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Sigmoidal Morphology and Eruptive Solar Activity

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Abstract. Soft X-ray images of solar active regions frequently show S- or inverse-S (sigmoidal) morphology. We have studied the Yohkoh Soft X-Ray Telescope video movie for 1993 and 1997. We have classified active regions according to morphology (sigmoidal or non-sigmoidal) and nature of activity (eruptive or non-eruptive). As well, we have used NOAA sunspot areas for each region as a measure of size. We find that regions are significantly more likely to be eruptive if they are either sigmoidal or large.

1. Introduction

As viewed in soft X-rays, coronal active regions consist of discrete bright loops. These loops often collectively form sinuous S or inverse-S shapes [Acton *et al.*, 1992]. This shape has been named “sigmoidal” by Rust and Kumar [1996], who studied the characteristics of sigmoidal brightenings in X-rays. They found that such brightenings typically evolve from a bright, sharp-edged sigmoidal feature into either an arcade of loops or a diffuse cloud. It is clear that such arcades of loops (loop prominence systems) and long-duration events (LDEs) are related to coronal mass ejections, though not necessarily in a one-to-one manner [Webb, 1992]. We expect transient sigmoidal brightenings to form within regions whose overall structure is sigmoidal and long-lived. We hold this expectation because the overall twist of active region magnetic fields observed in the photosphere and corona are related [Pevtsov *et al.*, 1997] and the overall twist of active regions seen in the photosphere hardly changes, except perhaps in association with major eruptive flares [Pevtsov *et al.*, 1995]. Hence, there is reason to expect long-lived sigmoidal structures in the corona to be associated with eruptive phenomena. In this study we explore this possibility observationally using the synoptic movie of full-disk X-ray images from the Yohkoh SXT [Tsuneta *et al.*, 1991].

The full-limb field of view and high sensitivity of the LASCO coronagraphs on SOHO [Brueckner *et al.*, 1995] have attracted attention to the halo-CME phenomenon associated with coronal eruptions directed along the Earth-Sun line. In those halo CMEs that are directed toward Earth, it is straightforward to study the relationship between the pre-CME and post-CME structures observed with any given instrument. Sterling and Hudson [1997] first used the Yohkoh SXT in this manner to study a single halo-CME event and found that a pre-event sigmoid disappeared, leaving a soft X-ray arcade and two “transient coronal holes” behind. Hudson et al. [1998] extended the relationship with a larger sample of CME-associated events, and found that the sigmoid to arcade pattern is a common characteristic of regions that have been the site of halo CMEs. In this study, we look to see whether this same pattern can be seen in all regions, not just those associated with halo CMEs. The principal motivation for this study is to determine whether the sigmoid shape might be a useful predictive tool.

2. Data Analysis

We picked 1993 and 1997 for study, since both years were characterized by an intermediate level of solar activity – neither so low as to include only a small number of samples nor so high as to show frequent active-region interactions [Canfield *et al.*, 1996]. We used Yohkoh SXT images to make a subjective visual classification of active regions according to their morphology (sigmoidal or non-sigmoidal) and activity (eruptive or non-eruptive). The images were viewed as time sequences, using the standard Yohkoh movie, a video-disk display of composite images (long plus short exposures) in the Al.1 and AlMg analysis filters. This movie has an average of about 50 composite images per day. With this cadence, except for unusual data gaps, we do not miss the sigmoid-to-arcade events of interest here, since they are known to be associated with long-duration events, or LDEs [Webb, 1992], which typically last for many hours.

We classified the morphology of active regions as sigmoidal if S or inverse-S shapes were evident in either their overall structure, as defined by a pattern of multiple loops, or individual loops, i.e., transient brightenings [Rust and Kumar, 1996]. The upper panel of Figure 1 shows, on the central meridian, a structure we would classify as sigmoidal (inverse-S), albeit asymmetric. East of it is another. As well, it shows other structures, such as the bright active region east of the two sigmoidal structures, which we would classify as non-sigmoidal; its shape seems consistent with what we would expect of a potential (current-free) magnetic field. Our classifications include only those regions which were present on the disk long enough, near enough to disk center, to confidently make a judgment. Morphology classifications (sigmoidal or non-sigmoidal, S or inverse-S) were made independently by two of us. No regions were judged

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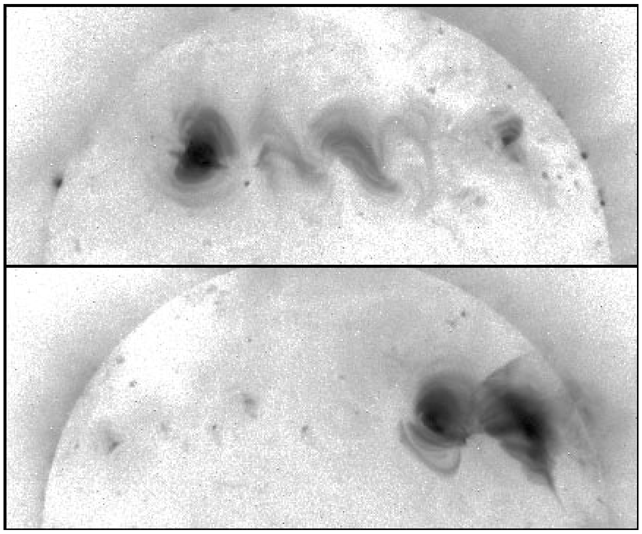

Figure 1. An example of three nearby active regions showing non-sigmoid and sigmoid configurations. The middle and right regions show clear sigmoidal patterns, in the reverse-S configuration expected for the north. The upper panel (May 15, 1998, 10:47 UT) shows regions at approximately E30, E08, and W07, of which only the eastern region had a NOAA number (NOAA 8222). By May 19, 12:03 UT (lower panel) the non-sigmoidal region had rotated to W25, and the strongly sigmoid middle region has erupted - note the cusp spikes extending to the NW and to the SW, and the bright ridge of emission along the arcade.

to be sigmoidal unless the two judgments agreed in both respects.

Previous work on S and inverse-S structures [Rust and Kumar, 1996] shows that the hemispheric rule (inverse-S in the North, S in the South) is weak. In the 1993 and 1997 datasets combined, we found 61 sigmoidal active regions, and only 41 (67%) adhered to the hemispheric rule. This result is consistent with Rust and Kumar's finding, if their transequatorial brightenings are not ignored.

We initially classified regions as eruptive if, during their disk transit, we observed in several successive frames of the SXT movie one or more of three signatures of eruptions: (1) transient X-ray loops of either cusped or arcade form, (2) moving large-scale brightenings, or (3) transient coronal holes. In practice, cusped loops were seen in about 80% of the observed eruptive events, arcades in about 30%, and moving large-scale brightenings and transient coronal holes in only a few. Neither moving large-scale brightenings nor transient coronal holes proved to be useful signatures, using our simple classification techniques. Without spectroscopic evidence it is hard to determine with confidence that a moving large-scale brightening is really due to moving coronal material, and not the successive excitation of adjacent structures. Without differencing images before and after eruptions [Sterling and Hudson, 1997; Hudson *et al.*, 1998], it is difficult to detect the relatively subtle changes found in many events. Hence, we dropped signatures (2) or (3) from use in this study. As with the morphology classifications, judgments regarding the signatures of eruptions were made independently by two of us, noting the date, time, and nature of the signature, and no events were included if our independent judgments differed.

Table 1. Sigmoidal Active Regions

NOAA	S/N	E/I	Area[a]
7386	S	E	212
7389	S	I	13
7391	S	E	63
7406	N	E	74
7416	N	I	34
7418	S	I	181
7420	S	E	713
7425	S	E	89
7427	S	E	50
7430	S	E	54
7433	N	E	212
7434	S	E	109
7454	S	E	5
7461	N	E	212
7465	S	E	231
7477	S	E	245
7480	S	E	73
7483	S	E	123
7490	N	I	67
7493	S	E	56
7496	S	E	192
7500	N	E	382
7509	S	E	0
7519	N	E	60
7530	S	E	204
7533	N	I	10
7538	N	I	46
7547	N	E	66
7552	N	E	78
7555	S	I	29
7588	N	E	22
7590	S	E	789
7597	S	I	29
7613	N	E	449
7616	S	E	4
7626	N	I	10
7629	N	E	109
7635	N	E	41
8011	S	I	17
8015	S	E	61
8020	N	E	54
8026	N	E	73
8027	S	E	39
8032	S	E	32
8038	N	E	69
8048	S	E	76
8056	N	E	24
8059	S	E	10
8066	N	E	8
8074	N	E	34
8083	S	E	351
8085	S	E	371
8086	S	E	86
8088	S	E	197
8090	S	E	29
8092	S	E	6
8096	N	E	29
8097	N	E	48
8100	N	E	448
8103	N	E	63
8108	S	E	272

[a] Spot area, 10^{-6} hemisphere

Table 1 identifies by NOAA number all sigmoidal active regions we found in 1993 and the first eleven months of 1997. The second column gives the morphology of the sigmoid – S or inverse-S (N in the table). The third column specifies

Table 2. Morphology and Activity Distribution, 1993 & 1997 Combined

	Non-Sigmoidal	Sigmoidal
Eruptive	28	51
Non-Eruptive	28	10
Total	56	61

whether the region was found to be eruptive (E) or not (I), and the fourth column gives the area, computed as discussed below. Regions that do not appear in the table either were classified as non-sigmoidal or could not be classified because they were not sufficiently long-lived or they emerged substantially west of the central meridian. Table 2 summarizes the data for all regions that could be classified. We find that 51% of all regions are sigmoidal, and they account for 65% of the observed eruptions.

It is readily shown that active region size, measured by spot size in our study, is also a factor in eruption. Table 1 includes the areas of the spots in each active region, averaged over the time period the region was observed. The data are taken from the spot areas, in millionths of the visible hemisphere, tabulated in Solar Geophysical Data.

The histogram in Figure 2 shows how the categories given above are distributed by spot area for the combined 1993 and 1997 datasets. Several clear trends can be seen:

1. Sigmoids in all size categories show eruptive signatures.

2. Non-eruptive sigmoids are typically small, but even in the smallest size category, at least twice as many show eruptive signatures as don't.

3. In the smaller size categories, non-sigmoids appear to be less likely to show eruptive signatures.

4. Size and morphology are independently related to eruptive signatures.

In Table 1, all regions with spot areas above 200 millionths had eruptive signatures, regardless of morphology.

Quantitative analysis of our combined 1993 and 1997 dataset of $n = 117$ regions shows that those with sigmoidal morphology, regardless of size, are 68% more likely to be eruptive than non-sigmoidal regions. The ϕ coefficient [Daniel, 1990] is designed for evaluation of statistical significance in studies using such dichotomous variables, which can take on only one of two mutually exclusive values. This coefficient is related to chi-square values through $X^2 = n\phi^2$, which can be compared to tabulated chi-square values with one degree of freedom. For the full dataset we find $X^2 = 15.0$, which means that the null hypothesis (that there is no association between morphology and eruptive signatures) may be rejected at better than the 99.5% confidence level. As well, our dataset can be divided into large regions (spot area greater than 50 millionths, *cf.* Figure 2) and small ones (less than 50 millionths). By the same measures, large regions are 73% more likely to be eruptive than small ones, $X^2 = 17.2$, and the null hypothesis can be rejected at better than the 99.5% confidence level.

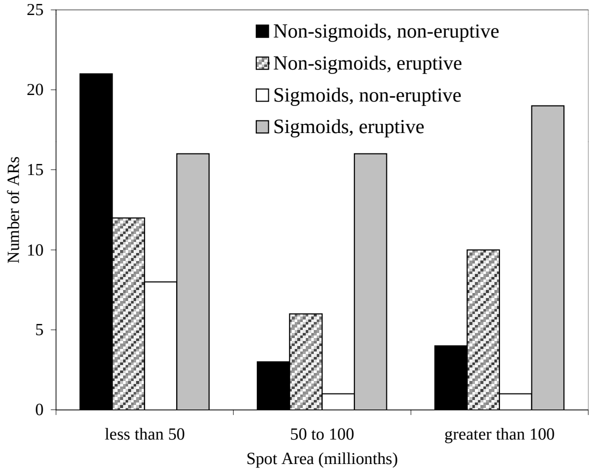

Figure 2. Distribution of the classified regions with NOAA spot area, for the combined 1993 and 1997 datasets .

3. Conclusions

This simple study has found statistically significant evidence for two independent factors which indicate enhanced tendency of active regions to erupt: (1) clearly observable sigmoidal morphology and (2) large sunspot area. We have not yet incorporated into our study quantitative observations of the amplitude of the twist of the sigmoids that we have observed, but our result motivates such improvements. Even without such improvements, it appears that both size and morphology of solar active regions are useful tools in estimating probability of eruption.

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