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CMEs 'en rafale' observations and simulations

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Abstract. A CME is triggered by the disappearance of a stable equilibrium as a result of the slow evolution of the photospheric magnetic field. This disappearance may be due to a loss of ideal-MHD equilibrium or stability as in the kink mode, or to a loss of resistive-MHD equilibrium as a result of magnetic reconnection. We have obtained CMEs in sequence by a time dependent magnetohydrodynamic computation performed on three solar radii. These successive CMEs resulted from a prominence eruption. Velocities of these CMEs decrease in time, from a CME to another. We present observational evidences for large-scale magnetic reconnections that caused the destabilization of a sigmoid filament. These reconnections covered half of the solar disk and produced CMEs in squall (sequential CMEs).

Keywords. coronal mass ejections, magnetic fields, prominences, instabilities

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1. Introduction

The slow evolution of the photospheric magnetic fields often result in the destabilization of coronal arcades as filaments and trigger coronal mass ejections. Occurrence of kink instabilities or loss of resistive MHD equilibrium as a consequence of magnetic reconnections rule the equilibrium disappearance and trigger CME.

We have obtained CMEs in 'rafales' (sequence) by a time dependent magnetohydrodynamic computation performed on three solar radii. A prominence destabilization triggered more successive CMEs. We have called this type of ejections "CMEs in squall or en rafales". Velocities of these CMEs decrease in time, from one CME to another, unlike the cannibal mass ejections, where next CME has greater velocity than the precedent, including and devoring it.

We present observational evidences for large-scale magnetic reconnections that caused the destabilization of the filament. These reconnections covered half of the solar disk, as the whole disk Standford magnetograms indicate, and produced CMEs in squall.

2. Numerical simulations

The MHD equations are solved, in two dimensions, with SHASTA method used by Alfven code, developed by Weber (1979), taking into account the gravitation and a complete energy equation. This code was described by Forbes & Priest (1982) and also by Dumitrache (1999). We have considered periodic boundary conditions.

Starting with a current sheet initial configuration and with $\beta = 0.5$ and $Rm = 10^3$, we have performed this numerical experiment on 3 solar radii. No heating has been added ($\sigma = 1$) in the sheet. We obtain a prominences configuration at the Alfven time $t = 0.026$, when the temperature in the sheet is about 5000 K. After that, magnetic reconnections occurred naturally in the sheet and a few CMEs produced in squall. Figures 1 plot

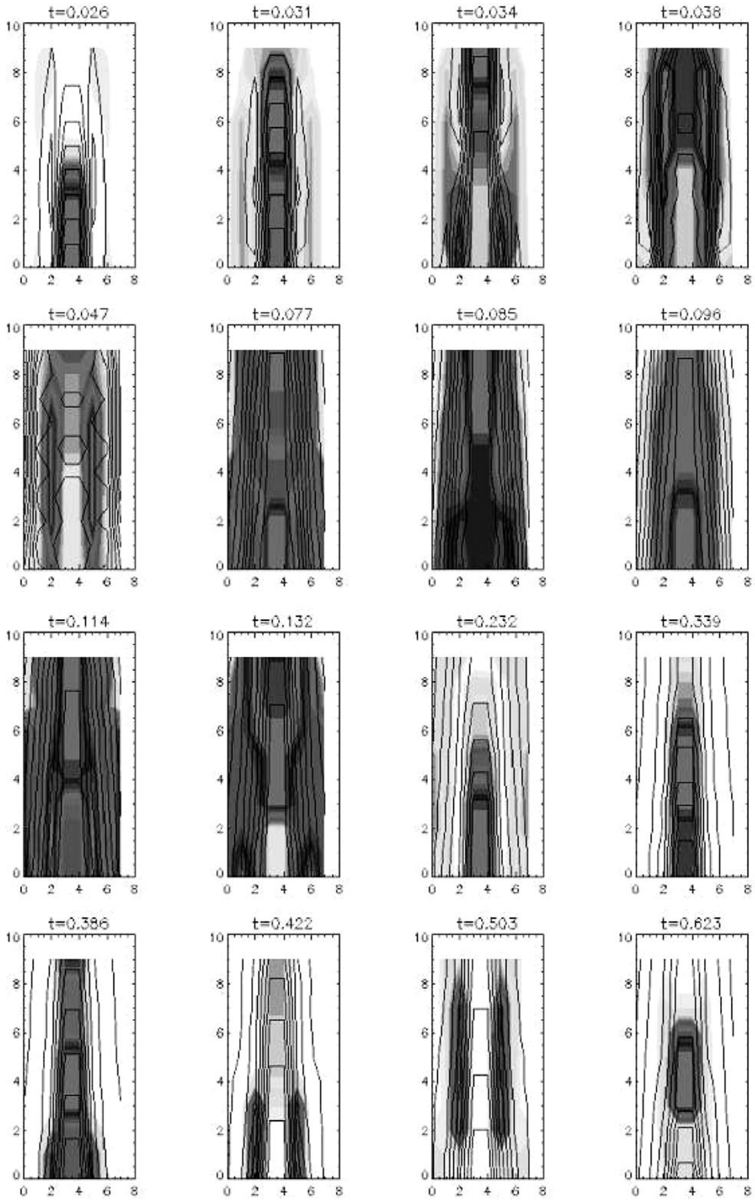

Figure 1. Numerical simulation - CMEs in squal (see the text for explanations).

this prominence and the cartoon of CMEs evolution: the density contours are filled and magnetic field lines are outlined. At $t = 0.031$ the first CME occurred with 1289 km/s. After that one, many other CMEs were triggered and rose with decreasing velocities. The second CME occurred at the Alfven time $t = 0.038$, the third at $t = 0.045$. Later we had more CMEs at $t = 0.085$, 0.114, 0.120 and $t = 0.386$.

After Alfven time $t = 0.623$, a post-CME coronal streamer formed and the maximum velocity increased again at significative values. This phenomenon was described by Dumitrache (2007). Practically, these CMEs took place during 40 minutes.

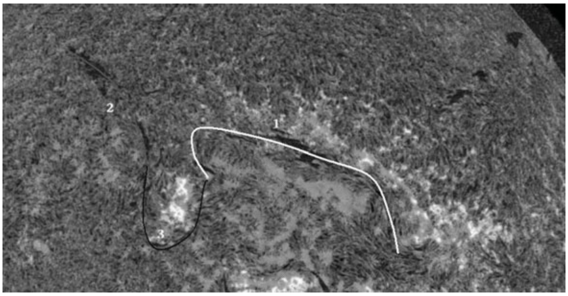

Figure 2. Hα filament superimposed on MDI magnetogram.

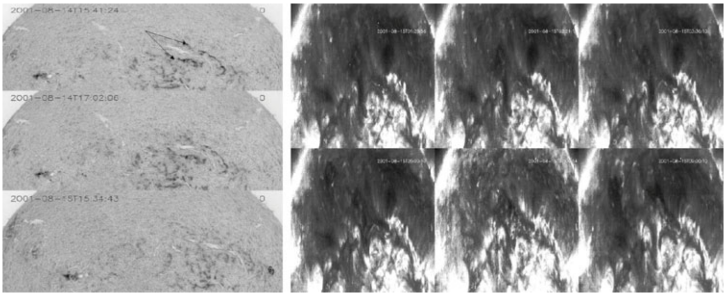

Figure 3. (a) Hα filament in different moments; (b) EIT images of different moments in the filament eruption on 15 August 2001.

3. Observational evidences of sequential CMEs

A large scale magnetic reconnections and shear motions produced CMEs 'en rafale' on 15 August 2001. An important source of these CMEs is a double S filament. This filament is a huge polar feature - no active region exists in its neighborhood. This filament was registered on the solar disk between 11 and 19 August 2001. It appeared as two parallel filaments, but on 13 August a double S-shape linked these two filaments forming a single huge feature. Figure 2 plots the Hα observations superimposed on the MDI magnetogram for that day. We have denoted with (1) the main Western part of the filament, with (2) the Eastern part and with (3) the bend part linking first two ones.

Figure 3a displays images of the filament in Hα for three important moments, on 14 and 15 August 2001. In the picture on top, a two ribbons flare can be observed (indicated by arrows), where the filament denoted by (1) is placed between the ribbons. This flare was observed also in X-ray, by Yohkoh. In the bottom image 3a of the Hα observations both parts of the filament, denoted by (2) and by (3), disappeared after a few CMEs occurred on 15 August. One CME produced on 14 August, issued from the X-ray flare. On 15 August 2001 a few CMEs 'en rafale' produced, having as origin this complex filament: first filament (1) erupted giving a CME at 1:32 UT, but after that, both filaments (1) and (2) erupted violently at 2:54 UT (as seen in C2/LASCO images). The last CME was like a halo, with two branches because of the plasma ejected from both filament parts (2-left and 1-right). A new CME produced later, in the body (1) of the filament. Figure 4 displays few moments observed by C2/LASCO, but more relevant for the CMEs onset are EIT observations. On the EIT movie one can see very well two separated masses erupting from both filaments (1 and 2) and two EIT waves traveling across the Sun, in opposite directions. EIT images of filament changes during CMEs are displayed in Figure 3b. Because of lack of high cadence Hα observations during the time interval of the CMEs onset, we could not say when filaments (2) and (3) disappeared. A new CME occurred

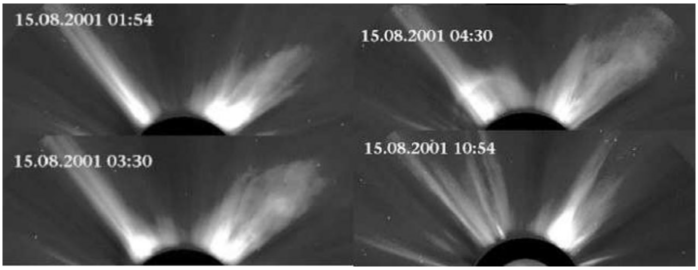

Figure 4. C2/LASCO observations of CMEs in squall.

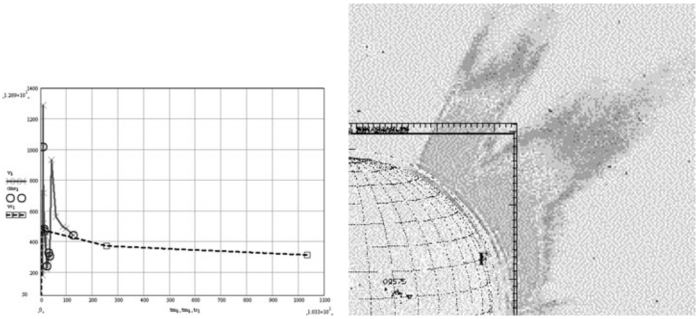

Figure 5. (a)CMEs' velocities plot: simulations and observations; (b)MDI and C2/LASCO image of filament (F) zone on 19 August 2001.

at 10:33 UT. After the last CME, occurred on 15 August 2001, filament (1) continues to exist on the disk but as an S shape (Figure 3a).

According to CDAW Data Center Catalogue, the following data were registered: a CME at 1:31 UT, of 477 km/s velocity; a CME at 2:54 UT, of 370 km/s and a CME at 10:33, of 311 km/s. If we plot these velocities versus time expressed in seconds, we obtain the dashed curve marked with boxes, as in Figure 5a. The continuous line in the same figure represents velocity evolution in time as obtained by our numerical simulations, where the moments of CMEs are marked by circles. We remark that both lines are in continuation. We notice that a new CME occurred on 16 August 2001, and another on 19 August, when the filament (1) reached the visible solar border. After these catastrophic events we should expect that a such huge filament would disappear soon, but surprise: the filament reformed in the same complex S shape (filaments 1+2+3) next solar rotation. This fact indicates us that the magnetic structures supporting the complex filament are strongly rooted in the subphotospheric layers.

The filament arrived at the solar border on 19 August 2001 and figure 5b shows the presence of a coronal streamer above the filament.

4. Discussions

The biggest question is what has caused these successive CMEs and the catastrophic disappearance of the filaments (3) and (2), while filament (1) only changed its shape. Investigating the variations of the tilt angle and differential rotation velocity of all three filaments composing the complex, we notice a sudden increase of the tilt angle for filament (2) after 14 August, while a decrease of these parameters for filament (1) and (3). The differential rotation velocity decreased for filaments (1) and (3) and remained constant for filament (2). We have also computed the shear velocity induced by the differential

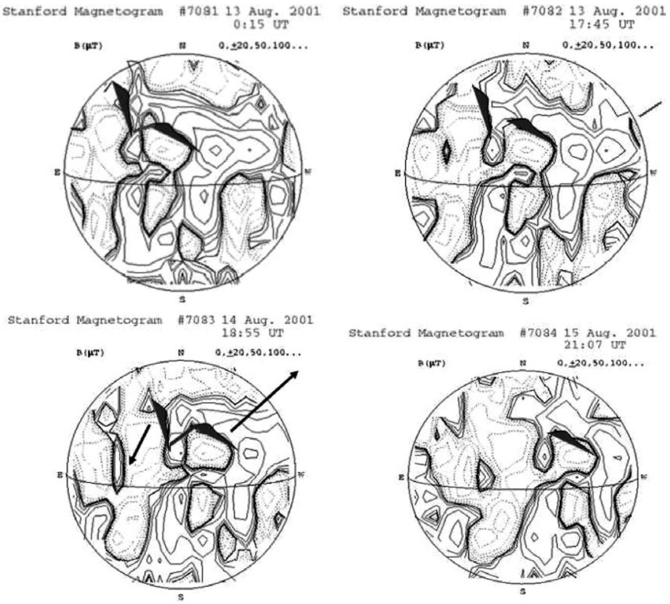

Figure 6. The filament plotted on the Stanford magnetograms

rotation and concluded that shear motions destabilized the filament after 13 August. The images obtained by running difference method applied to Hα observations and also to He observations (Mauna Loa source) indicate height shear motions along the filament channel. This means that the sheared motions were transmitted at all solar atmosphere heights.

We think the key answer is displayed in Figure 6, where Stanford magnetograms are plotted. An important island of positive polarity separated on 13 August and linked again later the same day - it was the day when filament(3) became visible in Hα. On 14 August this magnetic island separated again and also teared in two parts - it was the day when the flaring filament (1) produced a CME. On 15 August both split parts from the central island linked, but each one in another part. It is the day when few successive CMEs occurred and when filaments (2) and (3) disappeared.

We conclude that the filament lost its equilibrium as a result of magnetic reconnections. These reconnections covered half of solar disk and produced CMEs 'en rafales'. After these catastrophic successive coronal mass ejections the double-S filament reformed and was a long-lived entity. The filament lost its stability only temporarily as a consequence of large scale magnetic reconnections and photospheric sheared motions transmitted high into the corona through the solar chromosphere. Since the filament reformed later we believe that the filament magnetic field was strong enough and the filament was very well rooted into the subphotospheric layer, so the magnetic arcades have not been totally affected by large scale magnetic islands reorientation.

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