NANOFLARES HEATING OF SOLAR CORONA BY RECONNECTION MODEL

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Abstract. *Abstract.* A number of mechanisms have been proposed that predicts heating by discrete events of various energies. By taking the facts that when two oppositely directed magnetic fields come closer to form a current sheet (treated as diffusion region), the current density of plasma increases due to which magnetic reconnection and turbulence takes place. We investigate the energy range 10^{23} to 10^{26} ergs (called nanoflares), by steady state of magnetic reconnection. Here the magnetic energy convert in to the thermal energy and heating exist by the process of reconnection model. This process is also the principle source of heat for solar X-ray corona. We reported that the energy release in current sheet also matches with the observations of Yohkoh satellite. From Yohkoh X-ray observations the fluctuation in brightness is of the order of 10^{23} – 10^{26} ergs over times of 100 sec.

Key words: Sun, Solar corona, Magnetic reconnection, Coronal heating, Solar flares.

1. INTRODUCTION

The enigma of coronal heating represents one of the most challenging problems in Astrophysics at present time. The Sun's outer atmosphere (solar corona) contains a highly ionized atoms that can only form at a temperature of millions degree. While the underlying region photosphere (temperature 4500K–6000K) and chromospheres (temperature 4500K–10000K) are much cooler. Thus there should be some extra source to create steep temperature gradient on the transition region and corona. The energy budget needed to power the solar corona is quite small (about 0.01%) relative to the global solar energy output. It is well known that any coronal heating mechanism can only be observed indirectly in form of radiation resulting from the heat that is created by the several processes. Therefore, a number of models mechanisms were proposed by (Parker, 1983). 2D and 3D reconnections models have been proposed in this field. In 2D, quasi-steady reconnection of magnetic fields enables the coronal plasma to dissipate magnetic energy, a process that has been proposed to yield direct plasma heating of the corona (Parker, 1963, 1972, 1979, 1983; Sturrock and Uchida, 1981; Van Ballegooijen, 1986) or to supply direct plasma heating in flares (Sweet, 1958; Parker, 1963; Petschek, 1964; Carmichael, 1964; Sturrock, 1966). The corona contains a large assembly of high temperature elemental magnetic filaments or loops, created together with the coronal magnetic field through randomly distributed impulsive heating agents responsible for nanoflares (Parker, 1988). A major class of mechanisms for heating the corona involves three dimensional magnetic reconnection in current sheets (Priest and Forbes, 2000), but at least six reconnection models have been proposed (Priest *et al.*, 2005).

1. In first model reconnection takes place at coronal null points that is driven by photospheric motion. For example in case of X-ray bright points, reconnection takes place due to emergence and cancellation of flux system (Priest *et al.*, 1994; Parnell *et al.*, 1994; Buchner *et al.*, 2004; Parker, 2005).

2. The second model is Parker's classical model of topological dissipation. In this model complex braiding motions of photospheric foot points cause current sheets into the corona (Parker, 1972, 1981, 1994).

3. Binary reconnection model is the third model (Priest *et al.*, 2003). Due to relative motions of pairs of magnetic fragments in the photosphere reconnection takes place that causes magnetic waves to propagate and dissipate in medium. A non-linear force also builds up that subsequently relax.

4. There are some other types of reconnection namely, spine, fan, and separator reconnection (Priest and Titov, 1996) associated with null points. The fourth reconnection model is separator reconnection for coronal heating. It was found that separator reconnection is the excellent source of heating. Numerical experiments have been conducted on separator reconnection (Galsgaard and Nordlund, 1997; Parnell and Galsgaard, 2004; Longcope, 1996; Longcope and Silva, 1998; Longcope and Kankelborg, 1999; Longcope, 2001). The time-dependent formation of a sheet along a separator in reduced MHD has been modelled (Longcope and Van Ballegooijen, 2002).

5. In fifth model turbulent reconnection takes place in each domain. It is due to magnetic fields that may be nonlinear force-free rather than potential and so can relax by turbulent reconnection to a lower energy state (Heyvaerts and Priest, 1984; Heyvaerts, 1992; Van Ballegooijen, 1985; Gomez and Ferro Fontan, 1988; Browning *et al.*, 1986; Vekstein *et al.*, 1991; Nandi *et al.*, 2003).

6. In sixth coronal heating reconnection model, current sheets are formed along the separatrix surfaces that bound each domain. The Coronal Tectonics Model

of coronal heating (Priest *et al.*, 2002) includes the effects of heating at both separators and separatrices.

There are two possible prominent mechanisms for coronal heating as follows:

i. The energy in the corona is dissipated via MHD waves (if $t_A > t_R$)

ii. Through small scale random electric current sheets formed by two opposite magnetic fields (if $t_A < t_R$).

The second mechanism (ii) of continual stressing of magnetic field which leads to numerous, discrete burst of energy in form of flares through the corona. We have just tried to solve the problem by taking neutral current sheet model.

2. ENERGY OF A CURRENT SHEET FORMED BY STEADY STATE MAGNETIC RECONNECTION

The occurrence of current sheets has important implications for the heating of the solar corona. When two magnetic fields of opposite polarity come closer a current sheet is formed (Fig.1). This current sheet of finite region is called diffusion region, where the density of the plasma increases, because the pressure P is proportional to the square of current density (Narain and Pandey, 2006). So that pressure inside the region also increases.

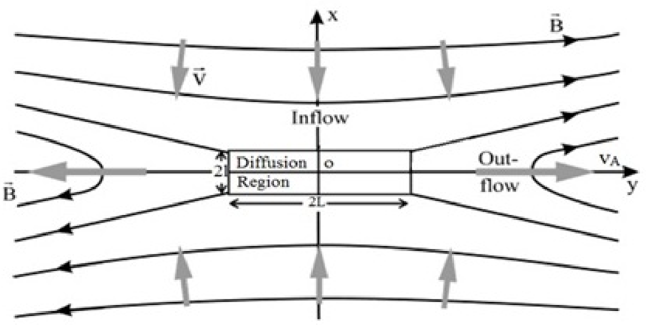

Fig. 1 – Basic 2D model of a magnetic reconnection process. In diffusion region plasma-β parameter is $\beta > 1$ (Schindler and Hornig, 2001).

Let the current sheet be a length $2L$, breadth of $2l$ along Y and X axis and it is independent with Z coordinate (Tandberg-Hanssen and Emslie, 1988). From the basic MHD equation in resistive medium (Aschwanden, 2004),

$$\rho \frac{\mathrm{d}v}{\mathrm{d}t} = -\nabla P + \rho g + (j \times B) \tag{1}$$

$$j = \frac{1}{4\pi}(\nabla \times B) \tag{2}$$

where P, v, ρ, g, j and B are pressure, fluid velocity, plasma density, gravity, current density and magnetic field. In static equilibrium $\mathrm{d}/\mathrm{d}t = 0$ and flows $v = constant$. Since the horizontal pressure is balanced, we neglect the gravity.

$$-\nabla P + \frac{1}{4\pi}(\nabla \times B) \times B = 0 \tag{3}$$

$$-\nabla P - \frac{1}{4\pi} B \times (\nabla \times B) = 0 \tag{4}$$

$$-\nabla(P + \frac{B^2}{8\pi}) + \frac{1}{4}(B.\nabla)\frac{B}{\pi} = 0 \tag{5}$$

The first term represents the gradient of total pressure (thermal and magnetic pressure) while the second term represents the magnetic tension. If the current sheet is not small it will not bent.

$$(P + \frac{B^2}{8\pi}) = constant \text{ (say P}'\text{)} \tag{6}$$

where P' is the pressure exerted by fluid motion from outside towards the neutral point 0. Thus, the total pressure has to be balanced by the thermal pressure outside.

$$P - P' = \frac{B^2}{8\pi} \text{ (magnetic pressure, see Fig.2)} \tag{7}$$

Since outside the region $|Y| > L$ the gas pressure is smaller, while $|Y| < L$ inside the current sheet) achieve higher pressure. So that fluid is ejected along the field lines reducing the built up pressure and allowing the oppositely directed field lines come closer. Thus during the formation of current sheet the magnetic energy converted into thermal energy. If v_A is the velocity of fluid along Y-axis and ρ is the matter density of fluid.

The magnetic pressure is equivalent to the kinetic energy per unit volume. By simply using Bernauli's theorem:

$$P - P' = \frac{1}{2}\rho v_A^2 \tag{8}$$

where

$$v_A = \frac{B}{(4\pi\rho)^{\frac{1}{2}}}, \tag{9}$$

the Alfv$\acute{e}$n speed along Y-direction and velocity of reconnection is v_{rec}. From the continuity equation in steady state,

$$v_{rec} L = v_A l \tag{10}$$

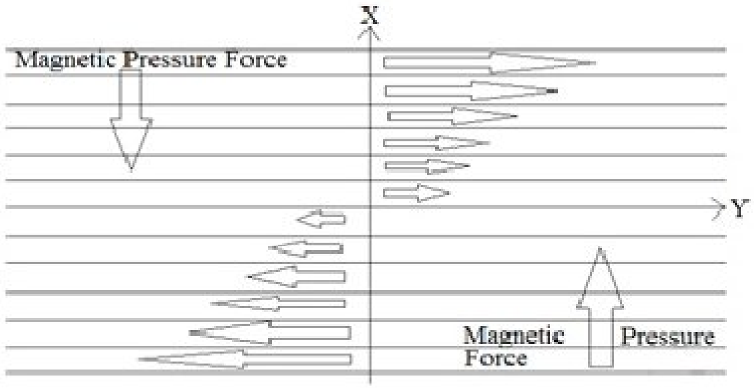

Fig. 2 – Basic 2D model of a magnetic reconnection process. In diffusion region plasma-β parameter is $\beta > 1$ (Schindler and Hornig, 2001).

where v_{rec} is inflow speed and v_A is outflow speed. From the Maxwellian equation,

$$j = \frac{c}{4\pi}(\nabla \times B) \ \text{(in esu unit)} \tag{11}$$

A fundamental assumption in MHD is nonrelativistic approximation when the speed of plasma motion v_A is much slower than the velocity of light $(v_A << c)$. The neglected term in Eq.11 is $\frac{1}{c}\frac{\partial E}{\partial t} \approx \frac{1}{c}\frac{E_0}{t_0} \approx \frac{1}{c}(\frac{v_A}{l_0})E_0 << \frac{B_0}{l_0} \approx (\nabla \times B)$, where l_0 represents the length scale L along Y-axis and $\nabla = \mathrm{d}/\mathrm{d}l \approx 1/L$. Though the coronal plasma has a very small resistivity the ohmic dissipation $\eta j^2 = \eta \frac{c^2}{16\pi^2}\frac{B^2}{L^2}$, as L is smaller *j* becomes larger, due to large current densities, large ohmic dissipation.

$$j = \frac{c}{4\pi}(\frac{B}{L}) \tag{12}$$

When two opposite magnetic fields $(\pm B)$ press together time of total energy dissipation considered as reconnection time and suggest that (Parker, 2005)

$$j = \frac{Bc}{4\pi}(4\pi\eta t_R)^{\frac{1}{2}} \exp(-\frac{L^2}{4\eta t_R}) \tag{13}$$

where η is the resistivity of the solar corona, $\eta \propto T_e^{\frac{-3}{2}} = 1.5 \times 10^{-7} T_e^{-1.5}$. The dissipation rate is from Eq.13 (Parker, 2005)

$$\frac{j^2}{\sigma} = \frac{B^2}{16\pi^2 t_R}\exp(-\frac{L^2}{2\eta t_R}) \ [\text{ergs cm}^{-3} \text{ sec}^{-1}] \tag{14}$$

The dissipation per unit area is (Parker, 2005)

$$2\int_0^\infty \mathrm{d}x \frac{j^2}{\sigma} = \frac{B^2}{8\pi}(\frac{\eta}{2\pi t_R})^{\frac{1}{2}} [\text{ergs cm}^{-2} \text{ sec}^{-1}] \tag{15}$$

Using Eq.12 and integrating Eq.15 under the limit of diffusion region we get

$$t_R = \frac{\sigma^2 \eta \pi L^2}{2c^4} \tag{16}$$

The longitudinal magnetic Reynolds number (ratio of convective term to diffusive term) is

$$\frac{|\nabla \times v \times B|}{|\frac{\eta c^2}{4\pi \nabla^2 B}|} \approx \frac{8\pi L v_A}{\eta c^2} = R_m \tag{17}$$

and we get

$$L = \frac{\eta c^2 R_m}{8\pi v_A} \tag{18}$$

From Eq.16 and 18

$$t_R = \frac{\sigma^2 \eta^3 R_m^2}{128\pi v_A^2} \tag{19}$$

Using Eq.9 and keeping the value of Alfvén velocity in Eq.19 we get

$$t_R = \frac{\sigma^2 \eta^3 R_m^2 \rho}{32 B^2} \tag{20}$$

From the above Eq.20 we found that the reconnection time t_R is inversely proportional to the square of magnetic field B or we can say that reconnection time decreases quadratically with increase of magnetic field. The rate of energy release per unit time in the current sheet is obtained by

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{B^2 V}{8\pi t_R} \tag{21}$$

where *B* is the magnetic field before reconnection and $V = L^2 l$ is the volume of current sheet. On putting the values of Eq.20 in Eq.21 we get

$$\frac{dE}{dt} = \frac{4B^4 L^2 l}{\pi \sigma^2 \eta^3 \rho R_m^2} \tag{22}$$

From the Eq.22 we found that the dissipative energy per unit time in a current sheet is varies as fourth power of magnetic field. The Reynold's no. of coronal plasma is $R_m \approx 10^8 \approx 10^{12}$. For our estimation by considering, $v_A = 2 \times 10^8$ cm sec^{-1}, $L = 10^{10}$ cm, $B = 200$ G, $\eta = 1.5 \times 10^{-7} T_e^{-(\frac{3}{2})}$, $T_e = 2$ MK. We get $\eta = 5.3 \times 10^{-17}$ esu and supposing $l = 200$ cm, $\rho = 10^9$ hydrogen ions/cm^3. The electrical conductivity, $\sigma = \frac{n_e e^2 \tau_c e}{m_e} s^{-1} = 6.96 \times \ln(\wedge)^{-1} Z^{-1} T_e^{\frac{3}{2}} \approx 9.7 \times 10^{15} s^{-1}, e = 4.8 \times 10^{-10}, m_e = 9.1094 \times 10^{-28} g$. The reconnection time from Eq.20 is $t_R \approx 109$ sec. Numerically, from Eq.22 we get

$$\frac{dE}{dt} \approx 10^{23}[\mathrm{ergs/sec}] \tag{23}$$

i.e. the energy release from the magnetic reconnection in a single current sheet, in steady state, obtained in the range of nanoflares. It also matches with Yohkoh X-ray observations observed by Katsukawa and Tsuneta.

3. CONCLUSIONS

The theoretical predictions show that nanoflare heating by steady state magnetic reconnection model is one of the heating mechanisms for the solar corona. Thus when $t_R > t_A$ then instead of waves stressed magnetic structures are built, which contain a large amount of energy. When two magnetic fields of opposite polarity are brought together a current sheet is formed. The energy of stressed field is released by reconnection. These reconnection processes usually occur suddenly like a flare. Here the magnetic energy converts in to thermal energy via magnetic reconnection and resulting turbulence like flares take place. Hence, the energy release from the magnetic reconnection in a single current sheet in steady state obtained in the range of nanoflares, *i.e.* 10^{23} ergs/sec. This energy range is also same as observed in Yohkoh X-ray observation in which the fluctuation in myriads is of the order of $10^{21} - 10^{23}$ ergs over times of 100 sec that helps for direct quantitative observational studies of phenomenon.

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