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XRT and EIS Observations of Evidence of Magnetic Reconnection

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Abstract. We perform a numerical simulation of a coronal mass ejection and an associated X-ray arcade. From the numerical results, we found: (1) the physical mechanisms of dimming. One of them is the rarefaction by reconnection inflow. (2) Shock structure associated with reconnection will be obsereved as a Y-shaped structure. (3) A characteristics of reconnection inflow is that it appears as a pair of blue and red shifted components just above the X-ray arcade.

1. Introduction

Magnetic reconnection has been believed to play an essential role in various solar activities for the conversion of magnetic energy to kinetic and thermal energies. Many solar physicists have found much observational evidence of reconnection such as cusp-shaped loops, the motion of flare ribbons, and so on. However, they are only indirect ones.

Also, the theory of magnetic reconnection has not been established. Imaging and spectroscopic observations of reconnection associated flows by Solar-B will improve our understanding of the basic process of magnetic reconnection in the solar atmosphere.

By the way, *dimming*, that is the decrease of intensity, is observed associated with a solar flare in soft X-ray and extreme ultraviolet (EUV) observations (Sterling & Hudson 1997; Zarro et al. 1999). Harrison & Lyons (2000) show that dimming is caused by the decrease of plasma density with EUV spectroscopy. Harra & Sterling (2001) show that plasma flow coincide with dimming. These authors conclude that the dimming is caused by outflow which supply mass to a Coronal mass ejection (CME). However, no mechanism of such outflow is shown. On the other hand, Tsuneta (1996) suggested that dimming caused by the rarefaction by reconnection inflow. We suppose that dimming is related to such reconnection associated flow.

In this paper, we perform a Magnetohydrodynamic (MHD) simulation of coronal mass ejection and associated X-ray arch. From the numerical results, we discuss the relation between dimming and reconnection with particlar emphasis on the expected observed feature with Solar-B, and predict observations with the experiments aboard Solar-B in order to detect direct evidence of reconnection.

2. Numerical Simulation

2.1. Numerical Model

Two and a half dimensional time-dependent resistive MHD equations including heat conduction and gravity are solved by multi-step implicit method (Hu 1989).

The initial condition is almost same as that in Chen & Shibata (2000) or Shiota et al. (2003). We set a magnetic bubble (flux rope) detached from the lower boundary in the configuration (see Fig. 1a). We adopt this configuration to mimic a cross section of an inverse-polarity filament and its surroundings. The parameters are set to satisfy the condition of giant arecade (see Yamamoto et al. 2002); $L_0 = 10^{10}$ cm, $n_0 = 10^9$ cm^{-3}, $T_0 = 1.5 \times 10^6$ K.

2.2. Numerical Results

The dynamics of the numerical results is almost same as that of Chen & Shibata (2000) and Shiota et al. (2003). The time evolution of density distribution is shown in Figure 1. Reconnection start at the X point $(x, y) = (0, 0.3)$ below the flux rope. Once reconnection begins, the upward reconnection outflow pushes the flux rope up. It is seen that the density above the flux rope and both side of the X point decreases gradually.

3. Discussion

3.1. Mechanisms of "Dimming"

We can see the decrease of density around the flux rope and the cusp-shaped loop in the numerical results (Fig. 1). The density decrease is observed as soft X-ray dimming (Fig. 2b). The position of dimming is consistent with observations (Sterling & Hudson 1997).

Hereafter, we use the term "dimming" as a term that expresses this density decrease Our numerical results provide some interpretations of the "dimming" mechanism. We itemized the processes of "dimming" found in the numerical results.

1. expansion of plasma in the magnetic loop covering the flux rope
   As the flux rope rises gradually, the flux rope extend the magnetic loops which initially lie over the flux rope and their footpoints connected to the photosphere. The extension of the loops caused the expansion of the inside plasma and the decreases of density and temperature (This is proposed by Forbes & Lin 2000).

2. expansion of the erupting structure

   The erupting structure is consists of the flux rope and the loop rising together. Because magnetic field strength in the initial condition decreases as $\sim y^{-3}$, magnetic pressure decreases very rapidly. When the flux rope

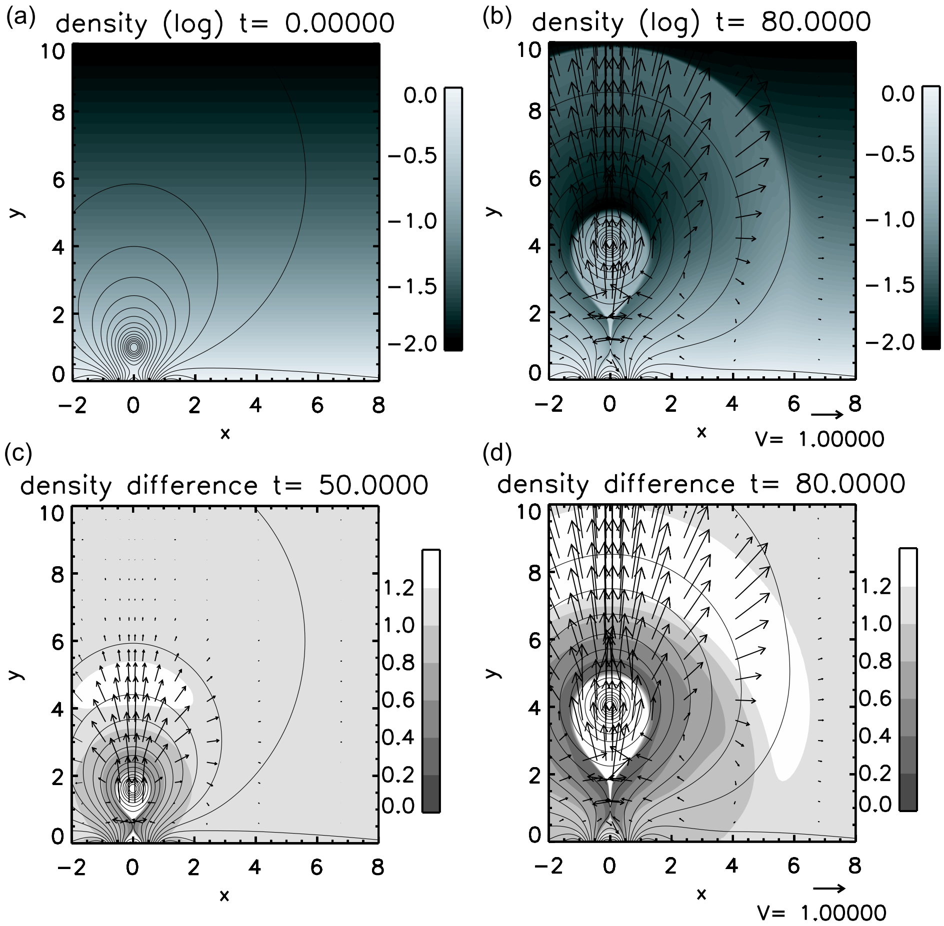

Figure 1. Density distributions and distributions of density difference. Panel (a) is the initial density distribution (gray scale). Solid lines show magnetic field lines and arrows show velocity field. Panel (b) the density distribution at $t = 80$. Panels (c) and (d) are density differences at $t = 50$ and $t = 80$, respectively. Density difference is defined as $\rho/\rho(t = 0)$.

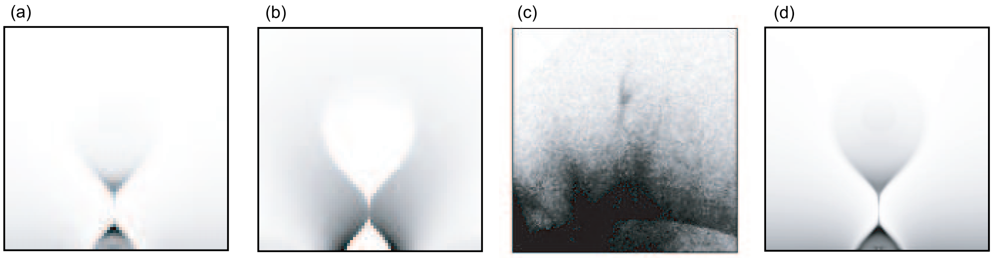

Figure 2. Calculated and observed soft X-ray images. (a) calculated X-ray image ($t = 50$) taking into account the filter response function (thin Al) of Yohkoh/SXT (Tsuneta et al, 1991) . (b) difference image produced by subtracting an calculated X-ray image at $t = 0$ from the image (a). In this image, only dimming region (the intensity decreases) is displayed (positive image). (c) SXT observation of Y-shaped structure on 1992, January 24 08:07:44 UT with AlMg filter with half resolution ($\sim 5''$). (d) calculated X-ray image (Solar-B/XRT Al poly filter). The scales of image (a), (b), and (d) are 2.7×10^{10}cm, and that of (c) is 5.4×10^{10}cm.

rises higher, the ambient magnetic pressure become lower. Therefore, the erupting structure expands as its height. The expansion also causes the decreases of density and temperature.

3. reconnection inflow
   It is found that there are strongly "dimming" regions in the vicinity of the X point in Figures 1. The regions are correspond to the regions just outside of the current sheet and the slow shocks associated with magnetic reconnection. Therefore, the strongly "dimming" regions are produced by the rarefaction by the reconnection inflow (originally proposed by Tsuneta 1996).

These three mechanisms works simultaneously in same region, both sides of the X point. Therefore, the region is the most strongly dimmed (Fig. 2b).

3.2. Observation of Shock Structure

The boundary between dimming region and non-dimming region (the inner boundary of "dimming" region) corresponds to slow shock associated with magnetic reconnection. When reconnection begins, the plasma both side of the X point flows in and then slow shock is formed.

Shiota et al. (2003) shows the slow shock structure can be appeared as a Y-shape structure, and a similar structure is observed by the Soft X-ray Telescope (SXT) aboard *Yohkoh* (Fig. 2a and 2c). If we can observe such shock structure with the X-ray Telescope (XRT) aboard Solar-B, we can know more detail condition that reconnection really occurs, because the spatial resolution of Solar-B/XRT is much higher than *Yohkoh*/SXT. We calculated an X-ray image (Fig. 2d) taking into account the filter response function (Al poly) of Solar-B/XRT. If we observe the sructure with Solar-B/XRT, the structure is also detected.

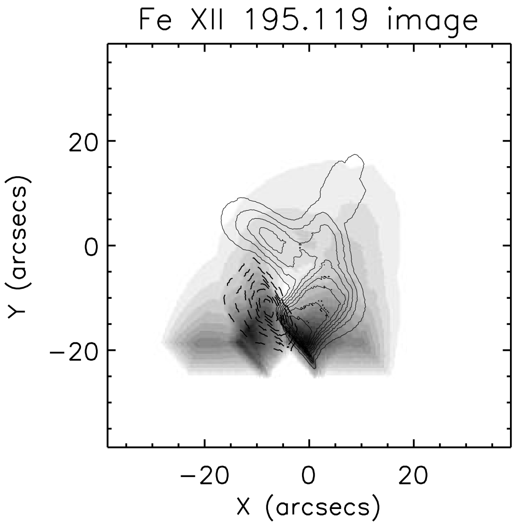

Figure 3. Synthesized image of Fe XII (195.119 Å) from the numerical results. Solid and dashed contours are blue and red shifted image, respectively.

3.3. Imaging Spectroscopy

The mechanism of dimming discussed in section 3.1 should be tested by observations. In particular, imaging spectroscopy of the dimming region by the EUV imaging spectrometer (EIS) is important to investigate the dynamics of CMEs. However, interpretation of the data is not straightforward because of three dimensionality, uncertaity of viewing angle, and integration of information along the line of sight. Comparison with numerical simulation is therefore useful for interpretation of the observational data.

In this section we present an example of synthesized image of Fe XII (195.119 Å) line from the results of the numerical simulation. If we neglect the difference along the neutral line, as is sometimes not a very bad approximation for giant arcades, we can make a pseudo three dimensional model from our two dimensional result. First, the temperature and density distributions are convolved with emissivity function of the Fe XII line to synthesize two dimensional emission measure distribution, i.e., a Fe XII image. Then the image and the velocity distributions are lined up along z direction to make 3D arrays. Velosity differential emission measure (VDEM; Newton, Emslie, & Mariska 1995) are calculated from these 3D arrays by assuming a viewing angle. From VDEM we can make Doppler shifted images.

Figure 3 shows an example. The line of sight is assumed at 45 degree to the x-y plane and at 45 degree to the x-z plane. The background image is the total intensity of the Fe XII line. Note that the image is negative; dark parts have larger intensity. Images of Dopper shifted componets are shown by countours. Solid and dashed contours are blue and red shifted image, respectively. The blue (red) shifted images are calculated by integrateing the components of the

VDEM with line-of-sight velocity of -(+) 60 ± 30 km/s. Most part of the red shifted componets shown in figure 3 is the reconnection inflow. On the other hand, the upper part of the blue shifted components is the ejecting flux lope, while the lower part is the reconnection inflow.

This example demonstrates that the blue shifted component, such as found by Harra & Sterling (2001), is not necessarily outflowing material of CME, but it possibly comes from reconnection inflow. In order to clarify the physical origin of the Dopper shifted components, spatial relation with the ejections and X-ray arcade is important. In particular, a characteristics of reconnection inflow is that it appears as a pair of blue and red shifted components just above the X-ray arcade. We therefore emphasize that coodinated observation of EIS and XRT should be carefully planned to detect the reconnection inflows and investigate the origin of dimming.

4. Summary

We perform a numerical simulation of a Coronal mass ejection and associated an X-ray arcade. From the numerical results, we calculated soft X-ray, and EUV images and compare them with observations. From the comparison, we found following results.

A physical mechanism of dimming is shown by the numerical results. (1)expansion of plasma in the magnetic loop covering the flux rope; (2)expansion of the erupting structure; (3)rarefaction by reconnection inflow.

Shock structure associated with reconnection will be obsereved as Y-shaped structure. It may correspond to the inner boundary of dimming region.

Reconnection inflow appears as a pair of blue and red shifted components just above the X-ray arcade.

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