of the cavity $d = r_{cav} - r_{prom}$, where $r_{cav}$ and $r_{prom}$ are the heliocentric distances of the top of the cavity and the top of the prominence, respectively. In both cases the value of $d$ in late phases decreases, or at least stagnates. The reason is the earlier beginning of the deceleration of the frontal rim than the prominence.

5. DISCUSSION

Figure 2 shows that the three-part structure elements of both CMEs exposed a generally synchronized main acceleration phase. However, a more detailed inspection reveals notable differences common to both events:

1. In the pre-acceleration phase, characterized by slow rising motion, the leading edge was considerably faster than the prominence. In the May 15 event the velocities were 70 and 15 km s$^{-1}$, respectively, and in the May 25 event the velocities were 140 and 4 km s$^{-1}$.

2. In both events the onset of the main acceleration phase of the prominence was delayed for about 10-20 min after the onset of the leading edge main acceleration.

3. The time profile of the prominence acceleration is narrower, especially in the May 15 event.

4. The deceleration of the frontal edge starts earlier than the deceleration of the prominence, which is reflected in a stagnation of the increase (or even a decrease) of the cavity thickness.

The first two items concern the onset of the eruption. Faster growth of the overlying arcade than that of the prominence indicates that the pre-acceleration phase was characterized by “swelling” of the cavity region. This implies that the buoyancy was increasing, possibly being the driver of the gradual evolution through a series of quasiequilibrium states (Low et al. 1982). In such a case the arcade and the embedded flux rope containing the prominence slowly rise till the critical point where the rope looses its equilibrium and erupts (Vršnak 1990, 1998).

The 3rd item explains why in both CMEs the prominence was at any instant slower than the frontal edge (as is often observed; Hundhausen, 1987) although the leading edge and the prominence attained almost the same maximum acceleration at about the same time (In the May 25 CME the maximum acceleration of the prominence was in fact somewhat larger than that of the leading edge.)
Since the CMEs were considerably faster than the ambient solar wind, the behaviour described in the 4th item can be straightforwardly explained by the aerodynamic drag. It is reasonable to assume that the Lorentz force decreases with the heliocentric distance, whereas the drag enhances as the velocity of CME increases. In the phase when the forces are approximately equal, the CME shows a roughly constant velocity. Gradually the drag becomes dominant, and the leading edge of CME starts to decelerate. The deceleration of the prominence is delayed due to its larger inertia (larger density). Furthermore, the information about the enhancing deceleration has to travel (at the magnetosonic speed) from the leading edge to the prominence. Bearing in mind the leading edge – prominence distance (several thousands of Mm) and the magnetosonic speed of several hundreds of km s\(^{-1}\) one finds the travel time in the order of an hour.

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REFERENCES