JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
29: S299 ~ S301, 1996

AN EXPLANATION ON TRANSIENT BRIGHTENING BY MAGNETIC RECONNECTION THEORY

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ABSTRACT

It has been discovered that active regions commonly have numerous flare-like transient loop brightenings. We use a magnetic reconnection theory driven by a ponderamotive force on account of the basic properties of a transient brightening: lifetime a few mins, total energy $10^{25} \sim 10^{29}$ erg. The numerical results are consistent with the observations.

I. INTRODUCTION

Soft X-ray Telescope aboard the Yohkoh Satellite has discovered that active regions commonly have numerous flare-like transient loop brightenings. Shimizu et al.(1995) have reported a transient brightening on 21 June 1992. This transient brightening took place at N25 W21 in active region NOAA 7201. A compact brightening feature with a dimension of $\sim 12\times5$ $arcsec^2$ is observed in Soft X-rays. The magnetogram reveals serveral localized compact positive- and negative- polarity magnetic flux elements around the location of the brightening. The time sequence of magnetograms reveals the existence of a small-scale emergence of magnetic flux at the location of the transient brightening, and this small-scale emergence start $\sim$ 8mins prior to the onset of the brightening. They find that the emerging magnetic flux can reach $\sim$ 1400 KM height above the photosphere, which may be at the mid-upper chromosphere. This suggests that this transient brightening releases the magnetic energy mainly not in the corona but in the lower atmosphere. Shimizu et al.(1994) give four multiple-loop brightening examples. Their lifetimes are 8 min, 10 min, 8 min and 4 min, respectively. It is valid that we take the duration of this transient brightening $\sim$ 8 min.

On the other hand, Li et al. (1994) presented a magnetic reconnection mechanism to explain the transient enhancements at the interaction of post-flare loop systems. In this theory they analyze the subtle interaction between the MHD and high frequency plasma waves and investigate the instabilities associated with electromagnetic solitary waves in a current sheet, and show that there is a resistive instability, which eventually turns into an eruptive instability at the onset of magnetic reconnection.

In the paper we try to use this theory of reconnection to interpret the transient brightening caused by interacting loops in Soft X-ray images.

II. INSTABILITIES BY SOLITARY WAVES IN LOOP INTERACTION

It appears that there is a subtle interaction between the MHD and the emission fields. On the other hand, according to the reconnection theory of solar flares, the thickness of the dissipation layer must remain at a very small value in order to provide sufficient power; but the hot plasma, resulting from the field dissipation, will tend to widen the current sheets. The key is to find a local eruptive instability for which dissipation products can be thrown out at a fast enough rate. Of course, an instability with a small scale inevitably involves a nonlinear interaction between the emission and the MHD media.

For a plasma with electromagnetic oscillations, we use two-fluid description; because of the large difference in electron and ion oscillation in solar plasma,the two-time-scale approximation is also relevant. In this case the plasma motion satisfies the global MHD equations with ponderamotive force F_p (Li et al.,1994):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \tag{1}$$

$$\rho \left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} \right] = \frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p + \mathbf{F}_p \tag{2}$$

$$\frac{\partial \mathbf{B}}{\partial \mathbf{t}} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \frac{c^2}{4\pi}\eta \nabla^2 \mathbf{B}, \tag{3}$$

$$\nabla \times \nabla \times \mathbf{v}_f + \frac{1}{c^2}\frac{\partial^2 \mathbf{v}_f}{\partial t^2} + \frac{\rho}{m_i}\mathbf{v}_f = 0, \tag{4}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}, \tag{5}$$

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{j}, \tag{6}$$

$$\nabla \cdot \mathbf{B} = 0, \tag{7}$$

where

$$\mathbf{F}_p = -\frac{1}{2}\frac{m_e}{m_i} \cdot \rho \cdot \nabla < v_f^2 > \tag{8}$$

is the ponderamotive force, $\mathbf{V_f}$ the fast oscillation velocity of the electron in the waves.

For convenience, we shall perform an incompressible analysis, which can be justified in the most physical region(Furth et al.,1963). A transverse plasmon oscillating is along the y-direction, and the unperturbed field is B_{0y} perpendicular to the x-direction. First let us examine the steady state:

$$\mathbf{u}_0 = 0, \qquad \rho_0 = \overline{\rho}_0 + \rho_{01}(x), \tag{9}$$

$$\mathbf{B}_0 = B_{0y}(x)\hat{y} = \overline{B}\tanh\left(\frac{x}{L_s}\right)\hat{y}, \tag{10}$$

Within the current sheet (i.e.,$|\ x\ |=|\ x/L_s\ |\ll 1$), the magnetic field can be approximated by

$$\mathbf{B}_0 = \overline{B}\frac{x}{L_s}\hat{y},$$

Due to the repellent of the ponderamotive force, the density within the current sheet is lower(Li et al.,1994):

$$\rho_{01}(x) \approx -\frac{1}{c_s^2}\frac{\overline{\rho}_0}{4}\mu(\overline{v}_0)^2 sech^2\frac{x}{\varepsilon_0}, \qquad (\mu = m_e/m_i)$$

here c_s is the speed of sound, $\overline{v}_0$ the amplitude of the fast oscillation $\mathbf{V}_{f0}$

$$\mathbf{v}_{f0} = \frac{1}{2}[\mathbf{v}_0 e^{i\omega_{pe}t} + c.c.], \qquad \left(\omega_{pe}^2 = \frac{4\pi n_e e^2}{m_e}\right)$$

ε_0 the width of the solitary wave:

$$\varepsilon_0 = (\sqrt{8}/\sqrt{\mu})\left(\frac{c}{\omega_{pe}}\right)(c_s/(\overline{v}_0)) \tag{11}$$

We see from the above that the ponderamotive force by transverse plasma waves excludes plasma, leading to diminishing the density with the current sheet.

Examing the perturbation state in the form

$$A(x,y,t) = (u_x, B_x) = A(x)e^{ik_y y}e^{\gamma t},$$

then from Equations (1) through (8) we obtain

$$\psi'' = \alpha^2\psi\left(1+\frac{\gamma\tau_R}{\alpha^2}\right) - iK_y\tau_R F u_x, \tag{12}$$

$$(\theta_0 u'_x)' = \alpha^2 u_x\left[\theta_0 + \frac{S^2}{\gamma^2\tau_R^2}G_0 + \frac{S^2}{\gamma\tau_R}F^2\right] + \frac{i}{k_y\tau_R}\psi\alpha^2 S^2\left(F - \frac{F''}{\gamma\tau_R}\right), \tag{13}$$

in which

$$\psi = \frac{B_x}{\overline{B}}, \quad \alpha = k_y L_s, \quad \theta_0 = \frac{\rho_0}{\overline{\rho}_0}, \quad F = \frac{B_{0y}}{\overline{B}_0}, \tag{14}$$

$$\tau_R = 4\pi L_s^2/(\eta c^2), \quad S = \tau_R/\tau_H, \quad \tau_H = 4\pi L_s\sqrt{\overline{\rho}_0}/\overline{B}_0, \quad \overline{x} = x/L_s; \tag{15}$$

and

$$G_0 = \left(-\frac{1}{4}\mu\frac{d}{dx}\mid \mathbf{V}_0\mid^2\right)\frac{\rho_0}{\overline{\rho}_0}\tau_H^2, \tag{16}$$

$$\mid \mathbf{V}_0\mid^2 = \overline{v}_0^2 sech^2\left(\sqrt{\frac{\mu}{8}}\frac{\overline{v}_0}{c_s}\frac{\omega_{pe}}{c}x\right) \tag{17}$$

where the superscript prime "$'$" represents the derivative with respect to $\overline{x}$. Therefore, we obtain the jump condition across the sheet in the outer region:

$$\Delta' = (\psi'_{+0} - \psi'_{-0})/\psi(0) = 2(\alpha^{-1} - \alpha)$$

On the other hand, under a constant ψ_0 approximation, one can get the jump condition within the current sheet in a similar way given by Furth et al.(1963). By equating both jump conditions, one has(Li et al.,1994)

$$4\pi\frac{(\gamma\tau_R)^{5/4}\Gamma\left(\frac{3}{4}\right)}{(\alpha S)^{1/2}\Gamma\left(\frac{1}{4}\right)}(1+\zeta)^{1/4} = 2(\alpha^{-1} - \alpha), \tag{18}$$

with

$$\zeta = d_0^2/(\gamma\tau_R), \qquad d_0^2 = \pi\mu^2\left(\frac{\overline{v}_0}{c_s}\right)^2\left(\frac{\overline{v}_0}{\overline{v}_A}\right)^2\left(\frac{L_s}{\varepsilon_0}\right)^4, \tag{19}$$

where Γ is the gamma function and $\overline{v}_A$ the Alfven velocity. Equation (18) is the key equation for determining the instability by solitary waves ($\zeta \gg 1$), and the growth rate of this instability can be deduced from Equation (18) in the form:

$$\gamma \approx \frac{1}{d_0^{1/2}}\frac{(\alpha S)^{1/2}(\alpha^{-1} - \alpha)}{2\pi}\frac{\Gamma(\frac{1}{4})}{\Gamma(\frac{3}{4})}\cdot\frac{1}{\tau_R}(\quad s^{-1}). \tag{20}$$

When the reconnection process occurs, the constant ψ_0 is no longer valid; in this case a localized instability would be involved. By introducing the Fourier transformation as suggested by Furth et al. (1963), one obtains from Equations (12), (13)(Li and Wu,1989)

$$\gamma_b \approx \overline{v}_A/d_{eff} \tag{21}$$

with

$$d_{eff} = \frac{\sqrt{4\pi}}{d_0}\alpha L_s, \tag{22}$$

This instability determined by (20) and (21) is responsible for carrying away the products of field annihilation at a fast enough rate.

III. COMPUTATION RESULTS

For this transient brightening the temperature and electron density in the region of the current sheet are $T_e = 10^4 K$ and $n_e = 10^{12} cm^{-3}$, respectively. If we use $\overline{B} = 100$ Gauss, $L_s = 4\times 10^5 cm$, we obtain $c_s = 9\times 10^5 cms^{-1}, \overline{v}_A = 2.1\times 10^8 cms^{-1}, \omega_{pe} = 5.6\times 10^9 sec^{-1}$. We use $\overline{v}_0 \geq (4v_{T_e}^2 N_D^{-1})^{1/2}$ (Hu et al.,1995), $\overline{v}_0 = 2\times 10^6$. If $\eta = 1\times 10^{-15} esu$, by using Eqs. (11), (14), (15), (16), (19) and (20) the results are $\epsilon_0 = 2.9\times 10^2 cm$, $d_0 = 3.7\times 10^2 cm$, $\tau_R = 2.23\times 10^6 (sec)$, $\tau_H = 6.4\times 10^{-2} (sec)$, $s = 3.48\times 10^7$, $\gamma =$

$2.05\times10^{-3}(sec^{-1})$, (here $\alpha = 10^{-3}$), and corresponding characteristic time-scale is

$$t = \frac{1}{\gamma} = 488sec. \approx 8.1min. \tag{23}$$

which related to the lifetime of a few minutes for the transient brightening as disscussed in Section I.

Furthermore, for magnetic energy dissipation, the estimated energy, E, released from the interaction region of the loop is as follows:

$$E \approx \frac{c^2\eta}{4\pi^2}\frac{B^2}{d^2}(Ad)t \approx \frac{c^2\eta}{4\pi^2}\frac{B^2}{d}At \tag{24}$$

where A is the area of interaction region, $A = 12" \times 5" = 3.1 \times 10^{17} cm^2$. d is the thikeness of the current sheet. Using the values d=100cm, B=100Gauss, and by the above values of t($\approx$ 488 sec.), we derive:

$$E \approx 3.45 \times 10^{26} ergs.$$

which is the same order of magnitude as those estimated in Thomas and Teske(1971).

The fine consistency of our computation results with the observational data indicates that the phenomenon of transient brightening can be depicted by this model of magnetic reconnection driven by a ponderamotive force.

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