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Slow and Fast MHD Shocks Associated with a Giant Cusp-Shaped Arcade on 1992 January 24

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Abstract

We performed magnetohydrodynamic (MHD) simulations of a giant arcade formation with a model of magnetic reconnection coupled with heat conduction, to investigate the dynamical structure of slow and fast MHD shocks associated with reconnection. Based on the numerical results, theoretical soft X-ray images were calculated and compared with the Yohkoh soft X-ray observations of a giant arcade on 1992 January 24. The Y-shaped structure observed in the event was identified to correspond to the slow and fast shocks associated with the magnetic reconnection.

Key words: conduction — MHD — shock waves — Sun: corona

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; for example, the cusp-shaped flare loops, arcade structure of the loops, and so on (MacCombie, Rust 1979; Hanaoka et al. 1986; Tsuneta et al. 1992a; Tsuneta 1996; Forbes, Acton 1996). The soft X-ray telescope (SXT) on board Yohkoh also revealed many arcades associated with non-flare CMEs or filament eruptions (Tsuneta et al. 1992b; Hiei et al. 1993; Hanaoka et al. 1994; McAllister et al. 1996). 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 (Yamamoto et al. 2002).

Although much evidence has been found to support the magnetic reconnection mechanism, the slow and fast shocks predicted by reconnection theories (Petschek 1964; Forbes, Priest 1983; Ugai 1987) have not yet been identified. Masuda et al. (1994) suggested that the hard X-ray source above the loop top in an impulsive flare may be a fast shock created by the collision of a reconnection jet with the flare loop (see also Shibata et al. 1995). It has sometimes been considered that the temperature discontinuity at the edge of the cusp-shaped loop of a solar flare may be slow shocks. However, in solar flares, the plasma temperature is so high ($\geq 10^7$ K) that an adiabatic slow shock is dissociated into a conduction front and an isothermal slow shock (Forbes et al. 1989; Yokoyama, Shibata 1997; Chen et al. 1999). Therefore, the edge of the cusp-shaped loop may be a conduction front rather than a slow shock, while there is no observational evidence of an isothermal slow shock.

As described above, in observations, it is difficult to identify the slow MHD shock associated with the reconnection. Hence, a comparison between the observations and models is important. For example, Forbes and Acton (1996) compared the observations of flares with a model of cusp-shaped loops, but their semi-analytic model revealed only the appearances of cusp-shaped loops, and did not predict any signature of shocks in soft X-ray images. In this letter, in order to clarify the relation between the observed features and the dynamical structures of the shocks associated with the reconnection, we describe 2.5-dimensional resistive MHD simulations coupled with heat conduction as a model of giant arcades, and compare the numerical results with a cusp-shaped giant arcade on 1992 January 24 (Hiei et al. 1993). The time-dependent MHD simulations for magnetic reconnection, including heat conduction, were performed by a few investigators (Yokoyama, Shibata 1998, 2001; Chen et al. 1999). However, these simulations have not been compared with observations of "giant arcades". In this sense, this paper is the first trial to apply a simulation model (including reconnection and heat conduction) to actual observations of a giant arcade.

2. Observations and Numerical Model

2.1. Giant Cusp-Shaped Arcade on 1992 January 24

The giant cusp-shaped arcade on 1992 January 24 occurred on the south-west limb. Figures 1a and b show the Yohkoh/SXT images in its early phase. This event was analyzed by Hiei et al. (1993) and Glukhov (1997). The cusp-shaped loop appeared at 09:20 UT, and began to expand. The size of the loop increased from 2×10^{10} cm to 4×10^{10} cm until about 23:00 UT. Glukhov (1997) derived the temperature

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and density of the loop at 21:00 UT. They are $10^{6.54}$ K and $10^{8.6}\,\mathrm{cm}^{-3}$ at the top, and $10^{6.33}$ K and $10^{9.1}\,\mathrm{cm}^{-3}$ at the footpoint, respectively.

Associated with this event, the ejection of a "string-like feature" (Hiei 1994) was observed in SXT images (figure 1a) around 08:00 UT. Because this feature shows a bifurcated shape, we call it a "Y-shaped" structure. Hiei (1994) suggested that this feature seems to show a reconnection point. However, it is not clear whether the structure is truly a reconnection point or not.

2.2. Numerical Model

To simulate this event, we used the CME model of Chen and Shibata (2000). Two and a half-dimensional nonlinear time-dependent compressible MHD equations were solved with a multi-step implicit scheme (Hu 1989) 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 (see subsection 2.1 for the event and Yamamoto et al. 2002 for other arcades), which are $L_0 = 2\times10^{10}\,\mathrm{cm}$, $\rho_0 = 3.2\times10^{-16}\,\mathrm{g\,cm}^{-3}$ (i.e., $n_0 = 2\times10^{8}\,\mathrm{cm}^{-3}$), and $T_0 = 2\times10^{6}\,\mathrm{K}$, respectively. The unit of magnetic field, B_0, was assumed to be 11.8 G, which makes plasma β around flux rope to be 0.01. Time was normalized by $\tau_{\mathrm{A0}} = L_0/v_{\mathrm{A0}}$, where the local Alfvén velocity ($v_{\mathrm{A0}} = B_0/\sqrt{4\pi\rho_0}$) around the flux rope is equal to $2571\,\mathrm{km\,s}^{-1}$ and $\tau_{\mathrm{A0}} = 77.8\,\mathrm{s}$.

The initial magnetic configuration was similar to that in Chen and Shibata (2000), i.e., a quadrupolar field with a detached flux rope whose center was located at $(x, y) = (0, 2)$ (see Low 1994 for a review of flux rope). 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 emerging process was realized by changing the magnetic field at the bottom boundary within $-0.2 \le x \le 0.2$. The initial value of density and temperature were set uniformly, i.e., $\rho = \rho_0$ and $T = T_0$. The resistivity (η) is taken as an anomalous type as follows:

$$\eta = \begin{cases} \eta_0 \min\left(1, \left|\dfrac{v_{\mathrm{d}}}{v_{\mathrm{c}}}\right| - 1\right), & |v_{\mathrm{d}}| \ge v_{\mathrm{c}}, \\ 0, & |v_{\mathrm{d}}| < v_{\mathrm{c}}, \end{cases} \tag{1}$$

where $v_{\mathrm{d}} \equiv j_z/n$ is the (relative ion–electron) drift velocity, j_z is the current density, and the dimensionless parameters are assumed as $v_{\mathrm{c}} = 0.03$ and $\eta_0 = 0.02$. It is known that an anomalous resistivity which is caused by plasma instabilities (Coppi, Friedland 1971) triggers fast reconnection.

In this simulation, the resistivity and heat conduction were included, but gravity and radiative cooling were neglected, because we focus on the dynamic evolution of the region around the loop top of the arcade in its early phase. Glukhov (1997) showed the time scales of radiative cooling in the arcade: $10^{5.2}$ s at the top of the loop and $10^{3.1}$ s at the bottom of the loop. In fact, the time scales of conductive cooling, radiative cooling, and reconnection in initial state are $t_{\mathrm{cond}} \equiv (3nk_{\mathrm{B}}L^2)/(\kappa_0 T^{5/2}) \sim 3\times10^3$ s, $t_{\mathrm{rad}} \equiv (3nk_{\mathrm{B}}T)/[n^2 Q(T)] \sim 4\times10^4$ s, and $t_{\mathrm{rec}} \equiv [(3nk_{\mathrm{B}}T)/(B^2/4\pi)]\times\tau_{\mathrm{A}} \sim 97$ s, respectively, where k_{B} is the Boltzmann constant, $n = n_0 = 2\times10^8\,\mathrm{cm}^{-3}$, $T = T_0 = 2\times10^6$ K, $L = L_0 = 2\times10^{10}$ cm, $B = 3$ G, $v_{\mathrm{A}} = B/\sqrt{4\pi\rho} \sim 4.7\times10^7\,\mathrm{cm\,s}^{-1}$, $\tau_{\mathrm{A}} = L/v_{\mathrm{A}} \sim 420$ s, κ_0 ($= 10^{-6}$ CGS) is heat conduction coefficient along magnetic field (Spitzer 1962), and $Q(T) = 10^{-22}\,\mathrm{erg\,cm}^3\,\mathrm{s}^{-1}$ is the radiative loss function (Raymond et al. 1976). These values are initial ones of around the neutral point below the flux rope. Since t_{rad} is much longer than t_{rec}, we could neglect the effect of radiative cooling for this reconnection problem. Though t_{cond} is also longer than t_{rec} at the initial state, the effect of conduction cannot be neglected, because temperature increases due to reconnection heating, so that t_{cond} becomes comparable to or even shorter than t_{rec}. According to other research concerning the adiabatic case (Shiota et al. 2003, in preparation), after reconnection starts, the temperature of the heated plasma becomes comparable to 10^7 K, and therefore $t_{\mathrm{cond}} \sim 50\,\mathrm{s} < t_{\mathrm{rec}} \sim 97\,\mathrm{s}$.

The simulation box ($-8 \le x \le 8$, $0 \le y \le 12.5$) was discretized by 321×501 grid points, which were distributed non-uniformly in the x-direction and uniformly in the y-direction. The left boundary ($x = -8$), the right one ($x = 8$), and the upper one ($y = 12.5$) were free boundaries where the plasma, magnetic field, and waves could pass through freely. The bottom of the simulation box is a line-tying boundary where all quantities, except for T, are fixed outside of the emerging flux region. T was determined by extrapolation, i.e., the value was specified to be the same as that at its neighboring point.

3. Numerical Results

The global evolution of magnetic fields was almost the same as found in our previous study (Chen, Shibata 2000). 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 2a and b show the density and temperature distributions at $t = 100$ when the magnetic energy is released most rapidly. The temperature of the outflow decreases gradually, and that of the loop is $1.3(\pm0.2)\times T_0 \sim 2.6\times10^6$ K. The theoretical temperature of a flare loop, in which reconnection heating is balanced with conductive cooling, is expressed by $T \simeq 10^7 (B/50\mathrm{G})^{6/7} (n/10^9\mathrm{cm}^{-3})^{-1/7} (L/10^9\mathrm{cm})^{2/7}$ K (Shibata, Yokoyama 1999). With $B = 3$ G, $n = 2\times10^8\,\mathrm{cm}^{-3}$, and $L = 2\times10^{10}$ cm, this formula leads to $T = 2.6\times10^6$ K. Hence, the simulation result is consistent with the theoretical prediction.

Figure 1c 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 (Tsuneta et al. 1991) with the assumption that the line of sight is parallel to the z-axis with a certain depth. In figure 1c, a Y-shaped structure and a cusp-shaped loop can be discerned. The Y-shape in the theoretical X-ray image is similar to the observational counterpart (figure 1a), which are shown by arrows.

What is the physical nature of the Y-shaped structure? The theory of magnetic reconnection (Petschek 1964) predicts the

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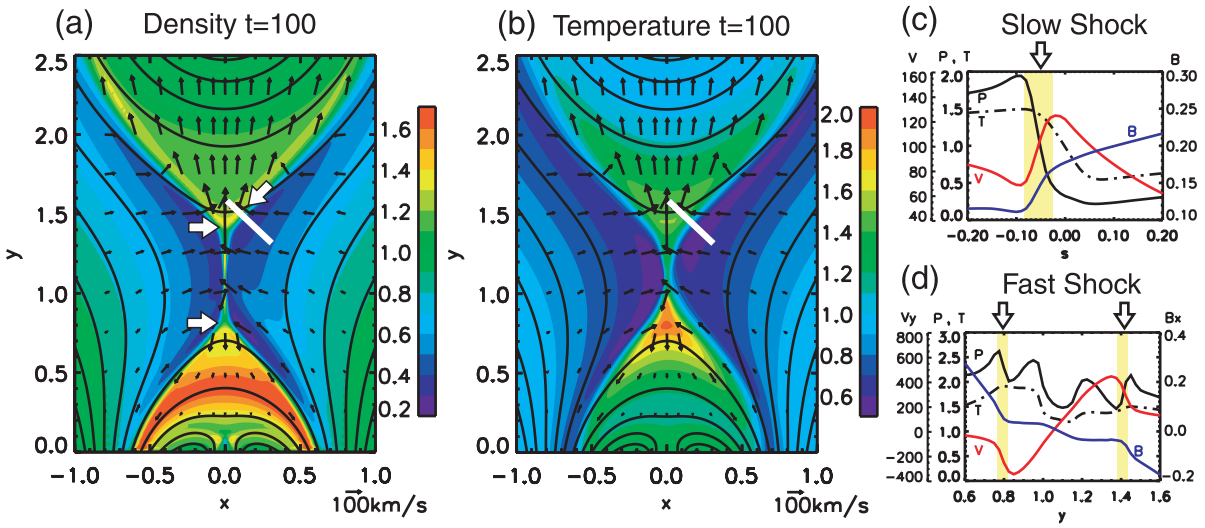

Fig. 2. Panels (a) and (b) show the density and temperature distributions at $t = 100$ in the simulation. The solid curves denote magnetic field lines, and arrows represent velocity vectors. Panel (c) displays distributions of gas pressure (P), velocity (v), magnetic field (B), and temperature (T) along the white line in panels (a) and (b). In panel (c), the slow shock region is highlighted by the yellow shadows, and the coordinate s is set along the white line whose center corresponds to $s = 0$. Panel (d) displays distributions of the physical quantities along the y-axis at $x = 0$, where the fast shock regions are also highlighted by the yellow shadows. The white arrows in panel (a) indicate the shock positions.

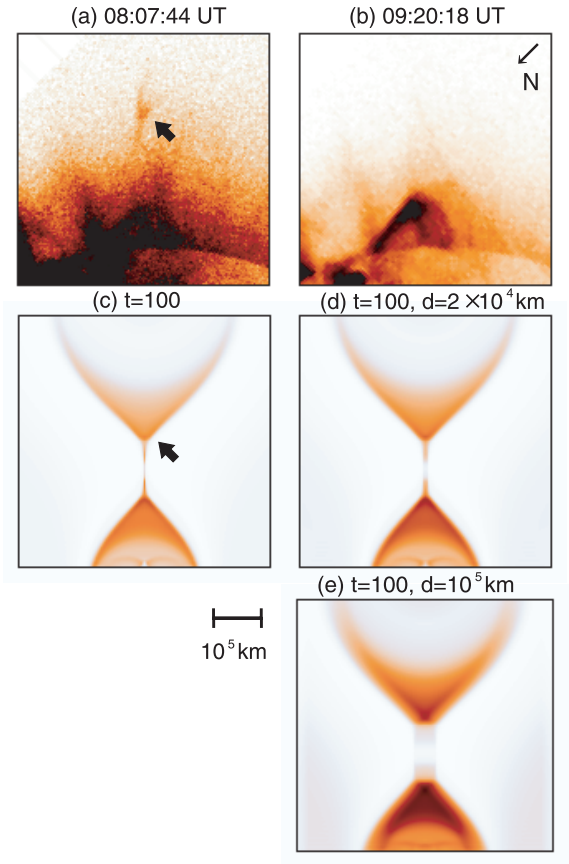

Fig. 1. Panels (a) and (b): Soft X-ray images of a giant arcade on 1992 January 24, taken with Yohkoh/SXT. Panel (a) was taken with AlMg filter at half resolution ($\sim 5''$) at 08:07:44 UT. Panel (b) was taken with Al.1 filter at quarter resolution ($\sim 10''$) at 09:20:18 UT. The north direction is shown in panel (b). Panels (c), (d), and (e): Theoretical SXT images with Al.1 filter calculated from the simulation results. Panel (c) is produced with the assumption that the plane is perpendicular to the line of sight. Panels (d) and (e) are viewed with a horizontal angle of $24.^\circ 2$ with the depths of 2×10^4 km and 10^5 km, respectively.

existence of a slow shock pair associated with reconnection. In figure 2c, we plot the distributions of several physical quantities (gas pressure, temperature, parallel component of velocity, and transversal component of magnetic field) along the white line shown in figures 2a and b. We can see a discontinuous region which corresponds to a shock (shown by the arrow in figure 2c). The quantities ahead of and behind the shock are roughly consistent with the Rankine–Hugoniot relations for slow shocks. Exactly speaking, these slow shocks are not the ones attached to the reconnection (as predicted by Petschek), but those attached to the plasmoid (e.g., Ugai 1995).

The reconnection theory also predicts fast shocks (Forbes, Priest 1983; Ugai 1987). The cross point of the Y-shaped structure is slightly brighter than the other parts in the calculated images (figure 1c), which may correspond to the fast shock. In order to confirm this, we show the distributions of some physical quantities along the y-axis in figure 2d. Discontinuous regions seen around $y = 0.8$ and 1.4 are fast shocks because the velocities in front of the discontinuous regions exceed the local fast-mode magnetosonic speed. Again, it has been confirmed that these quantities satisfy the Rankine–Hugoniot relations for fast shocks.

4. Discussion

In the previous section, we discussed an SXT image (figure 1c) based on numerical results with an assumption that the line of sight is parallel to the z-axis at a certain depth. However, the assumption in figure 1c is very optimistic since it is difficult to truly know the orientation of the loops. The orientation of the loops may have a huge effect on the appearance of the loops in the images, as has been demonstrated by, e.g., Forbes and Acton (1996) and Glukhov (1997). Therefore, we have to consider the effect of the orientation of the loops in order to compare the observed image with the calculated

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one. Glukhov (1997) analyzed the same event, and obtained an orientation of $\theta = 24.^\circ2$. We calculated the image of the arcade while assuming the orientation to be $\theta = 24.^\circ2$ and the depth to be 2×10^4 km (figure 1d) and 10^5 km (figure 1e), because we also cannot know the depth of the arcade from only the observed images. The two values are assumed to be equal to the width of the Y-shape and the arcade, respectively. The Y-shape in figure 1d is also similar to the observation (figure 1a). Furthermore, in figure 1e, we can see a faint current sheet-like feature observed above the arcade in figure 1b.

As discussed in section 1, the cusp-shaped structures, when discovered in flares or arcades, were thought to be slow shocks associated with reconnection. In flares, however, the temperature of reconnection outflow becomes so high that a slow shock is dissociated into a conduction front and an isothermal slow shock (Forbes et al. 1989; Yokoyama, Shibata 1997). Therefore, the outer edge of the cusp-shaped structures, i.e., the temperature discontinuity, in flares observed by Yohkoh/SXT is likely to be the conduction front (Yokoyama, Shibata 1998). On the other hand, the temperature of arcades is not as high as that of flares. Therefore, the slow shock may not be dissociated. In fact, in figure 2c, the discontinuous region of temperature is only slightly wider than those of other quantities. Therefore, we propose that in the arcade event, the Y-shaped structure corresponds to slow and fast shocks.

Figure 3 shows the observed height evolutions of the cross point of the Y-shaped structure (triangles) and that of the cusp (rectangles), where the solid and dashed lines were their counterparts in our simulation. It can be seen that the height evolution of the Y-shaped structure in the simulation is consistent with the observations, and that of the cusp has almost the same tendency as the observations with a $\sim 5 \times 10^9$ cm shift in the y-axis. The shift is simply due to the higher magnetic loop below the null point in the initial magnetic configuration of our model.

The simulated X-ray intensity (in figures 1c, d, and e) of the flux rope is stronger than the observational counterpart (figure 1a). This is probably because gravity was neglected in our simulations, and the density is larger than the actual one. Such an effect will be discussed in our future paper. Despite the differences, our model is sufficient for studying slow and fast shocks.

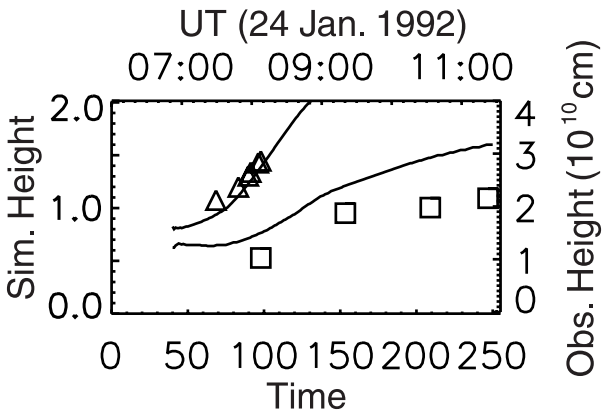

Fig. 3. Height evolutions of the Y-shaped structure (triangles) and the cusp (squares) in the observations. The height of the cusp is defined as the position where the intensity is $10\,\mathrm{DN\,s^{-1}}$. The height evolutions of the upper and lower fast shocks in numerical results are superimposed as solid and dashed lines, respectively. The units of height and time for numerical results are $L_0 = 2 \times 10^{10}$ cm and $t_0 = 77.8$ s. Note that the units of the simulation are not arbitrary, because the heat conduction coefficient varies with them.

We conclude that the Y-shaped structure observed on 1992 January 24 corresponds to the slow and fast shocks associated with magnetic reconnection. Consequently, we can say that the slow and fast shocks associated with magnetic reconnection are identified for the first time in solar flares.

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