Solar Flux Rope Formation and Eruption: MHD Simulation and Forward Modeling

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Introduction

A magnetic flux rope (FR) structure comprises a family of magnetic field lines collectively winding around a central axis more than once. The FR buried in the low atmosphere is believed to be the progenitor of a coronal mass ejection (CME). Magnetohydrodynamic (MHD) instabilities can destabilize the FR and trigger FR eruption [1]. The erupting FR stretches the magnetic field, leading to the formation of a current sheet (CS) where magnetic reconnection takes place. Energetic particles accelerated in the CS carry the energy released by reconnection to the chromosphere, producing hard X-ray foot-points. The heated chromospheric material evaporates upward to fill flare loops, creating soft X-ray loops. CMEs and the associated flares are different manifestations of a single process, and sometimes an eruptive prominence is associated [2].

To investigate the FR formation and eruption, we conducted a two-and-a-half-dimensional MHD simulation in a chromosphere-transition-corona setup. The extreme ultraviolet and thermal X-ray radiations are synthesised with forward-modeling analysis from MHD results.

Numerical model

A two-and-a-half-dimensional MHD simulation is conducted in a chromosphere-transition-corona setup. The initial arcade-like linear force-free magnetic field is driven by an imposed slow motion converging toward the magnetic inversion line at the bottom boundary. As illustrated in Figure 1, the convergence brings opposite-polarity magnetic flux to the polarity inversion line, leading to the formation of an FR. The FR rises due to catastrophe, and a CS forms underneath it. An embedded prominence also gets formed directly by levitating material from the chromosphere. For the detailed numerical setup, refer to Refs [3, 4, 5, 6].

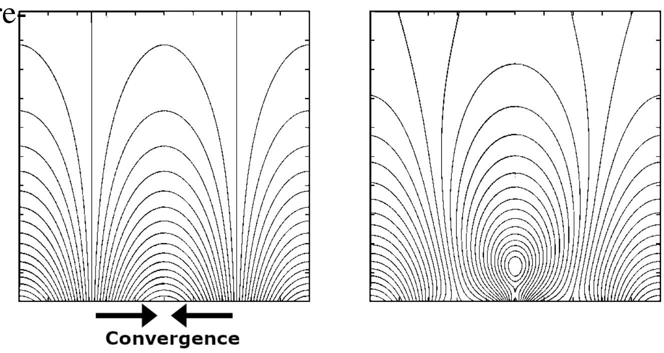

Figure 1: Illustration of FR formation driven by photospheric converging motion.

The CS evolution

The CS evolution during the FR formation and eruption in our MHD simulation can be divided into four stages. The first stage shows the CS forming and gradually lengthening. The start of the resistive instabilities marks the beginning of the second stage. Magnetic islands disappear in the third stage and reappear in the fourth stage. The FR undergoes a series of quasi-static equilibrium states in the first stage, and the impulsive acceleration starts from the beginning of the second stage. The temperature, density and the number of islands in the CS, as well as the time span of each stage are listed in Table 1, respectively. The density and temperature maps in the CS region are shown in the top and middle rows of Figure 2.

Stage	Time	Temperature	Density	Magnetic islands
First	$2112.5\,\mathrm{s} - 4304.0\,\mathrm{s}$	$3 \times 10^4\,\mathrm{K}$	$1.64 \times 10^{-13}\,\mathrm{g \cdot cm^{-3}}$	0
Second	$4304.0\,\mathrm{s} - 4577.1\,\mathrm{s}$	$3 \times 10^4 - 7 \times 10^6\,\mathrm{K}$	$2.0 \times 10^{-15} - 3.0 \times 10^{-13}\,\mathrm{g \cdot cm^{-3}}$	$\sim O(10)$
Third	$4577.1\,\mathrm{s} - 4973.0\,\mathrm{s}$	$6 \times 10^6\,\mathrm{K}$	$8.2 \times 10^{-16}\,\mathrm{g \cdot cm^{-3}}$	0
Fourth	$4973.0\,\mathrm{s} - 5564.7\,\mathrm{s}$	$5 \times 10^6\,\mathrm{K}$	$8.2 \times 10^{-16}\,\mathrm{g \cdot cm^{-3}}$	$\sim O(10)$

Table 1: The four-stage evolution of the current sheet.

Forward modeling

We conduct forward-modeling analysis based on the MHD simulation. Synthetic images and light curves of the seven Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA) channels, i.e., 94 Å, 131 Å, 171 Å, 193 Å, 211 Å, 304 Å and 335 Å, and the $3 - 25\,\mathrm{keV}$ thermal X-ray are obtained with forward-modeling analysis. To do so, we assume that the monochromatic emission coefficients of AIA channels are proportional to the square of the electron number density and the absorption is due to photo-ionization of neutral hydrogen and neutral and once-ionized helium. The relative populations of the various atomic levels are obtained by solving the Saha equation based on the temperature and density obtained from the MHD simulation. The thermal X-ray emission is assumed to come from optically-thin thermal bremsstrahlung. For the technical details about forward modeling, see Ref. [5]. The thermal X-ray distribution in the CS region at each stage is shown in the bottom row of Figure 2. The loop-top source and the coronal sources of the soft X-ray are reproduced in forward modeling. The SDO/AIA 193 Å image is shown in Figure 3 as a close-up view of the CS, where various waves and shocks are present in the CS. The light curves of the seven SDO/AIA channels start to rise once the resistive instabilities develop. The light curve of the $3 - 25\,\mathrm{keV}$ thermal X-ray starts to go up when the reconnection rate reaches one of its peaks. Quasi-periodic pulsations (QPPs) appear in several SDO/AIA channels, corresponding to the period of the intensive activity of the magnetic islands. We also study the physical properties and dynamics of magnetic islands in Ref. [6].

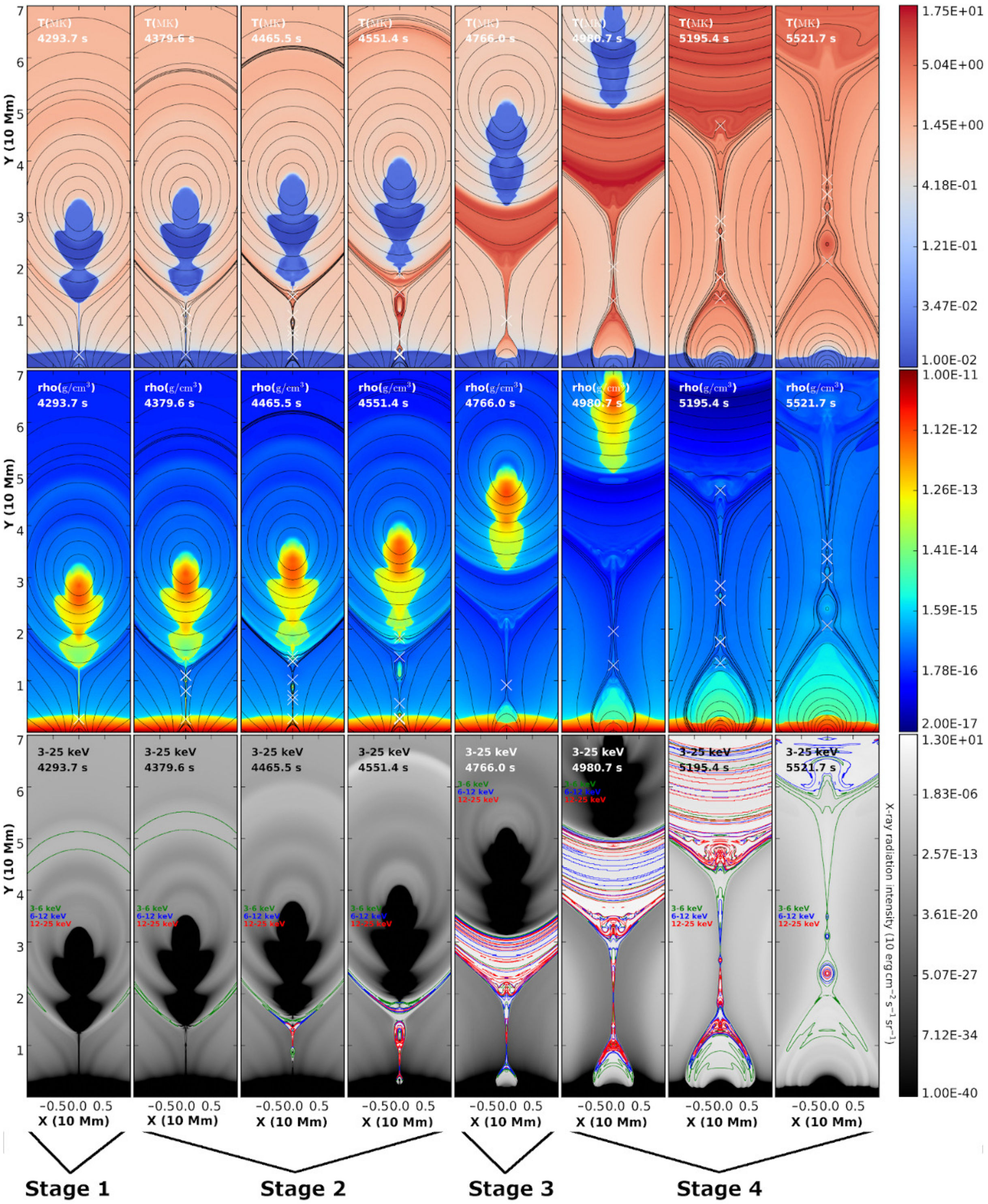

Figure 2: Evolution of temperature (upper row), density (middle row), and 3–25 keV X-ray intensity (bottom row) in the *x*-*y* plane, indicating the CS evolution. In the upper and middle rows, the solid black lines and the white crosses represent the magnetic field lines and the X-points, respectively. The contours of the 3–6 keV, 6–12 keV, and 12–25 keV X-ray intensities are plotted in the bottom row. The four stages of the CS evolution are indicated. Figure adapted from Ref. [5].

Summary

The left panel of Figure 3 shows the standard model of solar eruption, unifying the CME, flare and eruptive prominence together. Starting from a linear-force-free magnetic arcade in a stratified solar atmosphere, our simulation depicts the FR formation and eruption driven by photospheric converging motion and reproduces the standard solar eruption model. The right panel of Figure 3 shows a snapshot of temperature distribution obtained in our simulation with magnetic field lines overlaid, which is quite consistent with the model depicted in the left panel. The SDO/AIA 193 Å image in the right panel of Figure 3, which is obtained by forward-modeling analysis, shows the complex and dynamic structures of the CS.

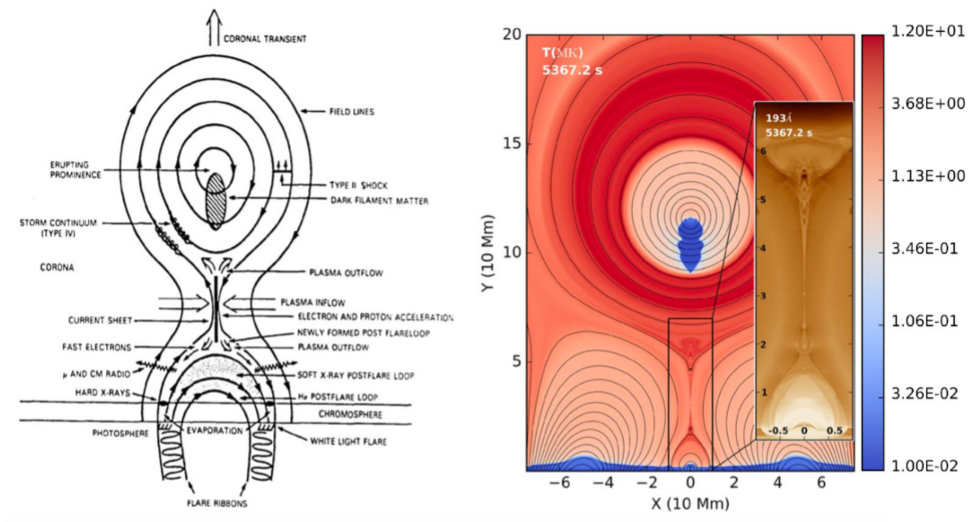

Figure 3: Figure adapted from Ref. [1]. The standard solar eruption model (left) from Ref. [2], contrasted with an MHD simulation (right) from Refs. [4, 5, 6].

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