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# Coronal mass ejections: structure and dynamics

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**Abstract**
We discuss in this paper some issues related to the relationship, currently thought to be relatively strong, between large scale solar eruptive events and twisted magnetic flux ropes (TFRs). We first consider the possibility to prove the presence of a TFR in a pre-eruptive configuration by using a model along with observational information provided by a vector magnetograph. Thus we examine, in the framework of a generic model in which the coronal field is driven into an evolution by changes imposed at the photospheric level, several mechanisms which may lead to the formation and the disruption of a TFR . We consider in particular the development of a MHD instability, and we address the issues of the energy and helicity contents of an erupting configuration.

## 1. Introduction

There is strong evidence that confined eruptive flares, eruptive prominences, coronal mass ejections (CMEs) and interplanetary magnetic clouds (IMCs) are different observational aspects of a unique phenomenon, the *eruptive event*. Their respective structures exhibit indeed many similarities. In particular, they quite often show, directly or indirectly, the presence of a twisted magnetic flux rope (TFR).

Let us first present few basic observational facts concerning these large scale eruptive phenomena to see how TFRs are actually involved (a detailed review of the many observations may be found in [38]). A typical CME consists of a front, a dark cavity and a plasmoid containing about $10^{16}$ g of material. The latter probably originates from a prominence, i.e. a sheet of relatively cold and dense plasma (compared with the surrounding corona) which may stay in quasi-equilibrium for long periods of time (prominences are highly interesting objects which have been given a great deal of attention by solar physicists; see the review paper by [35]). Such a prominence is often seen indeed to rise before the CME and an associated

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flare, and it may be naturally thought that it gets ejected with the CME at the average speed of $10^3\,\mathrm{km\,s^{-1}}$. By simply looking at the images provided by observations one may often guess the presence of twist in an eruptive prominence (as in the well-known one called 'Granddady'). Moreover, the presence in many cases of a TFR has been much supported by the quantitative study reported in [37]. The latter has shown indeed the clear appearance of a twisted structure during the eruptive phase (see also [39]).

In this paper, we report on some particular issues related to the possible role of TFRs in CMEs. We address, in particular, the following questions: is a TFR already present in a pre-eruptive configuration or does it get created during the eruption; does a TFR containing a prominence just traces out the visible CME phenomenon as a passive entity or does it play a role in the initiation of the ejection itself. Thus this is not a review paper on all the possible CMEs mechanisms. For detailed up-to-date interesting reviews on that more general topics, we refer the readers to, e.g. [38, 51, 54].

## 2. The nature of the pre-eruptive configuration

Let us start with some general remarks on eruptive phenomena. The first and most important one is that they have to be of magnetic origin. This conclusion appears quite inescapable if we just make a comparison between the various possible sources of energy present in the corona: magnetic, thermal, gravitational and kinetic. Only the first one has a sufficient magnitude to power a CME, say. The second point is that, in the pre-eruptive phase, the low corona appears to be in quasi-equilibrium, the magnetic, pressure and gravitational forces balancing each other. In fact, owing to the dominance of the magnetic energy, the equilibrium may be considered to a very good approximation as being force free, with the magnetic pressure being thus balanced by the magnetic tension, while the two other forces just intervene to fix the distribution of the plasma along the field lines [54]. The third point concerns the storage of the energy: it has to be associated with coronal electric currents. In fact, the magnetic field $\boldsymbol{B}$ can be expressed as the sum of a potential term created by the subphotospheric currents and of a term created by the coronal currents. The magnetic energy is the sum of the energies of these two fields, with only the second one being liable to get dissipated.

Unfortunately, the magnetic field cannot yet be accessed directly in the corona by observational means. One thus needs to build up models to try to understand the details of the processes leading to an eruptive event. Here, we shall restrict our attention to two classes of models which have a long tradition behind them and comprise a large variety of submodels: the TFR model and the magnetic arcade (MA) model.

The qualitative concepts of arcade and TFR are quite standard in solar physics, where they have proved to be relevant for interpreting in magnetic terms the shapes of many observed coronal structures. An arcade can be defined to be an elongated magnetic structure (length $L \gg$ width $l$) existing above a photospheric inversion line of length $L$ separating a region of positive polarity from a region of negative polarity. It is formed of magnetic lines connecting both regions by just bridging over the inversion line. The arcade is said to be unsheared when the lines are about perpendicular to the latter, and to be sheared when they make an appreciably smaller angle with it. A TFR is a quite different object. It can be defined to be a flux tube of length $L$ somewhat larger than its average diameter $R$ in which the magnetic lines are winding around each other by more than a half turn, say, which implies the presence of a non-negligible axial electric current. Most generally, a TFR is embedded in an arcade, whose overlying lines ensure its confinement. The presence of a TFR [11] is actually a generic feature of a variety of magnetic configurations which have been studied since the mid 1980s in the context of solar prominence modelling. The TFR gives indeed to a field the geometric properties needed to

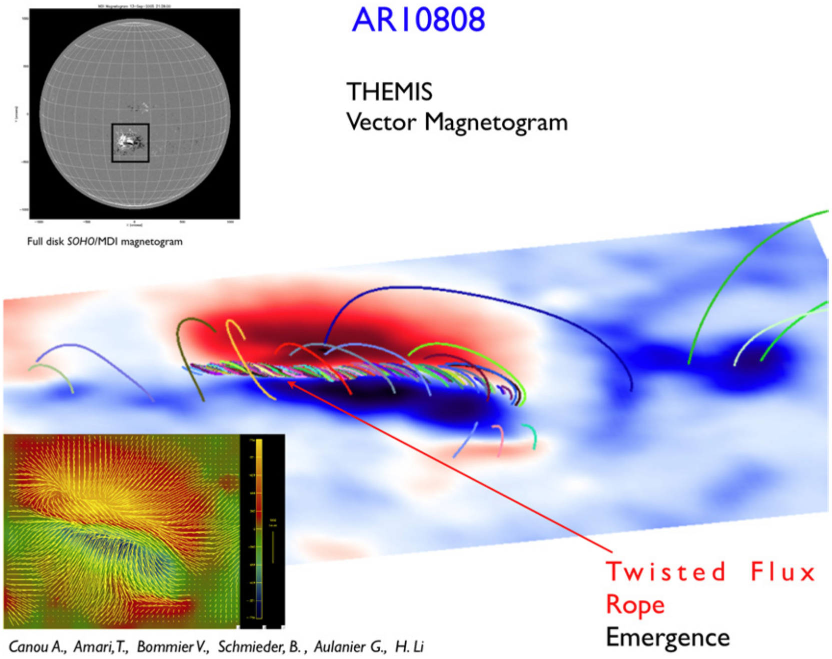

**Figure 1.** Nonlinear force-free reconstruction of a pre-eruptive configuration from THEMIS data. For the first time, a TFR produced by photospheric emergence is shown to be present in the corona. From [24].

(This figure is in colour only in the electronic version)

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ensure the support of cold material, as magnetic dips are obviously present, and a series of models of increasing complexities have been constructed to describe this support, star ting with simple pictures in which the prominence is represented by a line current in equilibrium either in a potential field [17] or in a linear force-free field [5], and ending with the much more sophisticated models reported, e.g., in [18, 48, 61]. See [35] for a more detailed discussion.

To prove or disprove the existence of one type of structure rather than the other in the pre-eruptive configuration is an important issue which may be solved to some extent by using the measurements performed at the photospheric level by a vector magnetograph, along with a good method to resolve the well-known 180° ambiguity on the transverse field, a problem which has been given recently a great deal of attention [45, 50]. The idea consists of reconstructing the coronal field from these data. This problem has been much considered in the last few years [4, 8, 57, 67] in relation with the availability of several ground based (IVM, SOLIS, ASP, THEMIS, EST) and embarked (HINODE) vector magnetographs, and the prospect of several new ones (SDO, SOLAR-ORBITER) in the near future. Evidence for the presence of a TFR in some pre-eruptive configurations has thus been reported in [23, 24, 56, 60] (see figure 1).

## 3. The coronal evolution problem

Assuming that configurations with TFR do exist, the question of their formation and evolution immediately arises. For about 35 years, this problem has been mainly studied in the framework of a general model in which the solar coronal magnetic field is made to evolve in response to changes occurring at the photospheric level, and this has led to the formulation of the *coronal* *evolution problem*. In the latter one starts from an initial potential or low beta force-free configuration, and makes it evolving by prescribing motions of either one of the following types on the photosphere: either shearing motions or flux emergence or submergence, both corresponding to some observations.

When considering a solution to that problem, one has to address the important question of the evolution of two basic quantities: the magnetic energy $W$—the source powering an eruptive event—and the relative magnetic helicity $H$ [12, 13, 28]. At least in a non-dynamical phase, the evolution of both quantities is essentially controlled by exchanges occurring at the photospheric level (through the Poynting vector for $W$). A question which thus naturally arises is that one of the possible existence of upper bounds on the amounts of energy and helicity which can be injected into the field by the photospheric motions.

As for the energy we underline the importance of two theorems which do apply to quasi-equilibrium configurations and are thus relevant indeed in a pre-eruptive phase (see [4] for a detailed discussion). They do involve two reference fields having the same distribution of photospheric normal component, $B_{\mathrm{n}}$, as $\boldsymbol{B}$: the potential field $\boldsymbol{B}_{\pi}$, and the open field $\boldsymbol{B}_{\sigma}$, the latter having all its lines being open and thus containing current sheets. Theorem 1 states that the energy $W[\boldsymbol{B}]$ of a force-free field $\boldsymbol{B}$ is bounded from below by the energy of $\boldsymbol{B}_{\pi}$, which justifies the third remark made at the beginning of the previous section. Theorem 2 [1] states that $W[\boldsymbol{B}]$ is bounded from above by a number depending only on $B_{\mathrm{n}}$. Moreover, it has been conjectured that the best possible upper bound—the so-called least upper bound—is equal to the energy of $\boldsymbol{B}_{\sigma}$, at least if one's attention is restricted to configurations having all their lines being connected to the boundary [1, 3, 59]. This guess has been supported by several theoretical arguments and simulations (see however [25]). In contrast, the energy may exceed $W[\boldsymbol{B}_{\sigma}]$ for fields containing TFR disconnected from the boundary. This has been shown by computing particular numerical examples of axisymmetric configurations [32, 40], and suggests that the presence of TFRs can help for storing a large amount of magnetic energy. Note, however, that no fully 3D configurations with disconnected TFR have yet been obtained.

That the absolute value of the magnetic helicity of a force-free field may be also bounded from above by a number depending only on $B_{\mathrm{n}}$ has been conjectured by [68], but no proof of that statement has yet been furnished. If true, this would imply immediately that imparting sufficient shear or twist to a force-free field leads in any case to a non-equilibrium process.

## 4. Formation and disruption of a twisted flux rope

In the first class of evolution problems which has been considered by solar physicists, the footpoints of the field lines of an initially potential configuration have been imposed shearing motions, and this problem has been treated both analytically and numerically for fields of increasing geometric complexity: translation invariant, rotation invariant about an axis (axisymmetric), and more recently fully 3D. In the latter case, the profile of the imposed photospheric flow has been found to be of crucial importance. For a flow exhibiting a strong shear localized near a neutral line, one observes the formation of a sheared arcade in equilibrium when the field topology is bipolar, with no disruption occurring ( [15]; in the corresponding 2D situation a plasmoid is ejected when a small resistivity is introduced [6]). In contrast, when the flow leads to a global twisting of the field (which is equivalent to a shearing only near the neutral line), the configuration evolves slowly through a sequence of quasi-equilibria up to a certain twist threshold of about one turn. Once the latter is exceeded, the configuration experiences a transition towards a dynamic evolution. A central flux rope is created, which pierces through the overlying field lines and erupts, but without disconnecting from the photosphere. This phenomenon has been called *very fast opening* [6] and it has been more recently revisited [19, 62]. Several features of this model may be related to observational facts. In particular, the existence of strong electric currents localized below the flux rope may explain the well-known characteristic sigmoidal structures. The fact that the TFR remains attached to the Sun while expanding in the solar wind and the interplanetary medium may explain why it may look open from the low corona point of view while appearing still closed in the interplanetary medium where it may be possibly identified as a magnetic cloud [29]. Moreover, the interaction of this expanding TFR with the overlying field, which leads to the appearance of strong currents at the interface, may be at the origin of EIT waves as recently proposed in [26, 27]. Finally, we point out that the very fast opening phenomenon involves here a partial opening rather than a total one (the open field conjecture is then not challenged). Therefore, a full opening is not necessarily implied in a disruption [7].

More recently the effects of photospheric flux changes have also been considered. They may mimic the emergence or submergence of flux through the photosphere, and, in particular, the so-called flux cancellation (FC) process. The latter is often observed on the Sun and it has been given a great deal of attention after [49]. It has been found for instance to occur in the big X 5.7 'Bastille day' event in 2000 [43]. Originally proposed as a mechanism leading to the formation of a prominence inside a TFR contained in a 2D equilibrium [65], and also to the formation of an erupting plasmoid in an axisymmetric configuration [34], FC has been studied in 3D [11, 47] as a possible process leading to the creation and the disruption of a TFR. If one starts from an initial sheared configuration containing a non-zero magnetic helicity, FC leads after a certain threshold to the creation of a TFR in equilibrium, which experiences later on a major global disruption. The key point here is that there is a decrease in the energy of the open field (which depends only on the photospheric distribution of the normal field component) while the energy of the evolving low beta coronal configuration (which is related to the presence of coronal currents) does not change significantly. Thus, both these energies become comparable at some critical time, which precludes the existence of a global equilibrium and leads to the disruption [11]. The TFR created by the FC mechanism may possibly explain several observed characteristics such as the presence of a prominence (there are dips), the presence of a sigmoid and the current sheet/cusp formation below the ejected rope.

Another mechanism associated with a flux change on the boundary has been proposed for explaining the following fact. During the death of an active region due to the dispersion of its flux, large scale eruptive events are nonetheless produced and reformation of filaments from remnants of previous eruptions is observed. Following [44, 66], this dispersion has been modelled by turbulent diffusion (TD) occurring at the photospheric level [10, 13]. This leads once more to a well-defined BVP in which one starts from an initial configuration supposed to represent the remnant of a previous eruptive field which has relaxed to a non-potential configuration and thus has a non-zero helicity. The field is thus made to evolve slowly due to TD, and it is found that in all cases the resulting evolution leads to the formation of a TFR in equilibrium. Depending on the initial helicity contents, either a confined disruption (moderate helicity) or a global one (large enough helicity) is produced eventually. Although this could seem to show that a minimum amount of magnetic helicity is necessary to trigger a CME, say, it should be noted that the total magnetic helicity of the configuration remains unchanged during the evolution. Once more, the results of this model are in agreement with several observational characteristics of eruptive events.

TFRs have also been shown to form when the evolution is driven by converging motions applied to an initial configuration with a non-zero helicity. This problem has been first considered in 2D [53] and more recently in 3D by [12]. By starting from the set of initial configurations previously used in the FC studies, it has been shown that the field evolves through a series of equilibria up to a certain threshold beyond which the topology changes to a TFR-like one. However, unlike in the FC or TD mechanisms the TFR is not in equilibrium, and it experiences a disruption. Here TFR formation and disruption appears to be associated.

## 5. Role of magnetic topology

As indicated above a very localized shear applied to a bipolar configuration does not lead to a disruption. The situation turns out to be quite different, however, if such a configuration is a part of a larger quadrupolar configuration. Taking such a complex topology field as an initial state in the BVP previously solved for the simple bipole, it is found indeed [15] that there is formation in a first stage of a strongly sheared arcade with dips favourable to prominence support. Beyond a critical threshold the field lines above the coronal X-point reconnect with the inner bipolar lines, thus triggering a large scale disruption. For this mechanism to be efficient, it is necessary that the current sheet which forms near the location of the initial X-point be maintained in equilibrium all along the first part of the evolution for otherwise only an insufficient amount of free energy would be stored (note that describing a current sheet is numerically difficult). This interesting mechanism is called the 'break out model' (BOM), and it has the merit of showing the role of the magnetic topology in an evolution. It should be noted, however, that this role was also pointed out in earlier 2D studies [33, 41].

Some observations have shown that several pre-eruptive configurations had a complex topology (this was the case, in particular, for the July 14, 1998 flare [20]), and one could be tempted to take this fact as evidence in favour of the BOM alone [46]. However, that a disruption occurs when the field has a complex topology is not the signature of a particular mechanism, it is just one component of the context in which the BOM may be relevant. In fact, if one takes a quadrupolar configuration as the one used in the BOM, and submit it to FC, then it is found that a TFR in equilibrium gets formed in a first phase in the inner bipolar part. A disruption is thus suffered by the configuration in a second phase [14]. Compared with the case of a simple dipolar configuration, it is clear that the overlying arcade has weaker confinement properties due to the presence of the X-point, which allows a faster expulsion of the TFR. To conclude this section, we note that the BOM and the FCM share the properties of weakening the confinement, and of producing a TFR. But they involve different processes and different structures in the lower part of the magnetic configuration, the TFR appearing before the eruption as an equilibrium structure in the FCM, while it is created in the BOM by a non-equilibrium process involving a shear transfer by reconnection between two initially disconnected topological cells.

## 6. Relation with MHD instabilities

As we have seen previously, a TFR may be produced in an evolving equilibrium which gets disrupted at some stage. Basically there are three possibilities to explain this disruption: (i) there exists no equilibrium compatible with the photospheric changes as in the FC mechanism; (ii) an equilibrium compatible with the photospheric changes may exist but it is too far to be reached (very fast opening mechanism) and (iii) an equilibrium exists but it is unstable. We now explore this last possibility in the context of ideal MHD, which may be used here because of the very high conductivity of the low coronal plasma. We first note that simple 2D arcades have never been found to be unstable, and that there is in 3D a known sufficient condition for a force-free equilibrium to be stable: it is that $\alpha L \leqslant 1$ [2], where $L$ is the typical length scale of the structure and $\alpha$ the order of magnitude of the force-free function ($\nabla \times \boldsymbol{B} = \alpha \boldsymbol{B}$). But no sufficient condition of instability seems to have been established yet.

What about configurations containing TFR? Some information can be drawn here from the many studies of cylindrical and toroidal configurations which have been conducted up to now in the context of thermonuclear fusion in magnetically confined plasma. For instance, cylindrical and toroidal TFR configurations have long been shown by plasma laboratory physicists to be subject to the kink instability when the poloidal component of the magnetic field becomes of the order of the axial one [36]. Solar physicists have thus looked for the possibility of the development of the kink in a cylindrical coronal TFR exhibiting a twist of about one turn around the axis when the anchoring of the footpoints in two horizontal plates representing the dense photosphere is taken into account [21, 22, 55]. The more realistic case of a toroidal line-tied field has also been studied, mainly by considering a particular 2D analytical model [61], and kink unstable TFRs have been obtained in spite of the stabilizing line-tying effect [63]. This mechanism may reproduce some of the observed characteristics of confined disruptions [30, 31, 64]. And finally similar conclusions have been suggested by the results of some non-symmetric simulations [9].

Another property of TFR, which also applies to toroidal fusion configurations, is related to the fact that a poloidal magnetic field exerts a net outward radial force per unit length on the toroidal current as a simple consequence of flux conservation [36]. In a tokamak there exist some restoring forces due either to the presence of a wall, which induces a restoring pressure build up in the external part, or to an external vertical field $\boldsymbol{B}_{\text{ext}}$. In the latter case, however, a too fast decrease in $\boldsymbol{B}_{\text{ext}}$ with the distance to the axis makes the resulting equilibrium unstable. This is the so-called *torus instability*, and it has been suggested that it could occur in the solar corona. In that case, the ‘external’ magnetic field is the one of the overlying arcade, and it has been proven indeed that the torus instability may develop for some shape of the inner TFR and some decreasing profile of $\boldsymbol{B}_{\text{ext}}$, with a coronal disruption thus being produced [42].

It is worth noting that although both the kink and the torus instabilities are interesting exact properties of TFR, their application to the disruption at the origin of eruptive events is not yet completely convincing. In the simple form used up to now, they do develop indeed in a pre-eruptive configuration with a high degree of symmetry. The latter then exhibits the well-known phenomenon of *symmetry breaking* once 3D perturbations are allowed. Such a symmetry certainly exists for a laboratory device such as a tokamak, but it seems quite difficult to think of a consistent mechanism which could produce a similarly constrained equilibrium in the solar corona. In fact, it should be clear from the above results that a low beta symmetric configuration, once twisted or subject to flux changes, evolves quite generally into a non-symmetric state. Moreover, it may be noted that although these models are able to produce interesting quantitative predictions for the acceleration profiles in CMEs, they may disagree with some recent observations [58].

## 7. Conclusion

Magnetic flux ropes are structures which may be easily formed in the solar corona by various mechanisms. They are good candidates to support prominence material which is denser and cooler than the coronal one around. They may lead to either confined disruption or large scale eruptive phenomena such as CMEs and two ribbon flares. Their interest also relies on the fact that they may be subject to various ideal instabilities such as the kink and the torus instabilities. There are several indications that they may be present in the corona prior to some eruptive event. In particular, this has been shown to be true in some cases by using boundary data provided by vector magnetographs and a force-free low corona model, without then making any extra assumptions on their origin. Considering only MHD mechanisms, TFRs have been shown either to exist in the pre-eruptive configuration or to be created only during the eruption through reconnection. They may also represent the magnetic structure of IMCs. Of course we do not mean that TFRs are the only way of triggering eruptive phenomena, and we acknowledge the fact that many other types of structures may produce such events. Determining whether TFR may also come from below is one of the main challenge of current research in solar physics. Answering this question requires the construction of a model allowing to follow TFR from their possible formation in the stable region beyond the convection zone, their rising through the latter, their piercing through the photosphere and their evolution in the corona. Much help should be also provided in this respect by the arrival of a new generation of vector magnetographs with low noise and high resolution such as those on board of HINODE or SDO or the future ground based EST.

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