Plasma Jet and Shock Formation during Current Loop Coalescence in Solar Flares

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ABSTRACT

We report on the results of plasma jet and shock formation during the current loop coalescence in solar flares. It is shown by a theoretical model based on the ideal MHD Equation that the spiral, two-sided plasma jet can be explosively driven by the plasma rotatinal motion induced during the two current loop coalescence process. The maximum velocity of the jet can exceed tte Alfvén velocity, depending on the plasma $\beta(=c_s^2/v_A^2)$ ratio.The acceleration time getting to the maximum jet velocity is quite short and less than 1 second. The rebound following the plasma collapse driven by magnetic pinch effect can strongly induce super-Alfvénic flow. We present the condition of the fast magnetosonic shock formation. We briefly discuss the high energy particle acceleration during the plasma collapse as well as by the fast magnetosonic shocks.

1. INTRODUCTION

The current loop coalescence model (Gold and Hoyle 1960; Tajima et al. 1982,1987; for a review see Sakai and Ohsawa 1987) provided keys to understanding many of the characterictic of solar flares (Svestka 1976; Sturrock ed. 1980; Kundu and Woodgate eds. 1986) such as explosive plasma heating, high-energy particle acceleration, and quasi-periodic oscillation of electromagnetic emission. Recent observations (Machado et al. 1988) showed that the interaction of current loops is an essential ingredient in the trigger of the solar flare energy release. During the coalescence of two current loops, the magnetic energy stored by the plasma current is explosively transformed to plasma heating as well as to production of high-energy particles through the magnetic reconnection process (see Fig.1). The energy release is achieved in a quasi-periodic fashion (Sakai and Tajima 1986) when the ratio B_p/B_t between the poloidal (B_p: produced by the loop current) and the toroidal (B_t: potential field) components of the magnetic field is greater than one. We here consider the reverse case, $B_p/B_t<1$. In this situation the two current loops begin to rotate around the reconnection point shown in Fig.1a. After the coalescence of two current loops, the single current loop can still do the plasma rotational motion as shown in Fig.1b-d. This rotational motion after the magnetic reconnection can be also observed

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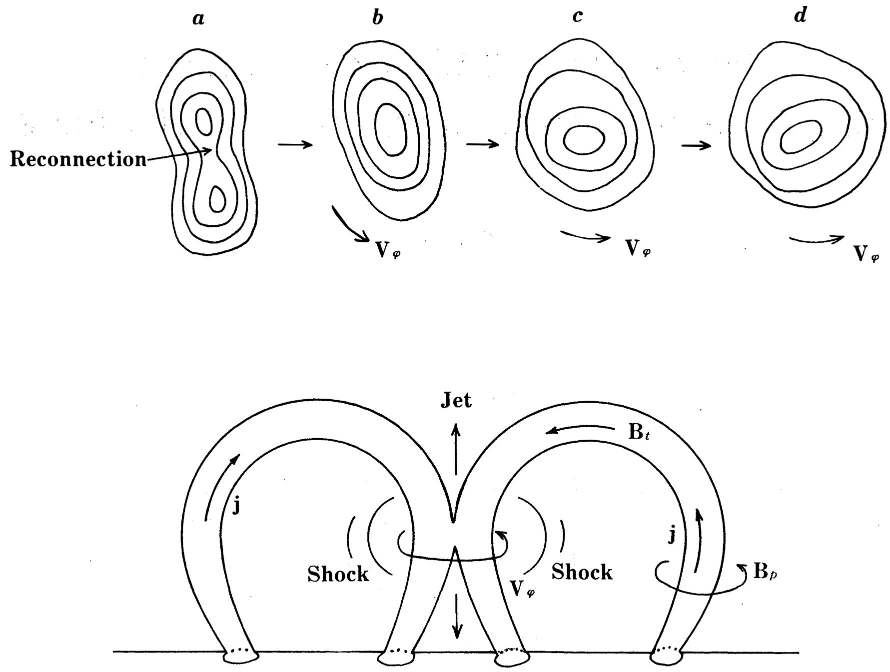

Loop-Loop Coalescence

Figure 1. Shemtic picture showing the two current loops coalescence (lower part) and plasma rotational motion (V_ϕ) induced during the loop coalescence process (upper part). Spiral, two-sided jets can be produced by the plasma rotational motion.

in the computer simulation of the two loop coalescence when $B_p/B_t<1$ (Zaidman 1986).

In this paper, we present the results of spiral plasma jet formation driven by the plasma rotational motion (V_ϕ) induced during the two current loop coalescence process. By means of a theoretical model based on the Ideal MHD Equations, we find that the spiral, two-sided jets can be explosively produced by the combination of the magnetic pinch effect (collapse) and the plasma pressure. The rebound following the plasma can strongly induce the super-Alfvénic plasma flow. which generates the fast magnetosonic shock waves.

2. THEORETICAL MODEL

We consider the single current loop which can be produced by the two current loop coalescence shown in the Fig.1. After the magnetic reconnection, the single current loop can be produced and the plasma can be heated by the magnetic energy dissipation. At the same time, the plasma rotational motion (V_ϕ) around the reconnection point can be induced during the loop coalescence process when the ratio B_p/B_t is less than one.

In order to represent the spiral plasma jet and spiral magnetic field structure associated with the jet, we assume the physical quantities as follows; for the velocity components,

$$V_r = (\dot{a}/a)r,$$
$$V_\phi = (\dot{c}_1/c_1)r, \tag{1}$$
$$V_z = (\dot{b}/b)z,$$

for the magnetic field components,

$$B_r = \frac{B_{10}}{a^2b}\left(\frac{r}{\lambda}\right),$$
$$B_\phi = \frac{B_{20}}{a^2b}\left(\frac{r}{\lambda}\right), \tag{2}$$
$$B_z = \frac{B_0}{a^2} - 2\frac{B_{10}}{a^2b}\left(\frac{z}{\lambda}\right)$$

where we used the cylindrical coordinates (r, ϕ, z), and the dot means the time-dependent scale factors, $a(t)$, $c_1(t)$ and $b(t)$ can be self-consistently determined from the ideal MHD Equations with the adiabatic law ($P \sim \rho^\gamma$; γ is the ratio of the specific heats). B_{10}, B_{20} and B_0 are constants and λ is a characteristic scale length which we are concerned with. From the continuity equation, we find the density ρ as $\rho = \rho_0/a^2b$, where ρ_0 is a constant. From the Maxwell equation, we obtain the current $j_z = cB_{20}/2\pi\lambda a^2b$, which flows along the loop. The time-dependent scale factors can be determined from the equations of motion as follows;

$$\frac{d^2a}{dt^2} = \frac{c_s^2}{\lambda^2 a^{2\gamma-1} b^{\gamma-1}} - \frac{2v_A^2}{\lambda^2 ab} + a\left(\frac{\dot{c}_1}{c_1}\right)^2 \tag{3}$$
$$\frac{d^2b}{dt^2} = \frac{c_s^2}{\lambda^2 a^{2\gamma-2} b^{\gamma}}, \tag{4}$$
$$\frac{d^2c_1}{dt^2} = \frac{2v_{A2}^2 c_1}{\lambda^2 a^2 b} + \frac{\dot{c}_1^2}{c_1} - 2\frac{\dot{a}}{a}\dot{c}_1^2 \tag{5}$$

where $c_s^2 = P_{10}/\rho_0$, $v_A^2 = B_{20}^2/4\pi\rho_0$, $v_{A2} = v_A(B_{10}/B_{20})^{1/2}$.
We here assumed that the pressure is given by

$$P(r, z, t) = P_0(t) - \frac{P_{1r}(t)r^2 + P_{1z}(t)z^2}{2\lambda^2} \tag{6}$$

where $P_0(t)$, $P_{1r}(t)$ and $P_{1z}(t)$ can be determined from the adiabatic law as

$$P_0 = \frac{P_{00}}{a^{2\gamma} b^{\gamma}},$$
$$P_{1r} = \frac{P_{10}}{a^{2(\gamma+1)} b^{\gamma}}, \tag{7}$$
$$P_{1z} = \frac{P_{10}}{a^{2\gamma} b^{\gamma+2}},$$

where P_{00} and P_{10} are constants.

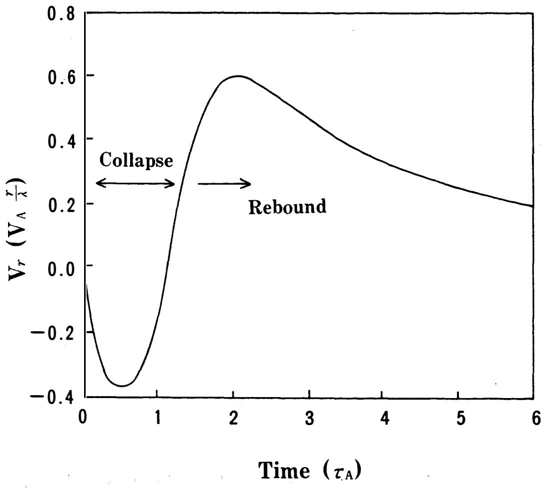

Figure 2. Temporal variation of the plasma radial flow velocity. At the early stage the plasma collapse ($V_r < 0$) can be induced and the strong rebound which produces shock waves can be enhanced by the magnetic collapse.

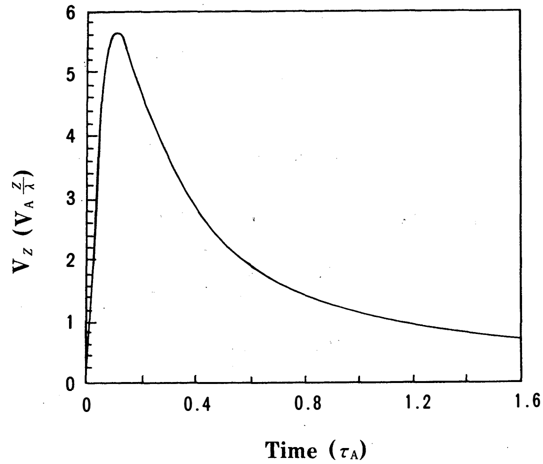

Figure 3. Temporal variation of the plasma jet flow velocity normalized by ($v_A z/\lambda$). The maximum velocity (5.64) occurs at $0.11\tau_A$.

3. JET FORMATION

We show numerical results obtained from Eqs. (3) -(5), which determine the all physical quantities such as the velocity field (1) and the magnetic field (2). The time is normalized by the Alfvén transit time $\tau_A = \lambda / v_A$. The velocity is normalized by tte Alfvén velocity v_A which is determined from the poloidal magnetic field B_{20}. The initial conditions for the velocities are $V_r = -10^{-6}(v_A r/\lambda)$, $V_z = 10^{-6}(v_A z/\lambda)$ and $V_\phi = 0.1\,(v_A r/\lambda)$. The plasma β ratio is taken to be 0.01. We take $B_{10} = B_{20} = -1$ and $\gamma = 5/3$. Figure 2 shows the time profile of the radial plasma flow velocity ($\dot{a}/a$) which is normalized by $v_A(r/\lambda)$. The initial plasma rotational velocity ($V_\phi = 0.1\,(v_A r/\lambda)$) can drive the plasma collapse ($V_r < 0$) mainly by the $j_z \times B_\phi$ force, which corresponds to the second term of the right-hand side of the equation (3). During the plasma collapse the explosive plasma jet in the z-direction can be produced as seen in Fig.3. The acceleration time getting to the maximum velocity of the jet is quite short and $0.11\tau_A$. The plasma jet can be driven by the combination of two forces, namely, the $j_z \times B_\phi$ (which drives

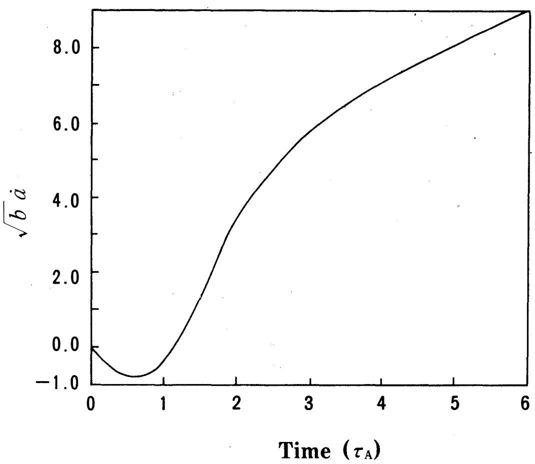

Figure 4. Shock formation condition: after the time when $\sqrt{b\,\dot{a}} > \sqrt{2}$ is satisfied, the shock waves can be generated.

the collapse) and tte pressure gradient $\partial P/\partial z$. The maximum velocity ($V_{z,max}$) obtained during the short period is not so sensitive to the initial rotational velocity. We found the same-results for the cases $V_\phi = 0.01 - 1$ ($v_A r/\lambda$). The most important parameter which determines the maximum velocity and the acceleration time is the plasma β ratio. The summary of the results is shown in the Table.When the plasma β ratio decreases, the maximum jet velocity decreases and the acceleration time becomes long. While the β increases, the maximum jet velocity increases and becomes super-Alfvénic within the very short time period.

The plasma jet obtained here shows the two-sided flows which originate from the current coalescence region as seen in Fig.1.

4. SHOCK FORMATION

As seen in the previous section, the strong spiral plasma jet can be produced during the plasma collapse ($V_r < 0$). The jet flow may become super-Alfvénic when the plasma β ratio increases. The super-Alfvénic jet flow can induce the Alfvénic shock waves along the current loop. On the other hand, the plasma rebound ($V_r > 0$) can occur following the plasma collapse (see Fig.2). The velocity of the rebound can be enhanced by the magnetic collapse and adiabatic compression. We here investigate the condition of shock formation by the rebound of the plasmaafter magnetic collapse. The fast magnetosonic shock waves can be induced by super-Alfvénic plasma flow when the velocity of the rebound,V_r becomes larger than the local magnetosonic velocity. In the low β plasma, the condition, $V_r > (V_A{}^2 + c_s{}^2)^{1/2}$, is given by

Table: Maximum jet velocities and acceleration times reaching the maximum velocity for different plasma β ratios with the same initial conditions.

β	$V_{Z,max}(V_A \frac{Z}{\lambda})$	Acceleration Time (τ_A)
10^{-4}	0.68	0.97
10^{-3}	1.77	0.38
10^{-2}	5.64	0.11
10^{-1}	18.73	0.035
10^{0}	55.92	0.01

$$\left[\dot{a}^2 - \frac{1}{b}\left\{1 + \left(\frac{B_{10}}{B_{20}}\right)^2\right\}\right]\left(\frac{r}{\lambda}\right)^2 > b\left(\frac{B_0}{B_{20}}\right)^2 \tag{8}$$

We obtain one condition which be satisfied in Eq.(8). Namely, the term with a parenthesis of the left-hand side must be positive,

$$\sqrt{b}\,\dot{a} > \left\{1 + \left(\frac{B_{10}}{B_{20}}\right)^2\right\}^{1/2} \tag{9}$$

If the condition (9) is satisfied, the shock wave can be generated in the region of $r > r_s$, where r_s is given by

$$r_s = \sqrt{b}\left(\frac{B_0}{B_{00}}\right)\left[\dot{a}^2 - \frac{1}{b}\left(\frac{B_{10}}{B_0}\right)^2\right]^{-1/2}\lambda \tag{10}$$

Figure 4 shows the time variation of $\sqrt{b}\,\dot{a}$ in the case of $B_{10} = B_{20} = -1$. The region where $\sqrt{b}\,\dot{a} > \sqrt{2}$ is satisfied can be observed in the Fig.4. The radius r_s where the shock wave can be produced is around the characteristic scale length λ.

5. DISCUSSION

We have shown from the simple theoretical model based on the ideal MHD equations that the two-sided plasma jets can be explosively produced within the short time period. If we take the characteristic scale length λ as $\lambda \sim 10^8$ *cm* which corresponds to the loop radius, and the Alfvén velocity $v_A \simeq 500 km/s$, te Alfvén transit time is $\tau_A = \lambda / v_A = 2$ seconds. Therefore the acceleration time getting to the maximum jet velocity is $0.1 \sim 1$ second, depending on the plasma β ratio. The two-sided jet flows originated from the current loop coalescense region may be observed during the impulsive phase (Doschek et al. 1986; Zarro et al. 1989).

During the plasma collape, the strong electric field, $\mathbf{E} = -(\mathbf{V} \times \mathbf{B})/c$ can be produced by the change of the magnetic field.This strong electric field can generate high energy particles ($\sim$ Gev) within 1 second (Sakai, 1989).

The high energy particcle acceleration by the shock waves is belived to play an important role in solar flares (Sakai and Ohsawa 1987; Ramaty and Murphy 1987). The shock formation mechanism has not been well examined in association with physical processes in the impulsive phase. The shock formation by the rebound following magnetic collapse is very effective,even though the colliding velocity of the two current loops is much less than the Alfvén velocity. The fast magnetosonic shock waves generated from the rebound after plasma collapse can strongly accelerate protons to the velocity $V \sim \sqrt{m_i/m_e}\, v_A$ within less than one second (Ohsawa and Sakai, 1987). If the magnetic field is rather strong ($\omega_{ce} > \omega_{pe}$), the fast magnetosonic shock wave can simultanously accelerate both electrons and protons to relativistic energies (Ohsawa and Sakai, 1988; Sakai and Ohsawa, 1987).

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