Numerical study of magnetic reconnection possibly occurring near heliospheric current sheet

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Abstract

The third-order accurate upwind compact difference scheme has been applied for the numerical study of the magnetic reconnection driven by a plasma blob impacting the heliospheric current sheet, under the framework of the two-dimensional compressible magnetohydrodynamics. The results show that the driven reconnection near the current sheet could occur in about 10–30 min for the interplanetary high magnetic Reynolds number, $R_M = 2000–10,000$, a stable magnetic reconnection structure can be formed in hour order of magnitude, and there appear some basic properties such as the multiple X-line reconnections, vortex structures, filament current systems, splitting and collapse of the high-density plasma blob. These results are helpful in understanding and identifying the magnetic reconnection phenomena possibly occurring near the heliospheric current sheets.

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1. Introduction

The magnetic reconnection is an important physical phenomenon that is paid broad attention to in solar physics and magnetospheric physics (Hones, 1984; Axford, 1984; Cowley, 1985; Lee, 1995). The problem whether the magnetic reconnection could occur in interplanetary space has not been answered for a long time. Previous works concentrate on finding the interplanetary remnants of the closed-structures formed by magnetic reconnection process occurring in the solar atmosphere, based on the inference from partial observations or the numerical study of the coronal mass ejection (CME) (Geranios, 1982; Dryer, 1994). There are little works on the direct observation evidences and the correlative numerical investigations (Moldwin et al., 1995). Recently, Wei et al. (1997) presented some preliminary results for the magnetic reconnections possibly occurring in interplanetary space, including the observational evidences obtained by Helios spacecraft and the numerical simulation study. New theoretical works and observational evidences for rapid magnetic reconnection in the Earth’s magnetosphere have been proposed (Shay et al., 1999; Drake et al., 1994; Deng and Matsuboto, 2001; Øieroset et al., 2001). Many investigations have been made in the symmetric driven reconnection in the solar atmosphere and the earth’s magnetosphere by incompressible MHD models (Lee, 1995; Cargill et al., 1996; Wang and Zheng, 1991; Liu et al., 1998). These progresses promote us to make some attempt in the numerical study of the magnetic reconnection phenomena in interplanetary space. Here, the third-order accurate upwind compact difference scheme with high accuracy and low numerical viscosity is first used under the framework of the two-dimensional compressible MHD, in order to ensure the reliability of
physically magnetic reconnection. The objective here is, by the numerical test, to probe into the possibility of the magnetic reconnection occurring near the heliospheric current sheet under high magnetic Reynolds number \( R_M = 2000-10,000 \) and to understand the related spacecraft’s observations (Wei et al., 1997; Klein and Burlaga, 1982).

2. Basic model and governing equations

We adopt a simple physical model to qualitatively understand the possibility of magnetic reconnection in interplanetary space. Because the key is the problem whether the reconnection could occur near the heliospheric current sheet under the typical interplanetary conditions, the work will be focused on the interaction between the moving plasma blob and the heliospheric current sheet. Here, the plasma blob is only a simplification of CME/magnetic clouds, in which some complex factors, such as their flux rope structure, propagation and the background solar wind structure, will not be involved. To this end in the model, we assume that a plasma blob with \( \rho = 5\rho_0 \) moves at the initial velocity \( V_M = 2V_{A0} \) at the driven boundary \( y = 8L \) towards one side of the current sheet, and magnetic field lines for \( y > 0 \) region are antiparallel to that for \( y < 0 \) region, and the current sheet is a region near \( y = 0 \). It should be noticed that when the blob reaches the current sheet, its velocity will decrease to \( \approx 0.4V_{A0} \) due to the resistance of the background medium. Where \( L \) is the half-width of the current sheet, \( 1.5 \times 10^5 \) km, and \( V_{A0} = \frac{B_0}{\sqrt{4\pi\rho_0}} \).

In order to study the asymmetric driven-magnetic reconnection possibly occurring near the heliospheric current sheet as mentioned above, a set of two-dimensional compressible MHD equations is adopted as follows:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} \left( \rho V_x \right) + \frac{\partial}{\partial y} \left( \rho V_y \right) &= -\frac{\partial p}{\partial x} - \beta \rho \left( V_x \frac{\partial \Psi}{\partial x} + V_y \frac{\partial \Psi}{\partial y} \right), \\
\frac{\partial V_x}{\partial t} + \frac{\partial}{\partial x} \left( \rho V_x^2 \right) + \frac{\partial}{\partial y} \left( \rho V_x V_y \right) &= -\frac{\partial p}{\partial x} - \beta \rho \left( V_x \frac{\partial \Psi}{\partial x} + V_y \frac{\partial \Psi}{\partial y} \right), \\
\frac{\partial V_y}{\partial t} + \frac{\partial}{\partial x} \left( \rho V_x V_y \right) + \frac{\partial}{\partial y} \left( \rho V_y^2 \right) &= -\frac{\partial p}{\partial y} - \beta \rho \left( V_x \frac{\partial \Psi}{\partial x} + V_y \frac{\partial \Psi}{\partial y} \right), \\
\frac{\partial \Psi}{\partial t} + \frac{\partial}{\partial x} \left( \rho \frac{\partial \Psi}{\partial x} \right) + \frac{\partial}{\partial y} \left( \rho \frac{\partial \Psi}{\partial y} \right) &= \frac{\partial}{\partial x} \left( \frac{\partial \Psi}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\partial \Psi}{\partial y} \right) + \frac{c^2}{4\pi} \left( \frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} \right), \\
\frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left( \rho \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left( \rho \frac{\partial p}{\partial y} \right) &= \frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y}, \\
p &= \rho RT,
\end{align*}
\]

where the magnetic field vector is \( \vec{B} \) expressed by a magnetic vector potential \( \Psi, \vec{B} = -\nabla \times (\vec{\Psi} \vec{e}_z) \). The parameters \( \rho, \beta, \mu, \vec{V}, \vec{B}, R, c \) and \( \gamma \) have their ordinary meanings, respectively. \( \eta \) is the magnetic diffusivity and the magnetic Reynolds number is defined as \( R_M = \frac{\beta \eta b^2 A_0^2}{\rho c^2} \). In our numerical simulation, the above set of the equations is used in a dimensionless form.

The initial equilibrium state of current sheet is considered to be one-dimensional form as follows:

\[
\begin{align*}
\vec{B}_0(y) &= B_\infty \tanh \left( \frac{y - y_0}{L} \right) \frac{y}{L}, \\
\rho_0(y) &= \rho_\infty + \frac{B_\infty^2}{8\pi RT_0} \sec h^2 \left( \frac{y - y_0}{L} \right), \\
V_0 &= 0.
\end{align*}
\]

The algorithm used in this paper has already been presented in the paper (Wei et al., 2002). In the numerical simulation here, the computational domain is \( 0 \leq x \leq 8L, -10L \leq y \leq 8L \), and \( x = 8L, y = -10L \) and \( x = 0 \) are, respectively, taken as the free and symmetric boundaries, which could not affect the vertical and transverse motions of the plasma blob. The grid mesh is chosen to be an equidistant mesh \( 66 \times 145 \), the time step still satisfies the stability condition, in which Courant constant \( C_i = 0.1 \). The typical interplanetary solar wind parameters, \( B_0 = 8.33 \text{nT}, N_0 = 5 \text{ Proton/cm}^3, T_0 = 1 \times 10^5 \text{K}, \gamma = 5/3, \beta = 2.0, \ R_M = 2000 \) are adopted in the simulation.

3. Main results and discussions

Fig. 1 shows the numerical result of the evolution of the magnetic field lines with time. The configuration at \( t = 0.0T_A \) is the basic state. Here, \( T_A = L/V_{A\infty} \approx 30 \text{ s} \), in which \( V_{A\infty} \) is the Alfvén speed away from the current sheet. After \( t = 10T_A \), the current sheet becomes thinner in the region impacted by the plasma blob. The motions of the plasma blob leads to the twist of the magnetic field lines and the magnetically closed structures begin to appear in the inner of the plasma.

Fig. 1. Magnetic reconnection driven by the plasma bulk moving towards the current sheet under the interplanetary conditions \( (R_M = 2000) \): the evolution of the magnetic configuration.
blob; when $t = 18 \tau_A$, the obvious single X-line recon-
nections begin to develop in the region of the current sheet, 
afterwards they evolve towards multiple X-line recon-
nection and form a number of magnetic island struc-
tures. They move towards the left and the right sides 
along the current sheet at the speed of about $0.5 V_A$, 
which is caused by the magnetic annihilation; meanwhile 
the complex evolution also occur among the magnetic 
islans with different scales in the inner of the plasma 
blob. After $t = 36 \tau_A$ the evolution slows down and 
becomes stable gradually. It takes about 15 min from 
the beginning of reconnection to its stabilized structure. 
The beginning of the magnetic reconnection will be $5 \tau_A$ 
later for $R_M = 10,000$ than that for $R_M = 2000$, but the 
magnetic island structures of the multiple X-line also 
exhibit more variety of patterns.

Fig. 2 plots the contours of the current density $j = \nabla^2 \psi$ at different times (the solid and dotted lines rep-
resent the positive and negative values, respectively). It 
can be seen that there are complex current systems, 
which correspond to the complex magnetic structures in 
the inner of the plasma blob. The heliospheric current 
sheet is basically coincident with the position of higher 
current density region, but the maximum current density 
appear in those parts where magnetic reconnections occur in the current sheet. From $t = 36 \tau_A$, the dense 
regions of the current show many branches, the multiple 
X-line reconnection regions are correspondent to the 
maximum regions of the current, and the whole current 
system gradually becomes stable. These fine current 
structures, possibly existing in the magnetic recon-
nction process under high magnetic Reynolds number, 
are revealed due to the application of the numerical sim-
ulation method with high accuracy (Wei et al., 2002).

Fig. 3 displays the numerical results of the evolution 
for the plasma density (upper) and the velocity vector (below). When $t = 10 \tau_A$, it can be seen from the figure 
that the high-density plasma blob moving to the current 
sheet makes the current sheet obviously being com-
pressed, a bow region with high density appears, and 
the plasma blob itself expands as a crescent moon with 
two bent hooks; when $t = 26 \tau_A$ the initial spherical plas-
ma blob is roughly divided into two blobs; and after 
t = 60 $\tau_A$, the blob is further split and collapsed (the par-
tial figures are omitted). Their evolution process could 
be seen from Fig. 3 with the velocity. When $t = 10 \tau_A$, the 
vortex system begins to form in the inner of the plasma 
blob such that the plasma mass distribution exhibit the 
crescent moon with the bent hook, and when $t = 26 \tau_A$, 
the vortex system splits into two basically independent, 
small vortex blobs, which make the plasma blob into 
two small blobs. Following the development of the mag-
netic reconnection, the magnetic island structures, the 
various discontinued structures and the vortical motions 
also develop further. These effects finally lead to those 
complex patterns as shown in Fig. 3 (with the density).
Fig. 4 (left) shows the variations of the basic parameters versus the distance, which would be recorded by an observer if it passes through the numerical test region of the magnetic reconnection along $y = -2.5L$ for $t = 22\tau_A$. It can be seen clearly that the two decreasing magnetic field ($B$) regions near the current sheet are, respectively, located at $x = \pm 3L$, where the correlative variations also are simultaneously recorded, such as about 180° variation of the azimuthal direction ($\phi$), sudden increase of the current density ($j$) and abrupt change in the direction of the plasma flow ($a$). These basic features imply that the magnetic reconnections occur in the regions located at $x = \pm 3L$. They could qualitatively explain the observed results given by the spacecraft in interplanetary space, such as some basic parameters $B$, $\phi$, NS (or EW) in a typical magnetic cloud observed at 11 February 1969 (Klein and Burlaga, 1982), as shown in the Fig. 4(right).

The numerical results mentioned above show that the magnetic reconnection could occur under the interplanetary condition with high magnetic Reynolds number. The time required in one evolution process, i.e., from the occurrence of the reconnection to the formation of the stable state, could be in a more wide time scale from minute to hour order of magnitude, which depends on the election of the initial state. Due to the turbulence in the magnetic reconnection with high magnetic Reynolds number and the limitation of the energy released by the annihilation of the weak magnetic fields, the structure and the evolution of the magnetic reconnection regions in interplanetary space would be very complex. Various complex changes in the signatures would be recorded by spacecraft when it travels across the magnetic reconnection region along different paths and at different instances.

In this case, identifying and catching the magnetic reconnection process and the original faces of the plasma flow and the magnetic fields certainly are a difficult task. This is also one of the main difficulties to observationally study the interplanetary magnetic reconnection. Therefore, it should be necessary to use the numerical simulation with the high accurate and the low viscosity algorithm for understanding the magnetic reconnection phenomena possibly occurring under the interplanetary conditions. This paper is only to make some attempts, by means of the numerical study, to the problem...
whether the magnetic reconnection would occur in interplanetary space from the angle of physical principle. Further work should put emphasis on the temporal and space evolutions, their effects on the basic processes in the solar–terrestrial space and possible reconnection mechanisms, especially in looking for the convincing evidence of interplanetary magnetic reconnection processes occurring in the magnetic diffusion region according to the spacecraft observations with high resolution.

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