



On the Magnetic Reconnection and Its Properties During a Flare Using a Magnetohydrodynamics Simulation

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Abstract

We study the magnetic reconnection during a flare by investigating flare ribbon dynamics using observations and data-constrained magnetohydrodynamics (MHD) simulation. In particular, we estimate the reconnection flux and the reconnection flux rates using flare ribbons of an M1.1 flare hosted by the active region 12184 utilizing the technique developed by Qiu et al. (2002). The reconnection flux and corresponding flux rates are found to be 10^{20} Mx and 10^{18} Mx s⁻¹ respectively. To understand the flare onset and the origin of flare ribbons, we perform an MHD simulation initiated by the non-force-free-field extrapolation. Importantly, the extrapolated configuration identifies a three-dimensional (3D) magnetic neutral point and a flux rope in the flaring region, which is crucial to the flaring activity. The reconnection initiates at the null point and, subsequently the flux rope rises and appears to reconnect there, which is favorable for the eruption of the filament. The surrounding field lines also seem to take part in the null point reconnection. In later stage, a current sheet is formed below the null point ensuing a secondary reconnection near an X-type topology, further contributing to the energy release process in the flare. We trace the footpoint evolution of the field lines lying over the flare ribbons and find a significant similarity between the observed flare ribbons and the evolution of footpoints computed from the MHD simulation. We estimated induced electric field during the flare and found it to be ≈ 0.52 V cm⁻¹, a slight less value, as per many past literatures. Additional findings are the enhancement of vertical current density near the flaring ribbons, a signature of successive reconnections near the null point. Overall, the present work contributes to the understanding of the ribbon formation in a flaring process and the involved magnetic reconnection.

Keywords Magnetic reconnection · Magnetohydrodynamics · Magnetic fields · Corona

1. Introduction

Magnetic reconnection is believed to be one of the underlying mechanisms of many solar transients viz. flares, coronal mass ejections (CMEs), and jets (Priest 2014). Magnetic reconnection involves the rearrangement of the magnetic-field topology along with a conversion of the magnetic energy into kinetic energy, heat, and acceleration of charged particles from the reconnection site and also upon the action of termination shocks (Priest 2014; Chen et al.

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2015). With the advent of new instruments for observations and improved numerical simulations, attempts have been made to explore the underlying physics of reconnection in the solar atmosphere (Priest and Forbes 1989; Priest 2014). However, a full understanding of reconnection physics is not yet achieved (Priest 2014), especially in three-dimensional (3D) settings.

Relevantly, the standard flare model or the CSHKP model (Carmichael 1964; Sturrock 1968; Hirayama 1974; Kopp and Pneuman 1976) provides a physical scenario for the eruptive flares. According to this model, a filament or magnetic flux rope escapes the over-arching magnetic-field lines while creating a current sheet below it, ensuing reconnection there. As a result, the accelerated charged particles are produced from the reconnection site and under the effect of termination shock and move along the field lines toward the denser plasma at lower heights — heating the dense atmosphere to create quintessential flare ribbons along with the formation of the post-flare loops. The reconnecting loops appear to move away from the polarity inversion line (PIL) while reconnecting site ascends in time.

In magnetic reconnection, one of the important parameters is the reconnection rate, which defines the amount of magnetic flux infused into the diffusion region per unit of time with an inflow (v_{in}), given by $v_{in}B$ (Isobe, Takasaki, and Shibata 2005). In non-dimensional form, the rate is expressed as $M = v_{in}/v_A$, where v_A is the Alfvén velocity. From the Sweet-Parker model (Parker 1957; Sweet 1958), the reconnection rate is $M_A = S^{-1/2} \approx 10^{-7}$, where $S = \frac{Lv_A}{\eta}$ is the Lundquist number with η being the magnetic diffusivity considering Spitzer resistivity (Spitzer 1956) for solar corona. Petschek (1964) estimated the rate to be $M_A = \pi/8 \log S \approx 0.01 - 0.1$ in two-dimensional (2D) models considering the slow sock effects. Biskamp (1986) through a numerical approach agreed to the Sweet-Parker model result, while Ugai (1986), Scholer (1989), Yokoyama and Shibata (1994) have proven the rate to be in favor of Petschek-type fast reconnection with an anomalous resistivity in their magnetohydrodynamics (MHD) simulations.

On the other hand, estimation of the reconnection rate from observations is challenging due to the difficulty in measuring the coronal magnetic field (B_{corona}) and the inflow velocity there. Noticeably, direct plasma flows were first seen in limb flares observed in EUV images of SOHO/EIT (Yokoyama et al. 2001; Narukage and Shibata 2006). Noticing the successive production of flare ribbons in the chromosphere is an indication of the successive reconnection at the coronal height, and flare ribbons in the chromosphere are then used to indirectly measure the reconnection rate (Forbes and Lin 2000; Lin 2004). In this approach, the reconnection rate in a 2D geometry is equal to the electric field in the reconnecting current sheet given by $E_{cs} = v_{in}B_{corona} = v_{foot}B_{foot}$, where B_{foot} is the magnetic field strength at the footpoint of the loops and v_{foot} is the footpoints separation velocity on the ribbons. Isobe et al. (2002), Isobe, Takasaki, and Shibata (2005) have adapted this relation to obtain the reconnection rate in a flare. A detailed discussion about the measurement method of reconnection rate using the flare ribbons can be found in Qiu et al. (2007, 2010). The method has been successfully and extensively utilized by Kazachenko et al. (2017) to understand the correlation between the flare ribbon fluxes and the peak X-ray flux for a large number of flares. Using the same method, a recent study by Qiu and Cheng (2022) infers the role of magnetic shear in influencing the reconnection rate.

Nevertheless, many flares are atypical by not falling into the standard flare model scenario. Li and Zhang (2014) in their study of a large set of confined flares reported the role of slipping motion of flares and ribbons near the quasi-separatrix layers (QSLs: Priest and Démoulin 1995). Notably, a QSL is a potential site of magnetic reconnection, where a sharp change in magnetic field connectivity is found. Further in their subsequent work, Li and Zhang (2015) reported the quasi-periodic slipping motion of flare loops during an X-class

flare. Again, Duan, Li, and Jing (2022) showed the role of slipping magnetic reconnection in a flare and later the slippage of the flux rope. Afterward, many observations were reported for other types of flare ribbons like circular flare ribbons, and not-so-symmetric parallel flare ribbons in many instances by Dudík et al. (2014), Li, Ning, and Zhang (2015), Dudík et al. (2016), Prasad et al. (2018), Zemanová et al. (2019), Chen et al. (2019), Liu et al. (2020). Hence, the variety in flare ribbon structures makes it difficult to explain the different properties such as the reconnection rate of the underlying reconnection process.

Against the above backdrop, in this paper, we have investigated the role of magnetic reconnection in the formation of non-parallel ribbons during an M-class flare on 23 May 2021 hosted by a complex active region in terms of the distribution of magnetic fluxes. For this purpose, we have utilized the extrapolation model known as the non-force-free-field (NFFF) extrapolation (Hu and Dasgupta 2006; Hu et al. 2008, 2010) to construct the coronal magnetic field configuration. The extrapolated configuration suggests the presence of a 3D null as well as a flux rope in the flaring region. To explore the dynamical evolution of the flare, we perform a data-constrained MHD simulation initialized with the NFFF extrapolated field using the numerical model EULAG-MHD (Smolarkiewicz and Charbonneau 2013). In the numerical model, the reconnections are achieved by the intermittent and adaptive numerical diffusion to the locations of under-resolved scales in the computational volume while fulfilling the flux-freezing condition elsewhere (Kumar and Bhattacharyya 2016; Kumar et al. 2017). The simulated dynamics documents the onset of reconnections at the 3D null that trigger the flaring activity and form the flare ribbons. These reconnections continue in time and allow the flux rope to reconnect at the null, which potentially leads to the filament eruption. Additionally, in the simulation, we have calculated the reconnection rate and reconnection flux rate near the flare ribbons. Notably, using the method by Qiu et al. (2002), we have also estimated the reconnection flux and reconnection flux rate observationally, which $\approx 10^{20}$ Mx and 10^{18} Mx s⁻¹ respectively. The values are one order less than the ones calculated in the simulation. Additional estimations on electric fields near the null point region are carried out along with current density on the ribbons. The derived reconnection rate from the simulation is found to be slightly less than the values obtained in earlier works.

The rest of the paper is arranged as follows. Section 2 outlines the progress of the flare from observations. Section 3 describes the extrapolation model, and presents the initial extrapolated magnetic field. Next, Section 4 describes the MHD model and the simulation set-up for the study. Section 5 discusses the results of the simulation. Lastly, Section 6 summarizes the work.

2. The M-Class Flare in AR 12824

We have studied the M1.1 flare on 23 May 2021 in the active region NOAA 12824, which was initiated at 10:48 UT and lasted for ≈ 40 minutes (hinode.isee.nagoya-u.ac.jp/flare_catalogue/). The progress of the flare is depicted in 1600 Å (panels (a) to (c)) and 304 Å (panels (d) to (f)) of Atmospheric Imaging Assembly (AIA: Lemen et al. 2012) onboard the Solar Dynamics Observatory (SDO: Scherrer et al. 2012; Pesnell, Thompson, and Chamberlain 2012) in Figure 1. Panels (a) and (d) show the flaring region at 10:48 UT which is ≈ 18 minutes before the peak time of the flare. Notable is the growth of the ribbons in panel (b), marked by yellow color box and then the decay phase comes, plotted in panel (c). The ribbons are not parallel and have a non-standard morphology. The 304 Å observations of the flare (panels (d) to (f)) document the eruptive motion of the filament (marked by a white arrow in panel (e)) during the flare.

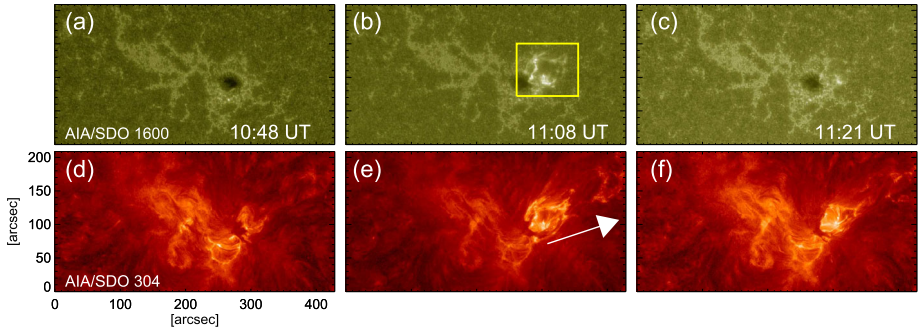


Figure 1 The history of the M-class flare: *Panels (a)–(c)* represent the evolution of the flare ribbons in 1600 Å of AIA/SDO. *Panel (b)* depicts the growth of the ribbons (marked by yellow box) at the peak time of the flare. *Panels (d)–(f)* show the evolution of the flare in 304 Å of AIA/SDO and white arrow in *panel (e)* shows the direction of the motion of the eruption. Important is the appearance of non-parallel flare ribbons.

3. The Non-Force-Free-Field Extrapolation Model

To construct the magnetic configuration of the flaring region, we extrapolate the photospheric magnetic field of the active region utilizing the NFFF model. The model is based on the minimum dissipation rate principle (MDR) where the relaxed state of a two-fluid plasma system is achieved by minimizing the total dissipation rate keeping the generalized helicity constant (Bhattacharyya and Janaki 2004; Bhattacharyya et al. 2007). The relaxed state is a non-force-free state and supports a non-zero Lorentz force, which is used to self-consistently drive the plasma in the presented MHD simulation. Briefly, The extrapolation solves an inhomogeneous double-curl Beltrami equation for the magnetic field \mathbf{B} (Bhattacharyya and Janaki 2004; Bhattacharyya et al. 2007, and references therein),

$$\nabla \times \nabla \times \mathbf{B} + a_1 \nabla \times \mathbf{B} + b_1 \mathbf{B} = \nabla \psi, \tag{1}$$

where a_1 and b_1 are constants. The solenoidality of \mathbf{B} enforces the scalar function ψ to obey Laplace’s equation. The solution to Equation 1, after solving a two-fluid steady state (Mahajan and Yoshida 1998), is a superposition of three subfields as,

$$\mathbf{B} = \mathbf{B}_3 + \sum_{i=1,2} \mathbf{B}_i, \tag{2}$$

where $\mathbf{B}_3 = \nabla \psi$ is a potential field and the other two \mathbf{B} s are linear force-free fields having two different α satisfying the $\nabla \times \mathbf{B}_i = \alpha_i \mathbf{B}_i$, and related by $a_1 = -(\alpha_1 + \alpha_2)$ and $b_1 = \alpha_1 \alpha_2$. Following Hu et al. (2010), an optimal pair of α is computed for $\mathbf{B}_3 = 0$ by minimizing the average normalized deviation of the magnetogram transverse field B_t from its extrapolated value b_t , given by

$$E_n = \left(\sum_{i=1}^M |B_{t,i} - b_{t,i}| \times |B_{t,i}| \right) / \left(\sum_{i=1}^M |B_{t,i}|^2 \right), \tag{3}$$

where $M = N \times N$ is the total number of grid points on the transverse plane. Additional minimization of E_n is done by using $\mathbf{B}_3 = \nabla \psi$ as a corrector field for the obtained pair of α . Details of the NFFF extrapolation models can be found in Hu and Dasgupta (2006), Hu et al. (2008, 2010).

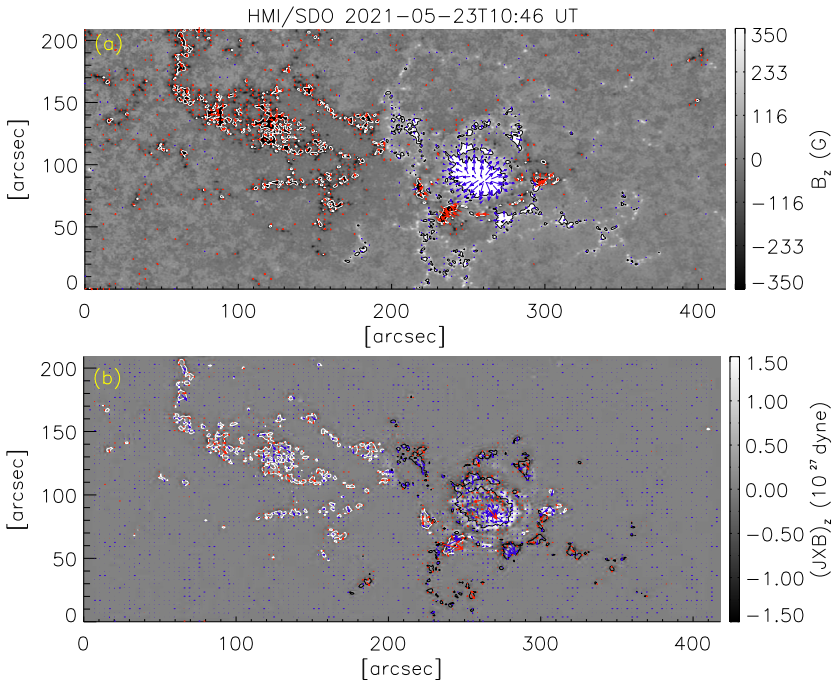


Figure 2 *Top*: vector plot of magnetic field, where *red* and *blue* arrows denote the transverse components and the *grayscale* denotes the longitudinal component of \mathbf{B} of HMI/SDO in *panel (a)*. *Panel (b)* shows the vector plot of the Lorentz force on the bottom boundary ($z = 0$) derived from the extrapolated 3D magnetic field.

3.1. The NFFF Extrapolated Topology of AR 12884

The NFFF model requires vector components of the magnetic field to perform the extrapolation. We have used the `hmi_sharp_cea_720s` magnetogram series with a temporal cadence of 12 minutes of Helioseismic and Magnetic Imager (HMI: Scherrer et al. 2012)/SDO with the Lambert Cylindrical Equal Area (CEA) Projection (Calabretta and Greisen 2002). The cutout is originally 836 pixels in x - and 418 in y -directions. We performed the NFFF extrapolation for a rescaled size of 384 in x - and 192 in y -directions to reduce the computational cost. The physical extent of the computational box is ≈ 300 Mm in x - and ≈ 150 Mm in both y - and z -directions. We have compared the magnetic topology for the extrapolated field with the original and the rescaled resolution, which is found to be unchanged (not shown). We calculated the Pearson-r correlation coefficient for the extrapolated (B_r) and observed transverse (b_r) field and found it to be 0.95, suggesting a strong correlation between them. Panel (a) of Figure 2 shows the observed magnetogram with B_z in the grayscale with the transverse positive and negative fields marked by blue and red arrows, respectively. Panel (b) shows a 2D map of the Lorentz force associated with the extrapolated field at the bottom boundary, with a z -component of it in grayscale and the transverse components marked by red and blue arrows.

Next Figure 3(a) shows the overall field lines of AR 12824 obtained from the NFFF extrapolated magnetic field. We have plotted the field lines using the Visualization and Analysis Platform for Ocean, Atmosphere, and Solar Researchers (VAPOR) software (Clyne et al.

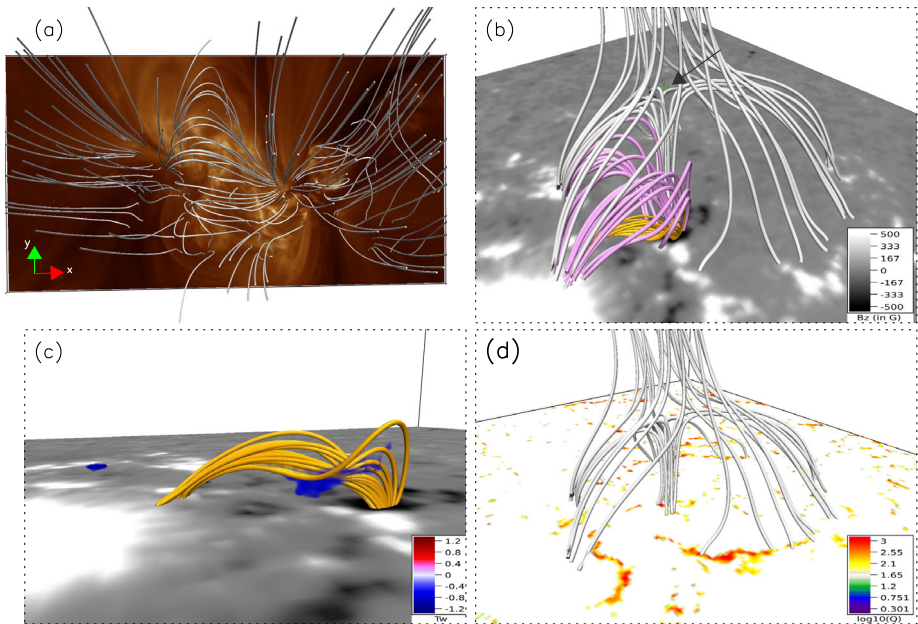


Figure 3 The NFFF extrapolated field: (a) overall topology of the active region AR12884 plotted on 193 Å of AIA. *Panel (b)* magnetic field structure with a magnetic null point, plotted in *white color*, the flux rope in *orange color*, and the surrounding arcade in *pink color*. The *black arrow* and the *cyan dot* mark the location of the null point. *Panel (c)* highlights the flux rope structure possessing a maximum twist value of 1.2. The distribution of the squashing factor is plotted in *panel (d)*. Notable is the presence of a high squashing factor near the footpoints of the fan field lines.

2007; Li et al. 2019). Near the flaring region as shown in panel-(b), we find a set of twisted field lines, plotted in orange color, and confirm it as a flux rope from the estimation of the volumetric distribution of twist parameter (Tw), as shown in panel-(c). The twist parameter is a measure of the circulation of magnetic field lines about their axis. To calculate Tw , we have used the code of Liu et al. (2016) which computes the value by estimating $\mathbf{J} \cdot \mathbf{B}/B^2$ in a 3D box. Further, a 3D magnetic null point is found near the flaring region. The field lines surrounding the spine and fan are plotted in white color. The null location is detected by using the method described in Nayak et al. (2020). The procedure is the realization of Dirac-delta function ψ in a Cartesian grid which is found by constructing a Gaussian indicator in the form of

$$\psi(x, t) = \exp\left[-\frac{(\mathbf{B} - \mathbf{B}_0)^2}{d_0^2}\right], \quad (4)$$

where $\mathbf{B}_0 = (B_0, B_0, B_0)$, while B_0 and d_0 are small constants compared with the magnitude of $|B|$ that define an isovalue of $|B|$ and the spread of the Gaussian, respectively. For $B_0 \approx 0$ and comparably small d_0 , the function ψ takes significant values only if $|B| \approx 0$. A 3D null is then within a small volume surrounded by an isosurface of ψ with a suitably large value ψ_0 . The method successfully identifies the null point locations in other examples as in Nayak, Bhattacharyya, and Kumar (2021) near another flaring region. The null is pointed by the black arrow and its height is found to be ≈ 20 Mm. In addition to the null point in the domain, a sheared arcade carrying a part of field lines of 3D null is also found lying below

the fan of the 3D null, plotted in pink color. For further confirmation, we have plotted the distribution of squashing factor (Q) which represents the sharp change in the connectivity of the magnetic field lines. Panel (d) illustrates 3D null field lines overlaid with the squashing factor (Q) — documenting its high values in the vicinity of the footpoints of the fan field lines.

4. The Simulation Set-up for EULAG-MHD Model

To trace the footpoints on the ribbon structure, and to analyze the dynamics of the above topologies near the flaring region, we have carried out the simulation by numerically solving the incompressible Navier–Stokes MHD equations under the assumption of thermal homogeneity and perfect electrical conductivity (Kumar et al. 2016, 2021). The MHD equations in the EULAG-MHD (Eulerian/Semi-Lagrangian Solver) model, in the dimensionless form, are

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla p + (\nabla \times \mathbf{B}) \times \mathbf{B} + \frac{\tau_A}{\tau_\nu} \nabla^2 \mathbf{v}, \quad (5)$$

$$\nabla \cdot \mathbf{v} = 0, \quad (6)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}), \quad (7)$$

$$\nabla \cdot \mathbf{B} = 0, \quad (8)$$

written in usual notations. The variables in the MHD equations are normalized as follows

$$\mathbf{B} \longrightarrow \frac{\mathbf{B}}{B_0}, \quad \mathbf{v} \longrightarrow \frac{\mathbf{v}}{v_A}, \quad L \longrightarrow \frac{L}{L_0}, \quad t \longrightarrow \frac{t}{\tau_A}, \quad p \longrightarrow \frac{p}{\rho v_A^2}. \quad (9)$$

The constants B_0 and L_0 are generally arbitrary, but they can be fixed using the average magnetic field strength and size of the system. Here, $v_A \equiv B_0/\sqrt{4\pi\rho_0}$ is the Alfvén speed and ρ_0 is the constant mass density. The constants τ_A and τ_ν represent the Alfvén transit time ($\tau_A = L_0/v_A$) and viscous dissipation time scale ($\tau_\nu = L_0^2/\nu$), respectively, with ν being the kinematic viscosity. Utilizing the discretized incompressibility constraint, the pressure perturbation, denoted by p , satisfies an elliptic boundary-value problem on the discrete integral form of the momentum equation (Equation 5); cf. Bhattacharyya, Low, and Smolarkiewicz (2010) and the references therein.

EULAG-MHD is based on the spatio-temporally second-order accurate non-oscillatory forward-in-time multidimensional positive definite advection transport algorithm MPDATA (Smolarkiewicz 2006). Importantly, MPDATA has the proven dissipative property which, intermittently and adaptively, regularizes the under-resolved scales by simulating magnetic reconnections and mimicking the action of explicit subgrid-scale turbulence models (Margolin, Rider, and Grinstein 2006) in the spirit of Implicit Large Eddy Simulations (ILES) (Grinstein, Margolin, and Rider 2007). The residual numerical dissipation is ineffective elsewhere in the domain but not at the sites of reconnection such as the region with steep gradient in magnetic values or null points. Such ILESs conducted with the model have already been successfully utilized to simulate reconnections to understand their role in the coronal dynamics (Prasad, Bhattacharyya, and Kumar 2017; Prasad et al. 2018; Nayak et al. 2019; Nayak, Bhattacharyya, and Kumar 2021; Kumar et al. 2022; Nayak et al. 2024) in different solar transients like flares and jets. Details of the EULAG-MHD model can be found in Smolarkiewicz and Charbonneau (2013).

The NFFF extrapolated field is supplemented as the initial magnetic field and the initial velocity field is set to $\mathbf{v} = \mathbf{0}$. At the bottom boundary, the z -components of \mathbf{B} and \mathbf{v} are chosen to be fixed to their initial values throughout the simulation period (also termed as line-tied boundary condition) as the flux change during the flare is found to be minimum. The side and top boundaries are kept to their initial values. The density is kept to unity in the whole computational box. As stated earlier in Section 3, the simulation is initially driven by the non-zero Lorentz force associated with the extrapolated magnetic field, and the primary flow is generated by it. The resulting flow is however made incompressible following the Equation 6, an assumption also adapted by Dahlburg, Antiochos, and Zang (1991), Aulanier, Pariat, and Démoulin (2005). Since our focus is to understand the onset of the flare through the topological changes, the assumption seems to be justifiable in the tenuous coronal medium.

The computational domain in the simulation is of the same size to that of the extrapolation i.e. uniform grid resolution with 384 grid points in x -, and 192 in both y - and z -directions. The spatial unit length δx is 0.0052 and the time step δt is set to 1×10^{-3} while satisfying the CFL condition (Courant, Friedrichs, and Lewy 1967). The dimensionless coefficient $\tau_A/\tau_v \approx 2 \times 10^{-4}$ in the simulation is roughly ≈ 15 times larger than its coronal value (Prasad et al. 2018). The parameter τ_A/τ_v is controlled by the spatial resolution and the time step whilst satisfying the von Neumann stability criteria (Crank, Nicolson, and Hartree 1947). The larger τ_A/τ_v , however, only expedites the evolution without an effect on the corresponding changes in the magnetic topology. The total simulation time is 4500 δt . To compare with the observational time, we multiplied the total simulation time by 15. Then, it corresponds to ≈ 33 minutes of the observational time.

5. Simulation Results and Discussions

5.1. Onset of the Flare

First, we have shown the evolution of the field lines of the null point skeleton (white and red colors), the flux rope (orange) and the sheared arcade (pink) found in the vicinity of the flaring region. We have compared the dynamics developed in different magnetic field configurations with AIA 131 and 304 channels. In Figure 4, we have overplotted the sample field lines with 131 channel on the background. From panels (a)–(f), we have shown the evolution of the field lines tracing over the flaring region from $t \approx 10:48$ UT to $t \approx 11:21$ UT covering the whole flaring period. Panel (a) denotes the initial state of the simulation, whereas panel (f) corresponds to end of the flare. Panels (b) to (e) denote snapshots before the peak of the flare time period. Initially, the red-colored field lines are situated under the dome of the 3D null (panel (a)) and, with time, the field lines come out of the dome (panel (b)). This clearly indicates a change in connectivity of the red field lines, suggesting the onset of the reconnection at the 3D null. These reconstructions repeat in time and can contribute to the brightening observed around the inner spine of the 3D null. Subsequent dynamics documents the rise of the flux rope toward the 3D null and its reconnection at the null (panels (c) and (d)). Similar rise and reconnection are also observed for the sheared arcade. Such rise and reconnection lead to development of a curved magnetic structure, marked by a dotted green line in panel (e). The structure has some similarity with the observed bright structures. In Figure 5, we have plotted the evolution of the field lines overlaid with 304 Å, highlighting the overlying of their footpoints in the brightened region near the peak of the flaring period. The opening of these different field lines along the outer spine of the 3D null may indicate a direction to

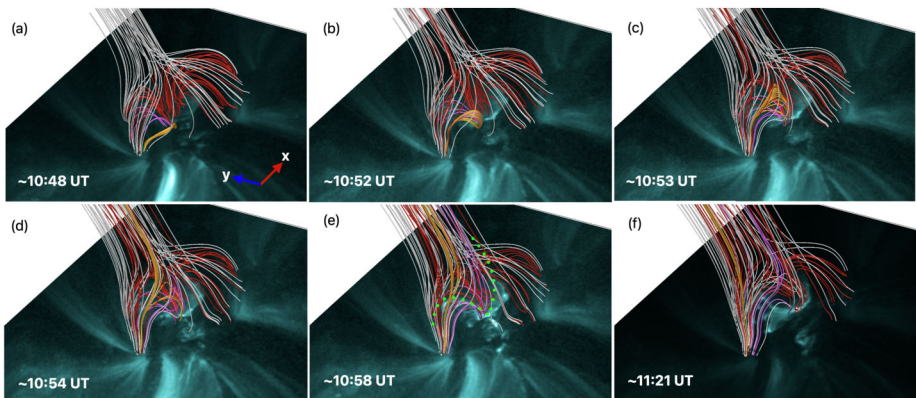


Figure 4 Panels (a)–(f) depict the evolution of magnetic field lines overplotted with 131 Å on the bottom boundary during the whole flaring event. The change in connectivity seen in red-colored field lines indicates toward a reconnection due to null point (panel (b)). Simultaneously, the orange-colored flux rope rises while untwisting itself and reconnect at the null point, shown in panels (b)–(d). The pink-colored sheared arcade also reconnects at the null. The dotted line in panel (e) indicates a curved shape of the field lines that approximately resembles the brightenings seen in the background 131 images.

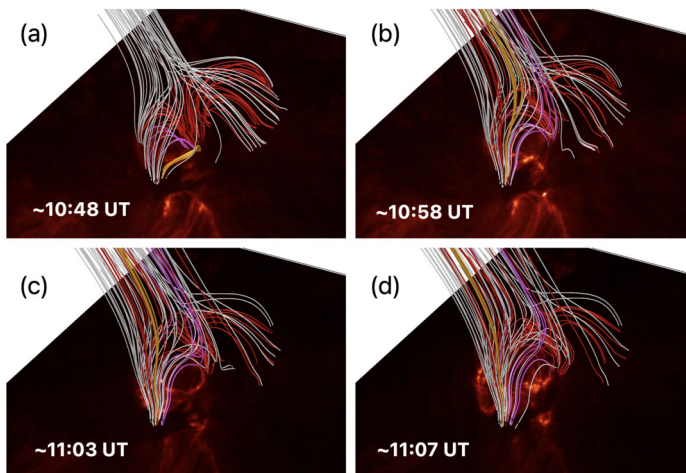


Figure 5 Evolution of the same field lines as in Figure 4 till the peak of the flare $t \approx 11:08$ UT with 304 Å images on the bottom boundary. Notable is the progress of the footpoints of the loops that coincide with the brightening and ribbons seen in 304 channel. These footpoints are considered as the sample field lines to trace the ribbon area later.

the plasma flow. Furthermore, we have seen the formation of a current sheet, as evident from the enhancement in $|J|/|B|$ in Figure 6. The inset in the panel (b) shows an X-shaped geometry of field lines, also marked by a dotted green circle, in the vicinity of the current sheet. As a result, magnetic reconnection is found to initiate there, which may also contribute to the observed flare brightenings in 131 Å.

To further examine the dynamics near the flux rope, in Figure 7, we have plotted the Lorentz force (marked by pink arrows) and the plasma flow (denoted by green arrows) at the initial time and few minutes after that in the vicinity of the rope. The Lorentz force seems

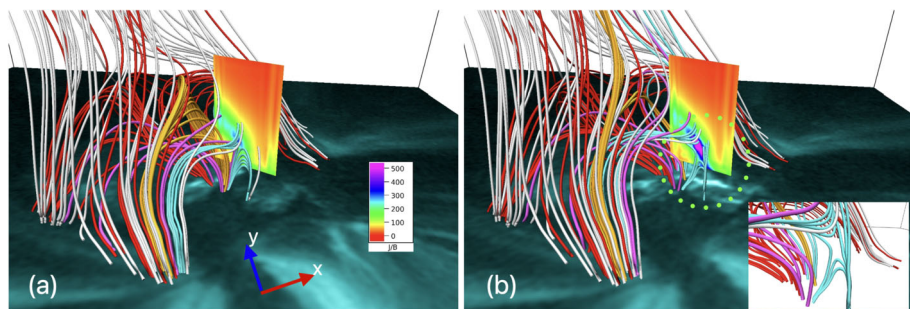


Figure 6 Panels (a) and (b) show the development of $|J||B|$ overlaid with 131 Å images at time $t \approx 10:54$ UT and $\approx 10:56$ UT, respectively. The figure documents the formation of a current sheet beneath the flux rope. The dotted green circle in panel (b) highlights the X-shaped geometry of field lines near the current sheet. The inset in the panel (b) provides its zoomed-in view.

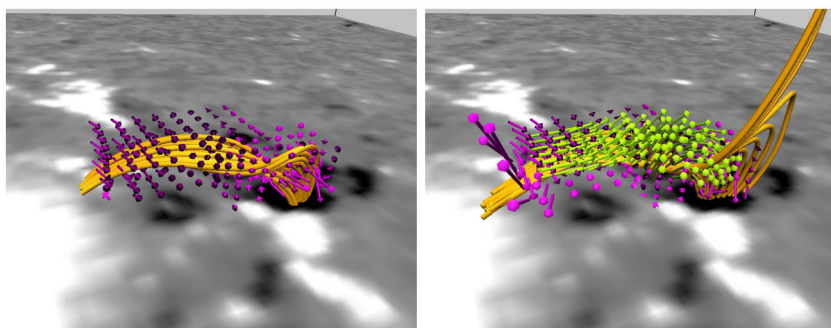


Figure 7 Left panel depicts the Lorentz force streamlines in pink surrounding the flux rope at the initial time, where plasma flow is absent. The grayscale on the background is for the B_z component. The right panel shows an interim state where the eventual development of plasma flow can be seen, plotted in green color. The surrounding Lorentz force helps in unwinding the flux rope first and then the ambient plasma flow adds to the dynamics of the flux rope.

to be initiating the untwisting of the flux rope (left panel), where the plasma flow is absent owing to the initial set-up in the numerical model. The right panel shows a development of plasma flow in the region that governs the dynamics of the rope field lines. Here, the untwisting of the field lines can be attributed to the complementary forcing due to the Lorentz force and the plasma flow. The unwinding of the flux rope is a telltale sign of the contribution toward loss of plasma materials inside it (Wyper, DeVore, and Antiochos 2019; Zhu et al. 2023). Moreover, in the right panel, the rope field lines appear to rise toward the 3D null to reconnect — another contributory factor to the material loss. Interestingly, recent works by Chen et al. (2023a,b) have attributed the outer null point reconnection for deciding the nature of the flare to be eruptive or confined in a breakout type model (Antiochos, DeVore, and Klimchuk 1999; DeVore and Antiochos 2008). According to them, the poloidal flux in a rope may be disrupted due to the null point reconnection occurring above it, and hence destructing its structure too. However, in our case, the inherent $\mathbf{J} \times \mathbf{B}$ and the developed plasma flow facilitate the rise and untwisting of the flux rope, that ultimately lead to the eruption.

5.2. Calculation of Reconnection Flux and Reconnection Flux Rate

5.2.1. Using Qiu et al. (2007)'s Method

To understand the reconnection process through flare ribbon dynamics, we have estimated both accumulated reconnection flux and reconnection flux rate using flare ribbons. For the purpose, we have adapted the method by Qiu et al. (2002, 2007) which quantifies the participation of magnetic fluxes in the flare. Following Equation 1 of Qiu et al. (2007) in the hindsight of the CSHKP model, the reconnection rate is expressed as

$$\frac{\partial \phi_r}{\partial t} = \frac{\partial}{\partial t} \int B_c dS_c = \frac{\partial}{\partial t} \int B_l dS_l, \quad (10)$$

which provides a relationship between the rate of change of the integration of coronal magnetic field (B_c) over the reconnection area S_c to the normal magnetic field component (B_l) in the lower atmosphere passing through the ribbon area (S_l). The algorithm in Qiu et al. (2007) uses the flare ribbons as a proxy to trace the footpoints of the magnetic field lines, reconnecting at higher heights. Then, it remaps those brightened pixels to the HMI magnetogram to extract the +ve (ϕ_r^+) and -ve fluxes (ϕ_r^-). For identifying the ribbon pixels used in the calculation of the reconnection flux and the corresponding rate, the method uses 1600 channel of AIA/SDO and B_z component of the magnetogram from HMI/SDO, shown in Figure 8. At every timestamp, the brightened ribbon pixels are selected when the intensity of the pixel is more than six times the median intensity and this is determined from the averaged 6-minute time cadence maps before the eruption of the event. The threshold corrects for the saturation or projection effects (He et al. 2022). We extracted the ribbons pixels which is shown in panel (a) of Figure 8. They are overlotted on the HMI/SDO magnetogram.

5.2.2. Using Simulated Data

For the calculation of the reconnection flux and reconnection flux rate in the simulation, we have followed the similar steps of Qiu et al. (2007)'s method, which basically rely on the sites involving ribbon pixels. First of all, we have identified the primary reconnection site which in this case is the 3D null point. Then we have traced the footpoints of the field lines of inner spine and fan of the null over the flare ribbons. This choice is based on the understanding that the charged particles accelerated by the reconnection at the null are expected to follow these field lines and, therefore, the corresponding footpoints are anticipated to co-locate with the flare ribbons. Relatively, an observation-based study by Isobe et al. (2002), Noglik, Walsh, and Ireland (2005) has used similar approach to identify the footpoints of reconnecting loops. In this study, they have used cusp-shaped loops in decay phase of a flare observed in Yohkoh Soft X-Ray Telescope, and Transition Region And Coronal Explorer (TRACE) data to extract the footpoints. To demonstrate the chosen field lines, in Figure 9, we have plotted the field lines over the ribbons in 1600 Å channel at the peak time of the flare. We have purposely avoided tracing the field lines with the same seed points during reconnection, as new field lines may reconnect there. During the evolution, we have extracted the footpoints of the sample field lines over each time step of the simulation that is passing through the flare ribbon areas and separated the +ve and -ve magnetic fluxes. As stated earlier in the boundary conditions in Section 4, the B_z component is not evolving throughout the simulation time, however B_x and B_y are changing over each time step. This is important as the connectivity changes each time and is essential for the tracking of ribbon pixels during the simulation. The justification behind the calculations is that the relation in

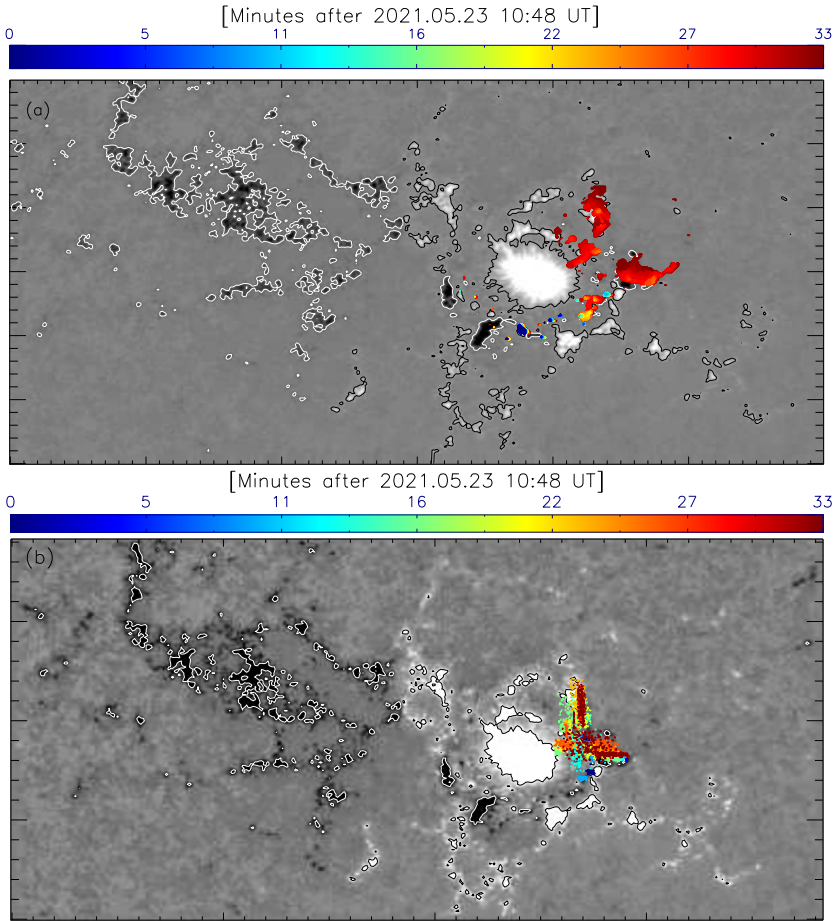


Figure 8 *Panel (a)*: time evolution of flare ribbons plotted over the B_z component of the magnetic field. The *black and white contours* depict the positive and negative polarities respectively. The whole observation duration here corresponds to the whole simulation period. *Panel (b)*: time evolution of ribbon area obtained by tracing the sample field lines from the simulation at certain time steps. Notable is the overall agreement with the time evolution of flare ribbons obtained in *panel (a)*.

Equation 10 is valid for a line-tied boundary condition (Qiu et al. 2007). After extracting the footpoints, we then calculated the reconnection flux, $\phi_{+/-}$ for the corresponding pixels using the following formula:

$$\phi_{+/-} = \sum_{i=1}^N A_i B_{z(+/-)i}, \quad (11)$$

where, N is the total number of pixels, A is the area of the pixel and B_z is the normal magnetic field. We have plotted those footpoints location in the panel (b) of Figure 8. The agreement can be seen near the kernel of the flaring region. Next, in Figure 10 we have plotted the estimated reconnection flux and reconnection flux rates from the observations for the considered simulation period. The dashed box in the bottom panel of Figure 10 highlights

Figure 9 The sample field lines are plotted on the ribbons observed in the 1600 channel. The footpoints of these field lines are traced to calculate the reconnection flux and flux rates.

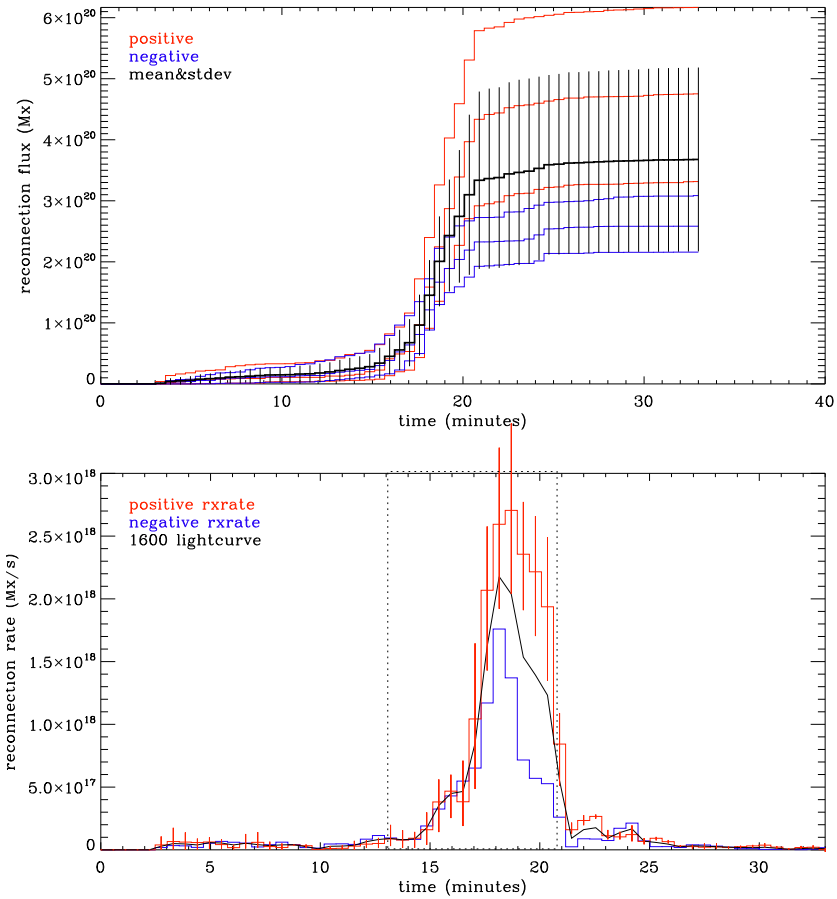
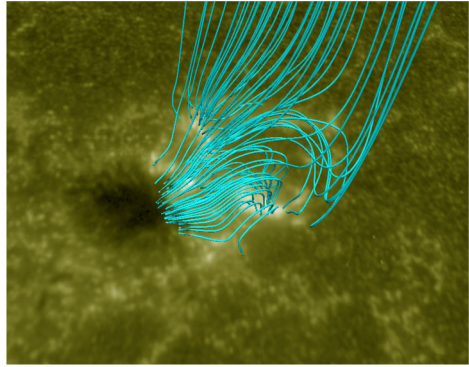
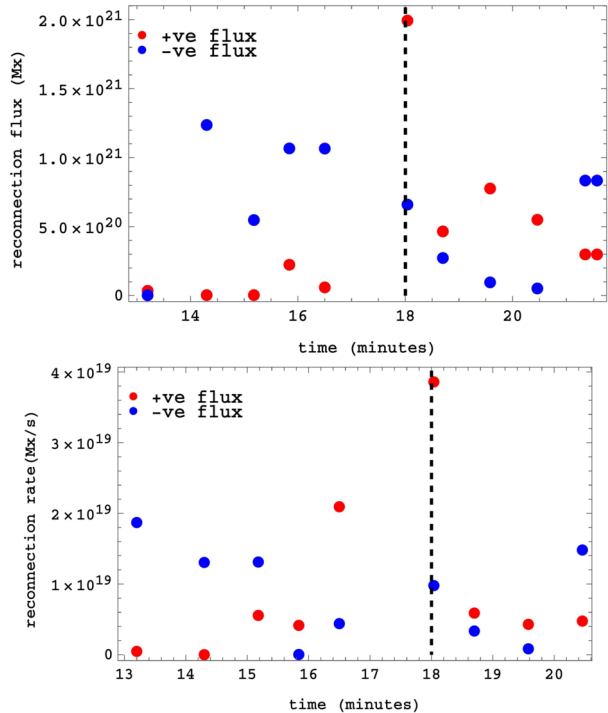


Figure 10 *Top panel:* the reconnection flux during the whole flare time, for both positive and negative polarities passing through the ribbon area which was traced by 1600 channel. *Bottom panel:* the reconnection flux rate derived from the above for both the polarities. The *dashed box* denotes the time window for which the reconnection flux and reconnection flux rates are calculated in the simulation.

Figure 11 The *top and bottom panels* represent the reconnection flux and the reconnection flux rate derived from the simulation within the ribbon area. Noteworthy is the similar pattern in comparison to the observation flux rate however 10 times higher than the observational values. The *dashed line in black color* highlights the peak time of the flare.



the range for the start of impulsive and the decay phases of the flare. We compared some estimations with the simulated ones. The simulated reconnection flux and reconnection flux rates are plotted in Figure 11. In the top panel, we can see the peak of the flux attaining an order of 10^{21} which is one order higher than the observed value. The plot in the bottom panel shows the flux rates, which is also one order higher than the observed rate. The extra one order may be attributed to the higher $\tau_A/\tau_v \approx 2 \times 10^{-4}$ in the simulation. However, in both the panels, the increasing profile of flux and flux rate of +ve pixels is found to be similar to that of observed +ve flux cases, whereas the simulated profile for -ve fluxes has some deviation from the observed one.

5.3. Induced Electric Field Near 3D-Null Reconnection Region

To understand the variation of reconnection electric field as another way to estimate the reconnection rate during the reconnection near the 3D null point, we have calculated the corresponding $|\mathbf{v} \times \mathbf{B}|$ parameter surrounding the null point. We have considered a volume of $25 \times 25 \times 25$ pixels in each direction keeping the null point in the center of this small cube. The left panel of Figure 12 marks the volume of interest. The right panel shows the profile of the $|\mathbf{v} \times \mathbf{B}|$ for the whole simulation time. We find the maximum value of the electric field reached during the flare is $\approx 0.52 \text{ V cm}^{-1}$, which is slightly less than the values obtained by Pudovkin et al. (1998), where they found the values to be $1 - 3 \text{ V cm}^{-1}$ in case of solar flares. Moreover, Kopp and Poletto (1986) have suggested the values of electric field intensity within a concrete flare to be $1 - 1.5 \text{ V cm}^{-1}$ from the velocity of flare ribbons, which provides a sufficiently large voltage along the reconnection line. Further, our estimated value is much lesser than that of Foukal, Miller, and Gilliam (1983) in case of post-flare coronal loops which was found to be 170 V cm^{-1} .

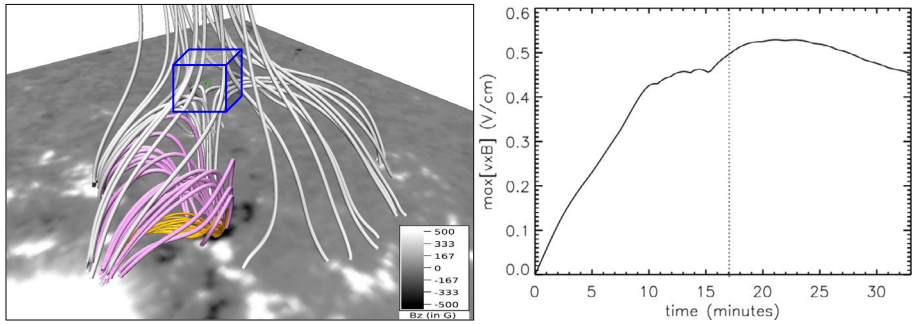


Figure 12 Estimation of $|\mathbf{v} \times \mathbf{B}|$ close to the null location showing the profile of reconnection rate: *blue box* in *left panel* denotes the volume under consideration used for the estimation. The *right panel* shows the temporal variation of $|\mathbf{v} \times \mathbf{B}|$ in that volume. The maximum value reached in this flare is $\approx 0.52 \text{ V cm}^{-1}$.

5.4. Evolution of the Current Density Near the Ribbons

Next, we have investigated the evolution of current density near the flaring region during the simulation. Ribbon areas marked in orange color boxes of the top panel of Figure 13. We have plotted the time profile of the different current components, depicted in the bottom panels, such as the averaged vertical current density (J_z), the horizontal current density (J_{hor}), and the total current density (J) in blue, cyan and orange colors respectively for the flare ribbons locations which correspond to photospheric (left-bottom panel) and near-chromospheric (right-bottom-panel) layers. The dashed line indicates the flare peak time. Interesting is a significant increase in J_z (marked by a shadowed region) during the pre-flare/near-impulsive phase of the flare in both layers. In their study of electric currents within the flare ribbons of AR 11158, Janvier et al. (2014) observed a comparable pattern (as illustrated in Figure 5 of their work) showing an increase in direct current during the impulsive phase of the flare. The only distinction noted was that the upward trend appeared a few minutes earlier in our analysis. This is again in congruent with the pattern in the reconnection flux in Figure 10. The increase in the currents and later decay of them suggest the dissipation of the magnetic energy via reconnection at the null point and its lower spine region. This is again in favor of the formation of the brightened pixels as ribbons.

To further aid the argument of the heating due to the currents, in Figure 14, we have overlaid the distribution of the vertical current density J_z on the ribbons computed from the simulation. The pattern of their distributions on the near-photospheric layer matches reasonably well with that of the ribbons. In their study, Janvier et al. (2016) also compares the traces of the photospheric currents to the evolution of flare ribbons in an eruptive flare and find the similar morphology and evolution there through a magnetofrictional method. Importantly, the high values of currents are found to coincide with the footpoints of the flux rope and the field lines of the 3D null. The topological evolution from Figure 4 and the evolution of J_z near the ribbons in Figure 13 indicate the increase in the non-potentiality first in the sample field lines and then followed by the dissipation with the continuous magnetic reconnection near the null point. These complementary actions of reconnection through the null point and the occurrence of high J_z are the precursors for the formation of ribbons. The flux rope loses its non-potentiality due to Lorentz force and rises as a result of null point reconnection and makes a passage for the plasma materials to escape later.

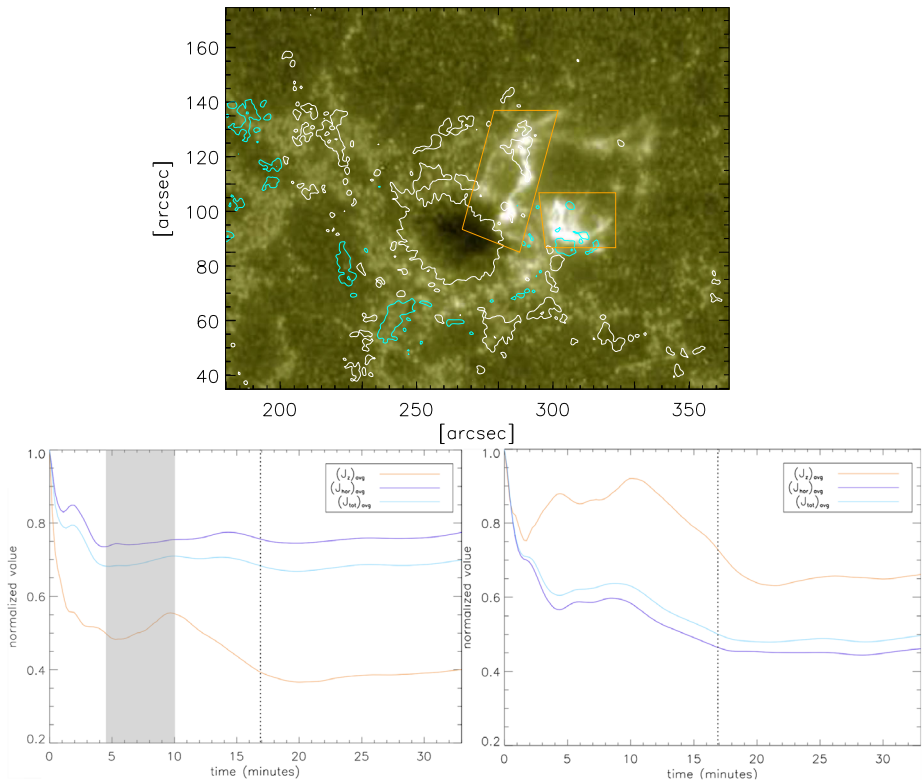
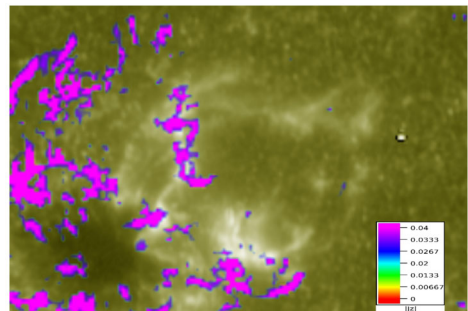


Figure 13 *Top Panel:* selection of ribbon areas for which different components of currents are calculated. The background image is from 1600 channel with $B_z \in (-100, 100)$ G contours on it. Evolution of averaged vertical current density (J_z), the horizontal current density (J_{hor}), and the total current density (J) obtained through simulation for the pixels under the *orange boxes* for the photospheric (*left-bottom panel*) and near-chromospheric (*right-bottom panel*) layers. Notable is the increase in the J_z before the peak of the flare, also marked by the *shadowed region*.

Figure 14 Distribution of J_z overplotted on the ribbons. The background is a snapshot from 1600 channel at peak time of the flare $\approx 11:08$ UT.



6. Summary

In this paper, we have studied the triggering mechanism and subsequent ribbon formation by the underlying magnetic reconnection of an M-class flare in the AR 12824. For this purpose,

we have performed a data-constrained magnetohydrodynamics simulation. We have extrapolated the active region's magnetic field using the non-force-free-field extrapolation model. The active region exhibits a complex magnetic field topology. In the magnetic field extrapolation, we find a magnetic null point and a flux rope near the flaring kernel. Importantly, the interaction of these structures is found to play a crucial role in initiating the eruptive event and provides insights into the onset mechanism. To explore the dynamics of these structures during the flare, we have studied the simulated dynamics and compared them to the contemporary observations.

We analyzed the reconnection scenario leading to the flare onset and its further development, and the effect of reconnection on the flare ribbon dynamics. Null point magnetic topology is found near the flaring region exhibiting a non-parallel ribbon structure which helps in the onset of the reconnection. The reconnection continues there, and due to the high-pressure gradient, the flux rope lying below the null point rises and participates in the reconnection, slightly mimicking a jet-type eruption. Eventually, a current sheet is also formed below the flux rope and a further X-type reconnection is followed there aiding to the brightenings near the flaring region. The footpoint imprints obtained from the simulation are catching up with the flare ribbons deduced from the observations. The estimation of reconnection flux and flux rates from the MHD simulation follows a similar pattern to that of observations, however, differ one order quantitatively when compared to the observationally computed values. We have calculated the flare-induced electric field surrounding the null point in the corona and found the maximum value reaching 0.52 V cm^{-1} during the peak of the flare which is slightly low compared to many earlier works. Lastly, the current enhancement in the flare ribbons during the impulsive phase of flare indicates the successive reconnections and formation of flare ribbons due to the bombardment of charged particles from the upper reconnection site.

Summarily, the work with data-constrained MHD simulation in tandem with observations presents the onset mechanism of a complex flare triggered by magnetic reconnection, analysis of the flare ribbon dynamics, and the driver for the ribbon formation in a complicated magnetic field configuration. Apart from the topological evolution, the simulation captures the flare ribbon dynamics which is well compared with the observations. Albeit the boundary conditions in the simulation model, the work succeeds in not only explaining the complex magnetic drivers for the flare and corresponding ribbons but also puts forward a scenario not seemingly following the standard flare model. However, the limits of simulation are to deliver a more realistic evolution of the fluxes, their role in driving the flare and particularly ribbons, the development of non-potentiality surrounding the flaring region and its impact on the eruption process, and the formation of flux rope in a complex magnetic region which are still unclear. In this direction, a future attempt will focus on improving the boundary condition for the studies of flare ribbon dynamics.

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Author Contributions S.S.N. and Q.H. constructed the goal of the work. S.S.N. carried out data acquisition, prepared plots, performed simulation, and wrote the main draft of the paper. W.H. helped in preparing Figure 6 and 8. Q.H. and W.H. contributed to the overall discussion of the work. S.K., and R.B. contributed to the interpretation of the simulation results. All the authors did a careful proofreading of the draft.

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Data Availability The data that support the findings of this study are available from the corresponding author upon request.

Declarations

Competing Interests The authors declare no competing interests.

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