NONThermal ELECTroNs IN ThE ThICK-TarGeT REVERSER-Current MoDEL FoR HARD X-Ray BREMSstrahlung

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Abstract. The behaviour of the accelerated electrons escaping from a high-temperature source of primary energy in a solar flare is investigated. The direct current of fast electrons is supposed to be balanced by the reverse current of thermal electrons in the ambient colder plasma inside flare loops. The self-consistent kinetic problem is formulated; and the reverse-current electric field and the fast electron distribution function are found from its solution. The X-ray bremsstrahlung polarization is then calculated from the distribution function. The difference of results from those in the case of thermal runaway electrons (Diakonov and Somov, 1988) is discussed. The solutions with and without account of the affect of a reverse-current electric field are also compared.

1. Introduction

The flare hard X-ray bremsstrahlung arises during inelastic collisions of fast electrons with ions in the solar atmosphere. The X-ray polarization characterizes, on one hand, the angular distribution of fast electrons and their energy spectrum. On the other hand, the behaviour of the distribution function along flare loops is determined by parameters of the electron distribution function in the primary source. Thus the theoretical analysis of the distribution function evolution along a flare loop may help to pick out the model of the origin of fast electrons. This is one of the key questions of solar flare physics.

Two possible models of the electron source are widely discussed: 'thermal' and 'nonthermal' (see, for classification, Somov and Syrovatskii, 1976). According to the former, fast electrons gain energy owing to some coronal plasma heating up to extremely high ($\geq 10^8$ K) temperatures. According to the latter, electrons are accelerated by a direct electric field or any other mechanism of particle acceleration. In this paper we study the nonthermal model in the thick-target variant, which is believed to be the most likely one for production of the power-law X-ray flux of a solar flare (Lu and Petrosian, 1989).

The problem was considered earlier in many aspects by many authors, e.g., Brown (1971), Syrovatskii and Shmeleva (1972), Kel'ner and Skrynnikov (1985), but they did not take into account a beam-neutralizing current. Hoyng, Brown, and van Beek (1976), Knight and Sturrock (1977), Emslie (1980) have established the strong necessity for the reverse current for fast electrons with an energetic power-law spectrum.

Usually to solve the kinetic equation one develops a complicated numerical method

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(e.g., Ljepojevic and McNeice, 1988). Diakonov and Somov (1988a) have developed a new technique to obtain an approximate analytical solution of the kinetic equation taking the reverse-current field into account. They have applied this technique to the case of thermal runaway electrons from a high-temperature plasma into a cold one during a solar flare. We shall use the same technique to study the behaviour of the electrons accelerated inside a high-temperature current sheet (see Somov, 1986) and escaped from such a hot source of flare energy. We shall find an analytical solution which allows us to trace the influence of the reverse-current field on the distribution function behaviour.

The plan of the paper is as follows. In Section 2 we discuss the physical and mathematical formulation of the problem. In Section 3 we derive a system of integro-differential equations to be solved. This can be done under some simplifying conditions applicable to the region with a strong electric field which drives the return current in flares. The effects of Coulomb collisions are also discussed here. In Section 4 we investigate the behaviour of the reverse-current electric field. It will be shown here that the electric field is really strong and does change slowly along flare loops near the primary energy source. The calculations of the electron distribution function are presented in Section 5. The numerical results of the X-ray bremsstrahlung polarization calculation are presented in Section 6. In Section 7 we summarize and compare the main results of the paper to the calculations made before.

2. Formulation of the Problem

In order not to obscure the essential physical points made in this paper, let us suppose that a high-temperature \( T_0 \approx 10^8 \) K plasma and a cold \( T_1 \approx 10^4 \) K one occupy two half-spaces. These plasmas are separated by a heat conductive turbulent front. It has been shown by Brown, Melrose, and Spicer (1979), Vlahos and Papadopoulos (1979) that the electrons with velocities

\[
v > v_0 = 2.8 \sqrt{kT_0/m_e}
\]

(2.1)

freely penetrate through such a turbulent front into the cold plasma. Low-velocity \( (v \leq v_0) \) electrons remain in the 'source', i.e., in the hot plasma. It is the aim of the present paper to find and examine the distribution function for the fast electrons which have escaped into the cold plasma and are propagating there.

Because of a supposed symmetry of the problem, the distribution function is of the form

\[
f(v, \theta, l) = f_{ff}(v, \theta) \Theta(v - v_0), \quad 0 \leq \theta \leq \pi/2,
\]

(2.2)

where \( \Theta = \Theta(\text{argument}) \) is the \( \theta \)-function; \( f_{ff} \) is the electron distribution function in the hot plasma (the Maxwellian function for the case of thermal electron runaway, or a superposition of thermal and nonthermal functions in the general case) normalized to