THREE DIMENSIONAL ANALYSIS OF SHOCK STRUCTURE AROUND MAGNETIC LOOP ASSOCIATED WITH SPONTANEOUS FAST MAGNETIC RECONNECTION

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ABSTRACT

Three dimensional dynamics of a magnetic loop is studied by magnetohydrodynamic simulations on the basis of the spontaneous fast reconnection model. In this model, petschek type fast reconnection is represented, so that a pair of slow shocks elongated from magnetic diffusion region and fast shock in front of magnetic loop top stand. It is interesting and important to study about three dimensional dynamics of these shock surfaces.

Key words: Magnetic Loop; Shock; Reconnection.

1. INTRODUCTION

A large scale magnetic loop have been observed in a various regions such as solar corona (Hanaoka and Sakurai, 2001), near-Earth magnetotail (Sergeev and Kubyshkina, 1996), and so on. Recent satellite observations have shown that dynamics of large-scale magnetic loop heating is fundamental for solar flares (Tsuneta, 1996). Masuda et al. (1994) analyzed the Yohkoh data for compact flares and discovered strong energetic plasmas in a spot-like region just ahead of the magnetic loop top, indicating that magnetic reconnection is fundamental even for compact flares. Shibata (1996) proposed that distinct solar phenomena may be interpreted in a unified manner in terms of drastic occurrence of magnetic reconnection. The fast magnetic reconnection process responsible for these magnetic loop heating should involve a large-scale motor effect as the dominant magnetic energy converter. Theoretical models on the fast reconnection mechanism have been studied mainly on the basis of magnetohydrodynamics (MHD). We have proposed the spontaneous fast reconnection model, which describes a new-type nonlinear instability in a long current sheet system (Ugai, 2001). The basic idea lies in the following positive feedback: the self-consistent coupling between (microscopic) current-driven anomalous resistivity and (macroscopic) global reconnection flow gives rise to simultaneous growth of localized anomalous resistivity and fast reconnection flow by enhancing each other.

The detailed 2-D structure of large-scale magnetic loop is demonstrated (Ugai, 1999); in particular, it is demonstrated that a fast shock builds up and impulsively stands in front of the magnetic loop top. It is fundamental to study the large-scale magnetic loop dynamics in three dimensions. As already shown in a simplified 3-D situation, the fast reconnection mechanism may build up and proceed in a finite extent in the $z$ direction Ugai et al. (2003). The fast reconnection jet, associated with the resulting slow shocks, is also confined in the $z$ direction. Therefore, we are interested in how the spontaneous fast reconnection model works to bring about a 3-D magnetic loop structure in the present specific situation.

2. SIMULATION MODEL

2.1. Initial and Boundary Problem

As an initial configuration, one-dimensional antiparallel magnetic field $\mathbf{B} = (B_x(y), 0, 0)$ is assumed: The plasma pressure $P(y)$ initially satisfies the pressure-balance condition,

$$P + B_x^2 = 1 + \beta_0,$$

where $\beta_0$ is the ratio of the plasma pressure to the magnetic pressure in the ambient magnetic field region, so that $P(y = 0) = 1 + \beta_0$ initially (in the present study, $\beta_0 = 0.15$ is taken); also, constant density $\rho(y) = 1$ is assumed with fluid velocity $\mathbf{u} = (0, 0, 0)$.

The normalization of quantities, based on the initial quantities, is self-evident: Distances are normalized by the half-width of the current sheet $d_0$, $B$ by the field strength in the magnetic field region $B_{\infty}$, and $P$ by $B_{\infty}^2/(2\mu_0); also, u by V_{A0}(= B_{\infty}/\sqrt{\mu_0 \rho_0})$, time


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2.2. Anomalous Resistivity

As in the 2-D model, a current-driven anomalous resistivity model is assumed in the form:

\[ \eta(\mathbf{r}, t) = \begin{cases} k_R [V_d(\mathbf{r}, t) - V_C] & \text{for } V_d > V_C, \\ 0 & \text{for } V_d < V_C, \end{cases} \]

where \( V_d(\mathbf{r}, t) = |J(\mathbf{r}, t)/\rho(\mathbf{r}, t)| \) is the relative electron-ion drift velocity, and \( V_C \) may be a threshold for microinstabilities. Here, \( k_R = 0.003 \) and \( V_C = 4 \) are taken. Then, as in the 2-D model, in order to disturb the initial static configuration, a localized resistivity is assumed in the 3-D form,

\[ \eta(\mathbf{r}) = \eta_0 \exp\left[-\left((x - L_x)/k_x\right)^2 - (y/k_y)^2 - (z/k_z)^2\right]. \]

Here, we take \( k_x = k_y = 0.8 \) and \( \eta_0 = 0.02 \) in the manner similar to the previous 2-D simulations; also, \( k_z \) provides the three-dimensional effects, and for the smaller \( k_z \), the three-dimensional effect becomes larger. This initial disturbance is imposed only in the time range \( 0 < t < 4 \), and the anomalous resistivity model Eq.2 is assumed for \( t \geq 4 \). Hence, the fast reconnection mechanism may be triggered at \( x = L_x \) in this model.

3. RESULTS

The first point to be examined is the three-dimensional reconnection process, discussed about fundamental three-dimensional fast reconnection mechanism. As mentioned in their paper, only when the central current sheet is sufficiently long in the \( z \) direction, that is to say, \( k_z \) in eq.3 is sufficiently large, the fast reconnection mechanism fully evolves. Fig.1 shows the temporal variations of the electric field \( E_z \) measured on the \( x=L_x \) line. Right panel in fig.1 is that projected the same profile with left panel to \( z-E_z \) plane so as to be easy to see. The finite resistivity observed in \( 0 < t < 4 \) simply corresponds to the initial disturbance, and for \( t > 4 \) there is no resistivity anywhere until the threshold \( V_C \) is exceeded. Then, magnetic reconnection rapidly evolve with finite width in the \( z \) direction. The width of diffusion region is almost constant all the time.

In order to see the formation and development of the 3-D magnetic loop, fig.2 shows the resulting plasma pressure configurations at \( T=36 \) (top panel), when the plasmoid has just arrived at the left (mirror) boundary and the magnetic loop begins to be formed. Bottom panel in fig.2 shows the plasma pressure configurations at \( T=45 \), when the 3-D large-scale magnetic loop is fully set up, and new strong high pressure region appears in front of magnetic loop. The high pressure region also appears around magnetic foot point at \( T=45 \). The resulting 3-D magnetic
loop remains to be effectively confined in a finite extent in the z-direction, despite that plasma pressure is notably enhanced inside the magnetic loop. The plasma pressure distributions in the magnetic loop at $t = 36$ and $45$ indicates that the magnetic loop at $t = 45$ is effectively confined in the z direction near the left boundary $(x = 0)$. Hence, the fast reconnection jet, accelerated by a pair of standing slow shocks with a small angle, is obstructed by the magnetic loop, so that if the fast reconnection jet becomes supersonic, a fast shock should stand at the interface between the magnetic loop and the fast reconnection jet. We find that the fast reconnection jet becomes supersonic (or superfast), so that a definite fast shock stands in front of the magnetic loop in the time range $40 < t < 50$.

In two dimensional cases, we examined the fast shock configuration in detail (Ugai, 1999). In order to examine the three dimensional structure of fast shock surface, fig.3 shows the time variation of three dimensional fast shock surface and magnetic field lines on the $(x,y)$ plane, at $T=45$ (left panel) and at $T=48$ (right panel). Fast shock stands in the very restricted extent in the z direction and in front of the new high pressure region mentioned above. The shape in the z direction changes as time goes by, however, curved shape on the parallel plane with the $(x,y)$ plane is kept while it appears. It moves to positive x direction, and then disappears around time $T=50$.

Nextly, we show the three dimensional slow shock surface configurations in fig.4. These figure shows the time profile of slow shock surfaces, at $T=36$ (left panel), $T=45$ (middle panel) and $T=48$ (right panel). A pair of slow shocks elongated from diffusion region keep the width in z direction and the length in x direction all the time. The width of that is nearly same with that of diffusion region. On the other hand, slow shock around magnetic loop is very clear and smooth curved surface at $T=36$. However, the shape of it collapses from positive z direction in gradually, but it around the region over x-axis is very clearly kept.

4. CONCLUSION

The three dimensional dynamics of shock surfaces following to magnetic loop is studied by precise magnetohydrodynamics simulations on the basis of spontaneous fast reconnection model. The initial disturbance eq.3 is imposed at $x = L_x = 10$ in a finite extent in the z direction ($R_Z = 5$), and the left plane boundary at $x = 0$ is assumed to be a mirror boundary across which plasma cannot flow. In this specific 3-D situation, our main concerns have been directed to how each shock surface is formed and growth in time.
Figure 3. Time profile of three dimensional fast shock surface and magnetic field lines on the \((x,y)\) plane, \(T=45\) (left panel) and \(T=48\) (right panel).

Figure 4. Time profile of three dimensional slow shock surface and magnetic field lines on the \((x,y)\) plane, \(T=36\) (left panel), \(T=45\) (middle panel) and \(T=48\) (right panel).
The major results may be summarized as follows:
(1) Fast shock surface forms in the very extent region, and have curved surface on the plane parallel to the \((x, y)\) plane. Fast shock propagates to positive \(x\) direction keeping the curved surface, and disappear within a short period. The shape in the \(z\) direction changes influenced strongly by the flow pattern as time goes by.
(2) A pair of slow shocks elongated from diffusion region have a almost same width with that of diffusion region, and it is kept for a long time.
(3) Slow shock surround large magnetic loop has very smooth and large shape until fast shock appears in front of magnetic loop. Then, it has lost its shape from the outside, that is, the region in positive \(z\)-direction.

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REFERENCES


