Magnetohydrodynamic Modeling of a Solar Eruption Associated with an X9.3 Flare Observed in the Active Region 12673

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Abstract

On 2017 September 6, the solar active region 12673 produced an X9.3 flare, regarded to be the largest to have occurred in solar cycle 24. In this work we have performed a magnetohydrodynamic (MHD) simulation in order to reveal the three-dimensional (3D) dynamics of the magnetic fields associated with the X9.3 solar flare. We first performed an extrapolation of the 3D magnetic field based on the observed photospheric magnetic field prior to the flare and then used this as the initial condition for the MHD simulation, which revealed a dramatic eruption. In particular, we found that a large coherent flux rope composed of highly twisted magnetic field lines formed during the eruption. A series of small flux loops were found to lie along a magnetic polarity inversion line prior to the flare. Reconnection occurring between each flux loop during the early stages of the eruption formed the large, highly twisted flux rope. Furthermore, we observed a writhing motion of the erupting flux rope. Understanding these dynamics is important in the drive to increase the accuracy of space weather forecasting. We report on the detailed dynamics of the 3D eruptive flux rope and discuss the possible mechanisms of the writhing motion.

Key words: magnetohydrodynamics (MHD) – Sun: coronal mass ejections (CMEs) – Sun: flares – Sun: magnetic fields

Supporting material: animations

1. Introduction

Highly energetic phenomena observed in the solar corona are mainly driven by coronal magnetic fields (Priest & Forbes 2002). These magnetic fields are distorted by the plasma flows associated with photospheric motions, e.g., the shear motion and converging motion (van Ballegooijen & Martens 1989; Amari et al. 2003; Park et al. 2013, 2018; Woods et al. 2018). The magnetic fields are largely deformed from their potential state, resulting in the accumulation of free magnetic energy which is eventually released (e.g., Aulanier 2014). This energy release is often observed in the form of solar flares, resulting in the heating of plasma and acceleration of particles (Janvier et al. 2015; Benz 2017). Eruptive magnetic fields and the accompanying plasma sometimes grow into coronal mass ejections (CMEs; Schmieder et al. 2015; Kilpua et al. 2017) which sometimes propagate through interplanetary space and interact with the Earth’s magnetosphere, resulting on occasions in large disturbances to the electromagnetic environment of near-Earth space.

The magnetic flux rope (MFR), which is a bundle of helically twisted magnetic field lines that carry the current density, is a key structure in considering these solar eruptions. This is because the MFR is believed to be one of the possible pre-eruptive configurations which is destabilized at the initiation of the eruption and becomes part of the core of a CME (Forbes 2000; Chen 2017). However, the origin and dynamics of MFRs are not fully understood. For instance, there is large gap between the estimation of the magnetic twist observed in the lower corona and interplanetary space (e.g., Wang et al. 2017). Several simulations, e.g., Gibson & Fan (2006) and Syntelis et al. (2017), suggest that the twist accumulation would be possible during an eruption through a tether-cutting reconnection (Moore et al. 2001). Furthermore, eruptive MFRs sometimes show rotation and deflection (Kay et al. 2017). These are key properties in determining the direction of the magnetic field observed in vicinity of the Earth, which is important for space weather forecasts. Although the writhing motion contributing to the rotation of the MFR is sometimes observed in the lower corona (e.g., Romano et al. 2003; Williams et al. 2005; Török et al. 2010; Kliem et al. 2012; Yan et al. 2014), quantitative analysis is difficult because no information about the 3D coronal magnetic field is available, which prevents us from fully understanding the dynamics of MFRs. Recently, data-constrained and data-driven magnetohydrodynamic (MHD) simulations have been rigorously performed (e.g., Inoue et al. 2015; Jiang et al. 2016; Muhamad et al. 2017; Amari et al. 2018; Prasad et al. 2018). Because these simulations clarify the 3D dynamics of the magnetic field bounded by the observed photospheric magnetic field, they have the potential to bring about more quantitative interpretations.

In this study, in order to clarify the dynamics of eruptive MFRs, we perform a data-constrained MHD simulation of a solar eruption. In 2017 September, the solar active region (AR) 12673 (e.g., Yang et al. 2017; Yan et al. 2018) rapidly grew over the course of a few days. The AR became very active from September 4, and produced many M- and C-class flares over two days, eventually resulting in the production of an X2.2 flare at 08:57 UT on September 6. Approximately three hours later, at 11:53 UT, an X9.3 flare was observed which was recorded as the largest flare of solar cycle 24. Since this flare is associated with a geo-effective CME, it represents a good opportunity to investigate the dynamics of the geo-effective solar MFR. The data available for this AR are rich;
nevertheless, it is hard to determine the 3D magnetic structure as current observations do not allow direct measurement of the coronal magnetic fields. To overcome this issue, nonlinear force-free field (NLFFF) extrapolations (Wiegelmann & Sakurai 2012; Inoue 2016; Guo et al. 2017), where 3D magnetic fields are extrapolated from the observed photospheric magnetic field under a force-free approximation, are employed. To investigate their dynamics during the X9.3 flare, we carry out MHD simulations using the NLFFF as the initial condition.

The rest of this paper is structured as follows: the observations and numerical method are described in Section 2, results are presented in Section 3, and important discussions arising from our findings are summarized in Section 4.

2. Observations and Method

2.1. Observations

As shown in Figure 1(a), AR12673 was very active, with M-class flares being observed four times from September 5. Eventually the X2.2 and X9.3 flares were observed to occur on September 6. Figure 1(b) shows the extreme ultraviolet image of the whole Sun observed by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) at 131 Å. AR 12673 is highlighted by the marked box in the lower western quadrant of the Sun. Figure 1(c) shows the photospheric vector magnetic field taken at 08:36 UT on September 6 taken with Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) onboard the SDO. This observation is shown in space weather HMI Active Region Patch format (Bobra et al. 2014). This was taken approximately 20 minutes before the X2.2 flare, from which the presence of sheared magnetic field lines along the polarity inversion line (PIL) can be identified. In this study, this photospheric magnetic field was used to perform an NLFFF extrapolation.

2.2. Numerical Methods

2.2.1. NLFFF Extrapolation

We first perform the NLFFF extrapolation using the MHD relaxation method described in Inoue et al. (2014a) and Inoue (2016). The photospheric vector magnetic field, as shown in Figure 1(c), is set as the bottom boundary where it is preprocessed according to Wiegelmann et al. (2006). To perform the NLFFF extrapolation and the MHD simulation we solve the following equations:

\[
\frac{\partial \mathbf{v}}{\partial t} = - (\mathbf{v} \cdot \nabla) \mathbf{v} + \frac{1}{\rho} \mathbf{J} \times \mathbf{B} + \nu \nabla^2 \mathbf{v},
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B} - \eta \mathbf{J}) - \nabla \phi,
\]

\[
\mathbf{J} = \nabla \times \mathbf{B},
\]

\[
\frac{\partial \phi}{\partial t} + c_s^2 \nabla \cdot \mathbf{B} = -\frac{c_s^2}{\rho} \phi,
\]

where the subscript \( i \) of \( \nu \) and \( \eta \) corresponds to different values used in NLFFF or MHD, respectively. \( \rho \) is the plasma density.
pseudo-density, $B$ is the magnetic flux density, $\vec{v}$ is the velocity, $J$ is the electric current density, and $\phi$ is a convenient potential to reduce errors derived from $\nabla \cdot \mathbf{B}$ (Dedner et al. 2002). The pseudo-density is assumed to be proportional to $|\mathbf{B}|$ in order to ease the relaxation by equalizing the Alfvén speed in space. In these equations, the length, magnetic field, density, velocity, time, and electric current density are normalized by $L^* = 244.8$ Mm, $B^* = 2500$ G, $\rho^* = |\mathbf{B}|^2$, $V^*_A = B^*/(\mu_0 \rho^*)^{1/2}$, where $\mu_0$ is the magnetic permeability, $\tau^*_A = L^*/V^*_A$, and $J^* = B^*/\mu_0 L^*$, respectively, $\nu_{\text{NLFFF}}$ is a viscosity fixed at $1.0 \times 10^{-3}$, and the coefficients $c_x^2$, $c_y^2$ in Equation (5) are fixed to the constant values 0.04 and 0.1, respectively. The resistivity in the NLFFF calculation is given as $\eta_{\text{NLFFF}} = \eta_0 + \eta_1 |J \times \mathbf{B}| \mathbf{B}$ where $\eta_0 = 5.0 \times 10^{-5}$ and $\eta_1 = 1.0 \times 10^{-3}$ in non-dimensional units. The second term is introduced to accelerate the relaxation to the force-free state, particularly in regions of weak field.

A potential field is employed as the initial state in the NLFFF calculation, which is extrapolated from the observed $B_z$ using the Green function method (Sakurai 1982). For both calculations, the density is initially given by $\rho = |\mathbf{B}|$ and the velocity is set to zero everywhere inside the numerical domain. At all boundaries except the bottom, the magnetic fields are fixed to be potential fields. The bottom boundary is fixed according to $\mathbf{B}_{\text{bc}} = \mathbf{B}_{\text{obs}} + (1 - \zeta)\mathbf{B}_{\text{pot}}$, where $\mathbf{B}_{\text{bc}}$ is the horizontal component, which is determined by a linear combination of the observed magnetic field ($\mathbf{B}_{\text{obs}}$) and the potential magnetic field ($\mathbf{B}_{\text{pot}}$). $\zeta$ is a coefficient ranging from 0 to 1. When $R = \int |J \times \mathbf{B}|^2 dV$, which is calculated over the interior of the computational domain, falls below a critical value denoted by $R_{\text{min}}$ during the iteration, the value of the parameter $\zeta$ is increased to $\zeta = \zeta + d\zeta$. In this paper, $R_{\text{min}}$ and $d\zeta$ have the values $1.0 \times 10^{-5}$ and 0.02, respectively. If $\zeta$ becomes equal to $1$, $\mathbf{B}_{\text{bc}}$ is completely consistent with the observed data. This process can suppress large discontinuities produced between the bottom and inner domains. The velocity is fixed to zero at all boundaries and the von Neumann condition $\partial\phi/\partial n = 0$ is imposed on $\phi$ in both calculations. We further control the velocity as follows: if the value of $v^* (=|v|/|\mathbf{B}|_0)$ becomes larger than $v_{\text{max}}$ (here set to 0.02), then the velocity is modified as $v = v_{\text{max}}/v^*$. These processes can also suppress large discontinuities produced between the bottom and inner domains.

2.2.2. MHD Simulation

Next we perform the MHD simulation using the NLFFF as an initial condition. The equations to be solved are identical to those used in the NLFFF extrapolation. The pseudo-density is used again in this simulation. The reason for this is that the dynamics in the lower corona are not so dissimilar from those produced using a mass equation, as shown by Amari et al. (1999) and Inoue et al. (2014b). Regarding the differences resulting from the NLFFF calculation, we set a uniform resistivity by fixing $\eta_{\text{MHD}} = 1.0 \times 10^{-5}$ and $\eta_{\text{DLFP}} = 1.0 \times 10^{-4}$. At the boundaries, only the normal component of the magnetic field ($B_z$) is fixed, while the horizontal components vary according to the dynamics, i.e., they are determined by the induction equation. The velocity limiter used for the NLFFF extrapolation is not used for the MHD simulation.

For both calculations, the numerical domain has dimensions of $244.8 \times 158.39 \times 195.84$ (Mm$^3$), or $1.0 \times 0.647 \times 0.8$ in non-dimensional units. The region is divided into $340 \times 220 \times 272$ grid points, resulting in a $2 \times 2$ binning of the original photospheric vector magnetic field.

3. Results

Figure 1(d) shows the NLFFF extrapolated from the photospheric magnetic field prior to the X2.2 flare shown in Figure 1(c). The extrapolation reveals twisted magnetic field lines along the north–south direction, as expected from the photospheric magnetic field. Next we show the results of the MHD simulation using the NLFFF as the initial condition. We first show the overview of the dynamics of the magnetic field (see also the online supplemental material). The left panel of Figure 2(a) shows some of the small MFRs located along the PIL prior to the eruption. After the initiation of the eruption, a large coherent MFR composed of highly twisted lines is formed through reconnection between the small MFRs (middle and right panels). This process is similar to that found in Inoue et al. (2018). In Figure 2(b), which shows the Figure 2(a) 3D field lines from a different angle, the eruptive MFR exhibits a writhing motion. Figure 2(c) shows the temporal evolution of $|J|/|\mathbf{B}|$ plotted on the $x$–$z$ plane set at $y = 0.38$. The $|J|/|\mathbf{B}|$ value is enhanced inside the MFR and a current sheet is formed below it, similar to the CSHKP standard model of flares (Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopf & Pneuman 1976). We further found the MFR launches in an eastward direction.

A more detailed description of the MFRs and their dynamics at early stages of the simulation is shown in Figure 3. Along the PIL at $t = 0.28$, we found three small MFRs, named FR1, FR2, and FR3. They are the same field lines shown in the left panel of Figure 2(a). FR1 expands upward at $t = 0.56$; its initiation mechanism will be discussed later. The black arrow in Figure 3(b) ($t = 0.56$) shows several elongated field lines of FR2, which now extend below FR1. These field lines are located above the strong current that develops underneath FR1 as the latter expands. This suggests that reconnection occurs in the strong current region. Figures 3(c) and (d) show additional field lines, named FR4, which are located under FR1 (not plotted here). The field lines of FR4 and FR2 reconnect through the strong current region and create a bigger MFR (i.e., FR2 + FR4 in Figure 3(d)). This MFR eventually reconnects with FR3, forming a large MFR, shown in Figure 4(a).

Figure 4(a) shows selected magnetic field lines at $t = 8.5$ with the $|J|/|\mathbf{B}|$ plotted on the $x$–$z$ plane. We can see the post-flare loops forming below the vertical current sheet and also the eruptive MFR. Figure 4(b) is a top and enlarged view of the post-flare loops, showing that the region close to the PIL is mostly dominated by the post-flare loops. Although the X9.3 flare, which took place approximately 3 hr after the X2.2 flare, requires highly twisted field lines to be energized, most of the low-lying twisted lines in our simulation have been converted to the post-flare loops. However, from observations of AIA 171 Å shown in Figures 4(c) and (d), we can see that the sheared magnetic field highlighted by the red arrow remains even after the X2.2 flare while the post-flare loops appear there after the X9.3 flare. Therefore we suggest that our simulation shows both the X2.2 and X9.3 flares. The X2.2 flare could be associated with the rise of a relatively small-scale MFR (FR1) early in the simulation ($t \approx 0.5$), while the X9.3 flare could be
associated with eruption of the large-scale MFR (FR2+FR3 +FR4) found later in the simulation. Note that the 3D NLFFF reconstructed from the photospheric vector magnetic field data approximately 20 minutes before the X2.2 flare was used for the initial state of the simulation.

For a more detailed understanding, we estimate the magnetic twist according to Berger & Prior (2006):

\[ T_w = \frac{1}{4\pi} \int \nabla \times B \cdot B \frac{dl}{|B|^2} \]

where \( dl \) is a line element. We compute \( T_w \) for the field lines rooted in the region shown in Figure 5(a), which shows the \( B_z \) distribution obtained at the same time as shown in Figure 1(c). The values of twist at \( t = 0.0 \) and \( t = 8.5 \), mapped on the photosphere, are plotted in Figures 5(b) and (c), respectively. Although the highly twisted lines are formed at \( t = 8.5 \) and the writhing motion is found during the eruption, the initial state is stable to kink instability (KI) because the twist value does not reach the required threshold \( (T_w \geq 1.75) \) (Török et al. 2004). At \( t = 8.5 \), we find that the value of \( T_w \) decreases in the region close to the PIL, where the post-reconnection arcade of Figure 4(b) is rooted. Figure 5(d) shows the temporal evolutions of the magnetic flux F1, F2, and F3 of regions that have \( T_w \) within the ranges \(-1.5 \geq T_w \geq -1.0\) and \(-1.0 \geq T_w \geq -0.5\) respectively.

Figure 2. Temporal evolution of the formation and dynamics of the eruptive MFR. Panels (a) and (b) show the field lines from different angles. E and S stand for east and south. An animation of these panels is available. Its duration is 4 s. (c) Temporal evolution of \( |J|/|B| \) distribution plotted on the \( x-z \) plane at \( y = 0.38 \) with a viewpoint from the south. (An animation of this figure is available.)
We find that $F_1$ and $F_2$ constantly increase with time, while $F_3$ constantly decreases. $F_1$, $F_2$, and $F_3$ all saturate after $t \approx 5.3$. This suggests that the highly twisted MFR is built up from the reconnection of moderately twisted lines ($\text{-}0.5 \leq T_w \leq -1.0$, and after $t \approx 5.3$, it expands upward without any further increase of its twist. We further plot the temporal evolutions of the total currents (TC1 and TC2) of the field lines satisfying $T_w \leq -1.5$ and $T_w \leq -1.0$, respectively. We define the "total current" as the total current vertically crossing the section ($S$) of the MFR, i.e., it is described as $\int (\mathbf{J} \cdot d\mathbf{S})$ where $d\mathbf{S}$ is the cross-sectional element of the MFR. In Figure 5(e) both TC1 and TC2 increase to $t \approx 3$. Thereafter, TC2 decreases, while TC1 remains constant up to $t \approx 5$, and then decreases. In this period, the highly twisted MFR is created. However, both TC1 and TC2 are found to decrease during the late stages of the simulation, in which the MFR travels upward while expanding.

4. Discussion

In this section we discuss possible mechanisms for the writhing motion of the erupting MFR and also for the initiation of the flare. Several possibilities can be raised to explain the writhing motion (Kliem et al. 2012) one of which is KI. The threshold of KI is derived from a winding number $N$ of a field line around the magnetic axis of the MFR (Hood & Priest 1979). The criterion corresponds to $N = 1.25$ for a cylindrical MFR (Hood & Priest 1979) and $N = 1.75$ for a semi-torus-type MFR (Török et al. 2004). Note that these values are obtained from a linear stability analysis which are not exactly applied to the MFR in the dynamic state. We therefore use them as an indicator. We define the average twist as

$$\langle T_w \rangle = \frac{1}{N_x N_y} \sum_{i,j(T_w \leq -1.0)} |T_w(x_i, y_j)|,$$

(7)

where $N_x$ and $N_y$ are grid numbers in the calculated area in the $x$ and $y$ directions. Note that the average twist is calculated in the region shown in Figure 5(a). We select field lines with $T_w \leq -1.0$ as being those consisting of the new MFR created during the eruption. Figure 6(a) shows that the maximum $\langle T_w \rangle$ does not reach the value 1.7. We further plot the temporal evolution for the ratio of the magnetic flux, described as

$$F_R = \frac{\int_{T_w \leq -1.75} |B_z| dS}{\int_{T_w \leq -1.0} |B_z| dS},$$

(8)

where $dS$ is a surface element on the photosphere. Figure 6(b) shows that the ratio of the photospheric magnetic flux of the field lines with $T_w \leq -1.75$ over the photospheric flux of field lines with $T_w \leq -1$ is 30%. We therefore suggest that KI is not
the main driver of the writhing motion of the MFR. Therefore, there are other possibilities for the rotating mechanism of the MFR. According to Isenberg & Forbes (2007), even if the field lines are initially aligned with the MFR current (i.e., no force acting on the MFR), once the MFR starts to move upward, that alignment ceases. Consequently, the $J \times B$ force becomes non-zero, acting on the MFR and rotating it (see Figure 11 of Isenberg & Forbes 2007). As seen in Figure 5(e), the MFR’s total current increases and TC1 in particular roughly maintains its value up to $t \approx 5$. Therefore, it might contribute to the writhing motion. Furthermore, Kliem et al. (2012) discussed the writhing motion due to the relaxation of the tension force of the twisted field lines during the eruption. They reported that, due to relaxation, the magnetic axis of the MFR deviated from its initial position by about 40° (see Figure 13 of their paper). This effect would also contribute to the writhing motion of the MFR found in this study. Consequently, the combination of several effects might contribute to the writhing motion. We intend to carry out a detailed analysis of this in future work.

To discuss the initiation of the eruption, in Figure 7, we show the magnetic fields along with upward velocity ($V_z$) immediately after the initiation of the simulation. Note that the MFR located in the center corresponds to the FR1 discussed in Figure 3. The red, black, and blue lines correspond to contours of the decay index $n$ with values of 1.7, 1.5, and 1.0, respectively. The decay index $n$ is defined as $n = -(\varepsilon / B_{ex}) \frac{\partial B_{ex}}{\partial z}$ (Kliem & Török 2006) where $B_{ex}$ denotes the horizontal component of the external field. Here we assume the potential field as the external field. We found that the upward velocity rapidly grows at the region where $n$ ranges from 1.0 to 1.7. Although the value of $n = 1.5$ is well known as the threshold of torus instability (TI, Kliem & Török 2006), it strongly depends on the configuration of the MRF and the line-tying effect (e.g., Démoulin & Aulanier 2010; Olmedo & Zhang 2010; Myers et al. 2015) and, eruptions can occur even when $n$ is less or greater than 1.5. (Zuccarello et al. 2015; Syntelis et al. 2017). Therefore, TI would be a possible candidate to explain the initiation. On the other hand, as we discussed previously, since the reconnection takes place at an early time of the simulation.
above which the FR1 starts to rise upward while expanding, it might play an important role in the initiation. For instance, this reconnection might "push" the MFR into a region where it becomes torus unstable. In order to draw a conclusion on the initiation of the eruption, therefore, a more detailed analysis is required. In addition, it is important to understand the formation process of the magnetic fields producing the strong solar flares. For this we need the temporal evolution of the NLFFF as shown in Kang et al. (2016) and Muhamad et al. (2018), as well as a detailed data analysis (Bamba et al. 2017; Woods et al. 2018).

The MFR shown in the simulation shows an eastward deflection in the early stages as well as a writhing motion. This might be important in explaining the magnetic fields observed in the vicinity of Earth. Because the AR was located 35° west in longitude, this deflection toward Earth could result in a strong-field part of the MFR passing the Earth's position. Furthermore, the writhing motion found in the lower corona might contribute to creating the southward magnetic field observed in the vicinity of Earth. Therefore, the writhing motion might be important in terms of space weather forecasting.

**Figure 5.** (a) Distribution of $B_z$ with PIL in black. (b), (c) $T_w$, obtained from the simulation, mapped on the photosphere at $t = 0$, and $t = 8.5$, respectively. The region is identical to that in (a) and the black line corresponds to the PIL. (d) Temporal evolution of the magnetic flux, $F_1$, $F_2$, and $F_3$, measured in the $T_w$ ranges $-1.5 \geq T_w \geq -1.0$, $-1.0 \geq T_w \geq -0.5$, and $-0.5 \geq T_w \geq -1.0$, in blue, red, and green, respectively. (e) Temporal evolution of the total currents (TC1 and TC2) of the twisted field lines satisfying $T_w \leq -1.5$ and $T_w \leq -1.0$, respectively. Blue and red lines correspond to TC1 and TC2, respectively.

**Figure 6.** (a) Temporal evolution of the average twist $\langle T_w \rangle$ defined in Equation (7). (b) Temporal evolution of the ratio of the magnetic flux defined in Equation (8).
Figure 7. Snapshot of 3D magnetic fields at \( t = 0.28 \) at which the eruption starts. The vertical cross section shows the \( V_z \) distribution at \( Y = 0.34 \) while the blue, black, and red lines correspond to contours of decay index values \( n = 1.0, 1.5, \) and 1.7, respectively.

Since this simulation is limited, in future work extended simulations will be required, covering a larger area to take into consideration the effects of the ambient field (Shiota et al. 2010). We also plan to examine a connection to the SUSANOO simulation, which is a global solar wind model including CME propagation, developed by Shiota & Kataoka (2016), toward a comprehensive understanding of the evolution of the MFR from the Sun to Earth.

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