COMPARATIVE STUDY OF CORONAL MASS EJECTIONS ASSOCIATED WITH ERUPTIVE PROMINENCES

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ABSTRACT
Coronal mass ejections (CMEs) associated with eruptive prominences often display a classical 3-part structure in white light, viz., a bright leading edge followed by a dark cavity devoid of material and an embedded prominence or core. However, the initiation of such CMEs and nature of their acceleration as they propagate outward in the corona are some of the basic questions that remain unsolved. In particular, the question of role of the prominence in triggering or driving the CME has not been settled yet. In this paper, we report observations of coronal mass ejections associated with eruptive quiescent prominences that occurred on June 2, 1998 and June 21-22, 1998. A comparative study based on multi-wavelength observations is presented. Various features in a three part structured, white-light CME as observed by the LASCO-C2 and C3 coronagraphs aboard SOHO were compared with features in other wavelengths, for example, in Fe XIV (green) and Fe X (red) emission lines from the LASCO-C1 coronagraph. These observations were combined with other data sets in H-alpha and radio wavelengths. The comparison provides an important clue to understanding the origin or the initiation of the CMEs. Measurements of speed and acceleration of these CMEs have also been made in order to understand the nature of propagation of the CMEs in the outer corona and the driver that triggers the onset of the CMEs.

1. INTRODUCTION
It is well established that very often Coronal Mass Ejections (CMEs) are associated with eruptive prominences. In white light the CMEs are displayed as classical 3-part structure, i.e., a bright leading edge, dark cavity and then prominence or core material (Hundhausen, 1984). The associated prominences are generally long-lived and can be tracked on the solar disk for several days prior to their eruption. Detailed studies of eruptive prominences, also known as Disparition Brusques have been made by several authors (Tandberg-Hanssen, 1995 and references therein). However, until now, no satisfactory explanation to their relation with the associated CMEs has been made. In particular their role in the initiation or the trigger of the CME and the propagation of the CME is not understood very well. Hu (1983a, b) suggested that prominences act as driver for the CME. On the other hand, Harrison (1995) argued that the CMEs and the prominences are consequences of the same cause and that one does not trigger other. Recently various authors have attempted to understand the inter-relation of the CME and associated eruptive prominence based on both observations and models, [Wilk (1997), Low (1997) and Gibson and Low (1998)].

Measurements of speeds and acceleration in CMEs and the associated prominences provide an important clue to the initiation and propagation of the CME in the outer corona. Based on a study of CMEs observed over a distance of 1.2 to 2.4 solar radii using a ground-based coronagraph, MacQueen and Fisher (1983) showed that the CME height-time curves could be broadly classified into two classes. One of them is generally associated with eruptive prominences showing acceleration up to 50 m s⁻². The other one occurs in association with flares. These often start with high speeds and hardly show any acceleration. More recently, Gopalswamy et al. (1996, 1997) determined the speeds and acceleration in a rising prominence and the associated coronal arcade using YOHKOH and radio data at 17 GHz.

With the increased field of view and sensitivity of the LASCO (Large Angle Spectroscopic Coronagraphs) instruments aboard SOHO (Solar and Heliospheric Observatory) it is now possible to track CMEs from 1.1
June 21-22, 1998 (LASCO-C1, Fe XIV)

until 30 solar radii (Brueckner et al. 1995). In this paper, we present a comparative study of two CMEs observed on June 2 and June 21-22, 1998 by LASCO. Both CMEs were associated with quiescent prominences, which could be followed for several days on the disk prior to their final eruption on the west limb. For the present analysis, the LASCO observations of these CMEs have also been combined with observations at different wavelengths recorded by other instruments.

June 22, 1998 (LASCO-C3, White light)

Figure 1: Time-lapse sequence of green-line transient recorded by LASCO-C1 instrument on June 21-22, 1998 showing a dense bright knot 'Pg' embedded within a large overlying loop 'L' (19:47 UT frame). The field of view of LASCO-C1 is from 1.1 to 3 solar radii. Each image shown here is subtracted from a reference image taken prior to the activity. Details of the instrument and image processing technique of the LASCO-C1 images can be found in Schwenn et al. (1997).

Figure 2: The CME of June 21-22, 1998 as observed in white light by LASCO-C3 showing the slow propagation of the leading edge 'LE', and the prominence material, 'PR' behind (10:06 UT frame). The selected frames are difference images obtained after subtracting a base image taken before the CME occurred.

2. OBSERVATIONS

2.1 June 21-22, 1998 CME:

LASCO observed a huge CME associated with an eruptive prominence at the north-west limb during June 21-22, 1998. The three LASCO instruments have been designed to observe the corona from 1.1 to 3, 1.7 to 6.0, and 3.7 to 32 solar radii, respectively. The initial phase of the CME was recorded by LASCO-C1 in Fe XIV (5302 Å) and Fe X (6376 Å) emission lines. In Fe XIV images, a slowly rising loop was observed from 10:47 UT until 01:31 UT on June 22. Figure 1 shows the temporal evolution of the transient in Fe XIV line. An examination of Fe X images (not shown here) reveals that there is no feature in Fe X corresponding to the overlying loop 'L' as seen in Fe XIV line, however the dense bright knot 'Pg' seen in Fe XIV line was visible as twisted feature in Fe X line. No observations were taken...
June 2, 1998 (LASCO-C1, Fe XIV)

Figure 3: Temporal evolution of the mass ejection in the inner corona as seen in Fe XIV line on June 2, 1998 by LASCO-C1. Each image has been subtracted from the same pre-event image. This mass ejection is morphologically similar to that observed on June 21, 1998 in green line with a bright knot 'Pg' embedded within an overlying loop 'L'.

on this day by EIT telescope which images the Sun in EUV. In white-light, the CME was tracked by LASCO-C2 and then by C3 until 17:35 UT on June 22. Figure 2 shows the typical three-part structure of a white light CME, with a bright leading edge, a dark cavity that is followed by a bright and dense core corresponding to the prominence material. The CME observations were supported by H-alpha observations of the erupting prominence during 18:47 - 22:14 UT, made using H-alpha telescope at Helio Research in La Crescenta, California and also from Nobeyama Radioheliograph which imaged the sun at 17 GHz during 22:45 UT/June 21 until 02:45 UT/June 22. It is worth pointing out that the associated prominence had already been observed on the disk from 12th June when it appeared on the east limb until its final disappearance on June 21. This is evident from H-alpha and Ca K3 daily images obtained from Meudon observatory. During its disk passage, the filament underwent structural changes prior to eruption owing to large-scale magnetic field restructuring in the nearby active regions. The details have been presented in another paper (Srivastava et al. 1999a).

June 2, 1998 (LASCO-C2, White light)

Figure 4: June 2, 1998 CME as observed by LASCO-C2 coronagraph in white light. All frames are differenced from a base image recorded before the CME. This is a very classical example of the three-part structure CME with a bright leading edge. The inner core or the prominence is observed as helical braided structure as it propagates out in the corona.

2.2 June 2, 1998 CME:

The June 2, 1998 CME was very similar in appearance to the June 21-22 event. This CME was also associated with an eruptive prominence on the south-west limb. It had been tracked throughout its disk passage during May 16 - June 2, 1998 as seen from H-alpha and Ca K3 daily images obtained from Meudon Observatory. In addition, the observations were recorded in Fe XII emission line (195 Å) with the EIT telescope aboard SOHO during the eruption of the CME. Figure 3 shows time-lapse images of the green line transient on June 2 as obtained by the LASCO-C1 instrument. The features in this case are analogous to the structures seen in June 21-22 CME, in green line. These images show a bright
tall loop in Fe XIV emission line. Inside the loop lies a twisted knot-like structure corresponding to the bright core/prominence material in the white light CME. In Fe X images, only the twisted structure of the prominence could be seen. Figure 4 shows the temporal evolution of the CME in white light as observed by LASCO-C2. These images show conspicuously the bright leading edge, LE, and the core or the prominence, PR, in the form of a helical twisted feature, inside. The projected speed of the CME in the outer corona was much faster than that of June 21-22 CME.

3. ANALYSIS AND DISCUSSION

Generally it is difficult to compare observations made by different instruments because of the different techniques that are used to image them. Attempts have been made to compare the white light CMEs with green line transients (Plunkett et al. 1997 and references therein). Because the two CMEs under study were very similar in morphology, we attempted to compare distinct features of the two CMEs i.e., the leading edge and the core or the prominence. We not only analyse the white light CME features as observed by LASCO-C2 and C3 coronagraphs and the green line (Fe XIV - 5302 Å) and red line (6374 Å) transients recorded by LASCO-C1 but also compare them with the observations in chromospheric H-alpha line (6563 Å). These observations were complemented by radio observations at 17 GHz for the June 21 CME and with EIT images in Fe XII (195 Å) in case of the June 2, CME. Combined height-time graphs for both CMEs including the observations from different instruments are presented in Figure 5.

From a close examination of identifiable features for each case, we find that the leading edge of the frontal loop visible in LASCO-C2 and C3 match well with the outer loop in Fe XIV images obtained by LASCO-C1. This overlying loop remains stable for a few hours before rising slowly in case of the June 21 CME. Further, the top of the bright core/prominence recorded in white light coincides with the location of the bright knot observed in Fe XIV images. The leading edge and the prominence/core continue to propagate outwards for several hours until they traverse the LASCO-C3 field of view. In contrast, the outer loop seen in Fe XIV images, in case of the June 2 CME does not remain stationary since its first appearance on the south-west limb, and it rises relatively faster. The mass ejection takes only about 10 hours to cross through the field of view of LASCO-C3 as compared to approximately ~16 hours in the former case. An estimate of projected speeds has been made from the height-time profiles shown in Figure 5. These derived values of projected speeds for individual features are plotted in Figure 6.

Figure 5: Distance-time plots for the two CMEs of June 02, 1998 and June 21-22, 1998 after combining the measurements of different features, i.e. the leading edge of the CME and the associated eruptive prominence, tracked in different wavelengths by different instruments up to 30 solar radii.

Figure 6: Speed versus distance profiles for different features of the two CMEs derived from the height-time trajectories of various features shown in Figure 5. The estimated errors are approximately ± 5 km s⁻¹ (C1), ± 10 km s⁻¹ (C2) and ± 50 km s⁻¹.

It is clear from Figure 6 that the maximum projected speed attained by June 2, CME is approximately 1000 km s⁻¹ and for June 21, 1998 CME is about 500 km s⁻¹. In fact, the projected speeds in the inner corona (< 4 solar radii) is about 400 km s⁻¹ for June 2, CME and about 200 km s⁻¹ for June 21-22, CME. The speed-distance profile in case of June 21 CME resembles that of slow solar wind profile (Sheeley et al. 1997) and falls in the class of gradually evolving CME (Srivastava et al. 1999b). Because the prominence at any instant is
In an attempt to understand the initiation or the lift-off phase of the CMEs, we plotted enlarged height time profiles of June 21, 1998 and June 2, 1998 CME features covering the inner corona from 1-4 solar radii. (Figures 7 and 8). It can be noticed in Figure 7 that the overlying loop or the leading edge observed in Fe XIV emission line remains stable at height 1.5 solar radii from the sun's center before rising gradually. The initial rise of these features is very slow the speed being less than 50 km s\(^{-1}\) within a distance of 2 solar radii from the center of the sun. This is consistent with the results of Gopalswamy et al. (1996). They found the onset of a CME to occur about 1.3 solar radii from the sun's center. The leading edge of the CME in their study rose with a low speed of approximately 16 km s\(^{-1}\).

The computed projected speeds were then used to obtain the acceleration of individual features of both CMEs under study (Figure 9). It is found that values of acceleration of different features of the CMEs increase gradually from a distance of 1.1 solar radii reaching a maximum value of 60-80 m s\(^{-2}\) in case of June 2, CME and 10-20 m s\(^{-2}\) in case of June 21 CME. These CMEs are representatives of eruptive-associated class of CMEs that show acceleration (MacQueen and Fisher, 1983). The maximum acceleration in both cases occurs between 3 and 6 solar radii. Beyond this distance, the acceleration decreases sharply for June 2 case and gradually for June 21 CME. The acceleration ends at around 20 solar radii. It therefore appears that the initial acceleration close to the sun plays a significant role in the propagation of CMEs in the outer corona.

Figure 9: A comparison of acceleration versus distance profiles for selected features of the two CMEs. The initial acceleration for June 2, 1998 CME is much higher (60-80 m s\(^{-2}\)) than that for June 21-22, 1998. The acceleration in the latter case, lies in the range 10-20 m s\(^{-2}\). For all the features of both CMEs the main region of acceleration lies within 4 solar radii from the center of the sun.
4. CONCLUSION

The two CMEs of June 2, 1998 and June 21-22, 1998 which are both associated with quiet prominence eruptions, show marked similarities and differences.

- The associated eruptive prominences were observed to be long-lived and quiescent in activity for many days prior to lift-off of the CME.

- Evidence of clear relation of the three part structure, white light CME was found with various features in Fe X, Fe XIV, H-alpha and 17 GHz images for both CMEs presented here.

- The pre-eruptive scenario shows a bright twisted feature (June 2, 1998 CME) and a bright knot (June 21, 1998) with a bright large overlying loop in Fe XIV at a height of 0.7 and 0.5 solar radii above the solar surface, respectively.

- The June 21-22 1998 CME is a typical example of a gradual or slowly rising loop type event seen rising for about 30 hours (Srivastava et al. 1999b). Initial speeds are less than 50 km s\(^{-1}\) (within 2 solar radii) and rise is gradual. In fact the rise is so slow that it is rather difficult to define an onset time of the CME. However, in the case of June 2, 1998 CME soon after the lift-off of the CME the rise is no longer gradual but is comparatively faster.

- Speed profiles are remarkably different. The maximum projected speeds achieved in case of June 2, CME is approximately 1000 km s\(^{-1}\) for that of the leading edge and 700 km s\(^{-1}\) for the associated prominence/core. However in case of June 21-22 CME the leading edge achieved a maximum projected speed of ~500 km s\(^{-1}\) and the associated prominence in the range 300-400 km s\(^{-1}\).

- The large difference in the maximum speeds attained by the two CMEs can be attributed to the initial acceleration of the CMEs. For both cases the region of acceleration is within 4 solar radii from the solar center. The maximum acceleration achieved is in the range 60-80 m s\(^{-2}\) for June 02, 1998 CME and for June 21-22, 1998 it lies in the range 10-20 m s\(^{-2}\).

- Similar behavior of the height-time profiles for the leading edge and the prominence in both the CMEs suggests that a common process drives both the CME and the prominence. Large-scale gradual restructuring of the magnetic field appears to be an important cause responsible for the eruption of a CME particularly in the case of June 21-22, 1998.

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