Thermodynamic evolution of a sigmoidal active region with associated flares

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(Mulay S. M., *et al.*, 2021, MNRAS, 504, 1201)

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Sigmoids

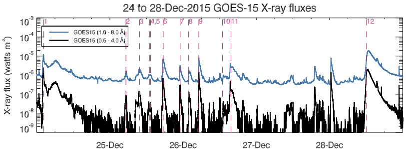
- **S shaped/reverse S/two J-shaped highly sheared and twisted loops** that are formed along the polarity inversion line - Considered to be one of the best pre-eruption signatures

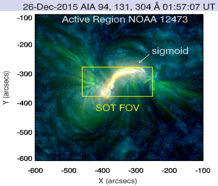
Objective

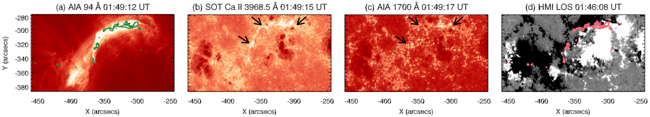
- Investigation of the temperature structure of a sigmoid during different phases of solar flares

Observations and instruments

- 24-28 Dec 2015 - 10C & 2M GOES X-ray flares
- **X-ray flares** - Geostationary Environmental Operational Satellite (GOES-15)
- **EUV images** - Atmospheric Imaging Assembly (AIA) onboard Solar Dynamics Observatory
- **X-ray images** - X-ray Telescope (XRT) onboard Hinode







Analysis of C1.6 flare on 26-Dec-2015 - The brightening along the sigmoid was observed in (a) and their chromospheric signatures in (b) and (c) - indicates **energy dissipation**

Methodology - Temperature analysis

- **Filter ratio method** - two XRT channels, AIA 94 and 131 Å channels, GOES X-ray fluxes from two filters
- **Emission measure analysis** (Cheung et al. 2015) - AIA images
- **Fe XVIII emission** (Del Zanna 2013) - AIA 94 Å channel

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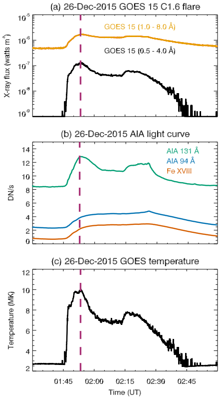
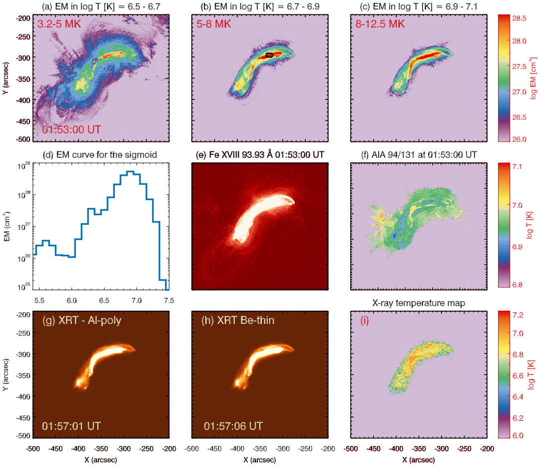
Temperature analysis of a sigmoid during C1.6 flare on 26-Dec-2015



(a) GOES C1.6 flare fluxes (b) AIA light curves for the sigmoidal region shows similar nature of curve as GOES. (c) Temperature of a sigmoid from the GOES channels



(a-c) AIA EM analysis at peak time of GOES C1.6 flare
(d) EM curve for the black boxed region (e) Fe XVIII emission
(f) AIA filter ratio temperature (g-i) XRT filter ratio temperature

- The variation in EUV intensities along the sigmoid and GOES X-ray fluxes confirmed that the flaring activity occurred along the sigmoid.

- The plasma along the sigmoid structure was multi-thermal with multiple strands emitting at different temperatures.
- The region outside the sigmoid shows plasma at temperature, log T [K] < 6.5 (3.1 MK) whereas the sigmoidal region is dominated by high-temperature plasma, log T [K] > 6.3. Few strands along the sigmoid were seen at higher temperatures $>$12.5 MK.

- The observed structures in the Fe XVIII image match very well with the EM maps obtained in the temperature bin log T [K] $=$ 6.7-6.9 (5-8 MK).

- We note that the temperatures corresponding to the peak EMs (8 MK) are lower than those estimated using the GOES-15 observations (10 MK) but show good agreement with AIA filter ratio temperature.

- The XRT temperature map, 4-min after the peak of the flare show plasma at 8-10 MK, which is in good agreement with the temperature obtained from all other methods.

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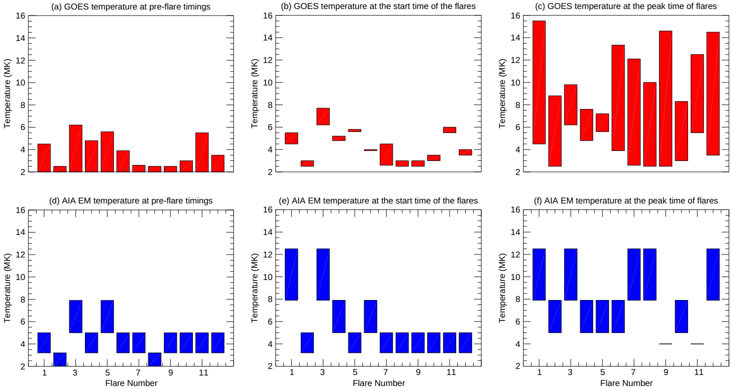
Temperature analysis for all flares



Bar plot of temperatures obtained from the GOES channels (red), and peak in the EM analysis (blue) at the pre-flare timings (left column), at the start (middle column) and peak (right column) times of the flares. The blank spaces in temperatures indicate that the AIA data are saturated.

- The EM analysis confirmed the presence of hot plasma of temperature around 10-12.5 MK in strands of the sigmoidal structure obtained at the peak timings of all flares.

- The temperature range of 8-12.5 MK from AIA filter ratio and 4-10 MK from XRT filter-ratio supports the notion that Fe XVIII emission formed at a temperature corresponding to the peak of the contribution function of Fe XVIII line.

- In our analysis, the peak temperatures of 10-12.5 MK obtained from all four methods are found to be within the range of temperatures provided by Feldman *et al.* (1996) for C and M-class flares.

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Summary

- The sigmoid activity started with a brightening in the AIA 94 and 131 Å channels followed by chromospheric brightenings in AIA 1700 Å and SOT Ca II images.
- The temporal and spatial correlation between the intensity variation along the sigmoid in the AIA channels and GOES X-ray flares was confirmed.
- A systematic delay in the intensity peak of the AIA (94 and 131 Å) and GOES channels indicate that there was an increase in the temperature of the sigmoid during the rise phase of flares. This was confirmed using various temperature diagnostic techniques.
- The sigmoid structure was seen to be multi-thermal (3-12.5 MK) throughout flaring activity. Some strands along the sigmoid were observed at a high temperatures 12.5 MK or greater at the peak time of the flare.
- We confirmed that emission from high temperature Fe XXI and Fe XVIII lines was present at the sigmoid location at the peak time of the flare. In some flares, this hot emission was confined to some strands which were part of the sigmoid and in some flares, the hot emission spread over the whole sigmoid.
- The temperature obtained from the EM analysis was found to be in good agreement with that obtained using the XRT, AIA and GOES filter-ratio methods.
- These results provide important constraints for the thermodynamic modelling of sigmoidal structures in the core of active regions. Moreover, this study also benchmarks different techniques available for temperature estimation in solar coronal structures.