# REMOTE TRIGGERING OF ENERGETIC EVENTS

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## Abstract

The Atmospheric Imaging Assembly (AIA) on the Solar Dynamic Observatory (SDO) together with the Helioseismic and Magnetic Imager (HMI) and the Extreme Ultraviolet Variability Experiment (EVE) allow observations of the entire Sun from 6000 K to 20,000,000 K with arcsecond resolution and a 12 second cadence (AIA), obtain doppler and continuum images at a 45 second cadence and Line of Sight and vector magnetograms (HMI) every few minutes, and integrated solar spectra from 1 to 100 nm on a 2 second cadence (EVE) 24/7. Because of the enhanced thermal and temporal coverage and the high dynamic range available with AIA, it has been able to discovery collective behavior associated with extreme solar events that are driven by the expansion of magnetic structures. Nearly half of the M and X class flares seen with AIA have impact over a solar hemisphere and sometimes nearly the entire sphere. The extent of the events are recognized by using co-temporal STEREO data. The rapidly expanding magnetic structures, speeds between 500 and 2000 km/s, trigger filament eruptions, CME's, and other flares. These "triggered" events are sometimes larger that the initial disturbance. The remote triggering makes flare prediction based upon local energy build up models less valuable, but suggests that with proper coverage prediction of solar events with potential for Earth impact can be made more reliable. Movies of sample events discovered in AIA together with STEREO and EVE data will be shown.

## Introduction

For more than six decades there have been suggestions that there were energetic solar events - flares, filament eruptions, coronal mass ejections (CME's) - that occurred in what appeared in near coincidence [1]. Statistical studies that tested the existence of "sympathetic" flaring have produced results that have ranged from random to a slight tendency of their existence [2]. The prevailing opinion in the literature seems to have been that the apparent coincidences are just apparent coincidences. The fundamental objection to the idea of long range coupling between well-separated energetic events has been the lack of the physical mechanisms that would cause the apparent remote triggering. Most triggering concepts for solar energetic events are based on energy buildup because of flux emergence, shear flows, helicity insertion, or a combination of these. The NASA Solar Dynamics Observatory and the STEREO missions have now accumulated a significant body of evidence that at least in the case of M and X class flares there is identifiable direct connections between multiple events. The compelling evidence for coupled events has stimulated modeling efforts that provide mechanisms that causing remote triggering [3].

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In the sections below the new observational capabilities that have allowed shown the physical connections to be observed will be briefly described. The direct evidence will be presented in the text and in associated movies that demonstrate the dynamic connections. Model calculations based on simulations are discussed. Finally the consequences for prediction will be explored.

## New Observing Capabilities

On February 11, 2010 the Solar Dynamics Observatory, was launched into geosynchronous orbit From this orbit high above the Earth SDO can observe the entire Sun 24/7 and continuously communicate with a single ground station at White Sands, NM at a data rate of 200 megabits/s. SDO caries three instruments AIA [4] that images the full Sun and the low corona in a series of spectral bands that span a temperature range from 6,000 to 20,000,000 K with a spatial resolution of about an arc second and a temporal resolution of 12 seconds, HMI [5] that collects data for full disk line of sight (LOS) velocity measurements on a 30 second cadence, LOS magnetograms on a 5 minute cadence, and vector magnetograms every 15 minutes; and EVE [6] that measures the total solar irradiance from 0.1 to 1.105 nm with 0.1 nm resolution with a temporal cadence of one second. The geosynchronous orbit allowed direct transmission of the data from all three instruments to be transfer continuously without any onboard storage. The data is available to the scientific community in near realtime.

On February 18, 2011 the two STEREO [7] spacecraft arrived at +/- 90 degrees from the Earth-Sun line and thus for the first time the entire Sun could be observed. All of the EUV spectral bands of the STEREO SECCHI instruments overlap with those on AIA. This allows tracking of events seen on the "front" side of the Sun to be followed over the entire solar surface, which increases the opportunity to detect coordinated events.

Energetic events on the Sun often create expansion fronts that propagate at LOS speeds up to 2000 km/s. This has several consequences for detection. First, if images are taken at a cadence of tens of minutes the expansion fronts maybe so poorly sampled that they are not recognized. Second, the intensity variations caused by the propagating fronts are usually at a low level and unless the imager's detectors have a high dynamic range they may be missed. This problem is further complicated by the fact that the energetic events are usually associated with a local strong increase in signal level. Because of the limited dynamic range of some instruments they usually contain automatic exposure controls to avoid saturation of the detector, which then makes the detection of small intensity variations associated with the expanding fronts difficult to impossible to detect. Finally, the limitations in telemetry from low Earth orbiting satellites combined with the desire to achieve the highest possible spatial resolution has usually driven instrument designs that trade off both cadence and field of view for spatial resolution.

The design of AIA traded off the highest possible spatial resolution that the optics were capable of for a field of view that covered the full disk and 5 arc minutes of the surrounding corona and a data rate that allowed the capture of eight 4096 x 4096 14 bit images every 12 seconds. The CCD camera systems on the telescopes allowed a dynamic range of $10^5$. During very bright energetic events automatic exposure control was used only on alternate 12 second cycles. That is, during the brightest phase of a big flare the effective cadence for small intensity changes dropped to 24 seconds.

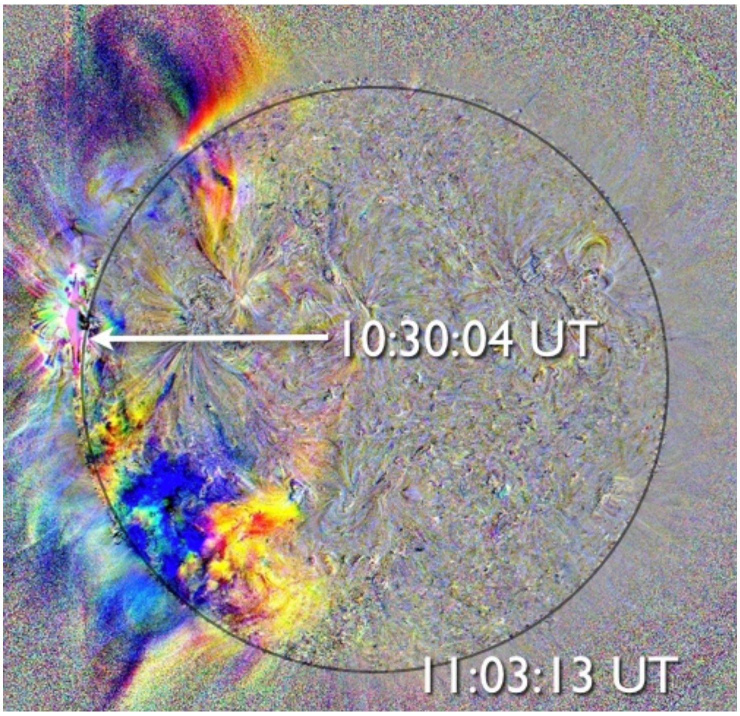
## The Observations

AIA began taking observations in April 2010 and even during the first few weeks there were clear impressions that large portions of the Sun were affected both by large flares and filament instabilities. The first example of multiple events for which there was direct evidence of global connections occurred on August 1-2, 2010. This event, which is described in a series of papers [8,9,10}, was associated with two flares and three filament eruptions seen by AIA on the visible disk and one seen on the portion of the disk seen by the STEREO B satellite. There were also three CME's associated with the flares and filament ejections. Another sequence of coupled events that were associated with an X class occurred on 15 February 2011 [11].

At this point in the AIA mission we have found more than half of the M and X class flares are associated with additional flares, CME's, and filament ejections. It is an error to think that the M or X class flares are the only triggers for the correlated events. The flares of August 1, 2010 were B and C class. There is evidence that flux emergence well away from the sequence of energetic events may in some cases be the ultimate source of the instability as evidenced by the August 1-2, 2010 events. We have also seen at least eight cases where the instability of one filament is directly followed by an adjacent near by filament.

Because energetic events are highly dynamic and have different characteristics in images that are responsive to different temperature ranges it is difficult to illustrate the events without movies. But the sensitivity of the AIA can be demonstrated in single frames. Shown in Figure 1 is a log ratio image that combines three temperature ranges 1.8 MK (red), 1.2 MK (green), and 0.75 MK (blue). A log ratio image is formed from the difference between the log of an image take at an instant in time minus the log of the immediately preceding image in time. What is illustrated is sample frame from a limb flare event. It captures position of the expansion front seen at 11:03:13 UT that originated from a limb flare that occurred 10:30:04 UT. This indicates that the average velocity of the expansion front is about 1100 km/s and the expansion region is on the order of a solar hemisphere. The yellow (red + green) color at the leading edge indicates that plasma between 1.2 and 1.8 MK travels together and the trailing blue area indicates cooler material behind the leading edges. This suggests that the front is heated and cooled adiabatically [11]. A website with examples of coupled events is at (TBD). The black circle indicates the limb of the Sun.

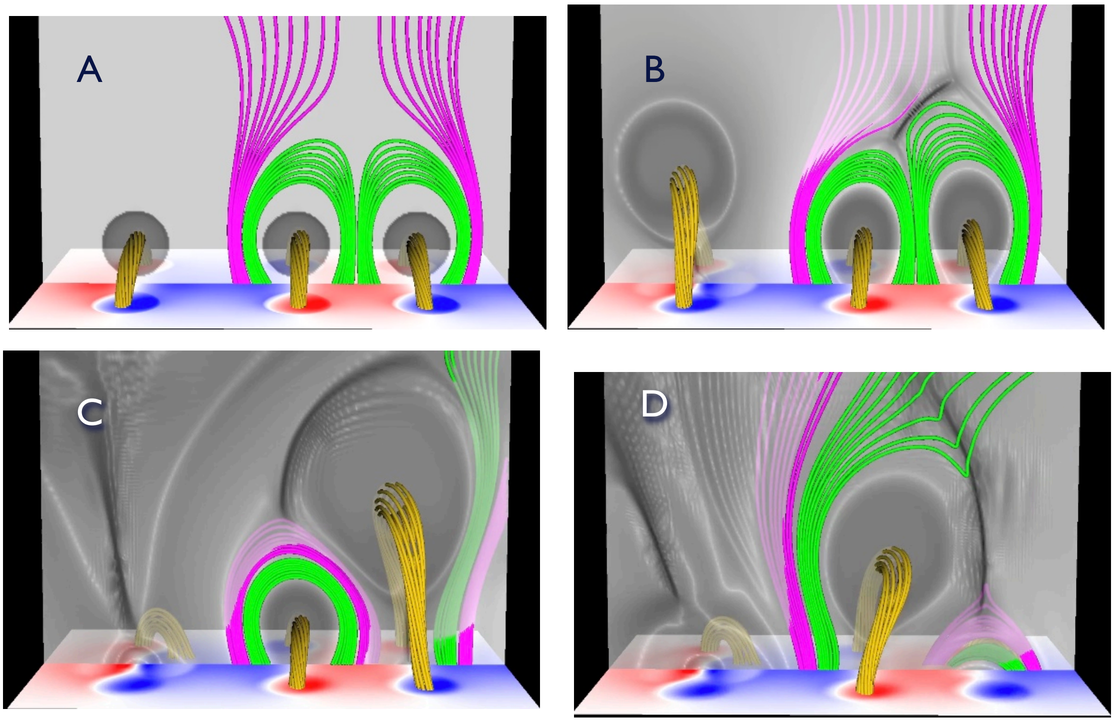
Figure 1: Combined log ratio image showing the expansion front a limb flare.



## Model Calculations

Torok [3]and his collaborators have constructed 3D Magnetoydrodynamic (MHD) models of sequential activation of adjacent filaments. This work was motivated by the observations of adjacent filament eruptions seen in the August 1-2, 2010 events. Subsequently at least eight similar multiple filament instabilities have been discovered in the AIA data. The model starts with a single filament that is driven to instability. As the initial filament erupts currents flow and the magnetic field above the adjacent structures expands which leads to their eruption. Shown in Figure 2 are a few frames from a movie of the coupled behavior. The filament in the left hand side of the in panel A is driven unstable. As it expands the filament on the right hand side of panels B and C erupts. Finally in panel D the center filament erupts.

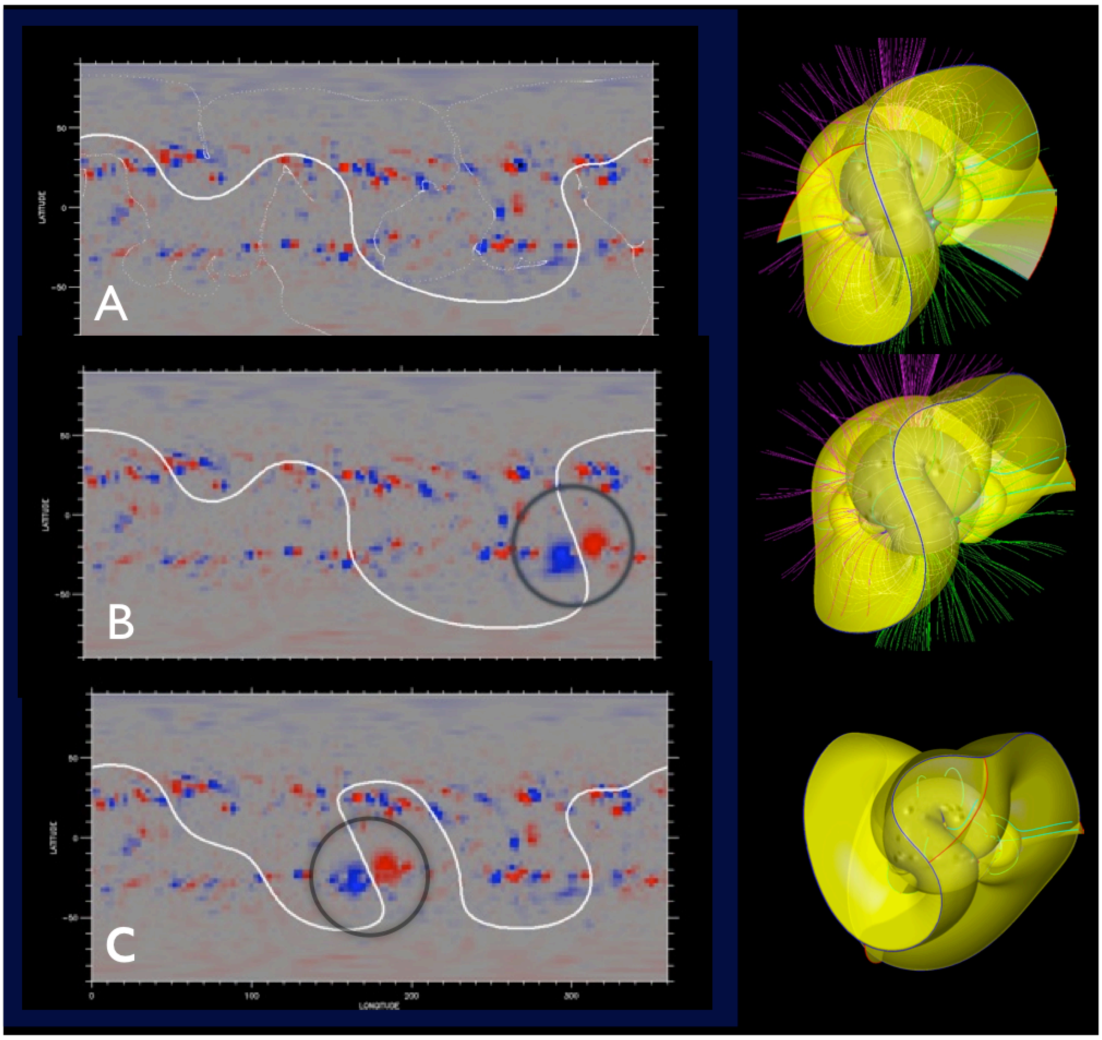
Figure 2: Sample frames form a MHD simulation of coupled eruptions.



As discussed in the paper on the August 1-2, 2010 events there is evidence that the trigger was the emergence a small active region on the portion of the Sun not visible from Earth at the time of the events. The new active region became visible a week later when in rotated on the visible hemisphere. Of course, its emergence could be seen in the STEREO B data at the time of the events. The concept for the remote trigger is that the flux emergence caused a significant change in the location of the heliospheric current sheet and an associated large scale restructuring of the entire solar field. Illustrated in Figure 3 in the left hand panels are three synoptic maps of the surface magnetic field upon which are drawn in white the its projection onto the solar surface of the calculated location of the current sheet. Case A is the initial state. Cases B and C are the modifications caused by the insertion of new flux in the circled locations. The right hand panels show the topological surfaces associated with the surface configurations. The models boundary conditions are the surface magnetic field and the assumption that the fields are normal to the surface at 2.5 solar radii. Fields above the white line leave the Sun and below return to the Sun.

The insertion of new flux at the location indicated in case B causes a relatively small relocation of the current sheet, but the effect of the insertion in case C causes a substantial modification of the current sheet and a corresponding large-scale change in the topology. It is too early to quantify how large a change in the large-scale topology results in coordinated energetic events. Insertion of new flux can only have an triggering effect if there are previously regions on the solar surface that have the potential to be driven unstable.

Figure 3: Synoptic Maps and large scale topology surfaces.



## Conclusions and Consequences

Flares, filament ejections, and CME's do not occur unless there is stored energy that can be suddenly released. However, when the energetic event occurs may not always depend on a critical build up of energy at the location of the eruption. Based on the AIA and STEREO observations there are several scenarios in which coordinated energetic events may occur:

1) Flux emergence remote from the energetic events. One plausible concept is that the new flux causes a significant restructuring of the large-scale solar field. Then reductions of the magnetic field above the stored energy regions allow them to go unstable. This is probably what happened in the events of August 1-2, 2010.

2) An initial region going unstable changes the field in the vicinity which allows the adjacent region or regions to go unstable. Depending of the number of potentially unstable regions there maybe a sequence of eruptions - a domino effect. The MHD model of coupled filament eruptions is an example of this type of situation.

3) As illustrated in figure 1 large flares can generate changes in the solar magnetic field the can sweep over a hemisphere or more which can allow instabilities to occur in the regions that the expansion front covers. Once one remote event is triggered it in turn can cause a domino effect.

This is good news and bad news. The good news is that it should not be surprising that flare predictions based upon observations from the Earth are often not successful. The bad news is that to improve predictions will require satellites that allow observations of the whole Sun. For the next few years STEREO and SDO will provide this capability, but after that there must be a new system of observatories, if we are to expect better predictions of violent solar events.

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## Biography

**Alan Title** earned his Bachelor in Mathematics from the University of California at Los Angeles and his Doctorate in Physics from the California Institute of Technology. He is the author of more than 180 papers in refereed journals on subjects that range over optical filter designs, telescopes, solar magnetic fields, and data management and analysis. He is a member of the National Academy of Science, the National Academy of Engineering, the International Academy of Astronautics, a fellow of the American Geophysical Union, and the Silicon Valley Hall of Fame. He has received the Hale Prize of the American Astronomical Society, the Goddard Medal of the SPIE, the Fleming Medal of the American Geophysical Union, and the Public Service and Outstanding Scientific Achievement Medals of NASA. He has served as the lead scientist or Principal Investigator for the H alpha telescopes on Skylab, the SOUP instrument on the Shuttle, the MDI instrument on ESA/NASA SOHO mission, the NASA small explorer TRACE, the Focal Plane Package for the ISAS/JAXA HINODE satellite, the AIA and HMI instruments of the NASA SDO mission, and the NASA small explorer IRIS. He is currently a Senior Fellow of the Lockheed Martin Corporation. His research interests are understanding the mechanisms that heat and maintain the solar atmosphere.