Flux emergence event beneath an eruptive filament

J. Palacios, C. Cid, A. Guerrero, E. Saiz, Y. Cerrato

SRG-Spaceweather
University of Alcalá (UAH), Spain
Introduction

- On 2013, September 29 a large solar filament rose smoothly, without any previous flare, nor significant brightening arcade. This filament lifted and created a **ribbon flare afterwards** and its X-ray flux reached the category C1.2 by GOES 1-8 Å. The eruption led to an **Earth-directed halo CME** (slow, 600 km/s).

- The interplanetary plasma interacted with the Earth’s magnetic field creating a moderate geomagnetic storm with effects on the ground.
Flux emergence phenomena are relevant for many solar scales. We have studied a supergranular-sized flux emergence region beneath a filament.

In this study we investigate the flux emergence blob and size, growth rates, and the possible implications on the filament lift-off.

In particular, the observed flux emergence reached hectogauss values. The flux emergence extent appeared just beneath the filament.

The emergence acquired a size of 33″ in 12 h. The LOS-unsigned magnetic flux is around $10^{20}$ Mx.

We have also studied the filament eruption speed, size and dynamics, under the torus instability hypothesis.
Data

- Data from Solar Dynamics Observatory (SDO, Pesnell et al. 2012). Data were acquired by the Atmospheric Imaging Assembly (AIA, Lemen et al. 2012) and the Helioseismic and Magnetic Imager (HMI, Scherrer et al. 2012). We used AIA multiwavelength data in 304 and 193 Å, and also AIA 94 Å, sampling the solar transition region to the corona.

- HMI data line-of-sight (hereafter, LOS) photospheric magnetograms.

- We have also used HMI full-disk Stokes data.

- Data cadence is 12 min from September 29 to October 1 on both AIA and HMI instruments. For some analyses, 1-min cadence was chosen instead (AIA).

- LASCO C2 and C3 were used too.

- HINODE-SP and HMI-HARPS were unavailable for this region.
Introduction

Green=positive polarity, blue=negative polarity

Inverse polarity type (respect to the filament boundaries).
Evolution of the event

- The filament developed from a short structure (Sept 25, 21:00 UT) to an inverse-S-shaped elongated in just one day (dextral).

- The length was about $\sim 0.40 R_\odot$ on Sept 25 to $\sim 0.63 R_\odot$ two days later. The height of the filament is around 100,000 km.

- The magnetic flux emergence started around Sept 29 at 00:00 UT. This emergence displayed small pores in continuum. There was a positive polarity where one of the barbs was located, and this region seems to be attaching the filament to the surface.
Filament eruption in 304 Å
Filament eruption in inverted-color 94 Å
Flux emergence

- We compute the magnetic flux to this small area in HMI LOS-magnetograms.
- We set a threshold of +(-)90 G, that is, ≈ 10σ for 45-s magnetograms (Liu et al. 2012). This threshold is high enough to account for the flux computations in the network, avoiding noise effects.

![Graph showing magnetic flux over time with flare onset marked]
Flux emergence

- The maximum total flux is \(3.4 \times 10^{20}\) Mx, and the total flux rate, \(4.29 \pm 0.01 \times 10^{17}\) Mx min\(^{-1}\).

- Calculating the emergence flux rate for the positive polarity (up to the middle of the plateau), it yields \(2.23 \pm 0.07 \times 10^{17}\) Mx min\(^{-1}\).

- For the negative polarity, we obtain \(-2.52 \pm 0.07 \times 10^{17}\) Mx min\(^{-1}\).
HMI flux emergence and AIA 304 Å and 94 Å
Expansion velocity of the flux emergence

- We also measured the expansion velocity of the emergence, with two main opposite polarities, from Sept 29 01:00 UT to 13:00 UT by different methods.

- The first one is the magnetic centroids, as detailed in Balmaceda et al. (2010) but computing the distance between the positive and negative polarities above the threshold of +(-)90 G. With this method, the expansion velocity is $0.165 \pm 0.006 \text{ km s}^{-1}$.

- The second method we have used is visually measuring the distance between the two main polarities (as a diameter and obtaining the radius), getting $0.100 \pm 0.003 \text{ km s}^{-1}$.

- The third procedure is the one described in Palacios et al. (2012), measuring the area and assuming it as circular, subsequently calculating the radius from it. It yields a velocity of $0.157 \pm 0.004 \text{ km s}^{-1}$. 
Full-disk linear polarization

- Taking advantage of the HMI full-disk Stokes imaging
- Trying to find the transverse field of the blob
- But there were some focusing issues

\[ \sqrt{U^2 + Q^2} \]
Linear polarization of the flux emergence

- SDO/HMI retrieves full disk imaging of Stokes parameters. We have used Stokes U and Q images to create linear polarisation images.

- These images are created with 6 points (line sampling of about 69 mÅ from the center line; Schou et al. 2012; Centeno et al. 2011) in the Fe I line at 6173 Å.

- For each frame, we have computed the linear polarization by the formula. Unfortunately, signal-to-noise ratio (S/N) is too low in the first part of the day.

\[ L_{\text{pol}} = \frac{1}{6} \sum_{i=1}^{6} \frac{\sqrt{U_i^2 + Q_i^2}}{\langle I \rangle} \]

Fig. 3. Computed magnetic flux on positive patches (solid line) on negative patches (dashed line) signed magnetic flux (dotted-dashed line) and unsigned magnetic flux (dotted line). A vertical line marks the time of the flare at (-:4) UT.

Fig. 4. AIA 94 Å image with LOS-magnetic field superimposed, with the same contours as Fig. 2. Orange and red contours mark levels of \( \approx 0.3, 0.6, 0.8, 0.9\% \) linear polarisation.
Weak field approximation

- Getting the Stokes profiles from full-disk Stokes.
- Weak field approximation (Landi Degl’Innocenti, 1992).
- Longitudinal yields around 1 kG values, similar to the HMI magnetograms.
Filament ascent

- Height-time plots (304 Å +LASCO C2+C3)
- Mean rising velocity (38 min): $115\pm5$ km s$^{-1}$, acceleration of $0.049\pm0.001$ km s$^{-2}$
- Exponential trend

![Graph showing filament ascent with height versus time.](image)

Diamonds = C2
Squares = C3
We have used the SSW Potential Field Source Surface (Schrijver & de Rosa 2003).

Extrapolated with quasi-synoptic HMI magnetograms.

\( n \) (decay index, Bateman 1978, Kliem & Török 2006) was computed in this box. *Instability larger than 1.5-1.7.* Values were clipped from 1.2 to 2.0.

Gridpoints: We have generated datacubes of \( n \) for Sept 25, 26, 28 and 29. We have selected a box of \( 10 \times 65 \times 66 \) gridpoints. This final volume of \( \sim 55 \text{ Mm} \times 357 \text{ Mm} \times 680 \text{ Mm} \) includes the filament and the flux emergence. The Y axis covers approximately the filament’s length, but considering its shape, it cannot be considered as wholly lying in the solar longitude selected plane.
Fig. 6. Top left: loop set corresponding to the filament region rendered by PFSS for Sept 29 data. A low-resolution magnetogram was used. Top right: Transverse slice of the decay index \( n \) across the volume that encloses the filament and emergence. The estimated height of the filament for Sept 29 is marked by a black cross (corrected), or small circumference (uncorrected). Bottom: Longitudinal slice of the decay index \( n \) along the volume that encloses the filament and emergence, and same symbols for the filament height.
Discussion

- Different models for initiation of eruption: flux emergence, cancellation, moving footpoints, and MHD instabilities.
  
  Breakout model (Antiochos, De Vore, Klimchuk 1999)
  
  Tether cutting (Moore et al. 2001)
  
  Torus instability (Török and Kliem 2007)
  Torus instability (Schrijver 2008)
  
  Kink instability (Török and Kliem 2005)
  
  loss equilibrium/approaching polarities (Forbes & Priest 1995)
  
  Ejective Eruption, Midlife
  
  Formation (Van Ballegooijen & Martens 1989)
Discussion

- We did look for flux rope emergence previous to the eruption, effects like ‘sliding door’ (Okamoto et al., 2008) or environments like in Kuckein, Centeno and Martínez Pillet (2012), but with negative results.

- We did look for strong magnetic cancellation and it is not evident (but for 94 Å).

- The smooth lift-off suggested a type of torus instability, but other instabilities could not be ruled out.

Sliding door (Okamoto et al. 2008)  
Flux rope emergence with important transverse field (Kuckein et al. 2012)
Discussion

But we did find an OP-type like Kusano et al (2012), Toriumi et. al (2013), similar to Chen and Shibata (2000). This configuration may trigger a eruption, maybe combined with a torus instability.

Kusano et. al (2012)

Kusano et al. (2012), Toriumi et al. (2013)
Conclusions

- Smooth filament lift-off (close to 1 h)

- The observed flux emergence blob exhibited hectogauss values, peaking in kilogauss. The emergence acquired a size of 33″ in \( \sim 12 \) h, about \( \sim 0.16 \text{ km s}^{-1} \). The rate of signed magnetic flux is around \( 2 \times 10^{17} \text{ Mx min}^{-1} \) for each polarity. We have also studied the eruption speed, size and dynamics.

- Filament dynamics and magnetogram results suggest that the magnetic flux emergence takes place in the photospheric level below the filament. The very smooth ascent is probably caused by this emergence and ideal instabilities (torus) may play a fundamental role.
References

Chen, P. F. 2011, Living Reviews in Solar Physics, 8, 1
Parenti, S. 2014, Living Reviews in Solar Physics, 11, 1
Acknowledgements

- The authors want to acknowledge and thank SDO/AIA and SDO/HMI Data Science Centers and Teams, also to GOES and LASCO teams.

- Special thanks to the IAU travel grant and IAUS305, and AYA2013-47735P

- We would like to thank to Virtual Solar Observatory (VSO) and Helioviewer for data acquisition and visualization, respectively.

- This research has made use of NASA’s Astrophysics Data System.
Thanks for your attention!
Zhang et al. (2008) studied events of flux emergence and cancellation 12 h prior to a CME initiation, finding that 91% are related. Wang & Sheeley (1999) also found filament eruptions close to flux emergence regions. Jing et al. (2004) detected that more than half of the eruptive filaments were related to flux emergence. Zhang et al. (2001) related relatively small flux cancellation areas with the filament eruption of the Bastille Day event.

However, many of these works were qualitative and statistical. Here we aim to describe quantitative the filament and assess its instabilities, and how a flux emergence can influence a filament lift-off.
For this event, we have fit the ascent height to different functions, since this can shed light about the physical mechanism and more adequate model that triggered the eruption. We have tried exponential, log – log, and parabolic function. Then we have evaluated them with the merit function $\chi^2$ (unreduced). The exponential fit for the time-height (uncorrected) yields $\chi^2 = 1.7$, while the log – log fitting yields $\chi^2 = 5.9$. In the case of projection-corrected height, the fitting is even better: $\chi^2 = 0.9$, while the log – log fitting yields $\chi^2 = 3.4$. Parabolic fittings get very large $\chi^2$.

We also have completed the study with SOHO (Domingo et al. 1995) LASCO C2 and C3 level 1 data (Brueckner et al. 1995). After centering and rotating, we have performed image base differences and then, a Sobel operator has been applied for enhancement. We have measured the apex in the filament images. The plate scale for C2 is 11.9″ pix$^{-1}$ and for C3 is 56″ pix$^{-1}$. We show the whole time-height scale for AIA304, C2 and C3 in Fig 5 (bottom). The $\chi^2$ for the whole sequence is 3.80.
Filament and coronal holes

- We have computed the area taking a sinusoidal window to follow the rotation. Areas are heliographic-angle corrected, and computed setting an image threshold. We have measured the southern section of the set (CH2+filament) and the size changes from $1.3 \times 10^{10}$ km$^2$ to $1.4 \times 10^{10}$ km$^2$, therefore, no significant area change in any of the coronal holes is detected. When the filament took off, we detected an area decrease in the set CH2+filament from $1.1 \times 10^{10}$ km$^2$ to $0.8 \times 10^{10}$ km$^2$. The image de-rotation method yields very similar results compared to the sinusoidal window technique. The northern one, CH1, decreased apparently due to the projection of the flare over CH1 and, when the two-ribbon flare finished, it is diminished caused by magnetic topology rearrangement in its surroundings. However, the apparent darkness is increased during several hours after the flare.
Introduction

- Some very recent and comprehensive summaries of the different models that can trigger the eruption of filaments and CMEs are Aulanier et al. (2010); Schmieder et al. (2013); Aulanier (2014); Parenti (2014) and references therein: the ‘magnetic breakout model’ (Antiochos 1998; Antiochos et al. 1999), a highly twisted flux rope, like in the ‘torus instability’ (Török & Kliem 2003, 2005; Kliem & Török 2006); different instabilities, as MHD (Klimchuk & Sturrock 1989; Sturrock 1989), catastrophic loss of equilibrium (Forbes & Isenberg 1991), or due to approaching polarities (Forbes & Priest 1995), moving features and magnetic cancellation (van Ballegooijen & Martens 1989; Forbes & Isenberg 1991) and the ‘tether cutting’ model, implying reconnection in the arcades below the flux rope (Moore & Roumeliotis 1992; Moore et al. 2001).

Considering the magnetic flux emergence, filament eruption due to flux emergence in the surroundings have been analysed in simulations by Chen & Shibata (2000). The magnetic configuration of active and quiescent filaments and their CME productivity have been studied in Feynman & Martin (1995). Slow and fast eruptive phases have been studied by Sterling & Moore (2005); Sterling et al. (2007). We will consider the observational features of these models to choose the most plausible one for this phenomenon.

- More particularly, in the review of Chen (2011), different works are revised: Zhang et al. (2008) studied events of flux emergence and cancellation 12 h prior to a CME initiation, finding that 91% are related. Wang & Sheeley (1999) also found filament eruptions close to flux emergence regions. Jing et al. (2004) detected that more than half of the eruptive filaments were related to flux emergence. Zhang et al. (2001) related relatively small flux cancellation areas with the filament eruption of the Bastille Day event.

- However, many of these works were qualitative, only with the presence and closeness of the flux emergence to relate with other magnitudes. Here we aim to describe quantitative the filament and assess its instabilities, and how a flux emergence can influence a filament lift-off.
Sketching the eruption