THERMAL ELECTRONS RUNAWAY FROM A HOT PLASMA DURING A FLARE IN THE REVERSE-CURRENT MODEL AND THEIR X-RAY BREMSSTRAHLUNG

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Abstract. The behaviour of the thermal electrons escaping from a hot plasma to a cold one during a solar flare is investigated. We suppose that the direct current of fast electrons is compensated by the reverse current of the thermal electrons in ambient plasma. It is shown that the direct current strength is determined only by the regular energy losses due to Coulomb collisions. The reverse-current electric field and the distribution function of fast electrons are found in the form of an approximate analytical solution to the self-consistent kinetic problem of the dynamics of a beam of escaping thermal electrons and its associated reverse current.

The reverse-current electric field in solar flares leads to a significant reduction of the convective heat flux carried by fast electrons escaping from the high-temperature plasma to the cold one. The spectrum and polarization of hard X-ray bremsstrahlung, and its spatial distribution along flare loops are calculated and can be used for diagnostics of flare plasmas and escaping electrons.

1. Introduction

The polarization of solar flare hard X-rays characterizes the angular distribution of fast electrons. They produce this emission during inelastic collisions with ions in the solar atmosphere (see, e.g., Syrovatskii and Shmeleva, 1972). The degree of polarization is determined by a number of factors such as: (a) anisotropy of the distribution function of electrons injected from their 'source', i.e. the region of their acceleration and/or heating, into the 'target', i.e. the region where they lose energy (see Korchak, 1971; Brown, 1972); (b) anisotropization of the nearly isotropic distribution of injected electrons while they spread in the target (Skrynnikov and Somov, 1982); (c) the Compton reflection of hard X-rays in the photosphere (Beigman, 1974).

Analysis of flare observations in microwaves and hard X-rays (e.g., Kundu et al., 1984; Gary, 1985) suggests the necessity of knowing the behavior of the distribution function along flare loops. One can then use the observational results to determine the parameters of the electron distribution function in the source. The distribution function of electrons in the target, and hence the polarization of X-rays, is sensitive to specific conditions in flare loops. Leach and Petrosian (1983) investigated, for example, the influence of the inhomogeneity of the magnetic field along a flare loop on the degree of polarization. Emslie (1980) examined a model problem with a 'nonthermal source' (see, for classification, Somov and Syrovatskii, 1976) of fast electrons, concluding that the

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reverse-current electric field could lead to significant changes of intensity and polarization of X-rays.

In this paper, we consider the so-called ‘thermal model with escaping electrons’. The problem was investigated by many authors in many aspects (e.g., Gurevich and Istomin, 1979; Skrynnikov and Somov, 1982; Shoub, 1983; Nocera, Skrynnikov, and Somov, 1985), but they did not take into account the reverse-current electric field. Gurevich and Istomin (1979) examined the case of a small temperature gradient. By using a perturbation analysis for the linearized, high-velocity form of the Landau kinetic equation, they have shown that the fast growth of the mean free path with increasing energy gives rise to ‘thermal runaway’ of electrons – an abrupt growth of the number of fast electrons in the region of the cold plasma. In addition to the usual heat flux, there appears a ‘convective energy flux’ carried by the fast electrons. At not too small temperature gradients, the convective transport of energy plays the principal role.

Smith and Lilliequist (1979), Vlahos and Papadopoulos (1979), Skrynnikov and Somov (1982), and Nocera, Skrynnikov, and Somov (1985) investigated the opposite case of an abrupt transition layer between a high-temperature plasma and a cold one with application to the problem of energy release in solar flares. Shoub (1983) has solved numerically the boundary value problem for the Fokker–Planck kinetic equation in the model of solar transition layer between the corona and upper chromosphere in quiet conditions. An excess of fast electrons has been found in the low transition layer region.

For the flare accelerated electrons with an energetic power-law spectrum, the necessity for a beam-neutralizing current in a thick-target scenario for impulsive heating of the solar atmosphere is by now well established (Hoyng, Brown, and van Beek, 1976; Knight and Sturrock, 1977; Emslie, 1981). We have included the reverse-current electric field in the cold plasma for the case of an abrupt transition layer between the hot plasma of a flare and the cold plasma in the solar atmosphere. In Section 2, we discuss the physical and mathematical formulation of the problem and evaluate the expected strength of the electric field. Section 3 analyzes the effects of Coulomb collisions. It is shown here that it is impossible to solve the reverse current problem self-consistently without taking collisions into account. The dependence of the current density on the distribution function of the escaping electrons is found. In Section 4, we have obtained an analytic solution of the kinetic equation taking into account Coulomb collisions. In Section 5, we derive the self-consistent reverse-current electric field.

The calculations of the escaping electron distribution function are presented in Section 6. To simplify and clarify them, we have used an approximate solution of the kinetic equation, but it does not have a significant influence on the accuracy of the calculations. The boundary distribution function for the back-flying electrons is determined from that of the forward-flying electrons. The distribution function of fast electrons in the target is also found. In Section 7, we evaluate the influence on the convective heat flux carried by electrons escaping from the hot plasma to the cold one. In the reverse-current target model, the convective heat flux can be many times less than that in the pure collisional target. In Section 8 the hard X-ray bremsstrahlung spectrum and polarization are calculated. In the conclusions we discuss the main results of the