

OBSERVATIONAL EVIDENCE OF THE KINK INSTABILITY IN SOLAR FILAMENT ERUPTIONS AND SIGMOIDS

D. M. Rust¹ and B. J. LaBonte¹

ABSTRACT

Two lines of observational evidence are used to infer that the MHD helical kink instability is associated with solar eruptions. The sense of twist and writhe are determined in images of 7 erupting filaments obtained at 10830 Å, 1600 Å, 195 Å and 171 Å. In every case the sense of twist is the same as the sense of writhe, as required for a kink. From images in the soft X-ray and EUV spectrum, measurements of the height/width ratio of 623 sigmoids show a mean value of 5.47, which is the ratio expected for kinked flux ropes.

INTRODUCTION

Sakurai (1976) was the first to identify kinked flux ropes with solar filament eruptions. Since then, there have been many relevant analytical and numerical models, e.g. (Baty 2001; Fan & Gibson 2004; Gerrard et al. 2001). The MHD helical kink instability may occur in twisted magnetic flux ropes that thread the corona and that have more than some critical twist, estimated to be between one and three turns from end to end (Hood & Priest 1979). For the kink instability to work, the flux rope writhe and twist must have the same sign. We will consider two lines of evidence that tend to show kinking actually happens on the sun. We start with observations of erupting filaments, in which dense, absorbing matter is entrained in twisted flux ropes (Aulanier, Srivastava & Martin 2000; Rust & Kumar 1994), and we show that when they writhe (form a loop or kink), the sign of the kink agrees with that of the twist in the filament as determined either before or during the eruption. These observations show that erupting filaments are converting twist into writhe, and *that* is the kink instability in action. In some cases, at least, the twisted structure of the flux rope is evident in all phases of an eruption, but in many cases of filament eruption (unexamined here) neither twist nor writhe is apparent.

Sigmoids (S- or inverse S-shaped bright features in coronal images) may be further evidence of kinked flux ropes (Rust & Kumar 1996). In this case, however, the kinked feature is not much denser than the surrounding corona and, in fact, the sigmoidal shape may highlight the fields passing through a current sheet instead of the kinked fieldlines themselves (Gibson et al. 2004; Kliem, Titov & Török 2004). We will show that sigmoids have exactly the shape of a kink in stable equilibrium, namely, that the distribution of the ratio of length to width of hundreds of sigmoids centers on 5.47, which is essentially the theoretically predicted ratio of 5.4. In sigmoids, flux ropes may be exhibiting an intermediate step between kinking and eruption, because sigmoids typically brighten and disintegrate just before onset of a coronal mass ejection (CME) (Canfield, Hudson & McKenzie 1999).

¹ The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723

THE 2003 FEBRUARY 18 FILAMENT ERUPTION

Hill et al. (2005) drew attention to observations of a filament that erupted from the solar northwest limb at 0130 UT on 2003 February 18. The filament exhibited all the characteristics expected of a kink, including conversion of twist into writhe of the same sign. The filament, as recorded in $H\alpha$, was a long-lived polar crown segment that, like most high latitude northern hemisphere filaments, had a pattern of barbs characteristic of filaments that are supported in magnetic flux ropes with a left-handed (negative) twist (Aulanier & Demoulin 1998; Aulanier et al. 1998; Rust 1999). Furthermore, virtually all magnetic clouds associated with the eruption of high northern latitude filaments have left-handed twisted fields (Bothmer & Rust 1997). So we infer that a left-handed flux rope threaded the filament before and during the eruption.

Between 0128 UT and 0338 UT, the Mauna Loa Solar Observatory (MLSO) recorded the eruption in the wings of the He I 10830 Å line. A Dopplergram movie shows the filament untwisting as it rose into the corona. Figure 1 shows two frames from the movie. Notice that the leg on the Earth-facing side of the sun was moving mostly toward the observer (black segments) while the opposite leg was moving mostly away from the observer (white segments), as expected in a Dopplergram of an expanding arch. But the image also reveals that the closest leg was rotating, because the top edge of the leg is black while the bottom edge is white, at least in part. The opposite leg was also rotating, but in this case the top of the leg in the Dopplergram is white and the bottom edge is black. This is the rotational pattern of an untwisting flux rope; but of course, since magnetic helicity must be conserved in such plasma, the twist can be removed by converting it to writhe.

Between 0152 UT and 0326 UT, the MLSO MKIV coronagraph recorded the erupting filament as it writhed and passed through the inner corona. It became part of a classic CME in which a bright loop is followed outward by a coronal void and then by a bright filament. In the MKIV movie, the northward leg, the one closest to the observer, is seen to cross over from north to south in a writhing motion that turned the arch into a loop. No additional writhing was observed beyond $2 R_{\odot}$, according to the LASCO coronagraph on the Solar and Heliospheric Observatory, but see Plunkett et al. (2000) for a description of the similar eruption of 1998 June 2 where writhing did take place in the LASCO field of view.

We interpret the February 18 data as follows: a filament with a negative helical field erupted and lost some or all of its twist as it kinked and became the core of a CME. The pattern of Doppler motions is consistent with untwisting in a left-handed flux rope. The pattern of writhe, with the foreground leg crossing from left to right, is consistent with a writhe of -1 in the filament (Berger & Field 1984).

WRITHING FILAMENTS IN TRACE MOVIES

The Transition Region and Coronal Explorer (TRACE) telescope produces series of images in the lines at 171, 195 Å and 1600 Å, inter alia, and many eruptive events have been found. Movies of them are readily available on the Web at vestige.lmsal.com/TRACE/POD/TRACEpod.html. We selected the movies labeled

‘filament eruption’ or ‘dynamic filament’ or some similar descriptor. Among those events, we found six that appeared to be writhing loops. Table 1 lists them and the inferred sign of twist and writhe. On 2003 June 12 there were two quite distinct loops observed in the same active region. The first and larger loop had positive twist and writhe while the second had negative twist and writhe. This result should not be surprising, considering that many active regions exhibit patches of both positive and negative current helicity (Pevtsov, Canfield & Metcalf 1994).

Table I shows that in every case the sense of twist and writhe agreed. In order to determine the sense of twist and writhe, one must know which leg of a loop is in the foreground and which threads of the loop are on the side closest to the observer. At the TRACE wavelengths, we usually see both absorbing and emitting threads in active loops. It is only necessary to examine the image sequences and use the instances when dark, absorbing material obscures a bright thread or knot to determine the sense of twist and writhe. Using TRACE images in this manner, Chae (2000) determined the chirality of an active filament, and Rust (2003) determined the sense of writhe in the 2002 May 27 event. The present paper is the first to use the technique systematically to determine both sense of twist and writhe in active filaments.

Table I. Erupting, Writhing Filaments in TRACE Movies

<i>Date</i>	<i>Time (UT)</i>	<i>Wavelength (\AA)</i>	<i>Sense of Twist</i>	<i>Sense of Writhe</i>
1999 Oct 22	0910 - 0930	171	+	+
2001 Jun 15	0926 - 1010	195	-	-
2000 Jul 19	2310 - 2348	171	+	+
2002 May 27	1800 - 1930	195	+	+
2003 Jun 12	0106 - 0117	1600	+	+
2003 Jun 12	0113 - 0120	1600	-	-

Figure 2 shows an image from the 2000 July 19 sequence that reveals that the loop segment that stretches from lower right to upper left is in the foreground because it obscures the horizontal segment behind it. Similarly, one can see that the bright threads everywhere run in a right-handed sense around a dark, absorbing core. We conclude that the sense of twist and writhe were both positive in this event.

Romano, Contarino & Zuccarello (2003) also analyzed this filament eruption. They also concluded that the filament was kinking, based on their measured decrease in the ratio between the pitch of the magnetic field lines and the filament width.

Figure 3 shows a pair of images in which a dark filament in the shape of an inverse S is transformed into a straight filament with a negative twist. The filament erupted from the sun during this transformation. As Rust and Kumar (1996) showed, a flux rope with negative twist can kink and take on the shape of an inverse S. Flux ropes with critical positive twist become S shaped. The present case is a filament that converts writhe into twist. Twisting a flux rope at its footpoints in the photosphere may result in the formation of a stable kinked equilibrium with some energy release (Gerrard, Arber & Hood 2002). Further twisting might result in a more dynamic energy release (Török, Kliem & Titov 2004) as occurred in this case.

ASPECT RATIO OF SIGMOIDS

Rust and Kumar (1996) used a simple model of the $m=1$ helical kink to describe the sigmoidal structures that brighten at the onset of CMEs. According to the model, the height of the S-shaped feature divided by its full width should equal 5.4. The distribution of height/width for their 55 measured sigmoids gave an average ratio of 4.5. A similar study (Leamon et al. 2003) of 191 sigmoids yielded an average ratio of 5.4, after our transformation of the authors' measurements into ratios. For the present study, we used an automatic sigmoid identification code (LaBonte, Rust & Bernasconi 2003) and a code developed originally for automatically classifying solar filaments (Bernasconi & Rust 2004). The first code compares inflections in the brightness contours of emitting features to the range of such inflections in sigmoids identified by visual inspection. The code recognizes sigmoids without imposing an aspect ratio criterion.

We analyzed images from the Yohkoh Soft X-ray Telescope (SXT), the NOAA GOES Soft X-ray Imager (SXI), and the SoHO Extreme Ultraviolet Imaging Telescope (EIT). Overall, the code identified 377 sigmoids. The identifications are not completely independent since the same sigmoid might be identified in successive images. Each identification had a degree of independence, however, since each had no reference to earlier or later measurements.

Starting with the 377 automatically identified sigmoids, we used the filament characterization code to define the spine of each sigmoid. The code starts by making a mask from the sigmoid so that all pixels are either definitely in or out of the sigmoid. Next, the code determines the diagonal of the rectangle that just encloses the sigmoid. This diagonal is then bisected and the two segments are fit to the centroid of the respective masked regions. This process is repeated until all segments of the spine are about 20 pixels long. See Figure 4 for an example of a sigmoid with its spine and limiting contour. The figure also shows how the aspect ratio was determined (white box).

To test the hypothesis that sigmoids represent $m=1$ kinks in flux ropes, we performed a metastudy, i.e., a compilation of measurements from different sources. We computed the weighted average aspect ratio from sigmoid measurements from Rust & Kumar (1996), Leamon et al. (2003), and the present automatic measurements. The weighted average of the studies of a total of 623 sigmoids as summarized in Table II is 5.47. This is remarkably close to the predicted ratio of 5.4 for the $m=1$ kink.

Table II. Summary of Aspect Ratio (L/W) Studies

<i>Source</i>	<i>Interval</i>	<i>Number of L/W Sigmoids</i>	
SXT (Rust & Kumar 1996)	1991 Oct to 1994 Oct	4.5	55
SXT (Leamon et al. 2003)	1991 Oct to 2000 Oct	5.4	191
EIT	2002 Jan – 2003 Mar	6.6	96
SXT	1998 Apr & May; 2001 Oct - Dec	5.6	81
SXI	2003 Mar – 2003 Aug	5.3	104
SXI	2004 Aug – 2004 Oct	5.1	96

CONCLUSIONS

Two lines of evidence were pursued to see if observations are consistent with the kink instability occurring in solar eruptions. First, we examined seven filament eruptions, including some in which the filament escaped from the sun and some so-called “frustrated eruptions” in which a filament rises up rapidly and then hesitates and disintegrates into flare loops. All but one of the filaments writhed, forming a loop as they rose into the corona. We found that, in each case, *the sign of the writhe matched the sign of the internal twist*, as inferred from the patterns of bright and dark threads. One event, 2001 June 15, began with an inverse S and ended with the filament twisting and then erupting. This seems to be a case in which a stable kink became unstable. The same thing could be happening in X-ray sigmoids, which *have exactly the shape of kinked flux ropes*.

In the filaments we examined – and they were all selected because they showed writhing motion – the stability was lost, probably by a change in boundary conditions or by added twist. In the case of sigmoids, the diaphanous plasma is free to kink without total destabilization and eruption from the sun. A change in boundary conditions or added twist probably destabilizes them and leads to the CMEs that so often follow.

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FIGURES

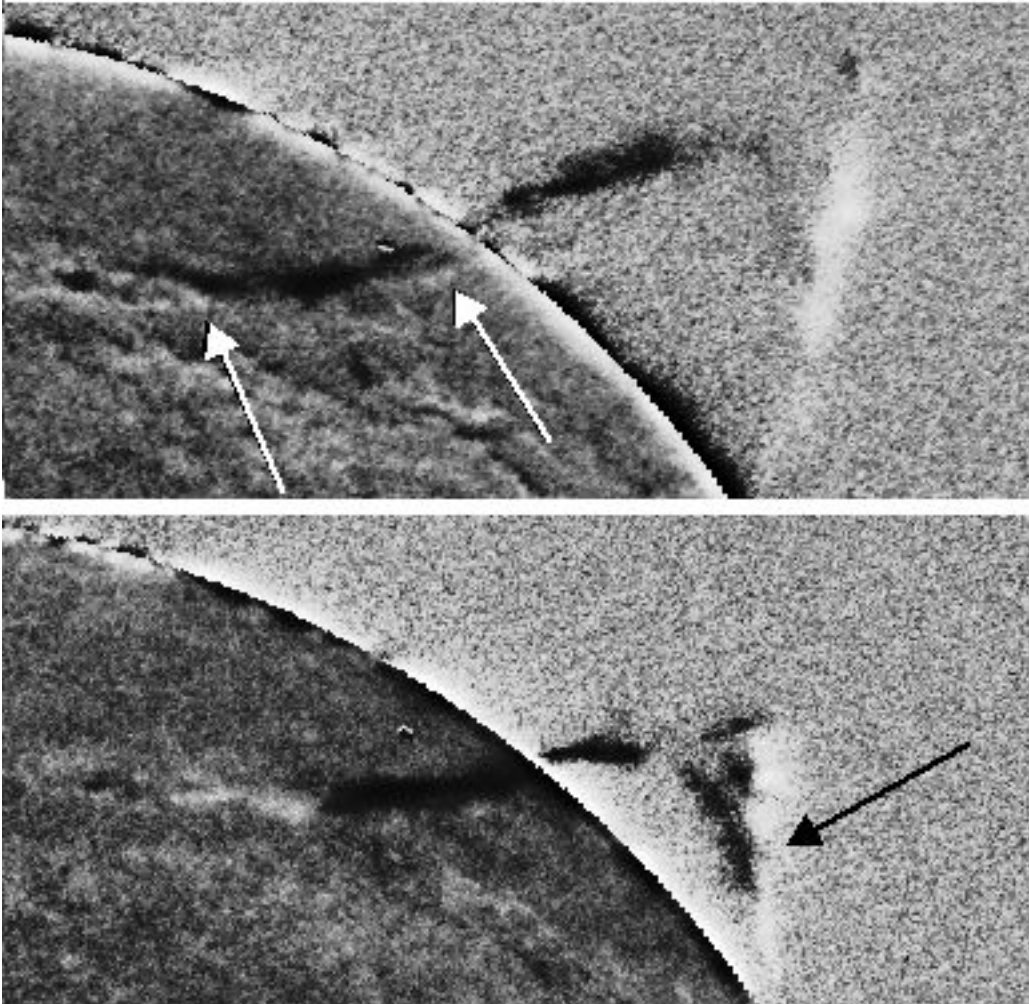


Figure 1. The filament eruption of 2003 February 18 recorded at 0202 UT (bottom) and at 0208 UT (top). This Dopplergram in the 10830 Å line of He I shows material moving toward and away from the observer in black and white, resp. The white and black arrows point to signatures of rotation in the foreground and background legs, resp.

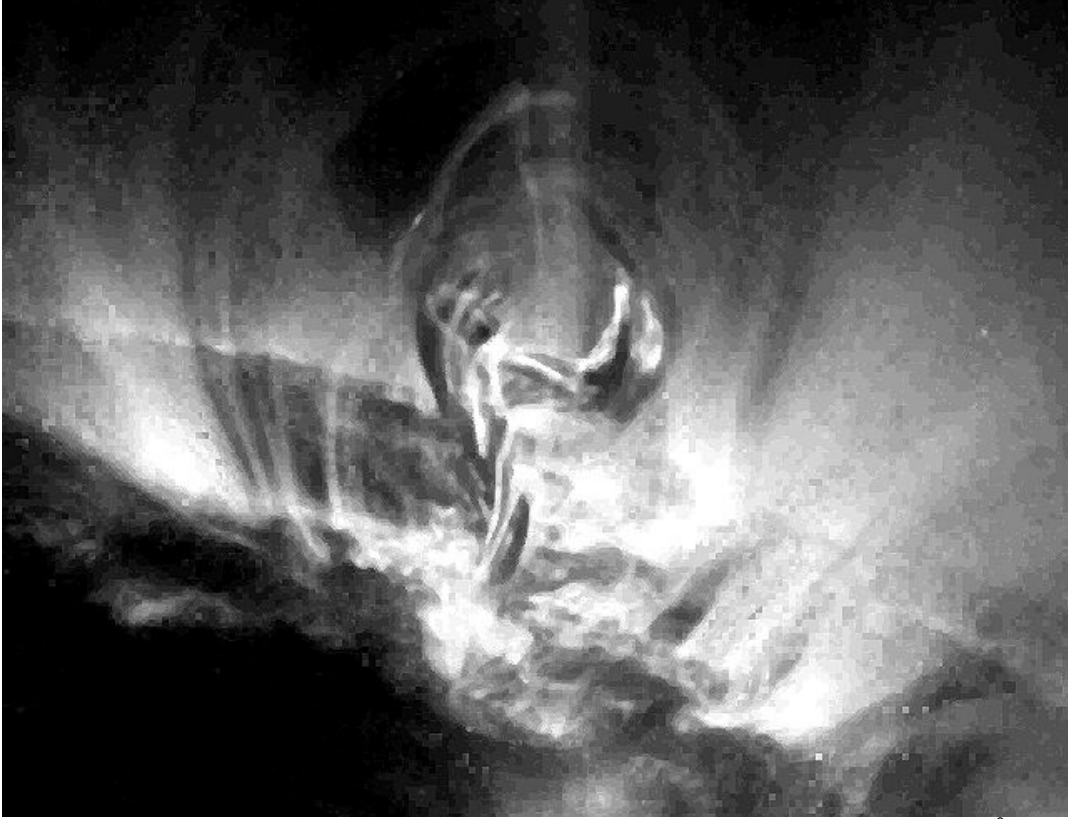


Figure 2. The filament eruption of 2000 July 19 recorded at 2322 UT at 171 \AA . At this stage the filament formed a loop with the foreground segment stretching upward from right to left. We interpret this as a writhe of +1 (Berger & Field 1984).

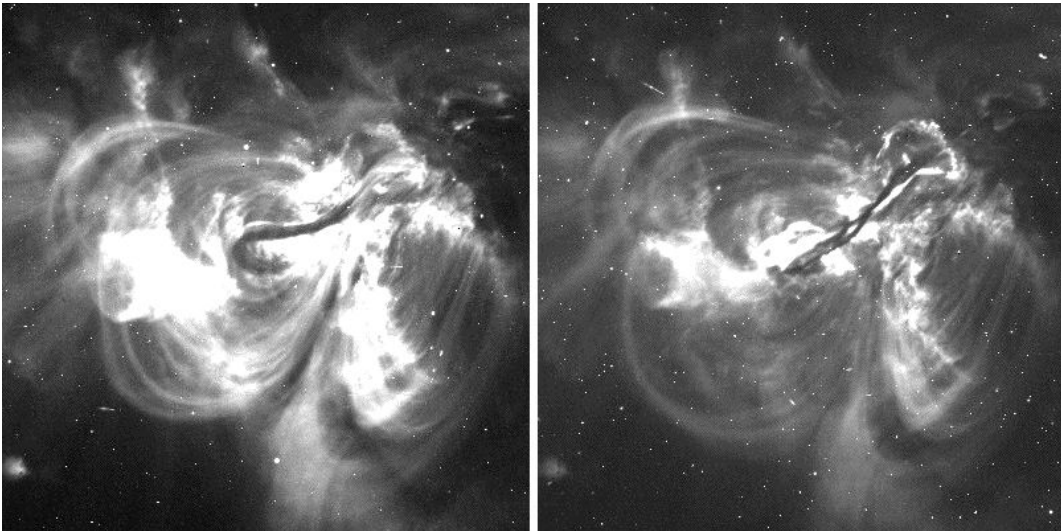


Figure 3. The filament eruption of 2001 June 15 recorded at 195 \AA . The filament (left) had an inverse S shape at 0956 UT, just before it erupted. At 1005 UT (right), in the early stages of eruption, the kink in the filament straightened out and some of the threads comprising the filament brightened, allowing one to infer that the sense of twist in the filament was left-handed.

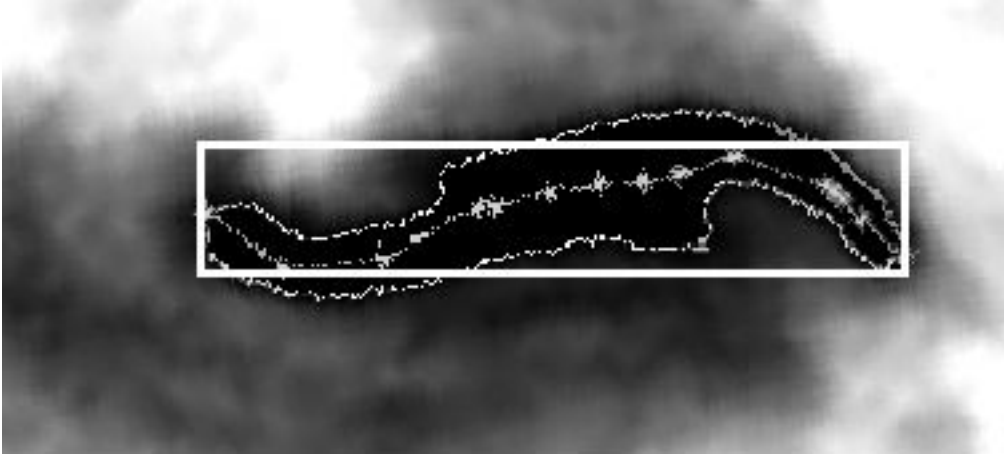


Figure 4. The contour of a typical Yohkoh SXT sigmoid shows the perimeter while the line with asterisks shows the computed position of the spine. The height/width aspect ratio was computed from the respective sides of the white rectangle.