Tests of the models of coronal magnetic loops inductive interaction within the SECCHI on the STEREO mission and their relation to CME phenomena

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ABSTRACT

We summarize here a few theoretical models, which employ the ideas of possible inductive interaction between the coronal electric currents usually confined within the current-carrying magnetic loops. These models are addressed to the basic dynamical processes in groups of solar coronal magnetic loops and can be related to the phenomena of CMEs, flaring "loop-loop interaction", and acceleration of charged particles. An information about the 3D structure of coronal loops and their global dynamics (rising, twisting, oscillation) is crucial for the considered models, and we expect that the data from SECCHI on the STEREO will appear as a good test for them.

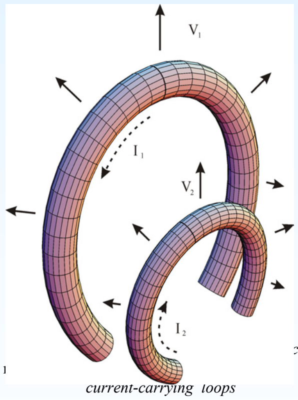
INTRODUCTION

The solar corona is a highly structured medium. Coronal loops, which trace closed magnetic field lines, are the primary structural elements. These loops are the evolving objects growing up and changing their shape. Complex dynamics of the loops together with action of possible under-photospheric dynamo mechanisms cause the majority of coronal magnetic loops to be very likely as the current-carrying ones [1]. In that connection none of the loops can be considered as isolated from the surroundings. Moving relative each other current-carrying loops should interact via the magnetic field and currents. The simplest way to take account of this interaction consists in application of the equivalent electric circuit models of the loops, as well as in the consideration of the ponderomotoric interaction of their currents. In these models each loop is considered as an electric circuit with variable parameters (resistance, inductive coefficients) which depend on the shape, scale, position of the loop with respect to neighbouring loops [2]. Plasma parameters in the magnetic tube as well influence the electric characteristics of the equivalent circuit.

MODELS

1. Inductive interaction of two current-carrying loops. „Loop-loop interaction"

It follows from observations that a large number of flares occurs in the regions where a new magnetic loop emerges and interacts with the existing loops [3]. Such events are known as the "interacting flare loops". Here we present a further development of the idea of the loop-loop inductive interaction, which was first suggested by Melrose [4] and later applied by Aschwanden et al. [5] for interpretation of observations.



current-carrying loops

In addition to [4] and [5], we note that the relative motion of the loops creates significant inductive electro motive forces in their electric circuits which appear as a powerful source for changing the currents in the loops. Change of the currents disturbs the pre-existed thermal equilibrium of the loops and results in a change of the plasma temperature, which in its turn influences the resistivity of the circuit and the *cted* energy losses. Therefore each of the rising magnetic loops (see Fig.1) in our model is described by two equations [2]: the equation for the electric circuit

(1)
$$I_i R_i = U_{0i} - \frac{1}{c^2}\left(L_i \dot{I}_i + I_i \dot{L}_i + M_{ij}\dot{I}_j + I_j \dot{M}_{ij}\right)$$

and the ener

,

(2)
$$\dot{T}_i = \frac{1-\gamma}{2 n_i k_B}\left(n_i^2 Q(T_i) - \frac{j_i^2}{\sigma(T_i)} - H_i\right)$$

where i,j are the

M_{ij} and L_i, mutual- and self- nductances;

n_i T_i, temperature and density of plasma in i-th loop;

$J_i = I_i$ $r_{0\,i}^2$ current density in the loop;

$Q(T_i)$, radiative loss function [6];

H_i, stationary background heating.

A thin torus approximation is applied for the loops ($R_{loop} >> r_0$). So the inductive coefficients are

$$L = 4\pi R_{loop}\left(\ln\frac{8R_{loop}}{r_0} - \frac{7}{4}\right) \qquad M_{ij} = 8\,(L_i L_j)^{1/2}\left[\frac{R_{loop\,i} R_{loop\,j}}{(R_{loop\,i} + R_{loop\,j})^2 + d_{ij}^2}\right]\cos\varphi_{ij},$$

where d_{ij} is the distance between the centers of the loops tori and φ_{ij}, the angle between the normal vectors to the loops planes.

A linear increase in time of the major radii of the loops $R_{loop\,i} = R^0_{loop\,i} + v_i\,t$, $i=1,2$ is considered, and the initial steady state and thermal equilibrium are assumed. One of the loops is taken to be initially current-free ($I_{20} = 0$).

The numerical solution of Eqs. (1), (2) for both loops indicates :

- Quick build up of the current in the initially current-free loop;
- Significant increase of the current and plasma temperature in the loops when they become to be of the same size (a flare);
- The most efficient interaction of the parallel loops ($\varphi_{12} = 0$)

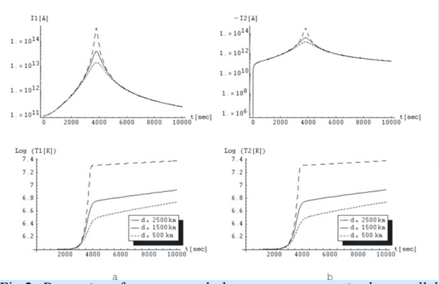
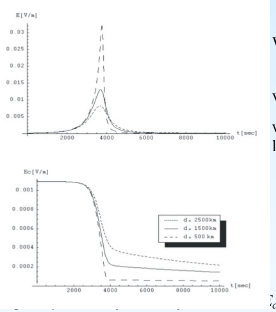


Fig.2: *Dynamics of currents and plasma temperature in the parallel (φ_{12}=0) loops in dependence on the distance d_{12}. ($R_{loop}{}^0{}_1 = 2\cdot 10^9$ cm, $R_{loop}{}^0{}_2 = 10^8$ cm, $r_{01} = r_{02} = 5\cdot 10^7$ cm, $v_1 = 5\cdot 10^5$ cm/s, $v_2 = 10^6$ cm/s, $n_1 = n_2 = 10^9$ cm^{-3}, $T_1(t=0) = T_2(t=0) = 10^6$ K, $I_{10} = 10^{11}$A, $I_{20} = 0$).*

The inductive electric field produced in the loop can be estimated



as $E = \dfrac{I_i^2}{(\pi r_{0i}^2)^2\sigma(T_i)}$. When the value of this field exceeds the value $E_c \approx 0.2\dfrac{4\pi n e^3}{k_B T} L_e$ where L_e is Coulomb logarithm, the main part of electrons appears to be in a run-away regime and can be accelerated by E.

According to Fig.3 such a situation takes place in our model for $t>2000$ s.

(for the case $\varphi_{12} = 0$). Finally we obtain that inductive field can accelerate electrons in the loop up to energies $W = q[e]\cdot E[V/m]\cdot l_{loop}[m] = 100...1000$ eV .

2. CMEs as rising magnetic loops. Acceleration of CMEs

Dynamics of a rising curr … op is defined by concur- … and magnetic stress force

$$F_{lift} = -\frac{\partial U}{\partial R_{loop}}$$

$$F_m = \frac{\partial}{\partial s}\left(\frac{B^2}{8\pi}\right)\boldsymbol{s} + \frac{B^2}{4\pi}\frac{\boldsymbol{n}}{R_{loop}}$$, where $$U = -\frac{1}{2c^2}\sum_{i,j} M_{ij} I_i I_j,\quad M_{ii} \equiv L_i$$ s

the potential force function of a system of currents.

F_m decreases when the R_{loop} increases. And in the case of $F_{lift} > F_m$ we have ***acceleration*** of the loop by the ponderomotive forces (Fig.4).

The MHD simulations in [7] find that a flux rope with sufficient magnetic energy density will erupt. The source of this energy comes from the ponderomotoric interaction of currents in the filament and the system of underlying loops.

In the model calculations we consider a symmetric group consisting of three current-carrying loops. The bigger loop in the center of the group is vertical whereas the lateral loops on both sides are inclined on the same angle but in different directions. In Fig.5 the dependence of the lifting force applied to the central loop on the height of the lateral loops is shown.

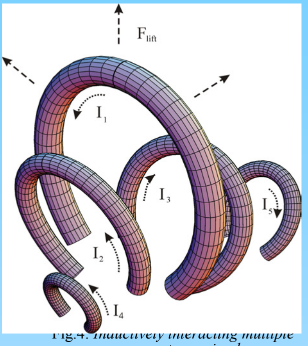
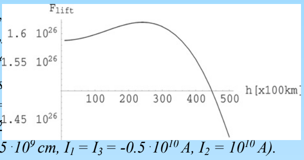


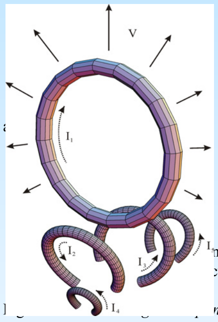
Fig.4: *Inductively interacting multiple current-carrying loops*

Fig.5: *Lifting force applied to the central loop in the system of three current-carrying loops as a function of height of the lateral loops ($R_{loop\,2} = 5\cdot 10^8$ cm, $r_{01} = r_{02} =$ $5\cdot 10^7$ cm, $d = 5\cdot 10^9$ cm, $I_1 = I_3 = -0.5\cdot 10^{10}$ A, $I_2 = 10^{10}$ A).*



3. Acceleration of charged particles by inductive electric fields in CMEs

We model CME as a rising and expanding closed current-carrying loop above the group of magnetic loops (Fig.6)



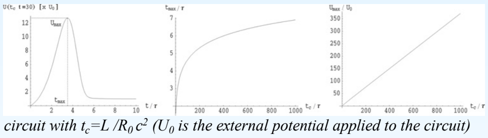
… nding magnetic loop above the group of loops

There are two possible ways of production of a significant electric field in a rising CME:

1. Temporal change of a magnetic flux through the circuit of the rising expanding magnetic loop

$$\oint \boldsymbol{E}_{ind} = -\frac{1}{c}\frac{\partial\Psi}{\partial t}$$

2. Fast break of the electric circuit of the rising current-carrying loop. This is equivalent to a fast increasing resistance $R(t) = R_0\,e^{t}$ switched into the circuit (see Fig.8).



circuit with $t_c = L/R_0 c^2$ (U_0 is the external potential applied to the circuit)

CONCLUSION

In order to apply the ideas of the above equivalent electric circuit models for explanation of physical processes in coronal magnetic loops and CMEs, a detailed information on the 3D structure and dynamics of these objects as well as data on their plasma characteristics are needed. The presence and structure of the currents in the spatial domains of interest can be detected from high resolution chromospheric and low corona images combined with the vector magnetograms data. ***All these tasks can be performed by the SECCHI remote sensing instruments [8]. The additional information on the magnetic field can be made available from Solar-B and the National Solar Observatory SOLIS magnetographs.***

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