GASDYNAMICS OF IMPULSIVE HEATED SOLAR PLASMA

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Abstract. Numerical solutions for problem of hydrodynamic response of the inhomogeneous (exponential) atmosphere on impulsive heating by energetic electrons or by very high-temperature thermal fluxes are discussed.

Impulsive heating of solar chromosphere during a single spike of hard X-rays (an "elementary flare burst" - EFB) can produce very fast motions. We consider them as two-temperature hydrodynamic plasma flows along a strong magnetic field. Let that be vertical one, for simplicity. Then the following equations are appropriate

$$\frac{\partial n}{\partial t}+n^2\frac{\partial v}{\partial \xi}=0, \tag{1}$$

$$\frac{\partial v}{\partial t}+\frac{1}{m_H}\frac{\partial}{\partial \xi}\left[nk\left(T_i+xT_e\right)\right]=\frac{4}{3}\frac{1}{m_H}\frac{\partial}{\partial \xi}\left[\eta_i n\frac{\partial v}{\partial \xi}\right]+g_\odot, \tag{2}$$

$$\frac{nk}{(\gamma-1)}\frac{\partial(xT_e)}{\partial t}-kT_e\frac{\partial n}{\partial t}+n\chi\frac{\partial x}{\partial t}=$$

$$=\mathscr{P}_c(n,T_e)+\mathscr{P}_e(n,\xi)-\mathscr{L}(n,T_e)-Q(n,T_e,T_i), \tag{3}$$

$$\frac{nk}{(\gamma-1)}\frac{\partial T_i}{\partial t}-kT_i\frac{\partial n}{\partial t}=\mathscr{P}_v(n,T_i,v)+Q(n,T_e,T_i). \tag{4}$$

Lagrange coordinate ξ is the plasma depth. Conductive heating and radiative cooling $\mathscr{L}$ are taken into account. Other designations, initial and boundary conditions etc. are in Somov et al. (1977, 1979) with one erratum there (the erroneous gravitational term in (4) must be omitted).

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Bearing in mind two possible interpretations of hard X-rays, we solve Eqs. (1)-(4) numerically for two models: nonthermal and thermal one. First of them assumes, as usually, rapid variation of the accelerated electron flux in accordance with the hard X-ray intensity. In our thermal model, electron temperature on the upper boundary of chromosphere follows that intensity.

For numerical treatment, the symmetrical EFB with a FWHM of 5 s is used. Note that Kostjuk and Pikel'ner (1974) solve the hydrodynamic problem for long-duration (100 s) heating by nonthermal electrons. In our treatment, very rapid ($t \ll 1$ s) change of plasma energy due to power radiative cooling is essential. This leads to the thermal instability (Somov and Syrovatskii, 1976).

Some results are shown in Fig. 1. For thermal model, the X-ray spectrum and emission measure (Fig. 2) are also calculated.

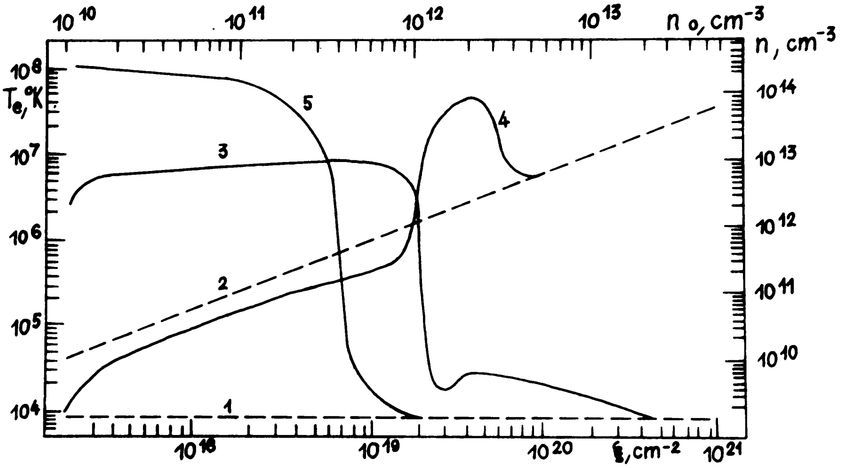

Fig. 1. Numerical solution at the time 5 s. (1) and (2) are initial temperature and density, respectively. (3) and (4) show the electron temperature and density in the nonthermal model. (5) is the electron temperature in the thermal model.

Conclusions are:

(1) Impulsive heating can be produced by nonthermal electrons, as well as heat conductive fluxes.

(2) In nonthermal model, the temperature in upper chromosphere rises to values of order 10^7 K. The heating in more dense layers is balanced by radiative cooling, that can give rise to short-lived EUV flash. As a result of radiative cooling and heat conduction, the thin flare transition layer (FTL) develops.

(3) Maximum velocity of the heat front propagation in the chromosphere is of order 10^3 km/s before the FTL is formed according to the

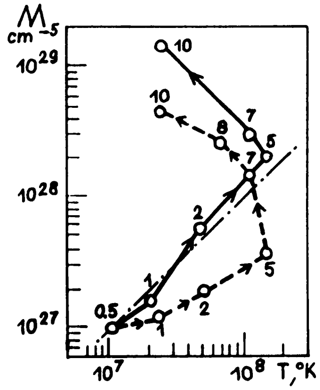

Fig.2. Relationship between emission measure M and effective temperature T_{eff}. The different lines correspond to different forms of limiting heat flux ($— \varkappa \sim T_e^{3/2}$, $--- \varkappa \sim T_e$). The time instants are indicated by figures (s). The dashed-dotted line corresponds to an adiabatic process.

thermal model.

(4) For both models, the thermal instability gives rise to cold condensation just below the FTL. That condensation moves downward at velocity exceeding the sonic one in the quiet chromosphere. The front shock fades gradually in denser layers.

(5) The heated high-temperature chromospheric plasma is ejected upward with velocity of order 1500 km/s. The plasma mass ejected during one EFB is of about 10^{-5} g per cm^2.

(6) In the impulsive ejected plasma, the ion temperature is more than two orders of magnitude less than the electron temperature.

(7) The thermal X-ray spectrum of the high-temperature plasma is approximated by the exponential law with some effective temperature T_{eff} well enough.

(8) The emission measure increases continuously even after the maximum of the T_{eff} (Fig.2). This differs the thermal model under consideration from the model with adiabatic compression and expansion (Matzler et al., 1978).

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DISCUSSION

Nakagawa: (Comment) Current accepted idea is heating by hard and soft X-rays to the chromosphere. However, regardless of the mechanism of heating, the gasdynamic responses are similar as you reported.