KINK INSTABILITIES TRIGGERING A FILAMENT ERUPTION

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Abstract. A huge complex filament was observed between 28 December 2000 and 7 January 2001. We analyze its dynamics and its sudden disappearance. We analyze the 3D coronal magnetic field extrapolated from the MDI photospheric magnetograms and compare with filament coronal images. The filament erupted in a CME after a mild helical upward movement of plasma on 7 January. We attempt to explain this CME event onset by kink instabilities. An approach to estimate the filament helicity and magnetic flux injection explain the filament destabilization.

Key words: Sun – prominences – CMEs – instability.

1. INTRODUCTION

Kink instabilities represent a process whereby the winding of magnetic field lines around an axis is converted to magnetic writhe (deformation of the axis itself). A magnetic coronal loop becomes kink-unstable if its total twist exceeds a critical value, variable from an author to another, but not less than $T \approx 2\pi$.

Solar eruptive events often show the phenomenology of a loop-shaped magnetic flux system with fixed footpoints at the coronal base and signatures of magnetic twist. Török and Kliem (2003) noted that the canonical instability of a twisted magnetic flux tube represents the kink instability and a small perturbation of a kink-unstable flux tube leads to an exponentially grow up of its helical distortion. Instability occurs when the magnetic flux $\Phi(r) = 2(L/r)B_{\varphi}(r)B_z(r)$ exceeds a critical value Φ_c. Here L stands for the length of the filament modeled as a cylinder with radius r, where B_z and B_{φ} are the axial and azimuthal field components, respectively.

The onset of the instability, i.e., the critical value of the magnetic flux, depends on the details of the considered equilibrium, in particular on the radial profile $\Phi(r)$, and on the aspect ratio, L/r, where r is the characteristic radius of the configuration. For the simplest possible model of a coronal loop Hood and

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Priest (1981) computed $\Phi_c = 2.49\pi$. Titov and Demoulin (1999) gave another value $\Phi_c = 3.4\pi$ for an approximate force-free equilibrium of an arched twisted flux rope that contains an already twisted and curved current-carrying flux tube.

Török and Kliem (2003) took the analytical model used by Titov and Demoulin (1999) as departure point, and carried out a numerical simulation. They found the critical value $\Phi_c = 5.1\pi$.

Generally speaking, the twist of a prominence/filament occurs due to the motion of the prominence footpoints, the Coriolis force action and magnetic flux cancellation. Most of the helicity necessary for the formation of a filament comes from below the surface while its associated active region emerges.In this paper we discuss the evolution and especially eruption of a huge filament that erupted in a helical shape after an accumulation of twisting plasma flows inside the filament. We estimate the filament helicity considering only the footpoints motions and the filament dynamical parameters as differential rotation velocity, the tilt angle on the solar parallel and the length variations. Their variations are directly influenced by magnetic flux emergence or dissolution of neighborhood active regions and so are signatures of large-scale magnetic reconnections.

2. OBSERVATIONAL FACTS

A complex and huge filament was observed between 28 December 2000 and 7 January 2001. This filament formed under 30° northern latitude, on the polarity inversion line between two remnant active regions, AR09245 and AR09249, observed in a previous solar rotation. We focus our analysis on the last stages of the filament evolution and its destabilization. Fig. 1 displays an Hα image of the filament registered on 4 January 2001 by BBSO, the last day when it was observable as a whole on the solar disk. The filament displayed high helicity in its latest stages of evolution and erupted in a spectacular coronal mass ejection (CME) on 7 January 2001.

Fig. 2 displays the EIT/SOHO 195 Å images of this CME. This coronal mass ejection was registered later by SOHO coronagraph LASCO/C2, and Fig. 3 displays it. We notice that the magnetic loops rope erupted in several steps: first, the western filament end footpoint detached from the solar corona at about 2:23 UT (more visible in EIT running difference movie), while at 4:12 UT we were able to see on the EIT images the twisted shape of the coronal loops. At about 4:36 UT, a new filament activation occurred and so new material was ejected in space. The last one was connected also with a surge occurred in AR09297, active region newly appeared on the solar disk after 4 January 2001, the day when major changes for the filament started to develop. Fig. 3 reveals the writhen shape of the last flux rope ejected from the filament.

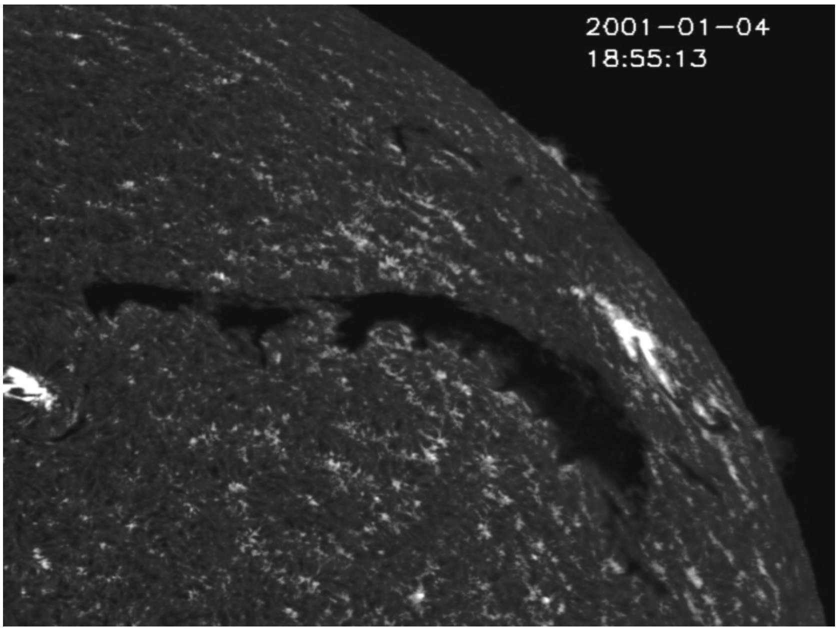

Fig. 1 – Hα filament image on 4 January 2001.

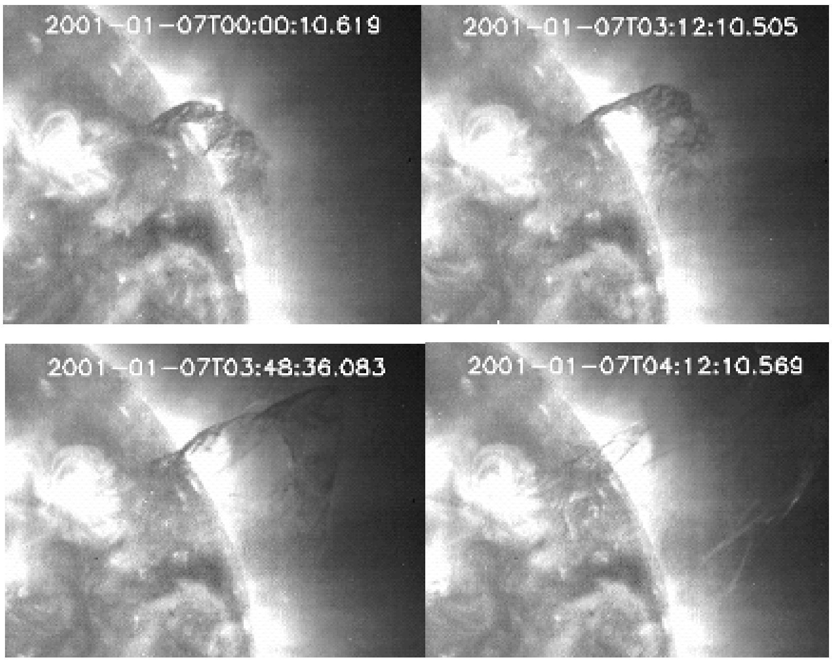

Fig. 2 – EIT/SOHO 195 Å images of the filament eruption.

Fig. 3 – EIT processed negative image – the arrow points
the last mass ejection, where the loops have a writhen shape.

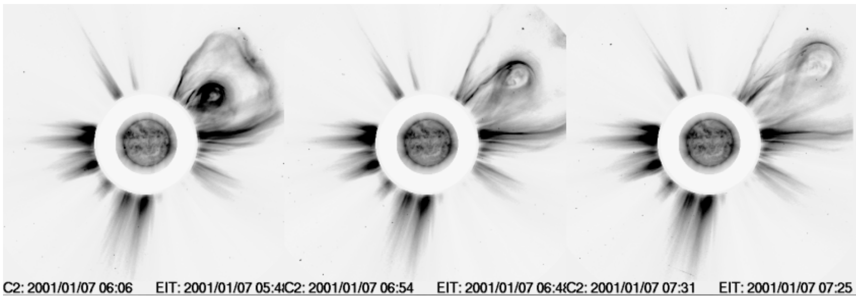

Fig. 4 – Composite images of EIT and LASCO/C2 registrations, where we see the CME twisted shape during its evolution. Here we displayed the negative of the images.

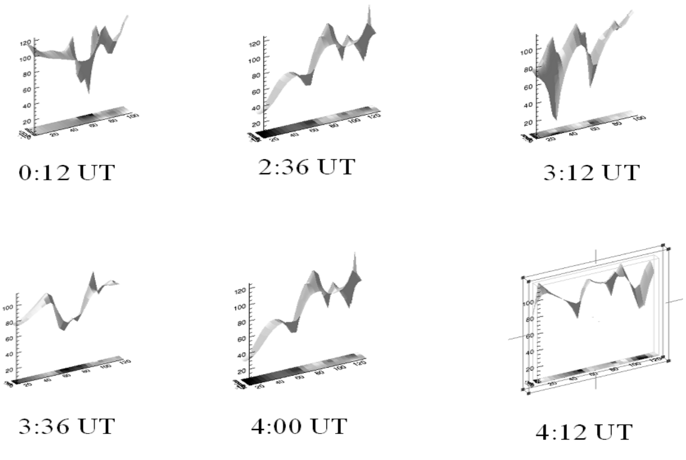

Fig. 5 – Filament evolution during its eruption as derived from 3D coronal magnetic field extrapolations.

The CME morphology, observed in EIT and LASCO/C2 images (Fig. 4), allowed us to consider that kink instabilities were the cause of a flux rope eruption. This aspect will be discussed in Section 3.

We have extrapolated the coronal magnetic field from MDI/SOHO magnetograms in the filament zone, obtaining a 3D evolution of the filament body during its eruption. The code used for these extrapolations was described by Lee et al. (2003). The results are displayed in Fig. 5 and are in good agreement with the information extracted from EIT/SOHO observations.

3. ANALYSIS OF THE FILAMENT EVOLUTION AND HELICITY ESTIMATION

The filament evolution can be described by the variation of its parameters like differential rotation velocity, the length, and its tilt angle on the solar parallel (Dumitrache 1997). In these computations the time t is expressed in day of the year unities (DOY). Since the filament was observed between years we have used the days of the year denominated continuously, i.e., 1 January 2001 is DOY = 367.

The length of the filament L and the angle made by the filament with the solar parallel u are computed by:

$$L = \arccos(\sin\varphi_1 \sin\varphi_2 + \cos\varphi_1 \cos\varphi_2 \cos(L_1 - L_2)), \tag{1}$$

$$u = \arcsin\left(\frac{\sin\varphi_1 - \sin\varphi_2 \cos L}{\cos\varphi_2 \sin L}\right), \tag{2}$$

where (φ_1, L_1) and (φ_2, L_2) are the coordinates of the end footpoints of the filament, $L_1 > L_2$. This filament has a dextral chirality and $u < 0$, according to the hemisphere chirality rule. The differential rotation velocity used is the well-known d'Azambuja law (d'Azambuja 1948):

$$w = 1.12 - 1.4\sin^2\varphi - 11.33\sin^4\varphi. \tag{3}$$

Fig. 6 plots the variations of these parameters in time (expressed in DOY). These variations can be regarded as signatures of large-scale magnetic reconnections in zone and when they occur observationally an explosive event, flare or CME, is registered. This method allows us to detect important days in the filament life and focus on a specific event.

Using a cluster analysis method (see Dumitrache 1997) we checked the accuracy of the filament end footpoints coordinates measurement and we deduced these coordinates also for 7 January 2001 (DOY = 373) where the filament arrived at the western solar border. From Hα records we remarks that a little tail appeared on 4 January 2001 (DOY = 370) and the filament extended. A helical upward movement started gradually inside the filament after 4 January 2001 and culminated with the total destabilization of the filament on 7 January 2001. After 5 January we observed the length decreasing continuously while the tilt angle decreased also (in its absolute value) – the filament constricted in that time. On 7 January we notice sudden variation of the differential rotation and tilt angle and the coronal mass ejection occurrence.

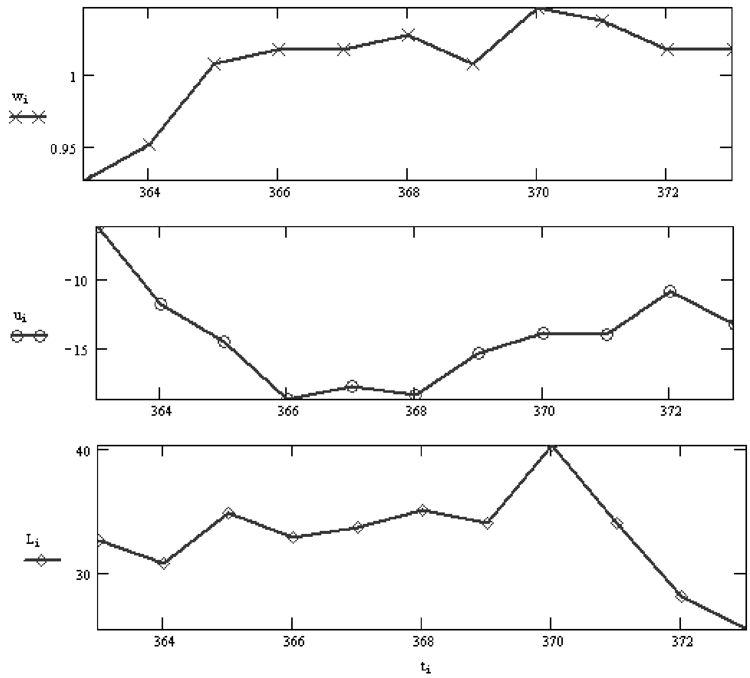

Fig. 6 – Differential rotation velocity (*w*), tilt angle (*u*) and filament length (*L*) variations, using the daily middle coordinates of the filament.

The magnetic helicity injected by the differential rotation velocity in the filament could be estimated by

$$\Omega = 2 \sin \varphi \cos^2 \varphi \,(b + 2c \sin^2 \varphi), \\ V_x = \mathrm{d}f_y \cdot \Omega. \tag{4}$$

Magnetic helicity injected in the filament footpoints is plotted in Fig. 7. A similar plot for the middle filament coordinates gives a curve that reveals a decreasing injected magnetic helicity before 3 January and a new pick of this on 4 January, when the new AR09297 and the filament tail too emerged. A new pick occurred in the day of the CME occurrence, when the filament disappeared. Looking at the filament footpoints (Fig. 7), we observe a different helicity injection after 4 January.

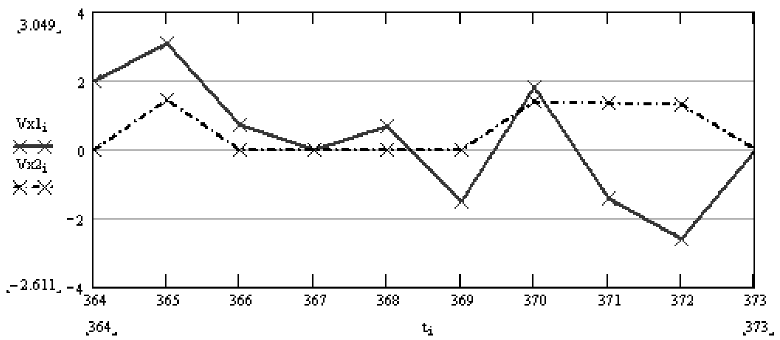

Fig. 7 – Magnetic helicity injected by the differential rotation velocity in the filament arcade.

We attempt to evaluate the filament helicity using its footpoints coordinates, as well as its dynamical parameters computed as above. We model the filament as a coronal loop:

$$\begin{cases} B_x = -\dfrac{1}{k}\cos(kx)\exp(-lz), \\ B_y = -\dfrac{\alpha}{k}\cos(kx)\exp(-lz), \\ B_z = k^2 \sin(kx)\exp(-lz), \end{cases} \tag{5}$$

where the length of filament is computed by (1) and occurs in (6)

$$\begin{aligned} l &= k^2 - \alpha^2, \\ k &= 2\pi / L. \end{aligned} \tag{6}$$

The α force-free field parameter is computed taking into account the chirality rules of the hemisphere and also Canfield and Pevtsov (1998) computations performed for active regions. In (7) u is the tilt angle of the filament axis to the solar parallel, computed via (2).

$$\alpha = -\pi \cdot \frac{\sin u}{L}. \tag{7}$$

We then computed the helicity of the filament Hf and its twist Tw by (8):

$$\begin{aligned} Hf &= -\alpha \ln(\cos(kz)), \\ Tw &= \frac{\pi}{4}\alpha L. \end{aligned} \tag{8}$$

The filament helicity could be computed also by (9) since the total helicity is composed by the twist *Tw* and by the writhe *Wr*:

$$H = \frac{\Phi^2}{2\pi}(Tw + Wr)\,, \tag{9}$$

where the magnetic flux is

$$\Phi = 2\frac{L}{R}B_{\varphi}\,, \tag{10}$$

and R is the curvature of the filament magnetic flux rope. Using the amounts computed above we could estimate also the writhe of the filament by:

$$Wr = \frac{(2\pi\, Hf - Tw/\Phi^2)}{\Phi^2}\,. \tag{11}$$

All these amounts are plotted versus time in Fig. 8 (expressed in DOY t_i, where $i = \overline{0,9}$). We observe the filament helicity and the magnetic flux reaching a maximum value during the filament evolution exactly in the day when the filament became kink unstable and the coronal mass ejection occurred. Our computation gave the value $\Phi_c = 3.423\pi$.

Fig. 8 reveals that the filament writhe grew up in time, while the twist decreased after DOY 368 and than had a sudden increase in the last day when it erupted. The parameter α had first a slow decrease before DOY 370, but increased after that and reached the value of 0.028 in the CME day.

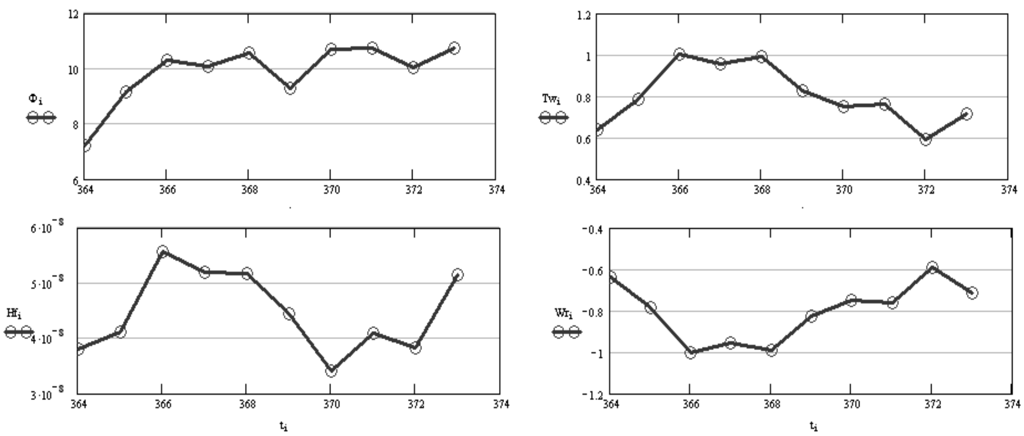

Fig. 8 – Filament helicity and magnetic flux (left); writhe and twist estimation (right).

4. DISCUSSION

We have studied the evolution and destabilization of a filament that gave a coronal mass ejection on 7 January 2001. The CME shape indicated us that kink instabilities represented the trigger mechanism.

We have applied a new method to estimate the filament helicity, twist, and writhe, to outline the increase of writhe and to prove that the filament became kink unstable. This method is very raw and sensitive to the measurement of the filament footpoints coordinates.

We have found that the filament erupted in the day when the magnetic flux exceeded the critical value $\Phi_c = 3.825\pi$, a very appropriate value to that found by Titov and Demoulin (1999).

Normally the writhe and twist must be balanced so that the total helicity be conserved. Kink instability is expected to occur as the twist in a magnetic flux tube exceeds some critical value. As the instability proceeds, the twist helicity is transformed into writhe helicity because of helicity conservation. Few authors, yielding conflicting results, treated the relationship between twist and writhe in active regions. So, using vector magnetograms obtained at Mees Solar Observatory, Canfield and Pevtsov (1998) found that both twist and writhe exhibited the same handedness. Tian et al. (2001) found an opposite handedness of the twist and writhe for magnetograms obtained at Huairou Solar Observing Station. Rust and LaBonte (2005) deduced observationally the same sign for the twist and writhe in the case of seventeen filaments.

In our case, the writhe and twist are symmetric (they have opposite sign) with respect to a zero axis in Fig. 8, and the twist exceeds the writhe at the 5th decimal in absolute value when the filament was still linked to the solar surface. The dramatic changes in rotation and so in the writhe enhancement produced after the filament undergone the first two stages of the CME, observable also on the EIT images. We also remind here that we have computed the force-free field parameter α having an opposite sign to the filament tilt angle u, which differs from the active region case.

Filament helicity represents a very thorny topic. We think anyway that our method gives a raw idea about the filament dynamics and destabilization when this occurs.

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