DYNAMICS OF ELECTRON BEAMS IN A CORONAL LOOP AND THE HARD X-RAY BURST

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Abstract. A numerical simulation has been made for the dynamics of non-thermal electrons (> 10 keV) injected with spatial, temporal and velocity distributions into a model coronal loop. The time variations of the spatial intensity distribution and the spectrum for the expected hard X-rays are computed for many models in order to find the important physical parameters for those characteristics.

The most important one is the column density of plasma, CD, along the loop. If CD is smaller than $10^{20}$ cm$^{-2}$, the expected X-rays behave like the solar impulsive hard X-ray bursts, that is the spatial maximum of X-rays shifts to the top of the loop in the later phase of the burst accompanying a spectral softening. On the other hand, if CD is greater than this value, 'quasi-steady decay' appears in the later phase. In this case the intensity distribution of X-rays above about 20 keV along the loop shows a broad maximum away from the loop top giving an extended spatial distribution of hard X-rays, and spectral hardness is kept constant. These characteristics are similar to the solar gradual hard X-ray bursts (the so-called extended burst which is not a hot thermal gradual burst).

1. Introduction

The aim of the present study is to make a numerical simulation for the dynamics of energetic electrons (> 10 keV) produced around the top of a coronal loop with rather high plasma density ($10^{10}$–$10^{11}$ cm$^{-3}$). Some of the electrons are lost by collisions producing X-rays in the course of propagation along the loop, some stream into the chromosphere producing thick-target X-rays and the rest are reflected back at the corresponding magnetic mirror point to be trapped in the loop.

The time variations of both the spatial intensity distribution and the spectrum of the hard X-rays are compared with observations in order to find the important physical parameters for the dynamics of electrons which produce X-rays.

Such a time dependent simulation has not previously been made, though Leach and Petrosian (1981, 1983) made a simulation for a steady stream of energetic electrons and Bai (1982) made a Monte Carlo computation for the transport of electrons. In some respects the present time dependent simulation gives results qualitatively similar to those of Leach and Petrosian. However, the time variations of the X-ray spectrum and spatial intensity distribution are difficult to guess from the steady mode.

In Sections 2 and 3, the model coronal loop and the scheme for the simulation are shown.

In Section 4, the result of the simulation is presented on the spatial distribution of the hard X-rays along the loop. In Section 5, the result for the X-ray spectrum is presented. If the column density along the model coronal loop is greater than $10^{20}$ cm$^{-2}$, a quasi-steady decay of the X-rays appears in the decay phase. In this case the X-ray
distribution along the loop shows a broad intensity maximum away from the loop top giving an extended X-ray source structure. This interesting characteristic is discussed in Section 6 using an analytical solution.

2. The Model

2.1. CORONAL MAGNETIC LOOP

The model loop in which the dynamics of energetic electrons are to be solved is as follows. The plasma in the loop is assumed to be in a steady state as given by the steady conduction model (Takakura, 1984), independently of the dynamics of the energetic electrons. The high-temperature loop (case 2), where the radiation loss from the loop is negligibly small compared with the conduction loss, is adopted throughout the present simulation. It is assumed that the cross-sectional area \( A \) of the loop and the magnetic field strength \( H \) are given by

\[
\frac{A}{A_m} = x^p, \quad \frac{H}{H_m} = x^{-p},
\]

where \( x \) is the normalized distance from the photosphere along the loop and the subscript \( m \) indicates the value at the top \( (x = 1) \) of the coronal loop. \( x_0 \) represents a footpoint of the loop. In this case the plasma temperature \( T \) and number density \( n \) are given by (Takakura, 1984)

\[
\frac{T}{T_m} = x^\alpha, \quad \frac{n}{n_m} = x^{-\alpha},
\]

with \( \alpha = (1 - p)/3.5 \). Note that \( p = 0 \) stands for a uniform magnetic field and \( p = 1 \) stands for homogeneous density and temperature. In one model (model 6), \( n \) is set to increase with time in a given time interval.

In the following treatment, another normalized distance \( Z \) is used instead of \( x \):

\[
Z = 0 \quad \text{at} \quad x = 1 \quad \text{(loop top)},
\]

and

\[
Z = 1 \quad \text{at} \quad x = x_0 \quad \text{(footpoint)},
\]

so that

\[
Z = \frac{(1 - x)}{(1 - x_0)}. \tag{2.3}
\]

The loop is assumed to be symmetric about \( Z = 0 \).

Throughout the present simulation, the following parameters are set unchanged: the footpoint of the loop \( x_0 = 0.05, T_m = 2 \times 10^7 \) K, and a half-length \( (Z = 1) \) of the loop \( l = 3 \times 10^9 \) cm \( \equiv l_0 \). However, the present results are applicable to models with different values of \( l \), since if \( n_m l \) is fixed we have the similar result under the normalised time \( \tau \) that is proportional to \( l \) as will be defined in the following subsection.