A Magnetohydrodynamic Simulation of Magnetic Null-point Reconnections in NOAA AR 12192, Initiated with an Extrapolated Non-force-Free Field

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Abstract

The magnetohydrodynamics of the solar corona is simulated numerically. The simulation is initialized with an extrapolated non-force-free magnetic field using the vector magnetogram of the active region NOAA 12192, which was obtained from the solar photosphere. Particularly, we focus on the magnetic reconnections (MRs) occurring close to a magnetic null point that resulted in the appearance of circular chromospheric flare ribbons on October 24 around 21:21 UT, after the peak of an X3.1 flare. The extrapolated field lines show the presence of the three-dimensional (3D) null near one of the polarity-inversion lines—where the flare was observed. In the subsequent numerical simulation, we find MRs occurring near the null point, where the magnetic field lines from the fan plane of the 3D null form a X-type configuration with underlying arcade field lines. The footpoints of the dome-shaped field lines, inherent to the 3D null, show high gradients of the squashing factor. We find slipping reconnections at these quasi-separatrix layers, which are co-located with the post-flare circular brightening observed at chromospheric heights. This demonstrates the viability of the initial non-force-free field, along with the dynamics it initiates. Moreover, the initial field and its simulated evolution are found to be devoid of any flux rope, which is congruent with the confined nature of the flare.

Key words: magnetohydrodynamics (MHD) – Sun: activity – Sun: corona – Sun: flares – Sun: magnetic fields – Sun: photosphere

Supporting material: animations

1. Introduction

The solar corona can be treated as a magnetized plasma with large electrical conductivity, its evolution being determined by the magnetohydrodynamic (MHD) equations (Priest 2014). The magnetic Reynolds number $R_M(vL/\eta)$, in usual notations) for the corona is of the order of $10^{10}$ (Aschwanden 2004), which makes Alfven’s theory of flux-freezing valid and ensures plasma-parcels remain tied to magnetic field lines (MFLs) during evolution (Alfvén 1942). The eruptive events (flare, coronal mass ejections (CMEs)) occurring at the corona are thought to be signatures of magnetic reconnection (MR), a process involving the topological rearrangement of MFLs with the conversion of magnetic energy into heat and kinetic energy of mass motion (Shibata & Magara 2011). Notably, the requirement to onset MRs is small $R_M$, which corresponds to small $L$, the length over which the magnetic field varies. The smallness of $L$ can either be pre-existing in a magnetic topology—manifested as magnetic nulls and quasi-separatrix layers (QSLs)—or can develop autonomously during the evolution of the magnetofoil. Such autonomous developments (owing to discontinuities in magnetic field) are expected from Parker’s magnetostatic theorem (Parker 1972, 1988, 1994), which states that for a perfect electrically conducting plasma, the conditions of flux-freezing and the equilibrium cannot be satisfied simultaneously by a magnetic field that is continuous everywhere. The reduction of $L$ and the consequent spontaneous MRs during a quasi-static evolution of the plasma under a near-precise maintenance of the flux-freezing have been identified in contemporary MHD simulations (Kumar et al. 2015a, 2016; Kumar & Bhattacharyya 2016). However, these studies were performed using idealized scenarios of initial bipolar magnetic fields that lacked the complexities often observed in solar active regions (ARs).

Presently, the coronal field needs to be extrapolated from the photospheric magnetic field because of a lack of direct measurements. For extrapolation, the use of the non-linear-force-free-fields (NLFFFs), a subset of force-free-fields (Wiegelmann 2008; Wiegellmann & Sakurai 2012), is customary. The NLFFF can be solved analytically (in spherical polar coordinates) under the assumption of axisymmetry (Low & Lou 1990; Prasad et al. 2014), but the analytical solution fails to effectively capture the complexity of an AR magnetogram, which is often non-axisymmetric. Such complexities are well replicated in NLFFF extrapolations (Duan et al. 2017). Recent MHD simulations based on NLFFF extrapolations were successful in simulating the coronal dynamics leading to eruptions (Jiang et al. 2013; Kliem et al. 2013; Amari et al. 2014; Inoue et al. 2014, 2015; Savcheva et al. 2015, 2016; Inoue 2016). Importantly, only the region sandwiched between the photosphere and the upper corona is relatively force-free, whereas at the photosphere—where magnetograms are obtained—the Lorentz force is non-zero (Gary 2001). Generally, to mitigate this problem within the framework of NLFFF, a technique called “preprocessing” is often performed on the photospheric data, which minimizes the Lorentz force in the vector magnetograms and provides a boundary condition suitable for NLFFF extrapolations (Wiegelmann et al. 2006; Jiang & Feng 2014).

An alternative is the extrapolation using non-force-free-fields (NFFFs) described by the double-curl Beltrami equation for the magnetic field $B$ (Hu & Dasgupta 2008). The equation has been analytically solved for an idealized corona
force, instead of prescribed flows (Amari et al. 2003; Aulanier et al. 2010), is envisaged here to initiate dynamics.

The paper is organized as follows. Section 2 discusses the flare event and the observations required for the NFFF extrapolation. In Section 3, we present the details of the initial extrapolated field. The MHD model is discussed in Section 4. The results of the simulation are presented in Section 5 and Section 6 summarizes important results.

2. Discussion of the X3.1 Flare Event

The AR 12192 was the largest of all the ARs that appeared in solar cycle 24, which produced a series of X-class flares (Chen et al. 2015). The X3.1 flare on 2014 October 24 around 21:15 UT was the strongest in a series that did not lead to any CME (Sun et al. 2015; Sarkar & Srivastava 2018). Since there is a very strong correlation between flare intensity and occurrence of CMEs (Yashiro et al. 2005), this event has been extensively studied. An absence of flux rope was suggested in Jiang et al. (2016) to explain the confined nature, whereas the onset of the flare was attributed to tether-cutting (TC) MRs (Moore et al. 2001) between sheared arcades. Further studies of successive strong X-class flares triggered by TC reconnections, in the same AR, were also reported in Chen et al. (2015). Contrarily, using NLFFF extrapolation, Inoue et al. (2016) found a multiple-flux-tube system located near a polarity-inversion line (PIL) to be favorable for the TC reconnections. They attributed the stability of the flux-tube-system to the overlying strong tethering MFLs. Similar results were also documented in Chen et al. (2015), where the mean decay index of the horizontal background field was found to be less than the typical threshold required for the torus instability (Kliem & Török 2006) to set in. An alternative explanation was provided by Zhang et al. (2017), who attributed the confined nature to the complexity of the involved magnetic field structures.

The confined X3.1 flare was of long duration, lasting for 6–7 hr, as shown in Figure 1(a). The figure shows the GOES 15 X-ray flux observed during this event in the 1–8 Å and 0.5–4 Å channels. It should be noted that no appreciable change in the vertical magnetic field flux was recorded during this period at the photospheric boundary. This is shown in Figure 1(b), which depicts the evolution of negative (dashed red line) and positive magnetic fluxes (continuous blue line), calculated using the photospheric vector magnetograms from the Heliospheric Magnetic Imager (HMI; Schou et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012). The magnetograms are taken from the “hmi.sharp_cea_720s data series” that provides full-disk vector magnetograms of the Sun with a temporal cadence of 12 minutes and a spatial resolution of 0.5′. In order to obtain the magnetic field on a Cartesian grid, the magnetogram is initially remapped onto a Lambert cylindrical equal-area (CEA) projection and then transformed into heliographic coordinates (Gary & Hagyard 1990). The dotted vertical lines mark the beginning and peak phases of the flare. Hence, to a good approximation, the vertical magnetic field \( B_z \) at the bottom boundary remains constant during the interval. Accordingly, the photosphere can be approximated to be line-tied—a boundary condition used in the simulation discussed later in the paper.

Importantly, a circular brightening was observed in the chromospheric flare ribbons at the ultraviolet (UV)
1600 Å channel, preceded by a brightening of the flaring loops in the extreme-ultraviolet (EUV) channel 131 Å of the Atmospheric Imaging Assembly (AIA) on board SDO (Lemen et al. 2012). The brightenings occur in the interval 21:20 to 21:35 UT in the 1600 Å channel (Figure 2(a)) and are co-located with the brightening in the 131 Å channel, as seen around 20:58 UT, which is just before the X-class flare. The circular flare ribbons are known to map MFLs constituting the fan plane of a 3D null on the photosphere (Masson et al. 2009).

To our knowledge, the generation of the circular ribbon was not reported in earlier works and is the main focus of the paper.

To simulate the evolutions of such MFLs, we select the vector magnetogram at 20:46 UT, roughly 30 minutes prior to the flare. Figure 3(a) shows the magnetogram of the AR where the positive and the negative polarities of the longitudinal component of the magnetic field are depicted in white and black, and the gray represents the background. The transverse components of the positive and negative fields are shown by blue and red arrows, respectively. The PIL is represented in the figure by green lines. The AR is visibly complex, with two main polarities and multiple small-scale features. The MFL topology can be inferred using the EUV channel data as observed at 171 Å, shown in Figure 3(b), which is plotted on the same CEA spatial grid as in Figure 3(a). The EUV coronal loops near the PIL are markedly sheared and twisted, indicating a high degree of complexity in the initial magnetic field topology.

3. Non-force-free Extrapolation of Magnetic Field

3.1. Description of the Numerical Extrapolation Algorithm

The coronal magnetic field of the AR 12192 is obtained using the numerical non-force-free extrapolation code developed by Hu & Dasgupta (2008) and Hu et al. (2008, 2010), where $B$ is constructed as

$$B = B_1 + B_2 + B_3; \quad \nabla \times B_i = \alpha_i B_i, \quad (1)$$

with $\alpha_i$ being constant and $i = 1–3$, rendering each sub-field $B_i$ to be LFFF and $\alpha_1 \neq \alpha_2 \neq \alpha_3$. Furthermore, without loss of generality, $\alpha_2 = 0$ is selected to make $B_2$ potential. Subsequently, an optimal pair $\alpha = \{\alpha_1, \alpha_3\}$ is obtained by an iterative trial-and-error method that finds the pair that
minimizes the average deviation between the observed \( (B_t) \) and the calculated \( (b_t) \) transverse field, as indicated by the following metric:

\[
E_n = \frac{1}{M} \left( \sum_{i=1}^{M} |B_{t,i} - b_{t,i}| \times |B_{t,i}| \right) / \left( \sum_{i=1}^{M} |B_{t,i}|^2 \right),
\]

where \( M = N^2 \), represents the total number of grid points on the transverse plane. Here, the grid points are weighted with respect to the strength of the observed transverse field; see Hu & Dasgupta (2008) and Hu et al. (2010) for further details.

3.2. Initial Extrapolated NFFF for AR 12192

We consider the magnetogram on October 24, 20:46 UT obtained from SDO/HMI. The vector field shown in Figure 3(a) corresponds to an original cutout with the dimensions 1024 \( \times \) 512 pixels. To reduce the computation cost, the field is rescaled and extrapolated over a computational domain with 256 \( \times \) 128 \( \times \) 128 grids in the x, y, and z directions. The corresponding physical extents are 360 Mm in the x direction and 180 Mm in the y and z directions. The best-fit values obtained for the \( \alpha \) parameters in this case are \( \alpha = \{0.1145, -0.0016\} \), which corresponds to an \( E_n = 0.31 \) (c.f. Equation (2)).

The contour plots for the transverse components of the observed and extrapolated fields at the photospheric boundary are shown in Figure 4. The figure indicates most of the large-scale magnetic features to be well-captured by the extrapolated field. The scatter plot of the observed and the extrapolated fields is shown in Figure 5. With the perfect correlation—exact agreement of the extrapolated field with the observed one—being marked by the red line, the plot shows the agreement to be better on the higher field side. The Pearson-r correlation between the two fields is 0.933, which is acceptable.

The top and side views of MFLs over the full vector magnetogram are shown in Figure 6; the field lines are printed in red. A smaller set of MFLs in the vicinity of the flaring region (around 21:15 UT) is shown in white. The white MFLs resemble the topology of a 3D magnetic null (Lau & Finn 1990) and are shown in greater detail in Figure 7. The similarity of the MFL morphology of the extrapolated field (panel (b) of Figure 6) with the observed EUV structure (panel (b) of Figure 3) indicates the effectiveness of the extrapolation. The MFL geometry is characterized by the presence of high- and low-lying loops.
Figure 4. Contour plots of the transverse field of the observed (panel a) and extrapolated (panel b) magnetic field shown at the photospheric boundary.

Figure 5. Scatter plot showing the correlation between the observed and extrapolated magnetic field. The red line is the expected profile for perfect correlation.
Notably, the low-lying MFLs, depicted in white, connecting the weak positive polarity with the surrounding negative polarity regions, generate the 3D null. Figure 7(a) shows the 3D null, complete, with a dome-shaped fan and an elongated spine. Panel (b) of Figure 7 depicts MFLs on a stack of planes that are approximately tangential to the spine. The MFLs are overlaid, with an isosurface in red of $|B|$ having an iso-value that is 2.5% of its maximum (magnified in the inset). The isosurface contains the 3D null. The height of the null point is roughly 3 Mm from the photospheric plane. Notably, the MFLs constituting the dome intersect the bottom boundary and generate footpoints that are distributed in a circular pattern. The MFLs below the null point form an elongated arcade, as seen in the inset of Figure 7.

Direct volume renderings of volume current density $|J|$ and Lorentz force $|L|$ are depicted in Figure 8. Noticeably, the regions of large Lorentz force and high current overlap with those of high values of $|B|$, which can be realized by a direct comparison with Figure 6(b). The values for $|J|$ and $|L|$ are mentioned in arbitrary units, as we are mostly interested in their variation with height. The figure reveals a sharp decay of the Lorentz force with height (by a factor of $1/5000$), while the current shows a decay by only a factor of $1/100$. The current thus becomes more and more field-aligned with increasing height, ultimately making the magnetic field force-free in the asymptotic limit.
4. Numerical Model

The evolution is governed by the incompressible Navier–Stokes MHD equations under the assumption of thermal homogeneity and perfect electrical conductivity (Bhattacharyya et al. 2010; Kumar et al. 2014, 2015b):

\[
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla p + (\nabla \times \mathbf{B}) \times \mathbf{B} + \frac{\tau_v}{\tau_p} \nabla^2 \mathbf{v}, \quad (3a)
\]

\[
\nabla \cdot \mathbf{v} = 0, \quad (3b)
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}), \quad (3c)
\]

\[
\nabla \cdot \mathbf{B} = 0, \quad (3d)
\]

written in the usual notations in dimensionless form. The normalizations for various terms in Equation (3) are as follows:

\[
\mathbf{B} \rightarrow \frac{\mathbf{B}}{B_0}, \quad \mathbf{v} \rightarrow \frac{\mathbf{v}}{v_{\alpha}}, \quad L \rightarrow \frac{L}{L_0}, \quad t \rightarrow \frac{t}{\tau_{\alpha}}, \quad p \rightarrow \frac{p}{\rho_0 c^2}. \quad (4)
\]
The constants $B_0$ and $L_0$ are fixed using the average magnetic field strength and length scale of the vector magnetogram, respectively. Here, $v_B \equiv B_0 / \sqrt{4\pi \rho_0}$ is the Alfvén speed and $\rho_0$ is the constant mass density. The constants $\tau_a$ and $\tau_v$, having dimensions of time, represent the Alfvén transit time ($\tau_a = L_0 / v_B$) and viscous diffusion timescale ($\tau_v = L_0^2 / \nu$), respectively. The kinematic viscosity is denoted by $\nu$. The ratio $\tau_a / \tau_v$ represents an effective viscosity of the system which, along with the other forces, influences the dynamics.

To solve the MHD Equations 3(a)–(d), we utilize the well-established magnetohydrodynamic numerical model EULAG-MHD (Smolarkiewicz & Charbonneau 2013), which is an extension of the hydrodynamic model EULAG that predominantly used in atmospheric and climate research (Prusa et al. 2008). The pressure perturbation, denoted by $p$, for a thermodynamically uniform ambient state, satisfies an elliptic boundary value problem, which is generated by imposing the discretized incompressibility constraint (Equation 3(b)) on the discrete integral form of the momentum equation (Equation 3(a)); cf. (Bhattacharyya et al. 2010) and the references therein. An identical procedure involving the gradient of an auxiliary potential in the induction equation (Equation 3(c)) is employed to keep $B$ solenoidal; see Ghizaru et al. (2010) and Smolarkiewicz & Charbonneau (2013) for details. For completeness, here we mention only the important features of EULAG-MHD and refer readers to Smolarkiewicz & Charbonneau (2013) and references therein for further details. The model is based on the spatio-temporally second-order accurate, non-oscillatory, forward-in-time multidimensional positive definite advection transport algorithm, MPDATA (Smolarkiewicz 2006). Note the proven dissipative property of the MPDATA, which, intermittently and adaptively, regularizes the under-resolved scales by simulating MRs and mimicking the action of explicit subgrid-scale turbulence models (Margolin et al. 2006) in the spirit of implicit large eddy simulations (ILES; Grinstein et al. 2007). Such ILESs performed with the model have already been successfully utilized to simulate MRs to understand their role in the development of various magnetic structures in the solar corona (Kumar et al. 2015a, 2016; Prasad et al. 2017). The simulations presented continue to rely on the effectiveness of ILES to regularize the onset of MRs.

Figure 8. Spatial distribution of volume current density (panel a) and Lorentz force (panel b) in arbitrary units. Notably, appreciable current is present throughout the volume, while most of the force is present only near the bottom boundary, which sharply falls to zero with an increase in height.

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5. Simulation Results and Discussions

The simulations are initialized from a motionless state, with the initial magnetic field given by the NFFF extrapolation and the magnetofluid idealized to be thermally homogeneous and having perfect electrical conductivity. The flow is generated as the initial Lorentz force pushes the plasma. To ensure the net magnetic flux is zero in the computational domain, all components of volume $B$ except for $B_z$ are continued to the boundaries for a given time-step (Kumar et al. 2015a). At the bottom boundary, $B_z$ is kept

Figure 9. Side view of the evolutions of four sets of magnetic field lines close to the location of the 3D null, shown at $t = 0, 200, 400, 600, 800, \text{ and } 1000$ in panels (a)–(f), respectively. The bottom boundary in all the panels represents the strength $B_z$ on the photospheric plane, similar to Figure 6 but now in grayscale for clarity. (An animation of this figure is available.)
constant (line-tied boundary) because the change of magnetic flux at the boundary is minimal (see Figure 1(b)). For the simulation, we set the dimensionless constant $\tau_a/\tau_v \approx 7 \times 10^{-3}$, which is roughly two orders of magnitude larger than its coronal value. The higher value of $\tau_a/\tau_v$ speeds up the relaxation because of a more efficient viscous dissipation, but without affecting magnetic topologies. The density is set to $\rho_0 = 1$ and kinematic viscosity is set to $\nu = 0.002$, in scaled units. The spatial unit step

Figure 10. Front view of the evolution of the magnetic field lines previously shown in Figure 9. In addition, we have shown the evolution of isosurfaces of the decay index close to the critical value of 1.5 to explain the halt in the rise of the field lines. (An animation of this figure is available.)
$\Delta x = 0.0078$, while the time-step is taken as $\Delta t = 5 \times 10^{-3}$ to satisfy the Courant–Friedrichs–Lewy (CFL) stability condition (Courant et al. 1967). The results presented here pertain to a run for 1000 $\Delta t$, which roughly corresponds to an observation time of 1.5 hr. Due to the constant mass density, the flow generated in the computation is incompressible, an assumption also used in earlier works (Dahlburg et al. 1991; Aulanier et al. 2005). Although the compressibility of the fluid is important for the thermodynamics

Figure 11. Panels (a)–(f), spanning $t = 0, 80, 160, 240, 320,$ and 400, illustrate rotation of the dome structure of the field lines constituting the 3D null. The cuboidal rake in the figure shows the volume where the seed points are chosen. The field lines are color-coded with respect to their distance in the $y$ direction. This helps us to visualize the rotation of the field lines.

(An animation of this figure is available.)
of coronal loops (Ruderman & Roberts 2002), our focus for the present is on their magnetic topology only. Notably, the $R_M$ throughout the simulation is infinity, except during MRs facilitated by the MPDATA-driven dissipation.

Figures 9 and 10 depict MFL evolution in the neighborhood of the 3D null at two different viewing angles. The $B_z$ contours are plotted on the bottom boundary. Four sets of MFLs are highlighted. The fan and the spine of the null are made by the yellow MFLs, whereas the red MFLs are overlying the null. The blue MFLs are located inside the dome, whereas the arcade below the null is formed by the green MFLs. With evolution, the null and the constituent yellow MFLs do not sustain an

**Figure 12.** Panels (a)–(f), spanning $t = 0, 200, 400, 600, 800, \text{ and } 1000$, illustrate the evolutions of magnetic field lines (yellow), velocity fields (green), and $|J|/|B|$. (An animation of this figure is available.)
appreciable ascent, whereas the red MFLs expand significantly to a threshold height ($\approx 78$ Mm), after which they contract. To explore the underlying physics, we note that the arcade MFLs (in green) and the dome (yellow) constitute an X-type geometry cf. panel (b) of Figure 7. As reconnection occurs at the X-type null, blue MFLs come out of the dome and overlay it. The consequent increase in local magnetic pressure pushes the red MFLs upward, resulting in their overall rise. Furthermore, the red MFLs get stretched as they rise, and at a certain threshold they generate enough magnetic tension to stop additional

Figure 13. Panels (a)–(f), spanning $t = 0, 200, 400, 600, 800, \text{ and } 1000$, illustrate the slipping reconnections in the MFLs (shown in yellow) spanning the dome of the 3D null. The streamlines of the flow are shown in green. The bottom boundary shows contours of high values of log $Q$.

(An animation of this figure is available.)
upward motion. The threshold corresponds to a critical value of $\approx 1.5$ for the decay index, where the decay index is defined as $n = -\frac{\partial (\log |B|)}{\partial (\log z)}$ (Kliem & Török 2006). Figure 10 confirms, in their maximal rises, that the MFLs can only attain $n \approx 1.3-1.4$, which is in conformity with the confined nature of the X3.1 flare. Moreover, like Jiang et al. (2016), we also fail to identify a flux rope, which further confirms the confined nature of the flare.

The simulated 3D null appears to rotate with evolution (Figure 11). To aid with visualization, the MFLs have been color-coded based on their distance along the y axis. We have also shown the volume wherein the seed points of MFLs are located. When viewed from the top, an anti-clockwise rotation of the MFLs is quite prominent, which matches very well with the similar dynamics seen in the AIA 131 Å channel. This correspondence with observations gives more credibility to the simulation. Figure 12 is also overlaid with streamlines (green) and $|J|/|B|$. Note the initial high value of $|J|/|B|$ near the null. The value increases with time, becoming maximum at $t = 400$, then subsequently decaying. The peaking of $|J|/|B|$ is indicative of MRs occurring near the null. The resultant outflow is shown by the red streamlines. For further investigation, Figure 13 plots the $Q$-map where the squashing factor $Q$ is calculated by following Demoulin et al. (1996) and Liu et al. (2016), and ascertains the dome to have a high gradient of magnetic connectivity, which results in slipping.
reconnections (Aulanier et al. 2007). The subsequent change in magnetic connectivity manifests as the seeming MFL rotation. For validation, we note that the co-located flow (in green) is not along the rotation and hence cannot cause it.

In panels (a) and (b) of Figure 14, we overlay intensity structures in wavelengths 1600 Å at 21:25 UT and 131 Å at 20:50 UT, with corresponding MFLs. The almost exact match of the footpoints with brightenings, for both wavelengths, not only establishes the importance of the 3D null in the circular flare ribbon but also is in agreement with the contemporary understanding of this phenomenon, and thus validates the effectiveness of the NFFF extrapolation for constructing a valid coronal field model.

6. Summary and Conclusions

This paper presents simulated dynamics of AR 12192 from 20:48 UT. The plasma is idealized to have perfect electrical conductivity while being viscous, thermally homogeneous, and incompressible. The simulations are initialized with MFLs extrapolated from SDO/HMI vector magnetograms using a new technique that employs a model where the corona is not strictly force-free and has some Lorentz force. Nevertheless, the Lorentz force decreases rapidly with height, making the corona force-free in an asymptotic limit—agreeing with the standard scenario for a coronal field. Advantageously, this non-force-free field extrapolation model self-consistently initializes the coronal dynamics without requiring prescribed plasma flows, which are somewhat custom-made.

The extrapolated magnetic field is found to have a 3D null located approximately at a height of 3 Mm from the photosphere and has a clearly distinguishable spine and a dome-shaped fan. Importantly, a magnetic arcade is found to be located within the dome and makes an X-type null with it. A Q-map of the initial field identifies the dome as having a region where the gradient of the field line connectivity is large.

The simulation focuses on a circular brightening recorded in the 1600 Å channel at around 21:21 UT. The absence of any flux emergence in the window of 19:00 UT—24:00 UT allows the vertical field at the bottom boundary to be assumed as line-tied. To optimize the computation cost, the simulation is performed on 256 × 128 × 128 grids along the x, y, and z, respectively, resolving a physical domain of 360 × 180 × 180 Mm³. It is initiated not by a prescribed flow, but by the initial Lorentz force, which initiates the evolution autonomously. Subsequently, favorable forces bring non-parallel field lines in close proximity of the 3D null, which ultimately leads to unresolved scales. In the spirit of ILES, MPDATA then generates locally adaptive residual dissipation to regularize the under-resolved scales with simulated MRs. Furthermore, the MRs are found to be consistent with the idea of slipping reconnection, standard at a 3D null, and imparts a sense of rotation to the footpoints of the dome. Such a rotation is also observed in 131 Å channel, corroborating the observed circular brightening to be caused by MRs at the 3D null.

MRs also occur at the X-type null formed by the MFLs belonging to the arcade and the spine. Interestingly, reconnections enable MFLs contained within the dome to come out of it and overlay the spine. The consequent increase in magnetic pressure raises the overlying MFLs further up, and in principle, could cause the X3.1 flare observed at 21:15 UT. The flare was confined in nature and resulted in no CMEs. In the simulation, the MFLs are found to never reach a height where the decay index becomes more than the critical value required for the torus instability to set in, further confirming the efficacy of the simulation at replicating the observation.

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