HYDRODYNAMIC RESPONSE OF THE SOLAR CHROMOSPHERE TO AN ELEMENTARY FLARE BURST

II. Thermal Model

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Abstract. Impulsive heating of the upper chromosphere by a very powerful thermal flux is studied as the cause of hard X-rays during a solar flare. The electron temperature at the boundary between the corona and chromosphere is assumed to change in accordance with the hard X-ray intensity in an elementary flare burst (EFB). A maximum value of about $10^8$ K is reached after 5 s, after which the boundary temperature decreases. These high-temperature changes lead to fast propagation of heat into the chromosphere. Numerical solution of the hydrodynamic equations, which take into account all essential dissipative processes, shows that classical heat conduction is not valid due to heat flux saturation in the case of impulsive heating from a high-temperature source. The saturation effect and hydrodynamic flow along a magnetic field lead to electron temperature and density distributions such that the thermal X-ray spectrum of a high-temperature plasma can be well enough approximated by an exponential law or by two power-law spectra. According to this dissipative thermal model for the source of hard X-rays, the emission measure of the high-temperature plasma increases monotonously during the whole EFB even after the temperature maximum. Some results for the low-temperature region are discussed in connection with short-lived chromospheric bright points.

1. Introduction

As well known, solar hard X-rays are often interpreted as the bremsstrahlung of energetic non-thermal electrons in a relative cold plasma (e.g. Brown, 1972; Syrovatskii and Shmeleva, 1972). This approach assumes that the main process in a flare energy source is a particle acceleration. The non-thermal electrons produce an impulsive heating of solar plasma via collisional energy losses. For this reason, in Paper I (Somov et al., 1981) fast hydrodynamic motions of chromospheric plasma heated by energetic electrons with power-law spectrum was studied numerically. Another interpretation assumes that hard X-rays are the thermal emission of a plasma with electron temperature $T_e \gtrsim 10^8 K$. This is the so-called thermal interpretation of hard X-rays (Chubb et al., 1966; Brown, 1975). For example, Hoyng (1975) pointed out that X-ray events of May 18, 1972, can be of thermal origin. Elcan (1978) has determined the photon spectrum for 38 events and most of them were fitted with an exponential law. He supports the single-temperature thermal model of impulsive hard X-rays with temperatures in the range 4.7–31 keV and emission measures of $8.4 \times 10^{43} - 6.0 \times 10^{46}$ cm$^{-3}$. Mätzler et al. (1978) have found a possible interpretation of the temporal structure of...
X-ray spikes in terms of adiabatic compression and expansion of a high-temperature plasma.

Current observational and theoretical status of the problem associated with hard X-ray generating electrons indicates the need to consider thermal or quasithermal models, or some combination of thermal and thick-target non-thermal models (see Emslie and Rust, 1980; Brown et al., 1980; Emslie, 1981a). The main conclusion is that the total energy in fast electrons is very large in non-thermal models, but much smaller if there is a ‘bulk energization’ of plasma to temperatures in excess of several tens of keV (e.g. Hoyng et al., 1978; Smith and Lilliequist, 1979). However, the truth of this conclusion depends on the density of plasma. In fact, the main difference between the models mentioned above lies in the energy losses from energetic electrons. In thermal models the dominant energy loss is due to the fast heat conduction from the high-temperature plasma (Brown et al., 1979; Sermulina et al., 1979; Smith and Lilliequist, 1979). In non-thermal models the dominant energy loss is Coulomb collisions with the cold electrons in the thick target. Since the collisional time decreases with the target density, one can show (see Smith and Auer, 1980) that the thermal model is more efficient for densities greater than those of about $10^{10}$ cm$^{-3}$. Smith and Lilliequist (1979), Smith and Auer (1980) have developed a one-dimensional, one-fluid, two-temperature thermal model with a uniform initial density of $n = 3 \times 10^{11}$ cm$^{-3}$ and the initial temperatures $T_e = T_i = 10^6$ K. These parameters are believed to appropriate coronal flare loops. In this paper we consider the thermal model of hard X-ray source in chromospheric plasmas. Fast plasma motions initiated by very powerful heat fluxes from some local high-temperature source, placed over the chromosphere in accordance with our model, will be investigated. In Section 2 we present the physical formulation of the hydrodynamic problem and discuss some features of its numerical solution. The results obtained are presented in Section 3 and their application is briefly discussed. In Section 4 we state our conclusions.

2. Formulation of the Problem

A physical model for hydrodynamic flows in the solar atmosphere under some simplifying assumptions is suggested by Somov and Syrovatskii (1976). All basic physical processes (except radiative cooling of the plasma) are considered as one-dimensional due to a strong magnetic field. For simplicity we treat a vertical magnetic tube and use the one-fluid, two-temperature approximation. Then we introduce the Lagrange variable $\xi = \int n(s) \, ds$ (cm$^{-2}$) which is the plasma depth from the source along magnetic tube into the chromosphere, $s$ is the length along this tube.

For the non-thermal interpretation of hard X-rays, the problem of non-steady plasma flows is solved numerically by Somov et al. (1977, 1979, Paper I) and the computational method is presented by Spektor (1979). The time profile of electron injection is taken in accordance with the variation of the hard X-ray intensity in an ‘elementary flare burst’ (EFB). A single EFB with symmetric rise and decay is used. It appears that the electron temperature in the upper chromosphere rises rapidly to the values of order $10^7$ K. The