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The Onset and Association of CMEs with Sigmoidal Active Regions

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Abstract. Previous studies of active regions characterised by Soft X-ray S or inverse-S morphology [*Canfield et al.*, 1999], have found these regions to possess a higher probability of eruption. In such cases, CME launch has been inferred using X-ray proxies to indicate eruption. Active regions observed during 1997, previously categorised as both sigmoidal and eruptive [*Canfield*, 1999], have been selected for further study, incorporating SoHO-LASCO, SoHO-EIT and ground based H-alpha data. Our results allow re-classification into three main categories; sigmoidal, non-sigmoidal and active regions appearing sigmoidal due to the projection of many loops. Although the reduced dataset size prevents a statistical measure of significance, we note that regions comprising a single S (or inverse-S) shaped structure are more frequently associated with a CME than those classed as non-sigmoidal. This motivates the study of a larger dataset and highlights the need for a quantitative observational definition of the term "sigmoid".

Introduction

Coronal Mass Ejections (CMEs) are known to originate from both active regions and the quiet corona. Recent studies into the onset of active region CMEs [*Hudson et al.*, 1998; *Canfield et al.*, 1999] have compared pre- and post-CME structures in a number of active regions in order to determine the nature of any changes to their overall morphology on CME launch. These surveys employed data from the Yohkoh Soft X-ray telescope [*Tsuneta et. al.*, 1991]. The X-ray feature found to have the highest probability of eruption was that of a bright, clearly defined S, or inverse-S, shaped loop. Termed "sigmoidal" by *Rust and Kumar* [1996], transient loop systems exhibiting an overall S-like morphology, were seen to evolve from a bright, sharp-edged S-shaped feature into either an arcade of loops or a diffuse cloud.

Hudson et al. [1998] considered the implications of this scenario in the context of halo CMEs only. Incorporating data from the SoHO Large Angle Spectroscopic COronagraph (LASCO) [*Brueckner et al.*, 1995], this survey found the "sigmoid-to-arcade" development a common feature of active regions associated with the onset of a halo CME.

Canfield et al. [1999] performed a similar study incorporating a much wider range of data. A high proportion of active regions visible during the periods 1993 and 1997 were reviewed with the intention of clarifying which X-ray features possess the highest probability of eruption. The results of *Canfield et al.* suggest a strong relationship between sigmoidal morphology and the potential for an active region to erupt. The bright sigmoidal feature will disappear during eruption to be replaced by a cusp; the presence of newly open field lines leading to the assumption of associated CME launch [*Kopp and Pneuman*, 1976].

This study extends the results of *Canfield et al.*, [1999], incorporating observations over an increased range in wavelength, with the intention of clarifying the relationship between the "sigmoid-to-arcade" development and CME onset.

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Observations

It was decided to approach this investigation by extending the results of *Canfield et al.*, [1999] to incorporate SoHO based instruments LASCO and the Extreme Ultraviolet Imaging Telescope (EIT) [*Delaboudiniere et al.*, 1995]. Addition of these instruments' active region observations to the previously studied Yohkoh/SXT full-frame data would provide further insight into the processes taking place; a CME could be observed directly using the LASCO coronagraphs as opposed to inferred using X-ray morphology changes.

Comparison between Yohkoh and SoHO data adds a further constraint to the original list of "sigmoidal" active regions studied by *Canfield et al.*, [1999]. The initial list incorporated active regions visible during the years 1993 and 1997. However, SoHO was not launched until 1996. Thus, extension of *Canfield et al.*'s results to incorporate comparison with SoHO data is only possible using the latter half of the initial list.

Big Bear Solar Observatory H-alpha data are also considered. These data were available at the rate of a single image per day. Active region prominences erupt on a timescale of 20-30 minutes, often reforming later [*Priest*, 1982]. As a result, actual filament eruptions were rarely seen in the daily H-alpha images. Filaments were classed as "eruptive" if they appeared smaller or disappeared sometime during the period of 24 hours surrounding the eruption.

As an initial step, the original Yohkoh SXT survey was repeated for active regions previously classified as sigmoidal and eruptive. Observations made by *Canfield et al.* were completed using data comprising approximately 50 composite full disk images, at either 4.9" or 9.8" resolution, per day. It was decided to repeat the observations using the full range of SXT data available, to include both full and partial frame images with cadence up to one image every two seconds, and spatial resolution up to 2.45" [*Tsuneta et al.*, 1991].

SoHO-LASCO CME data for 1997 was correlated with event times suggested by *Canfield et al.* [1999] by means of a height-time plot extrapolation; tracing the observed CME motion back to a candidate active region on the disk. CMEs were only discounted if a) an exact origin other than that of the candidate region could be determined, or b) if the

Table 1a. Sigmoidal Active Regions

NOAA	Date	CME	Filament	Dimming
8027	07-Apr	Y	E	Y/M
8032	17-Apr	N	N	-
8038	12-May	Y	N	Y/M
8090	05-Oct	N	N	-
8092	11-Oct	Y	E	Y/M
8100	06-Nov	N*	E	-
8108	19-Nov	N	E	-

*denotes AR erupts to produce a CME several hours prior to / after event time suggested by *Canfield* [1999]. This is most likely to be the event associated with an erupting lament during this 24 hour interval.

Table 1b. Projected-Sigmoidal Active Regions

NOAA	Date	CME	Filament	Dimming
8015	04-Feb	N	-	-
8020	09-Mar	N	-	-
8026	03-Apr	N	-	-
8048	01-Jun	Y	-	Y
8096	20-Oct	N	-	-
8097	21-Oct	Y*	E	Y

Table 1c. Non-Sigmoidal Active Regions

NOAA	Date	CME	Filament	Dimming
8056	25-Jun	N	N	-
8066	29-Jul	N	-	-
8088	24-Sep	N	E	-
8103	11-Nov	Y	-	Y

time interval between observed event time and extrapolated CME onset time exceeded 10 hours.

Whilst generally only a weak counterpart of the SXR sigmoid is observed in cooler EUV images [*Sterling et al.*, 1999], a dimming in the corona close to the active region is often observed on CME launch. Large, flare-related events may also be accompanied by a coronal Moreton wave [*Thompson et al.*, 1998]. Both phenomena, observed using the SoHO-EIT Fe XII filter, were incorporated into the extended survey, indicating the direction of CME propagation perpendicular to the plane of the sky.

Data Analysis

The initial survey published by *Canfield et al.*[1999] classified active regions as S or inverse-S if either configuration was deemed present in the overall active region structure, as observed using SXT full-frame observations.

The increase in SXT resolution from full to partial-frame allowed observation of each active region in greater detail than was previously available. The results of this increased resolution showed regions previously classified as sigmoidal and eruptive could be further divided into three categories as follows:.

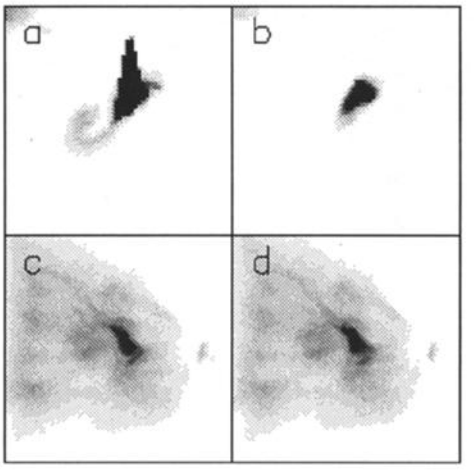

Figure 1. Sample active regions showing sigmoidal and projected, sigmoidal configurations. Panels a and b (11-Oct 08:52UT and 09:07UT) show evolution of NAR 8092, the sharp, sigmoidal feature disappearing with the onset of a CME. Panels c and d (09-Mar 15:42UT and 15:59UT) show NAR 8020 appearing sigmoidal due to projection of several features. No CME was observed in this case.

a) active regions appearing to comprise a single S (or inverse-S) shaped loop, prior to eruption,
b) regions found to comprise many loops, the projection of which onto the disk, causes them to appear sigmoidal,
c) active regions which, at increased SXT partial frame resolution, did not display any sigmoidal characteristics

Current theory describes a sigmoid as a single, twisted flux tube observed in projection against the solar disk as a bright S (or inverse S) shaped X-ray feature [*Canfield et al.*, 2000]. Category (a) was defined in accordance with this theory. Category (b) defines active regions which had previously been classified "sigmoidal". However, observation at increased resolution found these active regions' S shape to arise from the projection of a number of smaller, soft X-ray features. Whilst these active regions could certainly be described as complex, observations do not appear to comprise a single twisted flux tube. Accordingly, these active regions have been classified separately.

Tables 1a, b and c list the active regions considered during this investigation. Sample active regions falling into the first two categories can be seen in Figure 1. Table 1a shows that, of the initial 17 active regions, only 7 appear truly sigmoidal.

Previous studies into the origins of sigmoidal structures [*Rust and Kumar*, 1996] have postulated the existence of a hemispheric rule (inverse-S North of the equator and S to the South). Although weak, at approximately 60%, this rule holds for larger active region samples. Application of the rule to Table 1a, however, does not show any appreciable hemispheric trend, possibly owing to the small number of active regions classified as being "sigmoidal".

Comparison of Tables 1a, b and c with the data of *Canfield et al.* shows considerable difference in the number of active regions exhibiting sigmoidal morphology. SoHO-LASCO coronagraph data shows that only 6 out of a total 17 active regions considered during this study, appear asso-

Table 2a. Morphology and CME Distribution

	Sigmoidal	Projection	Non-S
Eruptive	3	2	1
Non-eruptive	4	4	3
Total	7	6	4

Table 2b. Morphology and Filament Distribution

	Sigmoidal	Projection	Non-S
Eruptive	4	1	1
Non-eruptive	3	-	1
Total	7	1	2

ciated with a CME. Similarly, only 35% of the re-classified sigmoidal active regions have an associated CME. Tables 2a and b, combined with Figure 2, give an overview of the morphology and activity distribution for the present study, illustrating that of the total 6 observed CMEs, only 4 (67%) are seen to be associated with erupting filaments.

The above illustrate that whilst each of the active regions in question appears in SXT full disk images to be sigmoidal and eruptive, analysis using higher resolution data, shows this not to be the case. 41% of regions initially classified as both sigmoidal and eruptive, are found to be sigmoidal. These account for 50% of associated CMEs observed using SoHO-LASCO. A further 35% of regions, thought to appear sigmoidal as a result of projection effects, account for 33% of the observed CMEs whilst the remaining 24% have no visible sigmoidal characteristics and account for the final 17% of observed CMEs.

Although re-classification from 100% sigmoidal into the above percentages has resulted in each category containing only a small number of samples, active regions showing a clearly defined S, or inverse-S, shaped soft X-ray structure did indeed appear to be associated with the highest proportion of CMEs.

It is interesting to note that the three clear incidences of coronal Moreton waves observed during the course of this study, all appear in association with the disappearance in soft X-rays, of a clearly defined single S, or inverse-S, shaped structure.

Conclusions

This study has extended the findings of previous investigations into the connection between sigmoid-to-arcade development and CME launch by the inclusion of white light, EUV and H-alpha data. By increasing SXT resolution to that of partial frame data, regions appearing sigmoidal at full disk resolution can be further divided into sigmoidal, projected-S and non-sigmoidal categories.

This extended survey has shown that regions having clearly defined single, sinuous S or inverse-S morphology do possess a strong tendency to erupt with the formation of an associated CME, coronal EUV dimming and, on occasions, a Moreton wave. Although the reduced dataset used during this study is too small to allow a statistical measure of significance, we note that features superposed onto one another

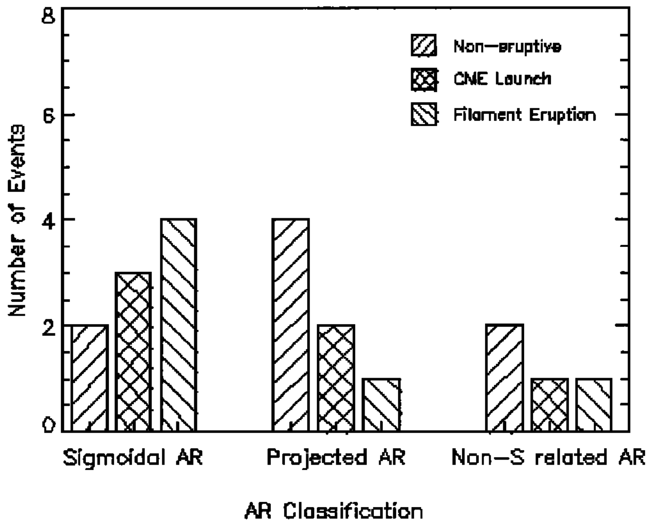

Figure 2. Distribution of events in terms of active region classification and activity. Non-eruptive events are associated with neither CME nor filament eruption

in projection, appear less likely to erupt; an observation consistent with their separate classification as projected S-like regions rather than "sigmoids". A further survey incorporating several years data from the above instruments may provide further examples of sigmoidal active regions thus allowing a more quantitative, statistical analysis of differing activity levels exhibited by active regions of each category.

Although a considerable amount of research has been carried out into the theoretical reasoning for soft X-ray observations termed "Sigmoids", the results presented in this letter emphasise the need for a quantitative *observational* definition of this term should these structures be used as a tool with which to predict CME activity. Although such a definition has yet to be enunciated, these conclusions indicate the need for such an approach.

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