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# The Contribution of the Flux Cancellation Mechanism in Coronal Mass Ejections

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**Abstract**

The coronal magnetic configuration of an active region typically evolves quietly for a few days before becoming suddenly eruptive and launching a coronal mass ejection (CME). The origin of the eruption is still under debate. The loss of equilibrium is one of the mechanisms that have been proposed to be responsible for sudden eruptions. The objectives of this paper are to discuss the contribution of flux cancellation mechanism in coronal mass ejections and to compare two possible mechanisms, viz., flux cancellation and breakout mechanism behind observed phenomenon.

**Keywords:** Coronal Mass Ejection; Flux Cancellation; Magnetic Field.

## 1. Introduction

Coronal mass ejections (CMEs) are the ejections of large amount of mass and magnetic flux from the sun to interplanetary space. The bulk of plasma with a mass of ~$10^{11}$ -$10^{13}$ kg is hauled up of the way out to the interplanetary space with a typical velocity of several hundred, or even more than 1000 km $s^{-1}$ with a chance to give an impact on our Earth, resulting in hazardous space weather conditions.

The energy released during the process is of the order of $10^{32}$ - $10^{33}$ ergs. Coronal mass ejections (CMEs) originate from coronal loop sized scale (~ $10^4$ Km), expand to cover significant part of the solar surface and further extend all the way from the low corona to the interplanetary space, through which they become the largest scale eruptive phenomenon in the solar system. During their propagation in the solar system, CMEs may frequently interact with the Earth (and other planets), producing a series of impacts on the terrestrial environment and the human high tech activities.

Although CMEs have been inferred in the early 20$^{th}$ century as an eruptive phenomenon, they were observed by the coronagraph on board the seventh orbiting solar observatory (OSO-7) satellite on 14 December1971, after 112 years of the first observation of solar flare. Statistical studies have reported variations in the observed properties and projected kinematics of CMEs [Cremades and Bothmer, (2004); Zhang et al.,(2004)] . They often rise with a small initial speed of a few kilometers per second, followed by a rapid upward expansion reaching several hundred or several thousand kilometers per second and eventually propagate through the interplanetary space as the ambient solar wind. CMEs involve many other much smaller sized solar eruptive phenomena, such as X-ray sigmoid, filament/prominence eruptions, solar flares, plasma heating and radiation, particle acceleration EIT waves, EUV dimming, Moreton waves, solar radio bursts, and so on.

CMEs present many different shapes, and much of the variety is believed simply due to the projection effects. However, fundamental difference can be found between narrow CMEs and normal CMEs. The narrow CMEs show jet like motions probably along open magnetic field, whereas normal CMEs are characterized by a closed frontal loop, as shown in fig.1 The typical morphology for normal CMEs exhibit a three part structure, consisting of a bright outer rim, a dark cavity behind the rim, and a bright inner core that is associated with erupted prominence material [Illing and Hundhausen ,1985]. The bright core corresponds to the erupting filament. The three part structure is considered to be the standard morphology for CMEs, although observations indicate that only 30% of CME events possess all the three parts. Among the events without a bright core, some are due to the filament materials drained down to the solar surface along the stretched magnetic field, some are those due to thermal instability had not started to form a filament in the pre- eruption structure, and others might not be related to filament or filament supporting structure at all.

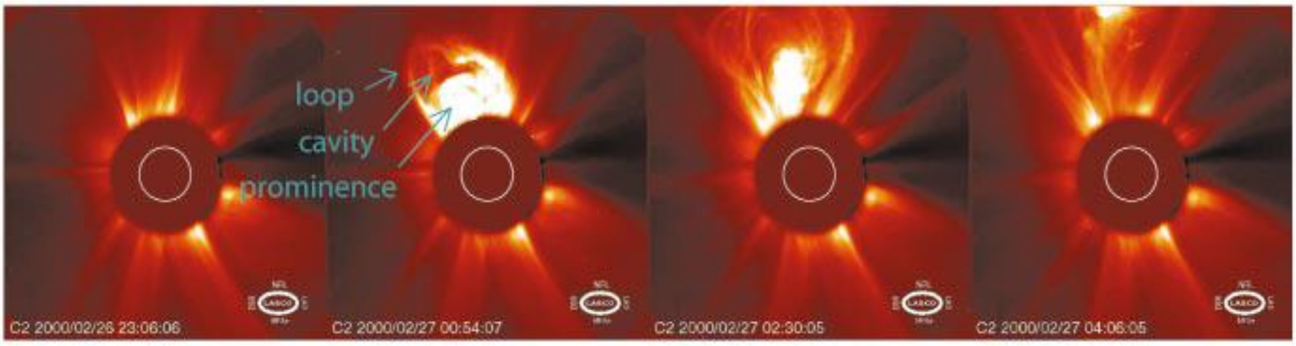


FIG. 1. : A CME observed with the SOHO LASCO C2 Coronagraph, on February 26 and 27, 2000. The dark disk is the occulting disk, and the white circle shows the position of the Sun's surface. The CME shows the typical 3 part structure of a bright loop, cavity, and prominence.

CMEs are often accompanied by solar flares and are thought to be signature of the same magnetic field. There might be some CMEs which are not associated with flare. In these flare less CMEs the lack of association may be due to (i) the source region being behind the solar limb (ii) the associated SXR flaring arcade or disk brightening below the CME being so weak that it is not registered as flare.

The association rate of CMEs and filament /prominence eruptions derived from observations depends on the observational sample and the wavelength. The strong associations between CMEs and flare /filament eruptions paved the way to construct the CMEs models from the heritage of flare and filament researches. It is now believed that, when they are associated, flare and CMEs are different aspects of one global magnetic eruption.

**2. Experimental**

The present work is a review of previous studies on the CMEs including the inner most corona employing white light coronagraphs, the SXR and EUV emissions of the corona, the very weak CME events in which the thermal and potential energies in the pre-eruption corona may contribute to the CME explosions, etc. The association rate of CMEs and filament /prominence eruptions derived from observations depends on the observational sample and the wavelength. CMEs accompanied by solar flares may be suggestive of some associated magnetic field, whereas the flare less CMEs may not suggest so due either to the source region being behind the solar limb or to the associated SXR flaring arcade below the CME being too weak to be registered as flare. The strong associations between CMEs and flare /filament eruptions help construct the CMEs models.

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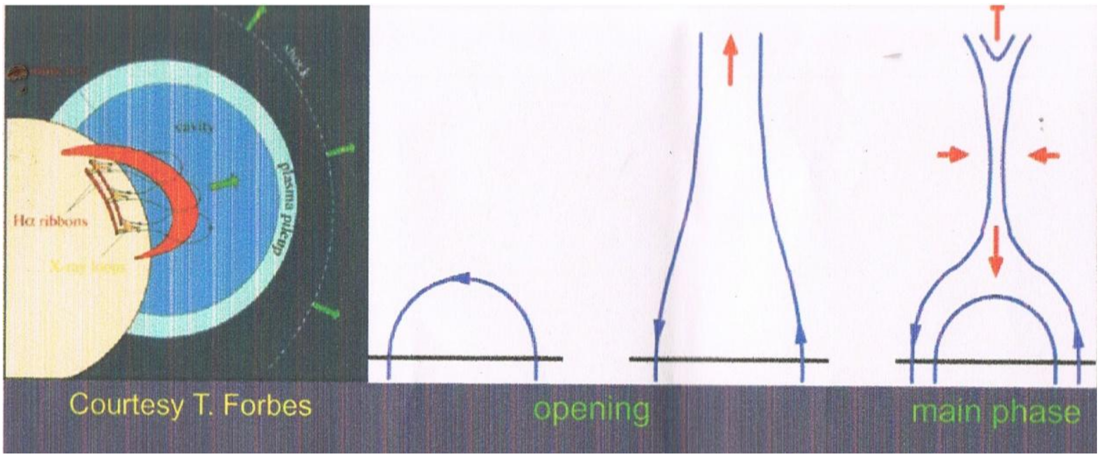


Figure 2 : (i) (ii) (iii)

(i) one underlying process: disruption + reconfiguration of coronal field [observations(flare, CME ,eruptive prominence) depend on initial configuration

(ii) opening phase(CME): geometry conserved; rapid acceleration and huge expansion—ideal

(iii) main phase(flare): reconnection + reconfiguration--resistive

**2.1 Basic principles of Theoretical models**

Constructing CME model is extremely important not only because CMEs are spectacular astronomical phenomenon, but also because they are the main driver for the space weather disturbances that strongly affect our high-tech life. For energetic CME events which are the most interesting in the space weather context the only possible source is the magnetic energy whereas for very weak CME events, the thermal and potential energies in the pre-eruption corona may contribute to the CME explosions. The basic theoretical concept is shown in Fig. 2.

Several Models have been proposed to explain the driving mechanism and observed properties of CMEs. A valid model must be able to produce the observed kinematics, dynamics and properties of CMEs. The understanding of CMEs relies mainly on the multi wave length imaging and spectroscopic observations. Observations provide several constraints for theoretical eruptions models. Observational constraints are shown in Fig. (3).

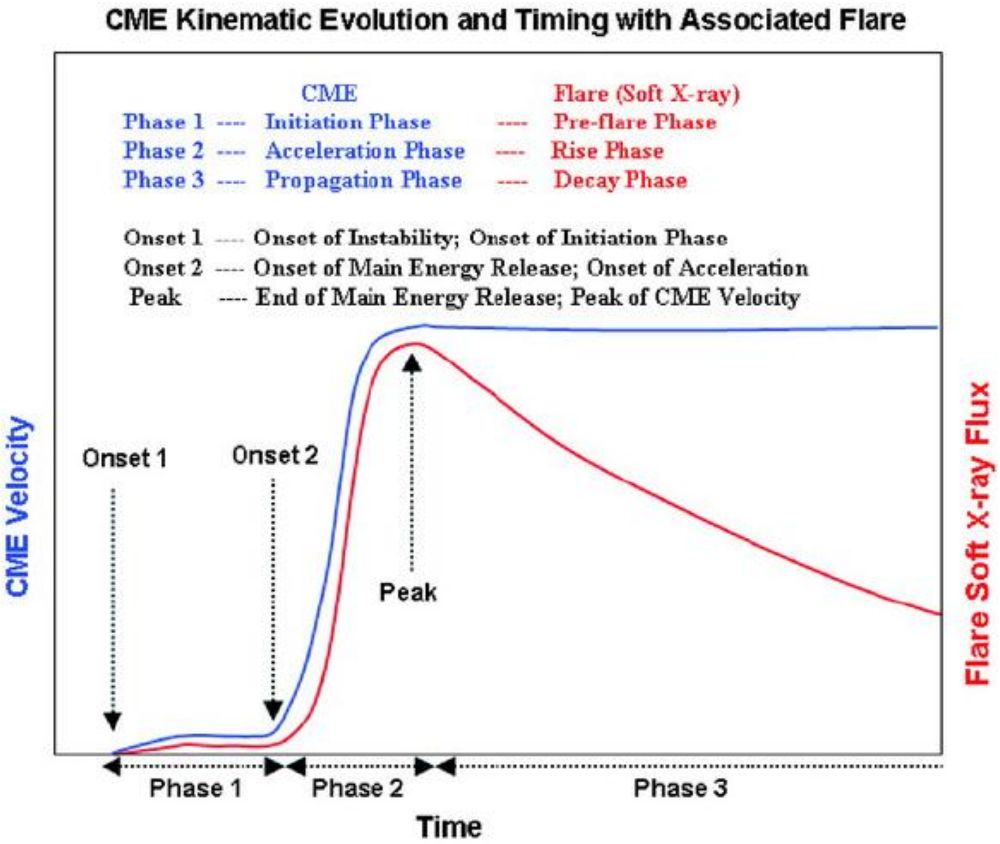


**Figure (3)**

With the following reasons the physical processes in CMEs are far from being fully resolved:

a) White light coronagraphs which observe the CMEs directly, always occult the solar disk and the inner most corona where CMEs originate.

b) Coronagraph observations favor the CMEs propagation near the plane of the sky, whereas the CMEs source region can be better diagnosed near the solar disk center.

c) The SXR and EUV emissions of the corona are optically thin, and it is still difficult for the spectrometers to possess both a wide field of view and high time cadence simultaneously.

Despite these difficulties much progress has been made in the past decades, along with many controversies. The fundamental theoretical question of how CMEs are initiated has been studied for many years [Forbes (2000); Low (2001)] but is still unanswered. It is generally believed that the energy that drives CMEs and other forms of solar activity is stored in the coronal magnetic field prior to eruption [Chen, (1996)]. Highly non potential coronal magnetic fields in active regions have been observed frequently [Gary et al.,(1987); Hagyard,(1988)] indicating that there is more than enough magnetic energy to drive coronal eruptions. How this energy is released is the key question that must be answered by a successful CME initiation mechanism. In this paper, we have discussed the contribution of the flux cancellation mechanism in Coronal mass ejections.

**2.2 Magnetic Flux Cancellation Mechanism**

Coronal mass ejections are frequently associated with prominence eruptions as well as solar flares. Prominences support cool (~$10^4$ K) dense chromospheres material ($10^{10}$-$10^{11}$ $cm^{-3}$) against solar gravity in the surrounding hot (~$10^6$K), tenuous corona ($10^7$-$10^9$- $cm^{-3}$). They are observed to lie above magnetic neutral lines in the photosphere and near the base of helmet streamers. The magnetic field in the prominence often exhibits "inverse polarity" meaning that when the coronal magnetic fields embedded in the prominence cross over the neutral line, they point in the direction opposite to that indicated by the photospheric magnetic field polarity [Martin et al.,(1985)]. The prominence magnetic field is itself nearly aligned with the filament channel indicating a highly sheared configuration.

The ingredients for what we refer to here as the "Flux Cancellation" mechanism date at least as far back as the Kuperus and Raadu [Kuperus and Raadu,(1974)] model for inverse polarity prominences. In that model, a current filament (in two dimensions) produces closed magnetic loops that can support prominence material above the photosphere. Since that time there have been numerous authors who focused on the support of prominence material by helical field lines, and held the disruption of these configurations as the possible cause of prominence eruptions and coronal mass ejections.

Flux cancellation has been defined observationally as the mutual disappearance of magnetic fields of opposite polarity at the neutral line separating them [Hagyard, (1988)], Observations have shown this process to be active at filament sites [Litvineko and Martin (1999)]. The investing sequences of force free equilibrium showed that flux cancellation at the neutral line of a sheared arcade configuration leads to the formation of a flux rope. The helical field lines of the flux rope are capable of supporting prominence material, and the rise in the equilibrium height of the flux rope with increased flux submergence suggests possible eruptive behavior. Calculations by various researchers [Forbes and Isenberg (1991); Forbes et al., (1994); Linker et al.,(1996)] have shown that once a flux rope is formed, continuation of the flux cancellation process can result in a loss of equilibrium. The new lower energy equilibrium contains a current sheet and a higher height for the flux rope; while the energy release in this ideal process is relatively small. The new equilibrium height of the flux rope can be many solar radii from the sun. Such equilibrium is untenable: the flux rope would be pulled outward by the solar wind. Significant magnetic energy release could occur through magnetic reconnection at the current sheet.

Two possibilities exist for the formation of the flux rope. The flux rope could emerge intact from below the photosphere or be formed as the result of motions at the photosphere or above. Here we focus on the second possibility that flux ropes are first formed and subsequently erupt as a result of flux cancellation at the photosphere. Once a flux rope structure is formed in the corona, the susceptibility of the structure to eruption should not depend on its origin.

**2.3 Resistive MHD Equations**

In the context of the resistive MHD equations (quite well understood), flux cancellation does lead to rapid energy release and the disruption of helmet streamer configurations, with material ejected into the solar wind.

The following set of equations represents resistive MHD equations is spherical coordinates:

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J} \quad (1)$$

$$\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \quad (2)$$

$$\mathbf{E} + \frac{1}{c}v \times \mathbf{B} = \eta \mathbf{J} \quad (3)$$

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \mathbf{v}) = 0 \quad (4)$$

$$\frac{1}{\gamma - 1}\left(\frac{\partial T}{\partial t} + \mathbf{v}.\nabla T\right) = -T\nabla.\mathbf{v} + S \quad (5)$$

$$\rho\left(\frac{\partial v}{\partial t} + \mathbf{v}.\nabla \mathbf{v}\right) = \frac{1}{c}\mathbf{J} \times \mathbf{B} - \nabla p + \rho g + \nabla.(\upsilon \rho \nabla \mathbf{v}) \quad (6)$$

where **B** is magnetic field; **J** is the electric current density; **E** is the electric field ; ρ,v ,P and T are the plasma mass density velocity, pressure, and temperature, respectively; $g = -g^0 r R_s^2/r^2$ is the gravitational acceleration (with $R_s$ the solar radius); η is the resistivity; and υ is the kinetic viscosity. In the energy eqn (5) S include radiation, thermal conduction, Coronal heating and resistive and viscous diffusion. The method of solution of (1) - (6) including the boundary conditions have been described in literature (Mikic and Linker ,(1994); Lionello, (1999); Mikic et al.,(1999); Amari et al.,(1999) ;Linker et al.,(2001) ]

**3. Results and Discussion**

### 3.1 Flux cancellation: theoretical interpretation

The recognition that flux cancellation is active at filament sites and during the eruptive process led to the interpretation that the cancellation was in fact the annihilation of magnetic flux at the photosphere through reconnection. The flux cancellation leads the formation of a flux rope. The helical field lines of the model flux rope contained dips capable of supporting prominence material and the rise in the equilibrium height of the flux rope with increased flux cancellation suggested possible eruptive behaviour. Once flux rope is formed, continuation of the flux cancellation process can result in a loss of equilibrium.

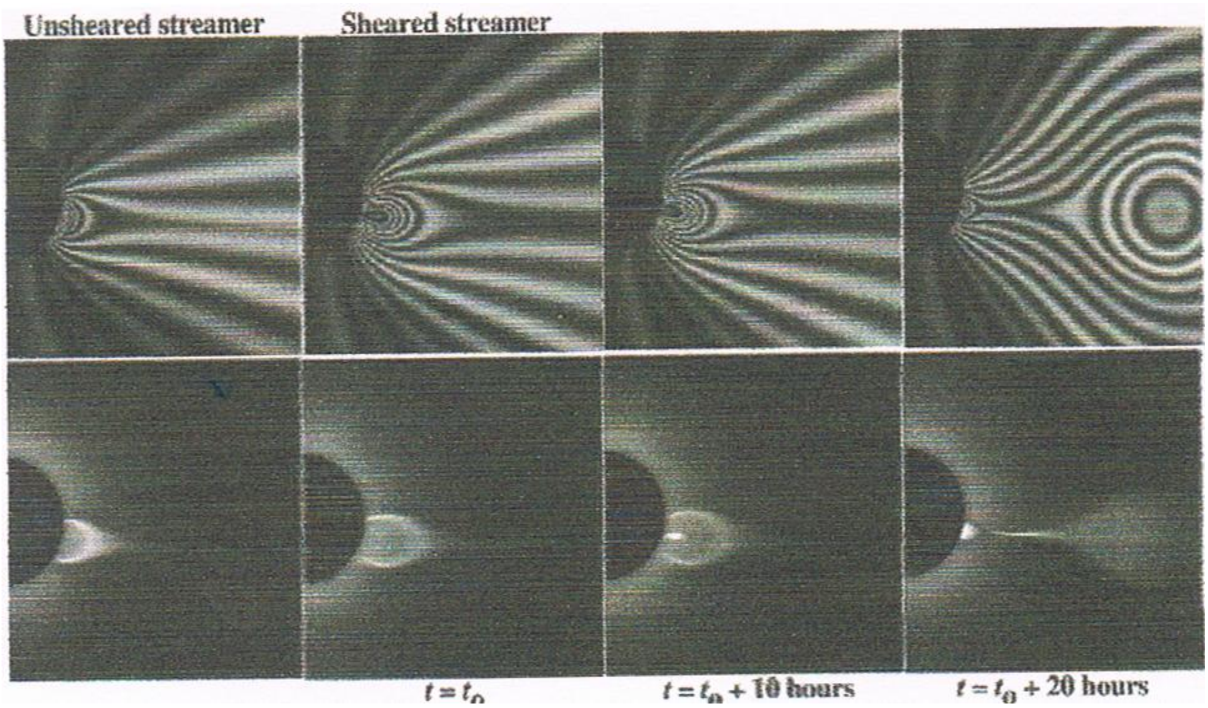


Figure 4. : Evolution of sheared helmet streoamer via flux cancellation. Top panels show contours of the magnetic flux function, which in two dimensions are equivalent to the magnetic field. Bottom panels show simulated polarized brightness. The four columns summarize : (1) the state of the unsheared corona; (2) the sheared crona; (3) the eruption of a flux rope at 10h following the cancellation of flux : and (4) the eruption of the flux rope after 20h, respectively.

The theories of flux rope CMEs generally start from the premise that CMEs are initiated by the release of energy stored in the coronal magnetic field [Forbes ,(2000)]. It is shown in literature [Lionello, (1999); Mikic et al., (1999); Amari et al.,(1999)] that eruptions could be initiated by photospheric motions that shear and twist the coronal magnetic field. The studies indicate that when the magnetic field is sheared beyond a critical value, helmet streamer configurations can erupt in a manner similar to “slow” CMEs, i.e., coronal mass ejections that are carried out of the corona by the solar wind. It has proven difficult to demonstrate that enough energy can be released rapidly enough by this mechanism to produce a fast CME that can drive an interplanetary shock. A more promising mechanism for producing fast CMEs is magnetic flux cancellation. The reduction in the magnetic flux (i.e. flux cancellation) near the neutral line of a sheared or twisted a configuration as shown in figure 4 can lead to the formations of magnetic flux ropes.

In practice, the change in flux is implemented through a tangential electric field at the boundary, which is equivalent to a temporarily varying radial magnetic field. In turn, this electric field drives flow toward the neutral line, consistent with observations. This has the effect of moving the foot points of the already sheared magnetic field closer to the neutral line, further reducing the component of the magnetic field perpendicular to the neutral line (leaving the tangential unchanged) and dramatically increasing the shear. When the flux cancellation reaches a critical threshold the entire configuration erupts with the release of a considerable amount of magnetic energy.

The remaining two columns of Fig. 4 show the launch of such a flux rope at 10h and 20h following the cancellation of flux. As can be seen, the origins of the flux rope lie in the closed magnetic field lines embedded within the streamer belt. As the flux rope erupts into the solar corona, overlying field lines, which are still connected back to the sun at the both end, are brought together under the flux rope. As they reconnect with each other, they contribute to both, the flux of the evolving flux rope to the right of reconnection site and to the re-growth of the streamer belt to the left of it. It is obvious that the flux rope develops an elliptical shape, with its major axis approximately horizontal. The reconnection site behind (i.e., on the sunward side) the erupting flux rope is visible in the simulated PB image at t=20h. This density enhancement was produced by the transverse (i.e. approximately parallel to the solar surface) flow of plasma into the reconnection region and has been observed in white light images of the low corona.

### 3.2 Comparison of Flux Cancellation and Breakout model

A number of theoretical models have been proposed in solar physics to explain CMEs eruption. Many of the pieces of the puzzle have been assembled, but how they relate to one another, and what role each one plays is not known. Each model addresses and is therefore consistent with some subset of the observed properties of CMEs. In fig. (5). we compare the "Flux cancellation" model with the "breakout" model. The models distinguish themselves primarily by the underlying structure of the region producing eruption. In principle, the breakout model can erupt either via photospheric shear or flux cancellation. The distinguishing feature of the breakdown model is the requirement of a more complex quadrupolar configuration. The outstanding difference between the two model results is that a single flux rope structure is produced in the flux can cancellation eruption, whereas, double flux rope appears in the breakout model. This leading 'flux rope' is not the same helical structure that is produced as the main ejecta since it contains essentially no azimuthal field component. It results from reconnection at the leading edge of the ejecta together with reconnection of the streamer belt further ahead of the event. The picture is however, quite suggestive and if further substantiated, may provide an explanation for some of the double flux ropes that have been observed in the solar wind. One feature that does appear to be robust is the requirement for the reconnection to proceed at the leading edge of the erupting flux rope in the breakout model. It is this reconnection that generates the necessary force imbalances to allow the CMEs to be able to escape the confines of the overlying field in the first place. Thus we expect reconnection to occur in both models behind the erupting flux rope.

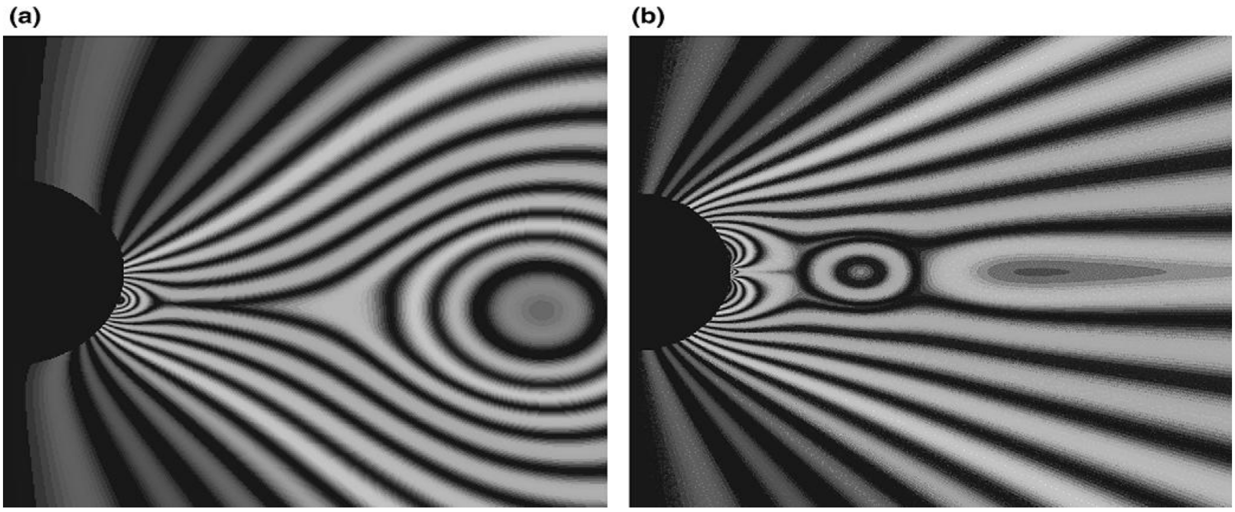


Fig. 5. Comparison of (a) flux cancellation and (b) breakout eruption profiles.

**4. Conclusion**

Magnetic flux cancellation is a promising mechanism for producing slow as well as fast CMEs. It is an attractive hypothesis for explaining both prominence formation and the initiation of CMEs with associated prominence eruptions. The change in flux, and in turn, the electric field drives flow toward the neutral line which move the magnetic field closer to the neutral line and further reduce the component of the magnetic field perpendicular to the neutral line (leaving the tangential unchanged) and dramatically increase the shear. When the flux cancellation reaches a critical threshold the entire configuration erupts with the release of a considerable amount of magnetic energy. The breakout model can erupt either via photospheric shear or flux cancellation. The distinguishing feature of the breakdown model is the requirement of a more complex quadrupolar configuration. The outstanding difference between the two models is that a single flux rope structure is produced in the flux cancellation eruption, whereas, double flux rope appears in the breakout model.

The study substantiates the existence of double flux ropes that have been observed in the solar wind. It also justifies the requirement for the reconnection to proceed at the leading edge of the erupting flux rope in the breakout model. It is this reconnection that generates the necessary force imbalances to allow the CMEs to be able to escape the confines of the overlying field in the first place. Thus we expect reconnection to occur in both models behind the erupting flux rope.

**5. Acknowledgements**

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