Magnetic Reconnection Coupled with Heat Conduction

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Abstract. Magnetic reconnection coupled with anisotropic nonlinear heat conduction is studied by using MHD simulation. Due to the heat conduction effect, the adiabatic slow-mode MHD shocks emanating from the neutral point are dissociated into conduction fronts and isothermal shocks. An MHD simulation of chromospheric evaporation is also performed.

1. Introduction

Heat conduction plays an important role in energetic phenomena in the solar corona. It is because the time scale of heat conduction is almost comparable with that of a flow, i.e., the Alfvén time scale, and is even faster when a flare occurs since heat conductivity increases with increasing temperature. Moreover, because heat conductivity is anisotropic depending on the field direction (e.g., Priest 1982), the physical structure of the energy release site should be affected by heat conduction. In the magnetic reconnection model of flares (e.g., Shibata et al. 1995), the magnetic energy is considered to be converted into the kinetic and the thermal energy at the slow-mode MHD shocks emanating from the magnetic neutral point. This released thermal energy could be transported due to the heat conduction effect. This effect would change the structure of the shocks and also change the release rate of the energy. In order to study this, we developed a numerical MHD code which includes anisotropic heat conduction (Yokoyama 1995). Using this code, we performed a two-dimensional simulation of the magnetic reconnection.

2. Models

The initial condition of the simulation is similar to that of the study by Ugai & Tsuda (1977). In the \(xz\)-plane, it is in magnetohydrostatic equilibrium with antiparallel magnetic fields (positive \(x\)-direction in \(z > 0\) and negative in \(z < 0\)), between which there is a current sheet. The plasma beta, the ratio of the gas pressure to the magnetic pressure, is taken to be \(\beta = 0.1\). The initial temperature is uniform and taken to be \(T = 10^6\) K. The initial density is \(10^9\) cm\(^{-3}\) outside the current sheet. In these initial conditions, the Alfvén transit time is comparable to the conduction time. The resistivity is localized near the origin in the current sheet, where magnetic reconnection occurs. The magnetic Reynolds number, which is defined by the thickness of the initial current sheet, the ini-
Temperature

**Without conduction**

**With conduction**

![Graph showing temperature distributions with and without conduction](image)

Figure 1. Two-dimensional distributions of the results for the case *without* heat conduction [upper panel] and that for the case *with* heat conduction [lower panel]. Temperature (gray scale), magnetic field lines (solid lines), and velocity vectors (arrows) are displayed. The levels of gray scale are shown to the left. The unit of velocity vectors is shown at the right top of the figure, whose size is $V = 5.0$ in units of the sound velocity outside the current sheet. The unit of length is the initial half-thickness of the current sheet.

Initial Alfvén velocity outside, and the resistivity at the origin, is $R_m \approx 30$. We solved the two-dimensional, nonlinear, time-dependent, resistive, compressible MHD equations. For heat loss and gain, Ohmic heating and heat conduction are taken into account. The conduction coefficient is the Spitzer-type one which is proportional to $T^{5/2}$ and anisotropic, working only in the direction along the magnetic field line. The specific heat ratio is taken to be $\gamma = 2$. We compared the results of calculations in the two cases *without* and *with* heat conduction.

3. Results

The upper panel of Figure 1 shows the results in the case *without* heat conduction. Note that Figure 1 shows only the half region, i.e. $x > 0$. Initially, $B_x$ is positive in $z > 0$ and negative in $z < 0$ and there is a current sheet in
Figure 2. Two-dimensional distributions of the temperature [left panels] and the pressure [right panels] for the case without heat conduction [upper panels] and that for the case with heat conduction [lower panels]. The others are the same as in Figure 1.

$-1 < z < 1$. Reconnection occurs at the origin in this current sheet where localized resistivity is assumed. The reconnected field lines together with the frozen plasma are ejected from the neutral point at the origin to the positive and negative $x$-directions due to the tension force of the reconnected field lines. To complement this outflow, an inflow takes place from positive and negative $z$-directions of the current sheet. At the boundary between this inflow and the outflow a slow-mode MHD shock is formed, which is predicted by Petschek (1964) in his reconnection theory. Since there are two sets of inflow, from the positive and the negative $z$-directions, a pair of the shocks is formed, emanating from the neutral point. The close-up plot (upper panels of Figure 2) shows a clear jump of the pressure at these shocks. The temperature in the region between these shocks is higher than that outside this region (Figure 2). This is due to the shock heating.

In the case with heat conduction, the apparent distribution of the temperature is very different from the previous case (lower panel of Figure 1). The high temperature region is broader than that in the case without heat conduction. The outer boundary of this high temperature region is a conduction front. Since the heat conducts only to the direction along the magnetic field line and the propagation of the conduction front is very fast, the conduction front traces the magnetic field line from the neutral point, namely separatrices. In the pressure distribution (lower right panel in Figure 2), there is a strong jump structure the position of which is not coincident with that of the conduction front. The velocity and the magnetic field change their directions and magnitudes at the pressure discontinuity. Nevertheless, there is no jump in the temperature. Thus, this discontinuous structure is understood to be an isothermal slow-mode MHD shock. We can interpret this result after Forbes et al. (1986) as follows: The plasma which crossed the shocks is heated due to the shock heating. Thus, there
Figure 3. Dependence of the reconnection rate and various energies on the density. Note that the heat conductivity decreases with the increasing density. The reconnection rate is measured as the electric field at the reconnecting point, namely the origin in the present simulation. The energies are the variation from the initial values and measured at a certain moment. The magnetic energy is $\Delta E_m$, the kinetic energy is $\Delta E_k$, and the thermal energy is $\Delta E_t$. The dotted line shows the results of the case without conduction.

formed a temperature gradient across the shocks. The temperature gradient generates a propagating heat conduction front, and hence the adiabatic slow-mode shock is dissociated into a conduction front and an isothermal slow-mode shock. This will end up in leakage of the heat due to the conduction across the shocks toward the upflow region. In summary, the effect of the heat conduction is to make the adiabatic slow-mode MHD shocks emanating from the neutral point to be dissociated into conduction fronts and isothermal shocks.

The dependence of the reconnection rate and the energy release rates on conductivity is another interesting issue. We studied this dependence by changing the value of the initial density. Since the time scale of the heat conductivity is proportional to the density, the conductivity decreases as the density increases. Figure 3 shows the results. Although we changed the value of the density by four orders of magnitude, there is very weak dependence. Thus, we conclude that the reconnection is weakly affected by the heat conductivity in the present model. However, this conclusion may be strongly biased by the resistivity model assumed in the present study, in which the resistivity is fixed in space as well as in time to realize the steady localized resistivity. This might give a strong limitation to the structure of the diffusion region near the neutral point. In other resistivity models, e.g., the model in which the magnitude of the resistiv-
Figure 4. Results of the simulation of chromospheric evaporation. The left and right columns show the temporal evolution of temperature and density distribution, respectively. The arrows show the velocity, and lines show the magnetic field lines. The unit of length, velocity, time, temperature, and density is 2000 km, 140 km s\(^{-1}\), 15 s, 10\(^6\) K, and 10\(^8\) cm\(^{-3}\), respectively. In the initial condition (t = 0) a dense region is located near the left side of the simulation box in which the density is about 10\(^5\) times that of the other region.
ity depends on the current density, there is a possibility that this conclusion will be changed. We need more study in order to see the effect.

4. Simulation of Chromospheric Evaporation

Chromospheric evaporation (Hirayama 1974) is an explosive ablation of chromospheric plasmas, which is associated with energetic phenomena in the corona, such as flares. The thermal energy released by magnetic reconnection in the corona is transported to the upper chromosphere. The dense chromospheric plasmas suddenly become hot and expand, leading to an upflow along the field lines. We performed a two-dimensional MHD simulation of this phenomenon. The initial conditions are similar to that of the simulation described in the previous sections. There are two main differences: 1) A dense region, whose density is $10^5$ times that of the other area, is located near the left boundary. This represents a very idealized model of a chromospheric plasma. The magnetic field lines are well line-tied due to the large inertia of the heavy plasma. 2) The resistivity-enhanced region is localized near the point $(x, z) = (30, 0)$ not near the origin, where magnetic reconnection is expected to proceed. Gravity is not considered for simplicity. Symmetric boundary conditions are adopted for the left boundary. The results are shown in Figure 4. The top panels indicate the initial conditions $(t = 0)$. The thermal energy released near the reconnection site $(x, z) = (30, 0)$ is conducted along the field lines as described in the previous sections $(t = 20)$. Two kinds of structures, the heat conduction front and the slow-mode isothermal MHD shock, are also found. However, in this simulation, the conducted heat goes further down into the dense plasma. It causes a pressure increase due to the penetrated heat and generates a back-flow of the dense plasma into the corona. The spike-like feature emanating from $(x, z) = (2, 3)$ to $(8, 4)$ in the panel of $t = 30$ is the evaporated plasma. The velocity of this back-flow is about local sound speed. At $t = 40$, it is seen that the reconnected loops whose footpoints are rooted at $-7 < z < 7$ are filled with the evaporated dense plasma. The hot region (left panel of $t = 40$) shows a clear cusp-like structure which is consistent with the Yohkoh observations of flares (Tsuneta et al. 1992).

References

Yokoyama, T. 1995, PhD thesis, the Graduate Univ. for Advanced Studies

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