# Magnetohydrodynamic Numerical Simulations of Coronal Mass Ejections and Associated Giant Arcades

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## Abstract

By extending the Chen-Shibata [1] model of coronal mass ejections (CMEs), we develop physical model of CMEs and associated giant arcades just below CMEs in two and half dimension, incorporating heat conduction. On the basis of the simulation results, the theoretical soft X-ray images are calculated and compared with observations of CMEs and giant arcades with Yohkoh/SXT (soft X-ray telescope). Detailed comparison between simulated X-ray images and observations revealed that (1) the Y-shaped ejection features, often seen at the bottom of some CMEs, might correspond to slow and fast mode MHD shocks associated with reconnection [3], (2) the dimming, often observed both sides of arcades, can be produced at least partly by reconnection inflow, (3) the back bone like bright soft X-ray features seen at the top of some arcades might correspond to fast mode MHD shocks just below reconnection jet.

## 1. Introduction

Magnetic reconnection has been believed to play an essential role in various solar activities, such as solar flares, eruptive prominences, and coronal mass ejections (CMEs), for the conversion of magnetic energy to kinetic and thermal energies. Many solar physicists have found much observational evidence of reconnection; the cusp-shaped flare loops, arcade structure of the loops and so on.

The Soft X-ray Telescope (SXT) on board Yohkoh also revealed many arcades associated with non-flare CMEs or filament eruptions. Among them, arcades with spatial scales comparable to the solar radius are called *giant arcades*. Since these giant arcades also show cusp-shaped structures, it is thought that they are produced by magnetic reconnection, the same mechanism as that of solar flares [5].

In this study, We performed 2.5-dimensional time-dependent MHD simulation with the model of magnetic reconnection coupled with heat conduction,

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under the condition of giant arcades. Based on the numerical results, the expected soft X-ray images are calculated, and compared with Yohkoh/SXT observations.

## 2. Numerical models

To simulate a giant arcade associated with a CME, we used the CME model of Chen and Shibata [1]. Two and a half-dimensional nonlinear time-dependent compressible MHD equations were solved with a multi-step implicit scheme [2] in the Cartesian coordinate system $(x, y)$, where $x$ and $y$ are in the horizontal and vertical directions, respectively. For a comparison with observations, the units of the length, density and temperature were assumed to be the characteristic values obtained from the Yohkoh observations [5], which are $L_0 = 2 \times 10^{10}$ cm, $\rho_0 = 3.2 \times 10^{-16}$ g cm$^{-3}$ (i.e., $n_0 = 2 \times 10^8$ cm$^{-3}$), and $T_0 = 2 \times 10^6$ K, respectively. The unit of magnetic field, $B_0$, was assumed to be 11.8 Gauss, which makes plasma $\beta$ around flux rope to be 0.01. Time was normalized by $\tau_{\rm A0} = L_0/v_{\rm A0}$, where the local Alfvén velocity ($v_{\rm A0} = B_0/\sqrt{4\pi\rho_0}$) around the flux rope is equal to 2571 km s$^{-1}$ and $\tau_{\rm A0} = 77.8$ s.

The initial magnetic configuration was similar to that in Chen and Shibata [1], i.e., a quadrupolar field with a detached flux rope whose center was located at $(x, y) = (0, 2)$. To satisfy the force balance within the flux rope, a perpendicular magnetic component (i.e., $B_z$) was introduced inside the flux rope. Here, an eruption was triggered by emerging flux below the flux rope. The initial value of density and temperature were set uniformly, i.e., $\rho = \rho_0$ and $T = T_0$. The resistivity is taken as an anomalous type. Heat conduction is taken as Spitzer type, in which heat is conducted only along the field lines.

## 3. Numerical Results

The global evolution of magnetic fields was almost the same as found in Chen and Shibata [1]. However, since heat conduction was included in this study, both the temperature and density show different distributions compared to the previous work. For example, the temperature becomes lower, whereas density becomes higher around the reconnection region. Figures 1(a) and (b) show the density and temperature distributions at $t = 100$.

Figure 1(c) shows the expected X-ray images calculated from the density and temperature in the numerical results at $t = 100$. These images were produced after taking account of the filter response function of the Yohkoh/SXT [4].

## 4. Discussion

We can see a Y-shaped structure in Figure 1(c). Yohkoh/SXT observed some similar Y-shaped structures, for example, associated with the giant arcade

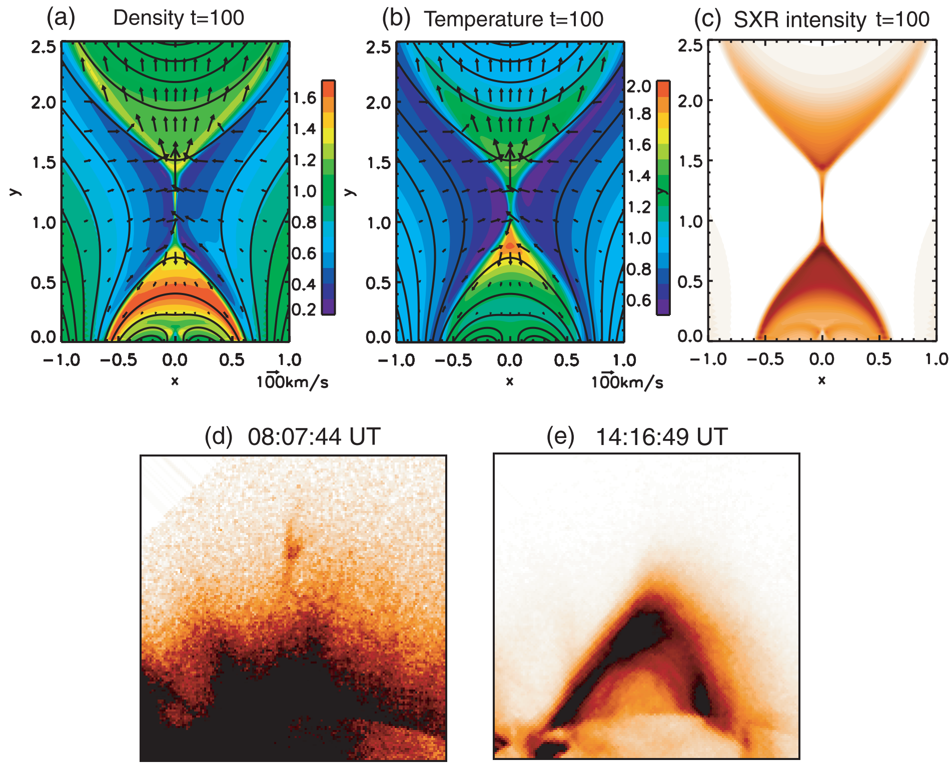


**Fig. 1.** The color contours of a, b, and c display the density, temperature, and soft X-ray intensity distribution (t=100), respectively. solid lines (a, b) show magnetic field lines, arrows show velocity field at the positions.(d) and (e) show Yohkoh/SXT observations of giant arcade on 1992 January 24.

on 1992 January 24. It is shown that the Y-shape in the simulation corresponds to the observed one, and the structure consists of slow and fast mode MHD shocks associated with reconnection [3].

Figure 1(c) also display the decrease in intensity just outside of the cusp-shaped loop and Y-shape (i.e., the reconnection region). These are caused by adiabatic expansion of the reconnection inflow.

In the solar corona, the decrease of intensity, so-called 'dimming', are observed by Yohkoh/SXT, associated with active phenomena such as flares and CMEs. 'Dimming' are often observed at both sides of flares or giant arcades. Therefore, we suggest that the dimming can be produced at least partly by reconnection inflow,

We can find from Figure 1(c) that the top of cusp-shaped loop is brighter than other parts of the loop, which corresponds to fast shock due to the collision of reconnection outflow with loops. If we imagine this numerical results are arranged along the neutral line, the bright points on each top of the loops appears like a

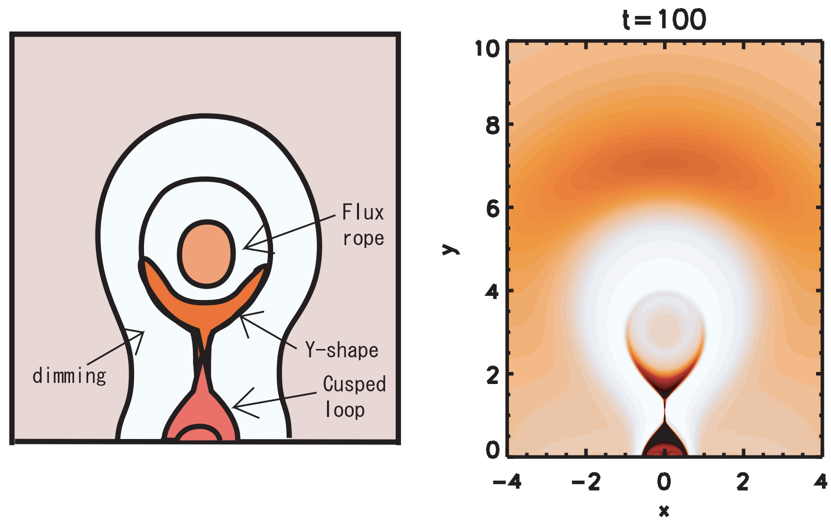


**Fig. 2.** (left) Schenatic cartoon of soft X-ray dimming. (right) The calculated X-ray image at t=100 (wide range).

back bone of the arcade. Many SXT observations of giant arcades also show the back bone like bright soft X-ray features. Therefore we suggest that the back bones of giant arcades might be fast shock of the each loop of the arcade.

## 5. Conclusion

We compared the results of MHD simulation under the condition of giant arcades with the observation of giant arcades, to examine dynamical structure of them. Cnsequently, we found the following points: (1) the Y-shaped ejection features, often seen at the bottom of some CMEs, correspond to slow and fast mode MHD shocks associated with reconnection [3], (2) the dimming, often observed both sides of arcades, can be produced at least partly by reconnection inflow, (3) the back bone like bright soft X-ray features seen at the top of some arcades might correspond to fast mode MHD shocks just below reconnection jet.

## 6. References

1. Chen P. F., Shibata K. 2000, ApJ 545, 524
2. Hu Y. Q. 1989, J. Comput. Phys. 84, 441
3. Shiota D, et al. 2003, PASJ 55, in press
4. Tsuneta S. et al. 1991, Sol. Phys. 136, 37
5. Yamamoto T. T. et al. 2002, ApJ 579, L45