FAN-SHAPED JETS IN THREE-DIMENSIONAL RECONNECTION SIMULATION AS A MODEL OF UBQUITOUS SOLAR JETS

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ABSTRACT

Magnetic reconnection is a fundamental process in space and astrophysical plasmas in which the oppositely directed magnetic field changes its connectivity and eventually converts its energy into kinetic and thermal energy of the plasma. Recently, ubiquitous jets (for example, chromospheric anemone jets, penumbral microjets, umbral light bridge jets) have been observed by the Solar Optical Telescope on board the satellite Hinode. These tiny and frequently occurring jets are considered to be a possible evidence of small-scale ubiquitous reconnection in the solar atmosphere. However, the details of three-dimensional (3D) magnetic configuration are still not very clear. Here, we propose a new model based on 3D simulations of magnetic reconnection using a typical current sheet magnetic configuration with a strong guide field. The most interesting feature is that the jets produced by the reconnection eventually move along the guide field lines. This model provides a fresh understanding of newly discovered ubiquitous jets and moreover a new observational basis for the theory of astrophysical magnetic reconnection.

Key words: magnetic reconnection – magnetohydrodynamics (MHD) – methods: numerical

Online-only material: color figures

1. INTRODUCTION

Recent observations have found ubiquitous plasma jets over the solar atmosphere in various plasma parameters and magnetic field configuration. The solar chromospheric anemone jets show a cusp- or inverted Y-shaped structure which are believed to be a result of magnetic reconnection between a magnetic bipole and a preexisting uniform vertical field (Shibata et al. 2007). The penumbral microjets show the apparent motion almost along the vertical guide field components in the interlocking-comb structure of magnetic field lines in the sunspot penumbra (Katsukawa et al. 2007). The umbral light bridge jets are ejected along the vertical field lines emanating from the light bridge in the sunspot umbra (Shimizu et al. 2009). There are many other chromospheric jets whose footpoints are not well resolved. It has sometimes been proposed that spicules may be produced by magnetic reconnection (Suematsu et al. 2008; Isobe et al. 2008). The three-dimensional (3D) magnetic field configuration at the footpoints of these jets are still puzzling. Especially, how these jets are accelerated is a fundamental question in solar physics, which would also give a hint to the understanding of the origin of astrophysical jets. The 3D numerical simulation may help us to understand this. For 3D magnetic reconnection, many simulations show that the reconnecting process is much more complicated and difficult than the two-dimensional (2D) case (Yokoyama & Shibata 1995, 2001; Chen et al. 1999, 2001; Isobe et al. 2005; Jiang et al. 2010). Some of the 3D simulations have shown generation of flows parallel to magnetic field lines as a result of non-null reconnection (Pontin et al. 2005; Ugai 2010). However, these parallel flows have not been analyzed in detail. In this Letter, we analyzed these flows in detail for the first time, because these flows are important as the origin of chromospheric jets and found that these jets ejected from the diffusion region move along the magnetic guide field and its 3D structure is similar to a fan-shape (hereafter referred to as fan-shaped jets), which differs from the classical reconnection theory (generally speaking, the reconnection jets move along the ambient magnetic field, hereafter ordinary reconnection jets) (Sweet 1958; Parker 1957; Petschek 1964; Priest & Forbes 2000). In this Letter, we give a description and analysis for these results.

2. NUMERICAL METHOD

We perform 3D magnetohydrodynamic (MHD) simulation of magnetic reconnection using a typical force free magnetic field. The mathematical form of this field is

\[ B_z = \begin{cases} 
-B_{ini} & \text{for } x < -\Delta h_x \\
B_{ini} \sin \left( \left[ \theta x - (\pi - \theta) \Delta h_x \right] / 2 \Delta h_x \right) & \text{for } |x| < \Delta h_x \\
B_{ini} \sin \left( (2\theta - \pi) / 2 \right) & \text{for } x > \Delta h_x 
\end{cases} \]

\[ B_x = \begin{cases} 
B_{ini} \cos \left( \left[ \theta x - (\pi - \theta) \Delta h_x \right] / 2 \Delta h_x \right) & \text{for } |x| < \Delta h_x \\
B_{ini} \cos \left( (2\theta - \pi) / 2 \right) & \text{for } x > \Delta h_x 
\end{cases} \]

where \( B_{ini} \) is the initial amplitude of magnetic field. The \( \Delta h_x \) is the half-width of the current sheet. \( \theta \) is the reconnection angle shown in Figure 1, and it can be four values in our simulation cases, i.e., \( \pi, 3\pi/4, \pi/2, \) and \( \pi/3 \).

The computational box is resolved by \( 240 \times 480 \times 480 \) grid points, as shown in Figure 1. Since the magnetic field in the current sheet is a function of \( x \), we use a non-uniform grid point distribution in the \( x \)-direction. The eight independent variables are density \( (\rho) \), velocity \( (v_x, v_y, v_z) \), magnetic field \( (B_x, B_y, B_z) \), and gas pressure \( (p) \). We studied four cases for different initial reconnection angles \( (\pi/3, \pi/2, 3\pi/4, \text{and}\ \pi) \), which are
Reynolds number is calculated using

discussion is in nondimensional for simplicity) of length, temperature, density,
to $x \rho v^2/\mu_0$. The reconnection angle for Figures 3(a) and (b)

- Initial magnetic field configuration. The box size is $-4 \leq x < 4$, $-16 \leq y < 16$, $-16 \leq z < 16$. The magnetic field lines rotate from $x = -0.4$ to $x = 0.4$. The initial uniform distributions of density and pressure are used in our simulations. The magnetic hydrostatic equilibrium is satisfied at the initial condition. The normalization units (the values used in our analysis and discussion is in nondimensional for simplicity) of length, temperature, density, pressure, time, velocity, and magnetic field are $L_0$, $T_0$, $\rho_0$, $\rho_0 T_0 k_B/m$, $L_0/v_0$, $(p_0/\rho_0)^{1/2}$, and $(p_0)^{1/2}$, respectively ($k_B$ and $m$ mean Boltzmann constant and molecular mass). We assume that an anomalous resistivity, with the form $\eta = \eta_{ini} \cos(\pi x/2) \cos(\pi y/2) \cos(\pi z/2)$ ($\eta_{ini}$ is the amplitude of resistivity in the diffusion region), is localized in a small region $(|x| \leq \Delta h, |y| \leq \Delta h, |z| \leq \Delta h)$, where $\Delta h = 0.4$. The typical magnetic Reynolds number, plasma beta, and Alfvén speed are 126, 0.8, and 1.58, respectively, where the Reynolds number is calculated using $\eta_{ini}$ (0.05), Alfvén speed (1.58), and the half-length of the computational box in the $x$-direction (4).

(A color version of this figure is available in the online journal.)

defined in Figure 1. Using the free boundary condition and the CIP-MOCCT numerical scheme (Yabe & Aoki 1991; Yabe et al. 1991; Kudoh et al. 1999), we solved 3D compressible resistive MHD equations. Note that there is no thermal conduction and gravity being considered in our simulations because what we are really interested in is the process of magnetic reconnection.

3. RESULTS

Figure 2 shows the 3D visualization of the gas pressure distribution at the time $t = 8.5$ and time $t = 11.5$ of our typical case (the reconnection angle is $\pi$). We added a cross section at $z = 0$ and a velocity field plane at $x = 0$ in the lower panels, in which we can see the $X$-shaped structure of ordinary reconnection outflow on the $x$-$y$ plane and the velocity distribution of the fan-shaped jets on the $y$-$z$ plane. The plasma is heated and the magnetic field lines disconnect and reconnect at central diffusion region. Then we have two kinds of jets. The one is the ordinary reconnection outflow which is shown by the X-shaped structure on the $x$-$y$ plane. Besides, it can be seen that there are two fan-shaped jets moving along the $z$- and $-z$-directions. The biggest feature of these jets is that they can move along the magnetic guide field. Since the magnetic field is shearing in the current sheet, the jets can move in different direction (the shearing magnetic field means the direction of the magnetic field lines is different if they have a different position $x$ in the diffusion region). The shape of ordinary reconnection jets on the $x$-$y$ plane is very similar to the results in 2D reconnection case and the velocity is about the local Alfvén speed at the $x = 11.5$ (the speed of the fan-shape jets is about half of Alfvén speed).

Figure 3 shows a schematic for explaining the fan-shaped jets (red arrows) and the ordinary reconnection jets (blue arrows). The fan-shaped jets are ejected from the central diffusion region in different direction which is due to the shearing magnetic field in the current sheet. Finally, we have a structure which looks like a fan-shape. The reconnection angle for Figures 3(a) and (b) is $\pi$, and that for Figures 3(c) and (d) is $\pi/3$. As we described above, the fan-shaped jets can move along the guide field in our typical case. For the small reconnection angle case, similar to the typical case, two oblique magnetic field can produce the fan-shaped jets in a narrow angle. This situation is very general in the solar atmosphere. If a vertical magnetic flux tube is twisted or sheared or if two magnetic field lines or tubes with different directions get close to each other (as shown in Figures 3(c) and (d) considering the $x$-$y$ plane as the solar surface), large electric currents are generated between them, resulting in fast magnetic reconnection with larger amount of energy released.

The ordinary reconnection jets and fan-shaped jets are ejected from the diffusion region simultaneously. Since the ordinary reconnection jets are almost parallel to the solar surface, they can only move a short distance and disappear. However, the fan-shaped jets can move upward and become the jets along the vertical field lines. It should be noted that the density stratification effect in the solar atmosphere can greatly increase velocity amplitude of the slow mode shock ahead of the upward fan-shaped jets when it propagates to the low density region (like the upper chromosphere and solar corona) and eventually become a faster jet accelerated by the slow shock (Shibata et al. 1982).

In order to understand why the jets move along the guide field, we investigate the driving force of the fan-shaped jet using Lagrangian fluid elements (test particles). These elements can move with the plasma but have no effect on the result of simulations, which can show us the detailed information at the position of these elements in the computational box. One of these fluid elements is located at the edge of the diffusion region at the initial time and finally the element is driven as a part of the fan-shaped outflow. Its forces and velocities are shown in Figure 4(a). There are two stages for acceleration. In the first stage (time $t = 8$–10), the Lorentz force (including the magnetic tension force and magnetic pressure gradient force) drives this element. After that it is dominated by the gas pressure gradient in the later stage (time $t = 10$–11.5). Hence, we conclude that the fan-shaped jets are accelerated by both gas pressure gradient force and the Lorentz force. That is different from the ordinary reconnection outflow which is only accelerated by the Lorentz force.

Figures 4(b) and (c) show the dependence of velocity on the resistivity and the reconnection angle. All the velocity is measured at the time when reconnection rate reaches to the maximum for different cases. As shown in Figure 4(b), velocity is almost constant with different resistivity value. That is to say, there is no remarkable dependence of the velocity on the resistivity value. The ratio of the velocity between two kinds of jets is approximate 0.5 (the velocity of the ordinary reconnection jets is comparable to the local Alfvén speed determined by the reconnecting component), which indicates that the mechanism for forming these two jets is different as we described above. In Figure 4(c), the velocity is sensitive to the reconnection angle. The large reconnection angle means a strong shearing magnetic field lines in the current sheet. If we use the reconnection angle $\theta = 0$ as an extreme case, there will be no reconnection process and no jets come out. Furthermore, we found that the maximum speed of fan-shaped jets is still around half of the ordinary ones.

4. DISCUSSION

Let us briefly discuss the application of our results to various jets in the chromosphere as shown in Table 1. Although the footpoints of these jets are not necessarily well resolved, we assume
that the 3D reconnection occurs in the photosphere or in the low chromosphere at the footpoints of these jets, and fan-shaped jets are ejected from the reconnection region along magnetic field lines in these layers. The Alfvén speed ($v_A$) in the photosphere...
and low chromosphere is about 10 km s\(^{-1}\) in a typical isolated flux tube outside sunspots, and is about 10–50 km s\(^{-1}\) in sunspot umbra and penumbra. Hence, the \(v_A\) in Table 1 shows such local Alfvén speed in the (hypothetical) reconnection region at the footpoint of these jets. Here, the \(v_{A,L}\) is the Alfvén speed based on the reconnecting component of magnetic field (we assume that \(v_{A,L} = 0.2v_A\)). The velocity of fan-shaped jets is only half of that of the ordinary reconnection flow (\(v_{fan} \sim v_{A,L}/2\)). Once the fan-shaped jets are ejected, the slow mode MHD shock is formed ahead of the jets and propagates along the vertical magnetic field lines. Since the density decreases with height, the velocity amplitude at the slow mode shock increases with height, namely, \(v_{fan,max} \sim v_{fan}\sqrt{0.5z/H}\) if the slow mode wave energy is conserved or \(v_{fan,max} \sim v_{fan}\sqrt{0.25z/H}\) if the shock is strong (Shibata & Suematsu 1982), where the value \(z\) is the height of the jets measured from the reconnection region and \(H\) is the pressure scale height. If \(z/H = 13.3\) (assuming the scale height \(H = 150\) km and the slow mode shock propagates over a height of 2000 km), we get \(v_{fan,max} \sim v_{fan}\sqrt{0.25z/H} \sim v_{fan}\sqrt{3.0} \sim 20v_{fan}\). Similar results are obtained also for the case \(z = 1000\) km when the wave energy is conserved (\(v_{fan,max} \sim v_{fan}\sqrt{0.5z/H}\)). Table 1 shows that the resulting velocity at the shock front (\(v_{fan,max}\)) when it reaches at the top of the chromosphere is comparable to the actual observed velocity of these chromospheric jets. Hence, our finding of fan shaped jets parallel to field lines are important for understanding the origin of chromospheric jets and seems to be successfully applicable to ubiquitous chromospheric jets.

We described fan-shaped jets by simulating the 3D reconnection process using a simple initial shearing magnetic configuration in this report. We found that the fan-shaped jets which are accelerated by both gas pressure gradient and Lorentz force can move along the magnetic guide field lines and the velocity of these jets is about half of the local Alfvén speed determined by the reconnecting component of magnetic field. This new finding provides us a new way to understanding the magnetic reconnection in 3D geometry and it is also a new model for explaining the solar ubiquitous chromospheric or more general astrophysical jets. The details of them will be studied in our future papers.

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![Figure 4](image-url)
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