ENERGY RELEASE IN CORONA MAGNETIC LOOPS

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It is found that thin magnetic tubes of radius about $10^7-10^8$ cm and longitudinal current $10^{11}-10^{12}$ A can be generated under the conditions of convective flows in the solar photosphere. Moreover, the so-called "magnetic holes," cylindrical magnetic structures with magnetic field decreasing towards the center, can be formed in divergent convective (Evershed) flows. It is shown that the steady-state Joule energy release (dissipation) at the photospheric footpoints of a magnetic tube increase towards the tube periphery in the upper photosphere and can exceed the optical radiation losses. In particular, this can lead to the occurrence of magnetic tubes with hot external envelopes.

We consider two models of magnetic flaring loops in the active region. One model describes the explosive energy release in an individual loop caused by the penetration of the dense partially ionized plasma of a prominence into the magnetic tube (in the upper part of the loop) due to flute instability or the penetration of the surrounding chromospheric plasma (in the chromospheric part of the loop). The inflow of these plasmas destroys the force-free structure of the magnetic tube and switches on an efficient mechanism of energy release due to ion-atom collisions in a non-steady-state plasma. We studied the dynamics of the joule energy release in such processes.

The second model of flaring energy release is based on the global approach in the study of the dynamics and energetics of solar active regions with allowance for their complex self-consistent evolution. The structure of the magnetic field of an active region was represented as an ensemble of inductively coupled current-carrying magnetic loops interacting with each other. Each loop, in turn, was simulated by an equivalent electric circuit with variable parameters as a function of the shape, scale, and position of the loop in the ensemble as well as of the plasma temperature and density in the magnetic tube. Using this model, we showed that a rising magnetic loop can cause thermal flare-like heating of one loop and cooling of other loops in the ensemble.

1. INTRODUCTION

Solar activity processes are closely connected with magnetic loops. A magnetic loop is the main structural element of the magnetic field in the chromosphere and in the corona and shows the complex configuration of the subphotospheric magnetic field due to convective motion of the plasma. Usually, the loop footpoints are located at the junctions of several supergranules where the convective plasma motion determines the density of the background magnetic field in thin magnetic tubes of radius about 100 km and magnetic intensity about $10^5$ G [1].

One manifestation of intensive energetic processes on the Sun is the solar flares. They occur in a great variety of forms, ranging from a simple localized enhancement to an extremely complicated phenomenon extended to almost the entire active region. The flares differ in complexity and in the duration of the phases. At the same time, in a conventional flare we can generally observe the preflare phase (precursor), which takes place about 10 minutes before the flare itself and characterizes the amplification of radiation in the soft X-ray region ($< 10$ keV). The precursor is followed by the pulsed phase with a duration of from 100 to 1000 sec, which is manifested by microwave and hard X-ray bursts ($> 30$ keV). Then usually follows the flash phase, which lasts a few minutes and is characterized by a rapid increase of the intensity and area of radiation. Finally, the principal phase comes, during which the radiation intensity decreases slowly for about one hour [2]. At the same time, flares in which the pulsed phase is absent are also observed sometimes; this can be an indication of only a marginal acceleration of particles. The increase of the radiation intensity to the maximum is slow in this case. Such events are called thermal flares [2].

Besides the large flares, which begin at several points of the active region and then spread to a considerable area [3], there are also simple loop (compact) flares. A compact flare is fairly small (on the scale of the Sun) and represents the enhancement of a magnetic loop. In this case, the loop is immobile and does not change in form. A simple loop flare is characterized by one hard X-ray flare of duration about 1 min. In such a flare, the main portion of energy is released in the pulsed phase. In the soft X-ray range, such flares have moderate volumes, large energy densities, and short temporal scales, while the slow flares generally belong to the thermal type.

In this paper, we consider the problems connected with the structure of the magnetic field in magnetic loops and the steady-state joule energy release in such loops. We analyze two models of the flaring energy release. The first model, which belongs to the so-called “circuit” models, shows the possibility of explosive energy release in a separate magnetic loop and can, from this point of view, be associated with a simple or compact loop flare. In the second model, conversely, we study the heating processes in an ensemble of inductively interacting magnetic loops, one of which changes in length and in height (in a fashion similar to the rise (surfacing) of a magnetic flow). In such a system, one separate magnetic loop is heated considerably while some other loops are cooled. By temporal characteristics and spatial scale, the processes described by the second model resemble thermal flares in the active region. What the two models have in common is that the magnetic loop as an object in which the flaring energy release takes place, is simulated by an equivalent electrical circuit. However, the mechanisms used to explain the energy release process are different in these models. For example, in the model of a flare in a separate magnetic loop, the energy release is stipulated by a considerable change in the resistance of the loop circuit by switching efficient dissipative mechanisms due to ion–atom collisions in a moving partially ionized plasma. The source of that plasma is the prominence in the upper part of the loop or the surrounding chromospheric plasma in the vicinity of the loop footpoints. However, in the model describing an ensemble of magnetic loops the heating of individual loops is caused by the loss of the thermodynamic equilibrium when the electrical currents in these loops are changed in the inductive interaction with the neighbors.

This paper is organized as follows. After the Introduction, in Sec. 2, we consider the steady-state structure of the currents and magnetic field in the loop under the conditions of a photospheric convective flow. In Sec. 3, we study the specific features of the steady-state joule energy release in magnetic tubes. Further, in Secs. 4 and 5, we consider the energy release processes described by the above two flaring models. In the Conclusion, we formulate briefly the main results and discuss the problems connected with the approximations which we adopted in this paper and the possible use of these models for interpretation of the observed flare phenomena on the Sun. In the Appendix, we derive analytical expressions for the inductance characteristics of the interacting magnetic loops in the ensemble.

2. ELECTRICAL CURRENTS IN MAGNETIC TUBES

Consider the structure of the electrical currents in steady-state magnetic tubes under the conditions of a horizontal convective flow of photospheric plasma. This analysis will be based on the equation of motion of the plasma

\[ \rho \frac{dV}{dt} = \frac{1}{c} [j \times B] - \nabla p + \rho g \]  

in the generalized Ohm's law

\[ E + \frac{1}{c} [V \times B] = \frac{j}{\sigma} + [j \times B] - \frac{F}{c^2 \nu_m \nu_a} [j \times B] \times B \]  

with allowance for the continuity equation

\[ \frac{\partial \rho}{\partial t} + \text{div}(\rho V) = 0 \]  

and the Maxwell equation

\[ \text{rot} E = -\frac{1}{c} \frac{\partial B}{\partial t} . \]