Birth and Evolution of a Jet-Base-Topology Solar Magnetic Field with Four Consecutive Major Flare Explosions

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Abstract

During 2011 September 6-8, NOAA solar active region (AR) 11283 produced four consecutive major coronal mass ejections (CMEs) each with a co-produced major flare (GOES class M5.3, X2.1, X1.8, and M6.7). We examined the AR's magnetic field evolution leading to and following each of these major solar magnetic explosions. We follow flux emergence, flux cancellation and magnetic shear build up leading to each explosion, and look for sudden flux changes and shear changes wrought by each explosion. We use AIA 193 Å images and line-of-sight HMI vector magnetograms from Solar Dynamics Observatory (SDO), and SunPy, SHARPkeys, and IDL Solarsoft to prepare and analyze these data. The observed evolution of the vector field informs how magnetic field emergence and cancellation lead to and trigger the magnetic explosions, and thus informs how major CMEs and their flares are produced. We find that (1) all four flares are triggered by flux cancellation, (2) the third and fourth explosions (X1.8 and M6.7) begin with a filament eruption from the cancellation neutral line, (3) in the first and second explosions a filament erupts in the core of a secondary explosion that lags the main explosion and is probably triggered by Hudson-effect field implosion under the adjacent main exploding field, and (4) the transverse field suddenly strengthens along each main explosion's underlying neutral line during the explosion, also likely due to Hudson-effect field implosion. Our observations are consistent with flux cancellation at the explosion's underlying neutral line being essential in the buildup and triggering of each of the four explosions in the same way as in smaller-scale magnetic explosions that drive coronal jets.

Introduction

Solar active regions (ARs) are locations on the sun with high levels of magnetic activity that can produce coronal mass ejections (CMEs), or large expulsions of plasma, and solar flares. GOES X-class flares release an estimated amount of energy equivalent to 10^{32} erg, and M-class flares about 10^{31} erg. CMEs pose risks to technology in orbit and on Earth, as the release of energy from these ejections can disrupt electrical systems and cause damage to satellites, which in turn affect Earth's communications. The processes that cause flares and CMEs are still being investigated, but efforts are being made by researchers to better understand their drivers. Flux emergence, cancellation, and magnetic shearing are thought to be sources of these events. Flux emergence occurs when both positive and negative magnetic polarities appear together in an active area. Flux cancellation takes place when these differing polarities merge and cancel, often resulting in magnetic energy releases such as solar flares. Shear can be measured by the difference between observed and theoretical angle of the magnetic vector field lines. For this project, we focused on the shear angles along the neutral line, or the area between the two regions of positive and negative energy. Most features (flares, filaments, etc) occur over the neutral lines.

	Flare Class	Date	Time
1	M5.3	6-Sept-2021	01:35
2	X2.1	6-Sept-2021	22:12
3	X1.8	7-Sept-2021	22:32
4	M6.7	8-Sept-2021	15:32

Goals & Hypotheses

The goal of this project is to contribute to the understanding of the drivers of flaring activity on the Sun. Following the flux and shearing over the evolution of a flare informs us of the trends occurring before and after flares. Previous research has shown that an increase in flux cancellation precedes a flare, which we wanted to investigate in the solar AR11283, which had four major flares over a four day period. In addition, we wanted to visualize and analyze the vector field lines of this AR using the SHARPKeys data algorithms, along with shear angle calculations, which we predicted would become increasingly horizontal around the neutral line around flare times.

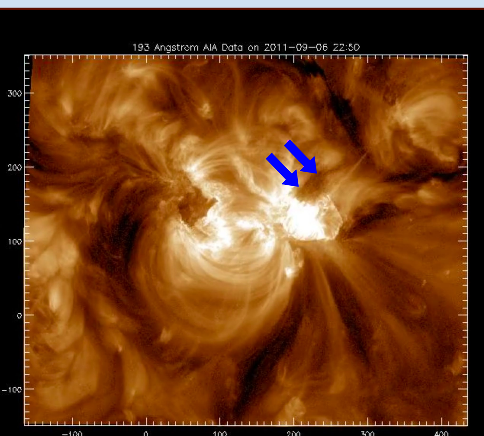


Fig. 1
During the first X-class flare a filament eruption can be clearly seen, indicated by the two arrows. The erupting cool plasma after the flare is due to the Hudson effect - the implosion of a field around the erupting core-region flux rope which triggers an eruption of a filament (Panesar 2016).

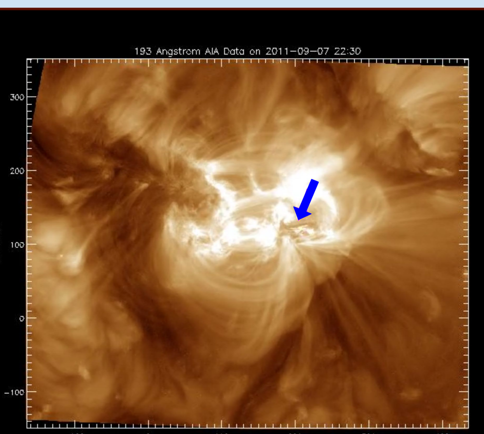
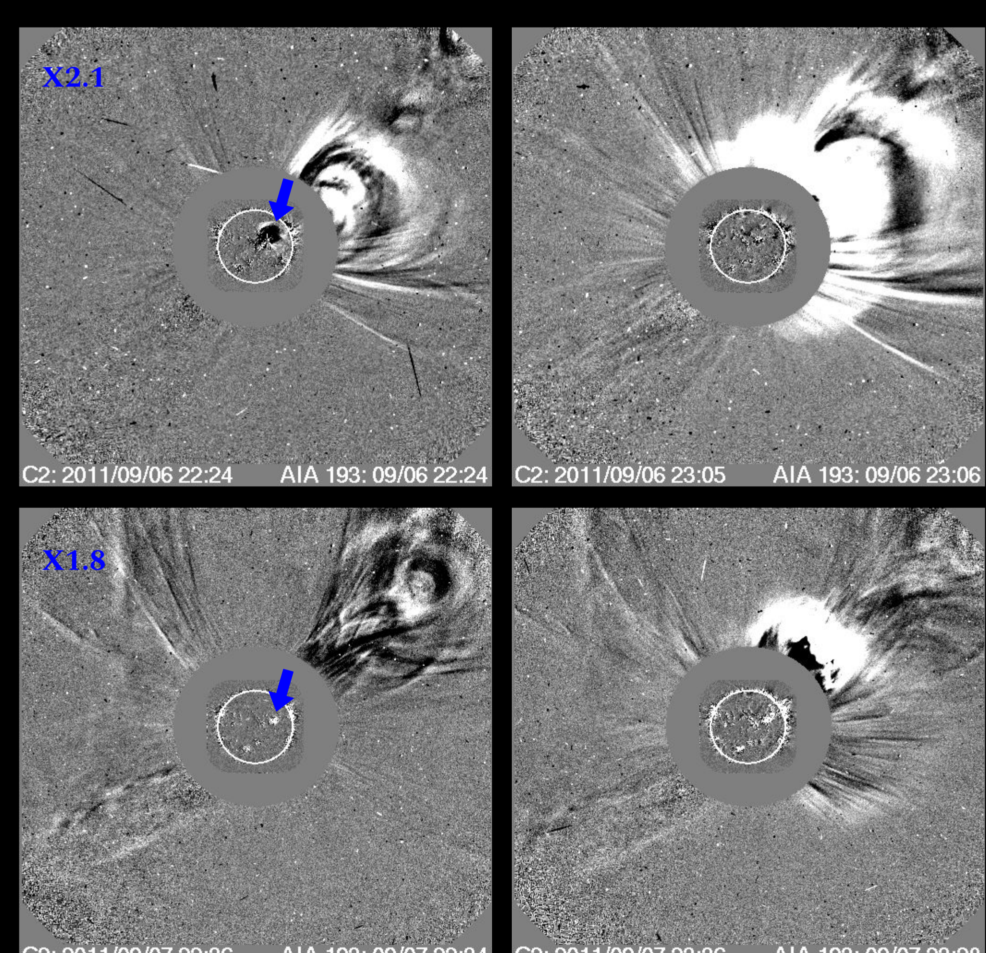


Fig. 2
In the second X-class flare, the filament erupts, accompanied by a flare and CME. In this example, the arrow points to the filament before the eruption.



Figs. 3-6
Images taken from the SOHO LASCO CME Catalog. The top row is the flare of class X2.1 and bottom row shows flare X1.8. On the left hand side in each row, the flare occurring in the active region is indicated by an arrow. The right hand side shows the accompanied CME from the flares.

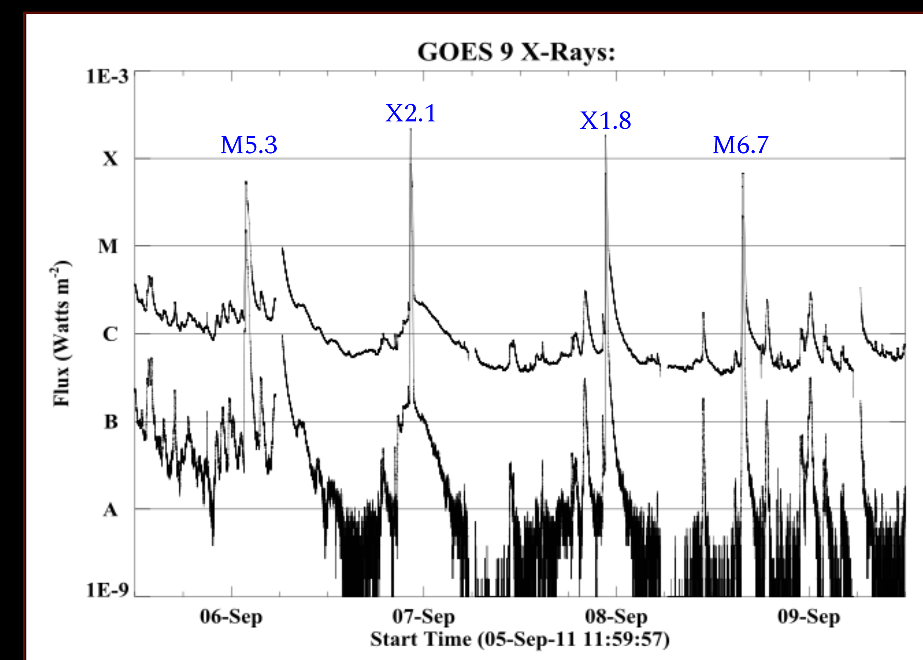


Fig. 7
Geostationary Operational Environmental Satellites (GOES) plot of the four day time period, with peaks corresponding to each flare. X class flares release energy equivalent to about 10^{32} erg, and M-class flares release about 10^{31} erg. The blue text indicates the flare class corresponding to each peak.

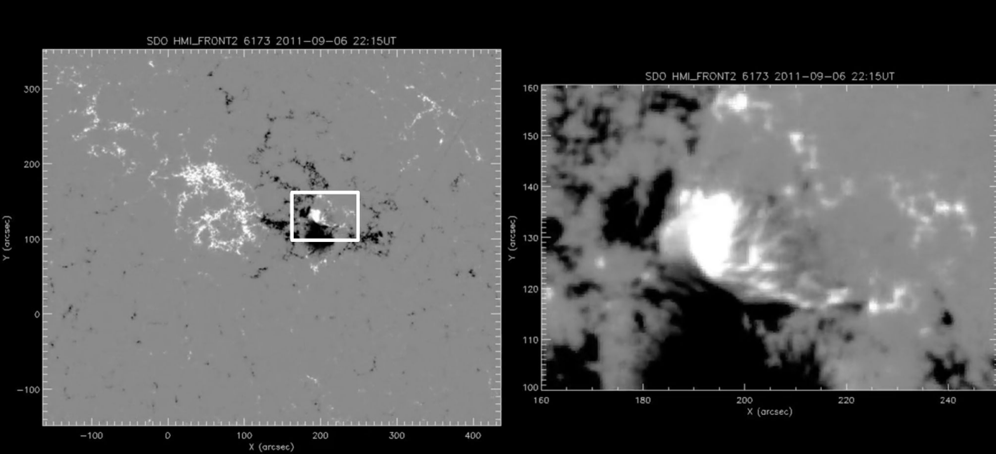


Fig. 8
HMI line-of-sight magnetogram of AR11283 during flare X2.1. The first image displays the larger AR, and second image is the area we investigated (also shown in the white box).

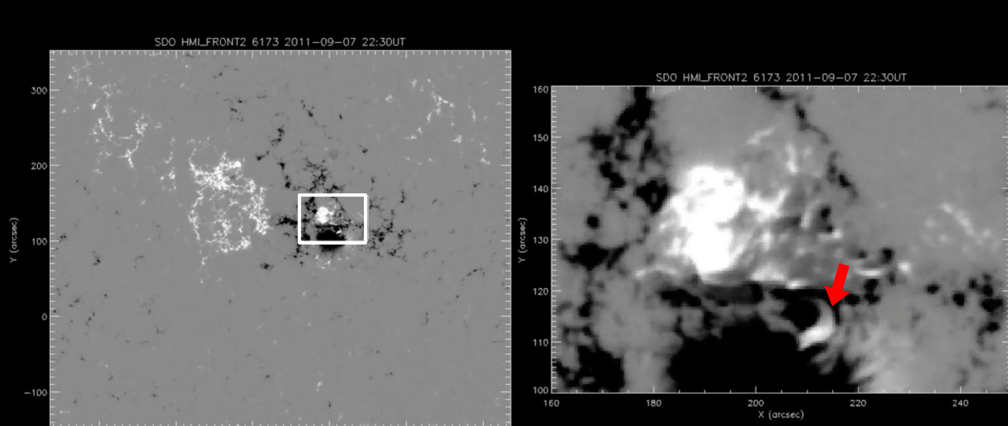


Fig. 9
HMI line-of-sight magnetogram of AR11283 during flare X1.8. In the second image of the neutral line some flux emergence can be seen, indicated by the red arrow, that contributes to the small peak in positive flux curve shown in Fig. 11 during this flare.

Methods

We use AIA 193 Å images and line-of-sight HMI vector magnetograms from the Solar Dynamics Observatory (SDO), and SunPy, SHARPkeys, and IDL Solarsoft to prepare and analyze these data. We downloaded data from the Joint Science Operations Center (JSOC) website. Our data is in the form of fits files, which we used to visualize the evolution of these flares. We began by derotating the data and by creating movies of the four day period when the flares occurred with both AIA and HMI data. For this project, we used HMI cadence of 15 minutes and AIA cadence of 5 minutes, as opposed to the available data of 45 seconds for HMI and 12 seconds for AIA. We analyzed vector magnetic field data in order to calculate the vector strength and shear angle at each pixel over the evolution of these flares using SHARPKeys. Following the movements of these vectors will allow us more insight into magnetic field emergence and cancellation, and the conditions required to produce these flares.

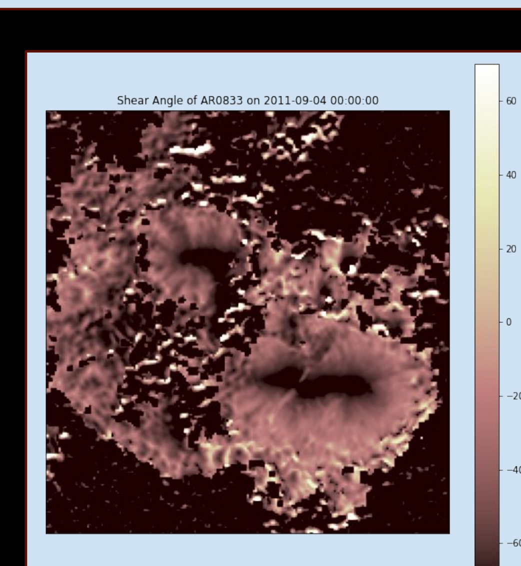


Fig. 10
Map of the shear angle in AR 11283 at each pixel, calculated from an adaptation of the SHARPKeys data algorithm computeShearAngle. Shear angle is a valuable measurement for understanding the evolution of vector fields near the neutral lines in AR.

Results & Discussion

We were able to successfully create visualizations in both Solarsoft and Python of the active region using both HMI and AIA data, as well as visualizations of the vector field lines. After performing this study, we found that all four flares are triggered by flux cancellation. The third and fourth explosions (X1.8 and M6.7) begin with a filament eruption from the cancellation neutral line. In the first and second explosions (M5.3 and X2.1) a filament erupts in the core of a secondary explosion that lags the main explosion and is probably triggered by Hudson-effect field implosion under the adjacent main exploding field, and the transverse field suddenly strengthens along each main explosion's underlying neutral line during the explosion, also likely due to Hudson-effect field implosion. During the third flare (X1.8), there is measurable flux emergence alongside the cancelation. Our observations are consistent with flux cancellation at the explosion's underlying neutral line being essential in the buildup and triggering of each of the four explosions in the same way as in smaller-scale magnetic explosions that drive coronal jets. These results are consistent with past work associating flux cancellation with solar flares.

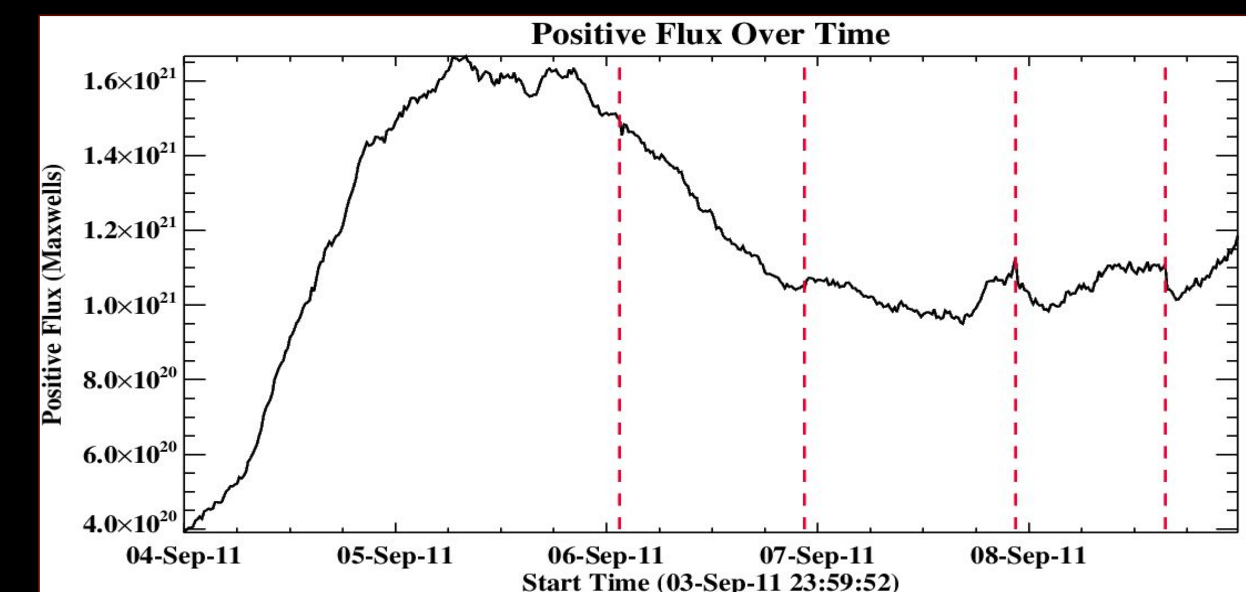


Fig. 11
Positive flux around the neutral line over the four days. The flux is calculated from the area as seen in figures 8 and 9. Flux cancellation is clearly identified by the decrease in positive flux after each flare. The red dashed lines show the flare times. The exception is in flare X1.8, the third to occur, where there is a small increase in flux due to some emergence of positive flux (away from the main neutral line) in the region that we used to compute the positive flux.

Conclusions & Next Steps

All of the studied flares display rapid changes in the vector magnetic field, and are triggered by continuous magnetic flux cancellation at the neutral line. This magnetic flux cancellation plausibly builds a magnetic flux rope, which is evident by the observed cool-plasma structure during each flare. Assessing the factors that affect how flares are produced are essential to having a complete understanding of solar active region processes and the drivers behind flaring activity.

More work has to be done, such as tracing shear angle and twist parameters before and after flares, in order to gain a complete understanding of active region systematics. We are currently working on obtaining measurements of shear angles at each pixel around the neutral line for the duration of each flare, in order to best understand how shear evolves with the active region. In addition, there is a great need to improve predictions of solar events, which have larger consequences as more of Earth becomes reliant on electrical systems. Our project contributes to this objective, as well as contributing to an understanding of stellar flare processes.

Major Flares in AR 11283 with Vector Field Lines

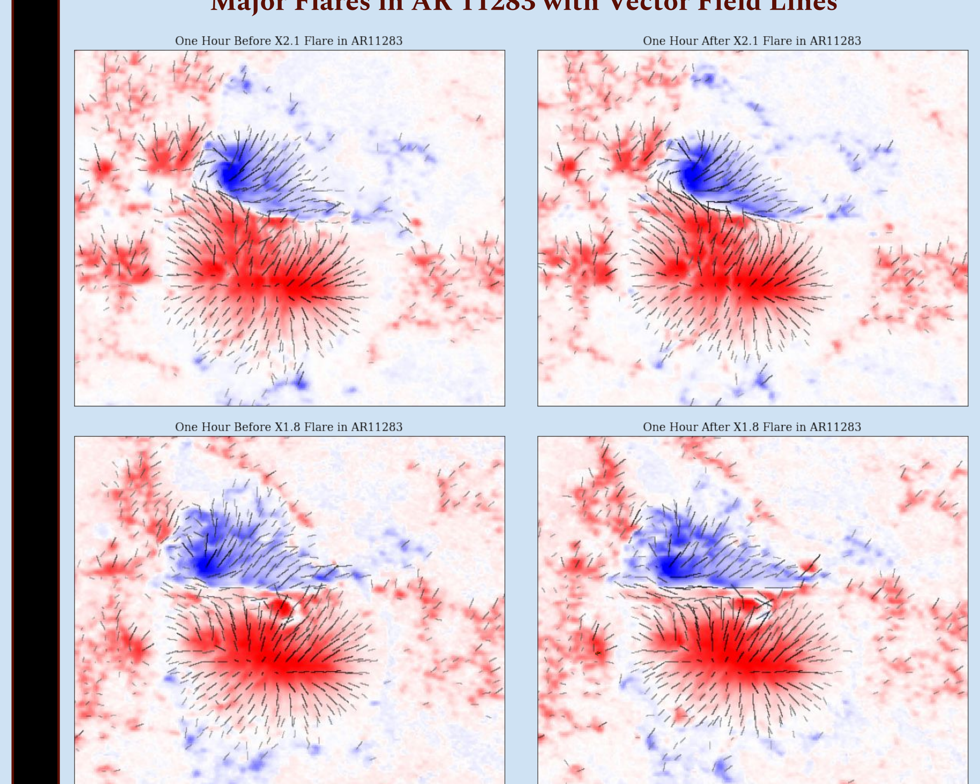


Fig. 12
Active region 11283 one hour before and after the two X class flares. The neutral line can be seen changing over this 26 hour time period. The color of the vector corresponds to the strength of the field line.

Acknowledgements

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