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MODELING PENUMBRAL MICROJETS BY TWO-FLUID SIMULATIONS

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ABSTRACT

We investigate how penumbral microjets, recently observed by the *Hinode* satellite, can be produced within sunspot penumbra. We consider two penumbral filaments with axial currents and axial flows. We assume that a vertical magnetic flux tube exists between two horizontal penumbral filaments. We also assume that the axial flows are not steady; a high-velocity axial flow is imposed on the background slow axial flow. We find that this high-velocity axial flow can trigger magnetic reconnection between one penumbral filament and the vertical flux tube. As a result, inclined bidirectional jetlike flows, driven by the magnetic reconnection, propagate along the vertical magnetic flux tube. Strong proton heating, up to 25 times their original temperature, is observed in these generated jets. Conversely, the neutral-hydrogen particles are only very weakly heated. We propose that these plasma jets explain the phenomenon of penumbral microjets, recently observed by the *Hinode* satellite.

Subject headings: MHD — plasmas — Sun: magnetic fields — Sun: photosphere

1. INTRODUCTION

Magnetic reconnection in weakly ionized plasmas is important in the interstellar medium (Zweibel & Brandenburg 1997; Heitsch & Zweibel 2003), as well as in the lower solar atmosphere (chromosphere and photosphere) (Sakai 1996; Bulanov & Sakai 1998; Litvinenko 1999; Furusawa & Sakai 2000; Sakai et al. 2006). The photosphere, chromosphere, and lower corona of the Sun are all in a highly dynamical state, as confirmed by the observed line shifts and nonthermal broadening seen in spectrographs. These indicate that mass supply to the corona and wave propagation is abundant throughout the solar atmosphere.

To understand the observed transient phenomena in the chromosphere and photosphere, Smith & Sakai (2008a) developed a new simulation code which describes the dynamics of two fluids, namely protons and neutral hydrogen, that couple through proton/neutral-hydrogen collisions, as well as recombination and ionization.

Recently Katsukawa et al. (2007) reported the discovery of small jetlike features in sunspot penumbra, using observations from the *Hinode* satellite's broadband Ca II H filter. The observed penumbral microjets are highly transient events with lifetimes of less than 2 minutes, lengths of ≈1000–4000 km, and widths ≈400 km. Jurčák & Katsukawa (2008) investigated the dependence of penumbral microjets inclination on the position within penumbra. They suggested that the penumbral microjets follows the opening magnetic field lines of a vertical flux tube that creates the sunspot.

In the present Letter, we numerically investigate how penumbral microjets are produced within sunspot penumbra, by using a two-fluid simulation code. In § 2 we present our simulation model, in § 3 we present our simulation results, and in the final section we summarize our results.

2. SIMULATION MODEL

We use a new two-fluid simulation code which describes the three-dimensional dynamics of protons (ions) and neutral hydrogen (neutral particles), which couple through proton/neutral-hydrogen collisions, as well as through recombination and ionization effects. In MHD the plasma is approximated as a single quasi-neutral fluid, in which the ion dynamics dominate. Therefore the fluid equations are solved for the ions only, ignoring the high-frequency plasma waves generated by the electron motions. Developed from a previous two-fluid code (see Sakai et al. 2006), this new code (known as "TwoYama") includes a number of important improvements, most notably MPI parallelization. In the energy equation we include Joule heating, heat conduction, and collisional heating, while we neglect the radiative cooling term. Continuous (zero gradient) boundary conditions were used for all directions. In this study, we neglect the effects of recombination and ionization. A detailed description of the numerical code and equations solved is given in Smith & Sakai (2008a). The normalization constants used in this study are summarized in Table 1.

For this study, we consider two horizontal penumbral filaments with axial currents and axial flows in the z-direction as shown in Figure 1. The y-axis corresponds to height in the photosphere/chromosphere. We consider a system size of $N_x = N_y = 256$, and $N_z = 64$. Two current loops ($i = 1, 2$) located parallel to the z-axis are assumed to be in an equilibrium state ($\boldsymbol{\nabla} p_i = \boldsymbol{J}_i \times \boldsymbol{B}_i/c$). This means that the initial state with two current loops is not in equilibrium. The magnetic field and proton pressure for each loop are given by

$$B_x = q_i B_z (y - y_{ci})/a, \tag{1}$$

$$B_y = -q_i B_z (x - x_{ci})/a, \tag{2}$$

$$B_z = B_{0i} e^{-(r_i/a)^2}, \tag{3}$$

$$P_i = \left(\frac{q_i^2}{2} - \frac{q_i^2 r_i^2}{a^2} - 1\right) e^{-2(r_i/a)^2} + 1.0, \tag{4}$$

where $r_i = [(x - x_{ci})^2 + (y - y_{ci})^2]^{1/2}$, and the centers of the two current loops are $(x_{c1}, y_{c1}) = (73, 128)$ and $(x_{c2}, y_{c2}) = (183, 128)$. The pressure profile is the same as the density

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TABLE 1
NORMALIZATION CONSTANTS

Symbol	Quantity	Constant	Value
t	Time	τ_0	$= 1$ s
n	Number density	n_0	$= 5 \times 10^{20}$ m^{-3}
T	Temperature	T_0	$= 4800$ K
ρ	Density	$\rho_0 = n_0 m_p$	$\approx 8.4 \times 10^{-11}$ kg m^{-3}
P	Pressure	$P_0 = n_0 k_B T_0$	$\approx 5.8 \times 10^{-3}$ Pa
V	Velocity	$c_0 = (P_0/\rho_0)^{1/2}$	≈ 8.3 km s^{-1}
x, y, z	Length	$\Delta = c_0\tau_0$	≈ 8.3 km
B	Magnetic field	$B_0 = (2\mu_0 P_0)^{1/2}$	$\approx 1.0 \times 10^{-2}$ T

profile. The twist parameter, q_i, is $q_1 = q_2 = 1$, and $B_{01} = B_{02} = 10.0$, which corresponds to about 10^3 G.

We assume that there exists a vertical magnetic flux tube between two penumbral filaments. The magnetic field B_y is given by

$$B_y = 0.8 B_{01} e^{-(r_3/ra_3)^4}, \tag{5}$$

where $r_3 = [(x-128)^2 + (z-32)^2]^{1/2}$ and $ra_3 = 10$. We also assume that the axial flows are not steady; a high-velocity ($v = 0.8$) neutral-hydrogen axial flow is imposed over the background axial flow:

$$V_z = v\{1.0 - \tanh[(z-5.0)/2.0]\} e^{-(r_2/40)^4} + v_1 e^{-(r_1/40)^2} + v_1 e^{-(r_2/40)^2}, \tag{6}$$

where $v_1 = 0.2$. The first term in equation (6) represents the high-velocity flow along filament 2, while the second and third terms represent the background axial flow along both filaments. Figure 2 shows the initial velocity distribution of neutral hydrogen in the x-z plane ($y = 128$).

3. SIMULATION RESULTS

We present numerical results representing a chromospheric plasma, with a neutral hydrogen–to–proton density ratio $\rho_n/\rho_p = 100$. First, in Figure 3 we show the time development of the proton flow V_z in the x-z plane at $y = 128$. Initially we impose only an axial flow of neutral hydrogen which then rapidly accelerates the protons to the same velocity, due to strong collisional coupling between neutral hydrogen and protons.

As seen in Figure 3, a high-velocity proton axial flow propagates along the right horizontal filament and approaches the vertical magnetic flux tube. In Figure 4, we see that the collision of this plasma flow with the vertical flux tube generates a strong flow in the negative x-direction. This in turn compresses the vertical flux tube, triggering the magnetic reconnection of the vertical flux tube with the right horizontal flux tube. Recently Smith & Sakai (2008b) showed that a neutral-hydrogen colliding flow can strongly enhance the magnetic reconnection of flux tubes. Figure 5*a* shows a vector plot of the magnetic field (B_x-B_y) overlaid on a contour plot of the proton flow V_y at $t = 100$ in the x-y plane ($z = 32$). We clearly see that magnetic reconnection of the vertical and horizontal (right) flux tubes has generated strong bidirectional plasma flows along the y-direction. These plasma flows have narrow jetlike structures with flow velocities reaching a maximum of $V_y = 0.5$ that corresponds to about 4.1 km s^{-1}. In Figure 5*b*, we show a contour plot of the proton temperature at $t = 100$ in the x-y plane ($z = 32$). It is clear that the protons in the plasma jet are

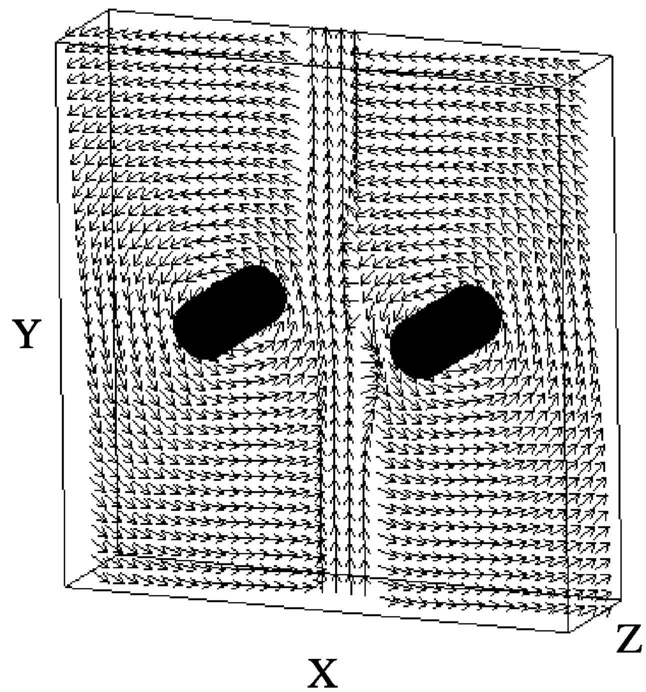

FIG. 1.—Initial magnetic field: vector (B_x-B_y) plot overlaid on a contour B_z plot. A vertical magnetic flux tube exists between two horizontal filaments.

strongly heated, by up to 25 times their initial temperature of $4800 \times 25 = 1.2 \times 10^5$ K.

Finally in Figure 6, we show the spacial distribution of proton temperature and proton velocity V_y in the y-z plane ($x = 128$). We see that the plasma jets described above propagate in the y-direction with a slight inclination, as observed by Katsukawa et al. (2007). The formation and lifetime of these jets depends on the interaction time between the high-velocity flow and the spacial width in the z-direction. We plan to explore the jet lifetime and speed further in the future. We note here that if we reduce the density of the background neutral hydrogen to 5×10^{19} m^{-3}, then we find supersonic jets with about $2c_s$, which corresponds to about 16 km s^{-1}, resulting in shock formation. These results will be published elsewhere.

4. CONCLUSIONS

We investigated how penumbral microjets recently observed by the *Hinode* satellite can be produced within the penumbra. We considered two horizontal penumbral filaments with axial

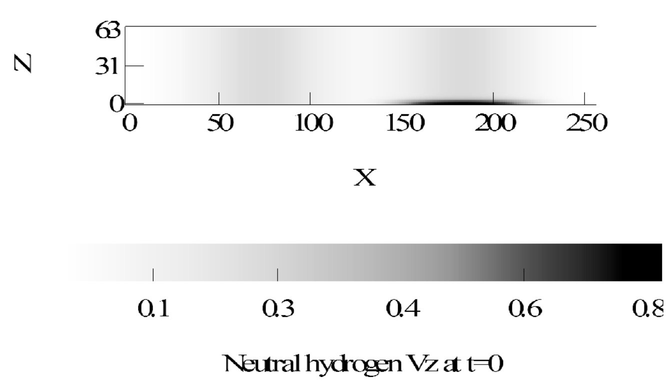

FIG. 2.—Initial velocity distribution of neutral hydrogen in the x-z plane ($y = 128$). The high-velocity axial flow in the right filament is imposed from below.

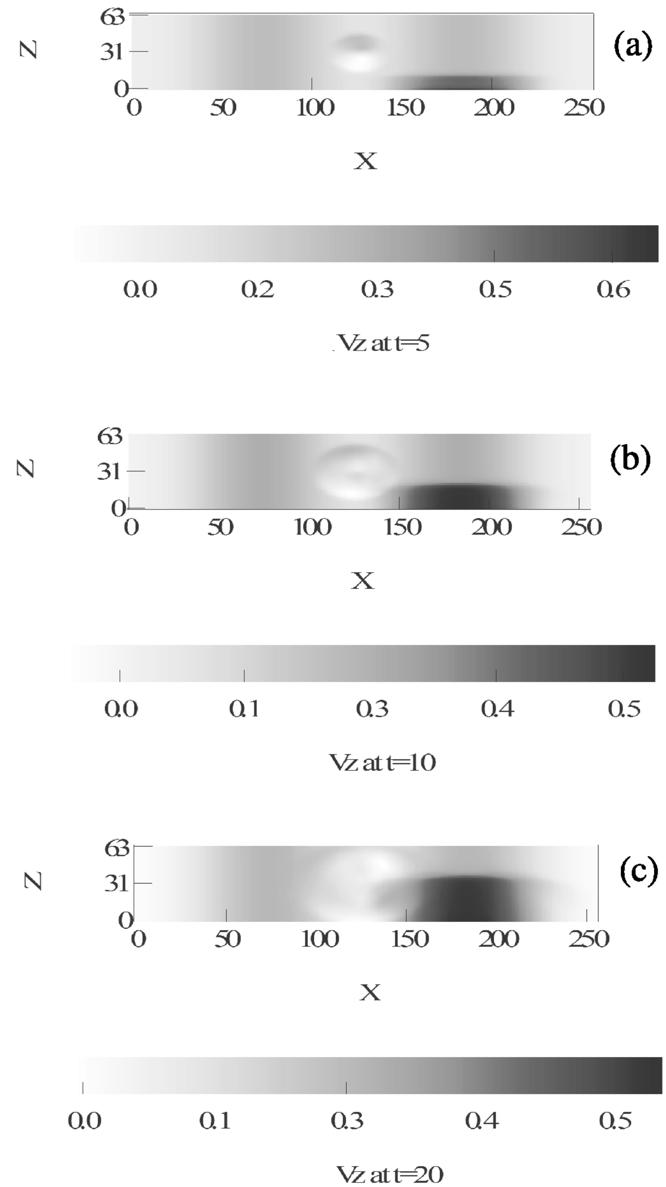

FIG. 3.—Time development of the proton axial flows. Contour plots of proton V_z in the x-z plane ($y = 128$).

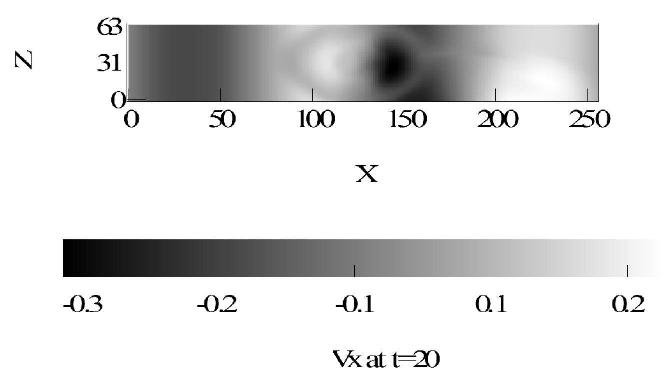

FIG. 4.—Contour plot of the proton flow V_x at $t = 20$ in the x-z plane ($y = 128$). A strong proton flow near the center of the system is seen to compress the vertical magnetic flux tube.

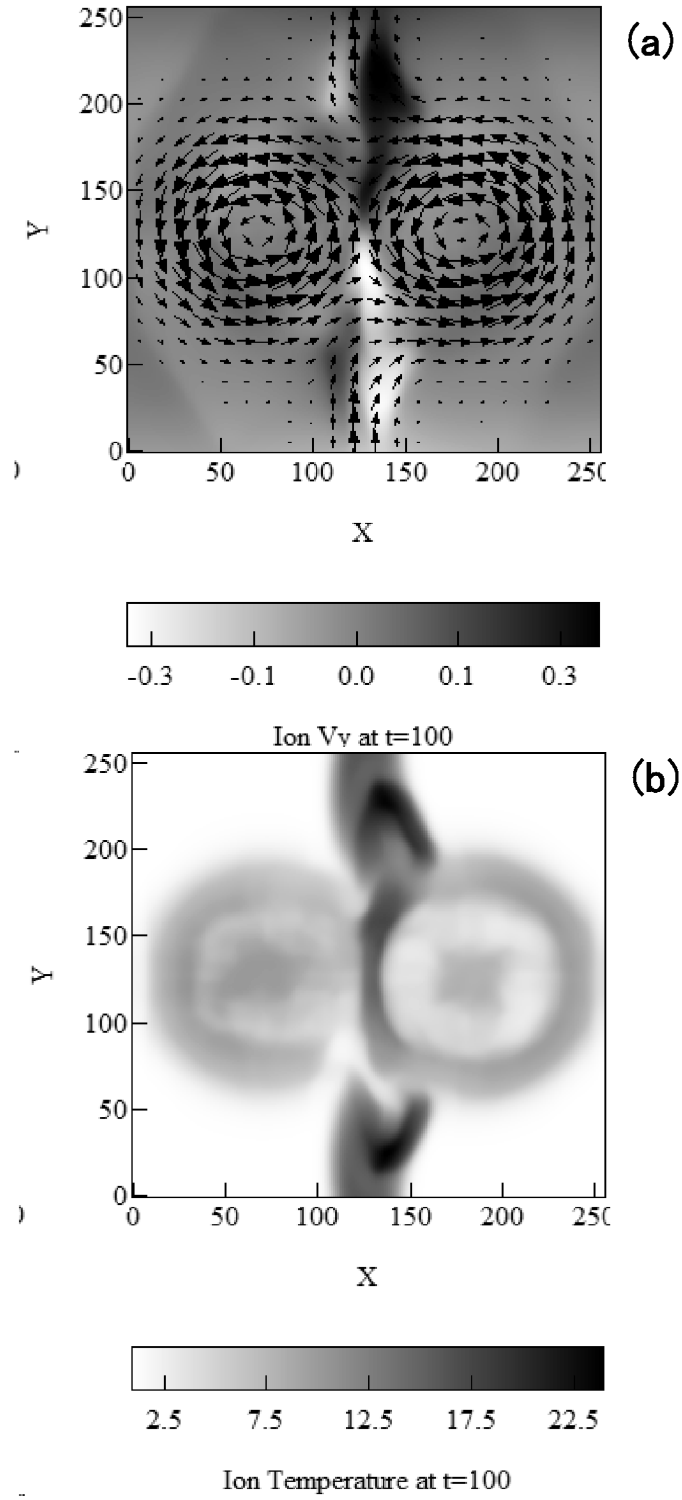

FIG. 5.—(a) Vector plot of the magnetic field (B_x-B_y) overlaid on a contour plot of the proton flow V_y at $t = 100$ in the x-y plane ($z = 32$). (b) Proton temperature distribution at $t = 100$ in the x-y plane ($z = 32$).

currents and slow axial flows. In between these filaments was a vertical magnetic flux tube. We assumed that the horizontal axial flows were not steady and thus initially imposed a high-velocity axial flow along one of the filaments.

We found that this high-velocity axial flow could trigger magnetic reconnection between one penumbral filament and the vertical flux tube. As a result, inclined bidirectional jetlike flows, driven by the magnetic reconnection, were observed to

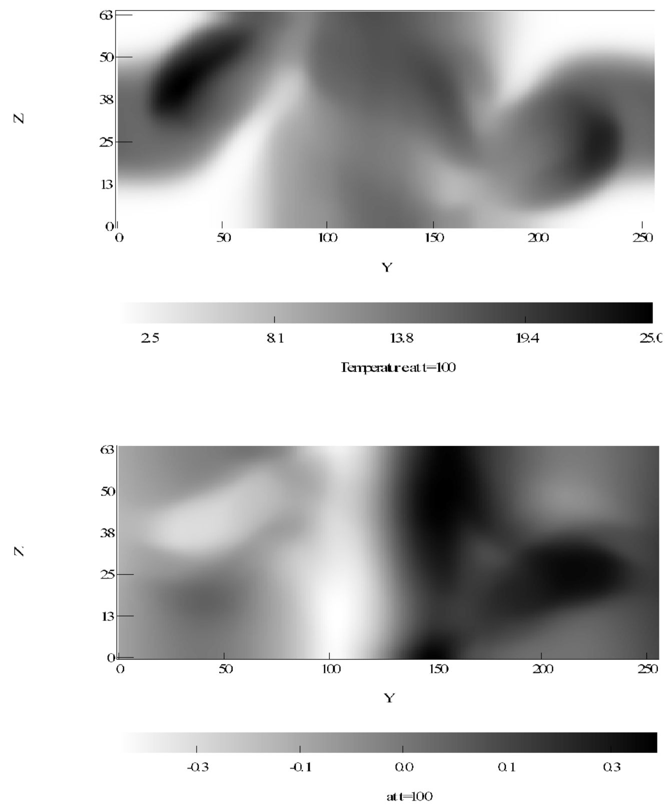

FIG. 6.—Contour plots of the proton temperature (*top*) and proton flow velocity V_y (*bottom*) at $t = 100$ in the y-z plane ($x = 128$).

propagate in the vertical direction. The protons in these jets were heated up to 25 times their initial temperature, reaching up to $\approx 1.2 \times 10^5$ K, while the neutral hydrogen was very weakly heated.

We propose that the plasma jets observed in our numerical simulations may explain the penumbral microjets recently observed by the *Hinode* satellite.

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