Solar and Stellar Magnetic Fields: Origins and Manifestations
Proceedings IAU Symposium No. 354, 2019
A. Kosovichev, K. Strassmeier & M. Jardine, ed.
doi:10.1017/S1743921319009967

Multi-flux-rope system in solar active regions

Yijun Hou[1,2], Jun Zhang[1,2], Ting Li[1,2] and Shuhong Yang[1,2]

[1]CAS Key Laboratory of Solar Activity, National Astronomical Observatories
Chinese Academy of Sciences, Beijing 100101, China

[2]University of Chinese Academy of Sciences, Beijing 100049, China
email: yijunhou@nao.cas.cn

Abstract. Magnetic flux rope (MFR) is closely connected with solar eruptions, such as flares and coronal mass ejections. The classical scenario assumes a single MFR for each eruption, but it is reasonable to expect multiple MFRs in a complex active region (AR). Statistically investigating AR 11897, we verify the existence of multiple MFR proxies during the AR evolution. Recently, AR 12673 in 2017 September produced the two largest flares in Solar Cycle 24. The evolutions of the AR magnetic fields and the two large flares reveal that significant flux emergence and successive interactions between different emerging dipoles resulted in the formations of multiple MFRs and twisted loop bundles, which successively erupted like a chain reaction within several minutes before the peaks of the two flares. We propose that the eruptions of a multi-flux-rope system can rapidly release enormous magnetic energy and result in large flares in solar AR.

Keywords. Sun: activity, Sun: atmosphere, Sun: filaments, Sun: flares, Sun: magnetic fields

1. Introduction

Solar flares and coronal mass ejections (CMEs) are explosive phenomena in the solar atmosphere and release dramatic free magnetic energy into the interplanetary space, which can severely affect the space environment around the earth. The magnetic flux rope (MFR) is a set of magnetic field lines winding around a central axis and is widely believed to play a key role in triggering the solar eruptive events (Priest and Forbes 2002; Schmieder *et al.* 2015). Thus, a complete research on the MFR is necessary to obtain a clear understanding of solar flares and CMEs, which will undoubtedly result in accurate forecasts of eruptive activities and associated space weather. With high-resolution observations, the existence of MFR in the solar atmosphere has been unambiguously evidenced (Guo *et al.* 2010; Cheng *et al.* 2011; Li and Zhang 2013; Chintzoglou *et al.* 2015; Hou *et al.* 2019). Moreover, some recent works have implied that MFRs may be ubiquitous on the Sun and could gather in the solar active regions (Zhang *et al.* 2015; Awasthi *et al.* 2018; Jiang *et al.* 2018).

2. Observations and Results

Based on observations from Atmospheric Imaging Assembly (AIA; Lemen *et al.* 2012) and Helioseismic and Magnetic Imager (HMI; Schou *et al.* 2012) of the *Solar Dynamics Observatory* (*SDO*; Pesnell *et al.* 2012), we statistically study MFR proxies in active region (AR) 11897. Then we investigate the X9.3 flare on 2017 September 06 occurring in AR 12673, which produced 4 X-class flares from September 04 to September 10. In the X9.3 flare, multiple MFRs were detected to successively erupt within five minutes before the flare peak. The results of nonlinear force-free field (NLFFF) modeling (Wiegelmann *et al.* 2012) also confirm the existence of a multi-flux-rope system in AR 12673. The similar phenomenon was also observed during the X8.2 flare on September 10.

Table 1. Distribution of the detected MFR proxies in AR 11897.

	Nov. 14	Nov. 15	Nov. 16	Nov. 17	Nov. 18	Nov. 19
Site1	3					
Site2	8	1				
Site3			2	5	1	1
Site4		3	4	1	1	

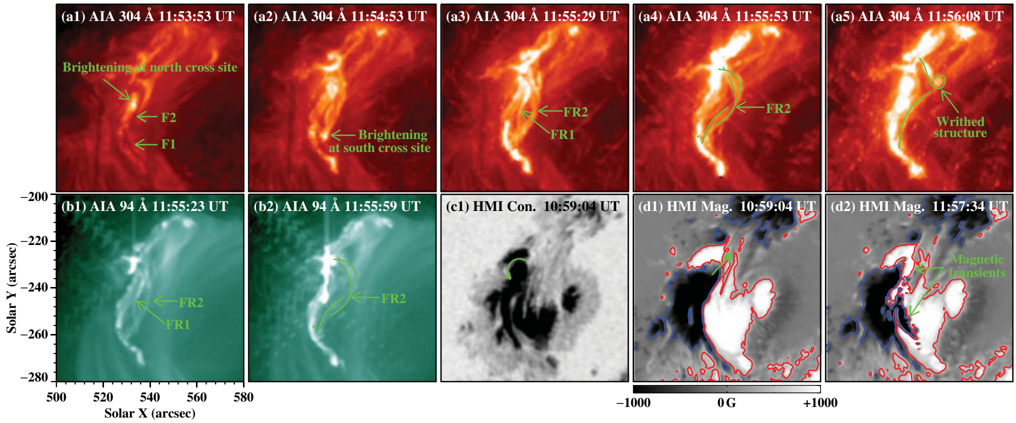

Figure 1. AIA 304 Å and 94 Å images showing eruption of the double-decker MFR configuration and corresponding HMI continuum intensitygram and LOS magnetograms displaying the magnetic fields of the AR core region before the flare peak at 12:02 UT.

During the evolution of AR 11897 from 2013 November 14 to 19, we identify MFR proxies for 30 times in 4 different sites, that is, 5 times per day on average. The daily distribution of these MFR proxies is shown in Table 1. Here we notice that some MFR proxies appeared in one location for several times. It is possible that 7 MFRs were detected in 4 different sites and repeatedly illuminated for 30 times in total (see more details in Hou *et al.* 2016).

On 2017 September 6, an X9.3 flare took place in AR 12673, which is the largest flare in Solar Cycle 24 (Yang *et al.* 2017; Yan *et al.* 2018; Liu *et al.* 2018). Here we investigate the evolutions of this large flare and the associated complex magnetic system (see more details in Hou *et al.* 2018). By examining the AIA 304 Å observations, we detected two sets of filament threads located in the AR core region before the occurrence of the X9.3 flare (see F1 and F2 in Fig. 1), which forms a double-decker MFR configuration (Liu *et al.* 2012). Around 11:53:53 UT and 11:54:53 UT, brightenings appeared at the north and south cross sites of these two filament threads (also two MFRs, FR1 and FR2), implying the interaction between rising FR1 and FR2 (see green arrows in panels (a1)-(a2)). The two MFRs then were tracked completely by the brightening material, and FR2 began to moved upward as well (see panel (a3)). In panels (a4) and (a5), FR2 showed obvious twisted threads and writhed structure, implying the occurrence of kink instability (Kliem *et al.* 2004; Török *et al.* 2011). In 94 Å channel, the two MFRs were also observed clearly (panels (b1)-(b2)). Panels (d1)-(d2) show that the north ends of the two MFRs were rooted in a negative-polarity patch. Before the onset of the X9.3 flare, this negative magnetic patch kept moving northwestward along the semicircular PIL and successively sheared with the adjacent positive fields. Meanwhile, the HMI continuum intensitygrams reveal that this negative patch exhibited a counterclockwise rotation motion (panel (c1)).

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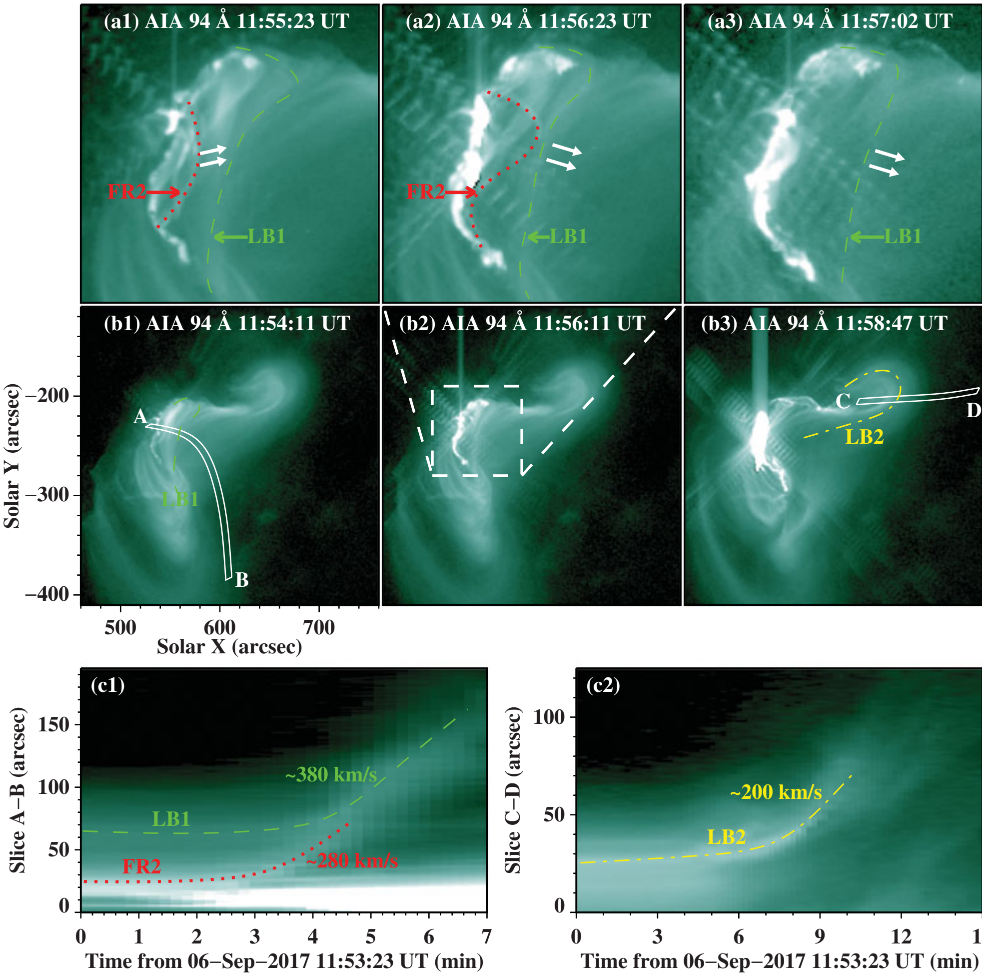

Figure 2. Dynamic evolutions of the complex system consisting of multiple flux ropes and twisted loop bundles during the X9.3 flare.

During the X9.3 flare, a total of two MFRs (FR1 and FR2) and two twisted loop bundles (LB1 and LB2) are identified in the flaring region (see Fig. 2). AIA 94 Å images of panels (a1)-(a3) show the interaction between the kink-unstable FR2 and the nearby loop bundles (LB1). Around 11:56:23 UT, FR2 and LB1 interacted with each other in their middle parts. Then LB1 began to rise up rapidly and disturbed another set of loop bundles (LB2) with a larger scale. Along the two white arc-sector domains "A-B" and "C-D", we make two time-space plots and show them in panels (c1) and (c2), where the eruptions of FR2, LB1, and LB2 are clearly visible. After the successive eruptions of multiple MFRs and twisted LBs, the X9.3 flare reached its peak at 12:02 UT. In order to verify these structures illuminated in EUV channels and study their magnetic topologies, we reconstruct 3D magnetic field above the AR and show the results in Figure 3. It is clear that before the onset of X9.3 flare, two MFRs (FR1 and FR2) with the twist number (T_w) $\leqq -1.0$ are located above the PIL in the AR core region. Two sets of twisted LBs (LB1 and LB2) are also tracked nearby.

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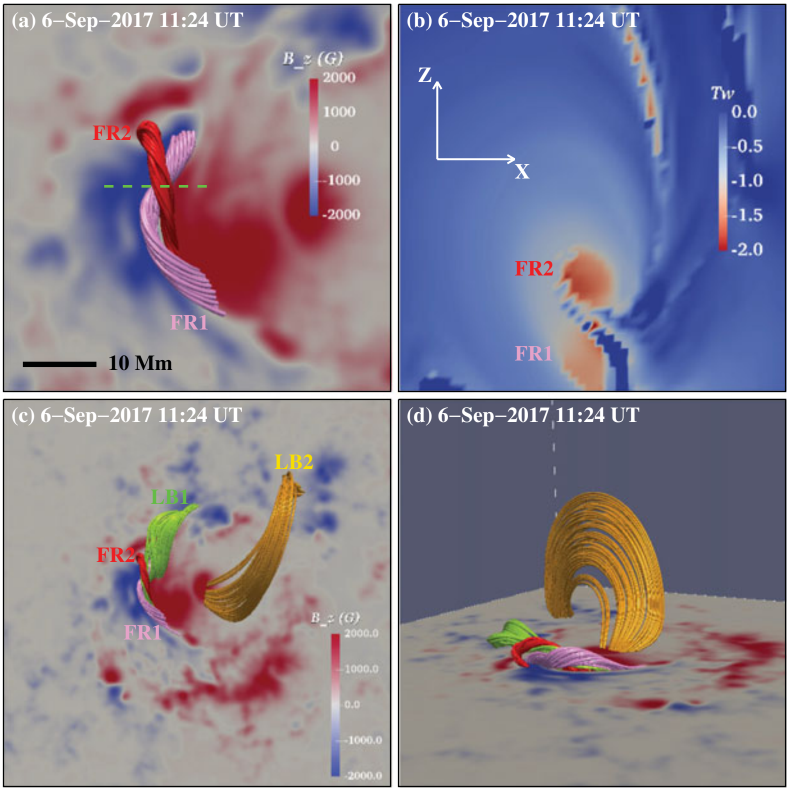

Figure 3. Extrapolated 3D NLFFF structures corresponding to FR1, FR2, LB1, and LB2 at 11:24 UT on 2017 September 6.

3. Summary and Discussion

Employing the *SDO* observations, for the first time, we detect multiple MFR proxies for 30 times in AR 11897 at four different locations during six days. These new observations imply that multiple MFRs can exist in an AR and that the complexity of AR magnetic configurations is far beyond our imagination. Furthermore, we investigate the X9.3 flare on 2017 September 06 occurring in AR 12673, which is the largest flare in Solar Cycle 24. Aided by the NLFFF modeling, we identify a double-decker MFR configuration above the PIL in the AR core region. The north ends of these two MFRs were rooted in a negative-polarity magnetic patch, which began to move along the PIL and rotate anticlockwise before onset of the X9.3 flare. The strong shearing motion and rotation contributed to the destabilization of the two MFRs, of which the upper one eventually erupted upward due to the kink-instability. Then another two sets of twisted loop bundles beside these MFRs were disturbed and successively erupted within five minutes like a chain reaction.

MFRs have been thought to be closely connected with CMEs and solar flares. The classical scenario assumes a single MFR for each eruption, but it is natural to imagine the existence of multiple MFRs if the AR is complex and has extended curved PIL (Liu *et al.* 2012; Shen *et al.* 2013; Awasthi *et al.* 2018). Török *et al.* (2011) presented a 3D MHD simulation to investigate three consecutive filament eruptions. In the observational domain, Shen *et al.* (2012) reported the simultaneous occurrence of a partial and a full

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filament eruption in two neighboring source regions. Therefore, based on the statistical and case studies mentioned above, we propose that the eruption of a multi-flux-rope system in solar AR could rapidly release enormous magnetic energy and trigger large flares, such as the largest flare in Solar Cycle 24: the X9.3 flare on 2017 September 6.

Acknowledgments

The data are used courtesy of the *SDO* science team. The authors are supported by the National Natural Science Foundations of China (11903050, 11790304, 11773039, 11533008, 11673035, 11673034, 11873059, and 11790300), the NAOC Nebula Talents Program, the Youth Innovation Promotion Association of CAS (2017078 and 2014043), Young Elite Scientists Sponsorship Program by CAST (2018QNRC001), and Key Programs of the Chinese Academy of Sciences (QYZDJ-SSW-SLH050).

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