TIME DEPENDENT FLARE MODEL WITH NON–LTE RADIATIVE TRANSFER

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ABSTRACT

The first results of a time dependent simulation of chromospheric response to a high energy electron beam are presented. The hybrid code, i.e. a combination of a 1–D hydrodynamic code and a test particle code, has been used to calculate the energy losses of a high energy electron beam propagating through the solar atmosphere and the consequent response of the ambient solar plasma to the energy deposition. The resulting time evolution of the solar plasma temperature, density, velocity and energy deposit on hydrogen has then been used as an input for a time dependent radiative transfer code in the MALI approach to determine the time variation of the Hα line profile. Non–thermal collisional rates have been included in the linearised ESE.

Key words: flare; electron beam; hydrodynamics; radiative transfer; simulation.

1. INTRODUCTION

The time series of optical line profiles with a high temporal resolution seem to be ideal for studies of chromospheric dynamic processes in flares. The disadvantage of observations of this kind is that the most suitable lines (e.g. Hα) are optically thick and there are no simple direct methods to interpret their profiles. A possible way to estimate the influence of various processes in flares on optically thick line profiles and their evolution, is to attack this difficult problem using numerical simulations in two stages. Firstly, by including all the important processes controlling the evolution of flare plasma into a numerical model to calculate the energy deposit and evolution of flare plasma. Secondly, to use the outputs from the first stage as an input for calculation of optically thick line profiles by methods of time dependent non–LTE radiative transfer.

Our simulation is based on the generally accepted model of flares proposed by Sturrock (1968), Kopp & Pneumann (1976), Forbes & Malherbe (1986), etc. According to this model the flare energy is released during a reconnection of coronal magnetic fields and then transported by high energy particle beams downwards to the chromosphere, where it is mainly, via Coulomb collisions, imparted to the ambient solar plasma, which consequently experiences a rapid heating accompanied by violent dynamic phenomena as the originally ‘quiet’ plasma in the lower atmosphere expands and fills the coronal part of the loop by dense and hot plasma.

To model this problem, we use two codes: the hybrid code, recently developed at the Ondřejov Observatory (Varady, 2002), and a time dependent radiative transfer code using the Multilevel Accelerated Lambda Iterations – MALI (Rybicki & Hummer, 1991), see Heinzl (1995). The particle part of the hybrid code calculates the propagation and thermalisation of an electron beam in the solar atmosphere, the hydrodynamic part gives the response of the ambient solar atmosphere to the thermalised energy of the propagating beam deposited into the ambient solar plasma. The results from the hybrid code are used as an input for the non–LTE radiative transfer code which, among others, calculates the time evolution of the Hα line profile (Kašparová et al., 2002).

2. HYBRID CODE

2.1. Electron beam thermalisation – particle code

The test particle code (Karlický, 1990) is based on formulas for high energy charged particle energy loss due to Coulomb collisions with partially ionised hydrogen plasma (Emslie, 1978):

\[
\frac{dE}{dt}_e = -\frac{2\pi e^4}{E} \Lambda(x_\varepsilon) n_H v ,
\]

\[
\frac{dE}{dt}_n = -\frac{2\pi e^4}{E} \Lambda(1-x) n_H v .
\]

Equations 1 and 2 give respectively the energy loss of an electron with energy \(E\) and velocity \(v\) due to collisions with free electrons and hydrogen. Hydrogen ionisation is expressed using parameter \(x \equiv n_p/n_H\), \(n_p\) is proton number density, \(n_H = n_p + n_n\), \(n_n\) is...
Figure 1. Energy deposit into electron component for initial VAL C atmosphere.

Figure 2. Energy deposit into neutral plasma component for initial VAL C atmosphere.

number density of hydrogen atoms and ε accounts for ionisation of non–hydrogenic elements. λ and λ’ are respectively Coulomb and effective Coulomb logarithms. The scattering of the electron beam due to Coulomb collisions has been included using the approximation of Bai (1982), who relates the rms deflection angle of an electron to its kinetic energy $E_0 = (\gamma_0 - 1)mc^2$ and energy loss $\Delta E$ providing $\theta_{rms} \ll 1$, as

$$\langle \theta^2 \rangle = \left( \frac{\Delta E}{E_0} \right) \left( \frac{4}{\gamma_0 + 1} \right),$$

where $\gamma_0$ is the Lorentz factor. The distribution of electrons in the azimuthal direction $\phi \in (0; 2\pi)$ is obtained with a random number generator and the new pitch angle of the particle is given by

$$\cos(\theta_0 + \Delta \theta) = \cos \theta_0 \cos \theta_\phi + \sin \theta_0 \sin \theta_\phi \cos \phi,$$

where $\theta_0$ is the pitch angle at the beginning of the particle path and $\theta_\phi$ is given by Equation 3 and by a two–dimensional Gaussian distribution, which models the random distribution of the deflection angle.

The particle code uses the formulas given above for clusters of many particles, rather than for each individual beam particle. The number of clusters is typically of the order of $10^4$ and their motion is followed with a short timestep during the beam propagation through ambient solar plasma, so at each moment the position, energy and pitch angle of each cluster are known. The main advantages of this approach are that the beam interacts with an atmosphere which changes in time due to the energy deposited before and it also naturally includes the effect of the beam travelling time. The quantities provided by the particle code also allow us to calculate the distribution of the hard X–ray flux along the beam path using the thick target model and the impact Hα line polarisation (Karlíka & Henoux, 2002).

A mono–energetic electron beam of energy 30 keV and energy flux $F_B(0, t) = 2.5 \times 10^{10} \text{ erg cm}^{-2} \text{ s}^{-1}$ at the point of injection in the corona has been approximated by a chain of electron clusters each containing typically $10^{10}$ electrons. The energy flux has then been sinusoidally modulated by changing the number of electrons in the individual clusters in order to get three one second pulses. The energies deposited into the electron and hydrogen atom plasma components have been calculated, and the energy deposited into neutrals has been used by the non–LTE code to calculate the non–thermal collisional excitation and ionisation of hydrogen. The energy deposited into the electron component has been used by the HD code to calculate the time evolution of the atmosphere.

The resulting energy deposit into the electron plasma component calculated initially for VAL C atmosphere (Vernazza et al., 1981) is shown in Figure 1. The sinusoidal modulation of the energy flux is obvious. The overshoot of the energy deposit into deeper layers at the very beginning of the simulation can be explained considering the higher concentration of neutrals in the initial unheated atmosphere. Starting chromospheric evaporation causes the little bumps in the energy deposit profiles visible on the ridges of the second and third pulse. The energy deposit into neutrals is shown in Figure 2. It is controlled by the density of neutrals, decreasing rapidly with temperature and by the variable energy flux. The modulation of the energy deposit is not so apparent here because the increase of the energy flux results in a decrease of the neutrals density and vice versa, so the two effects tend to compensate each other.

2.2. Hydrodynamics – HD code

The hydrodynamic code calculates the state and evolution of low $\beta$ plasma along magnetic field lines
which define the geometry of the problem. Due to the anisotropy introduced by the field and the validity of the plasma approximation in the solar atmosphere, the problem can be described in terms of 1-D hydrodynamics. It has been generally accepted that the main processes which control the evolution of plasma in flare loops are convection, thermal conduction, radiation and indeed flare heating, which is calculated by the particle part of the hybrid code. Under the conditions mentioned above, using one fluid approximation of solar plasma, the modelled problem can be described by the following system of hydrodynamic conservation laws

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_s)}{\partial s} = 0
\]

\[
\frac{\partial \rho u_s}{\partial t} + \frac{\partial (\rho u_s^2)}{\partial s} = -\frac{\partial P}{\partial s} + F_q + F_v
\]

\[
\frac{\partial E}{\partial t} + \frac{\partial (E u_s)}{\partial s} = -\frac{\partial}{\partial s} (u_s P) - \frac{\partial}{\partial s} \mathcal{F}_c + \Delta \mathcal{E}_p - \mathcal{R} + \mathcal{S}
\]

where \( p \) is plasma density, \( s \) is the spatial coordinate along magnetic field lines, \( u_s \) is plasma macroscopic velocity along magnetic field lines,

\[
P = \rho n_H (1 + x + \varepsilon) k_B T
\]

is plasma pressure and \( T \) is plasma temperature. Hydrogen ionisation is in the hybrid code calculated in the approximation given by Brown (1973). Energy \( E \) is given by

\[
E = \frac{P}{\gamma - 1} + \frac{1}{2} \rho u_s^2
\]

where \( \gamma \equiv c_p/c_v \) is the ratio of specific heats at constant pressure and volume. The source terms on the right hand side of Equation 6 include gravitational \( F_q \) and viscous \( F_v \) forces. In Equation 7 \( \partial \mathcal{F}_c/\partial s \) represents thermal conduction along field lines (calculated using Spitzer’s classical approximation), \( \Delta \mathcal{E}_p \) stands for the change of potential energy due to plasma transport, \( \mathcal{R} \) are radiative losses and \( \mathcal{S} \) stands for the sum of all energy sources, i.e. the flare heating, the viscous heating and the quiescent heating. The quiescent heating compensates for the effects of radiative losses and thermal conduction in the initial hydrostatic VAL C atmosphere. The radiative losses have been calculated using approximations given by Rosner et al. (1978) in optically thin regions and Peres et al. (1982) in optically thick regions of the solar atmosphere.

The system of HD equations has been solved by the timestep splitting method (Oran & Boris, 1987), convection was calculated using the LCPFCT algorithm (Boris et al., 1993) and conduction was treated using the Crank-Nicholson algorithm.

The outputs from the HD code, relevant for further processing by the non–LTE radiative transfer code are the time evolution of temperature, plasma density and velocity along field lines. The evolution of the temperature in layers, where Hα line is formed, is shown in Figure 3. Here, where the electron beam is thermalised predominantly the temperature is obviously modulated according to the incident energy flux variations. This is due to efficient radiative losses in the lower heated layers, given by the estimate of Peres et al. (1982). In the upper layers, the modulation gradually disappears. The changes of plasma density in the region of interest during the first second of simulation are within 30% of their original values and the maximum plasma velocity is about 10 km s\(^{-1}\).

3. RADIATIVE TRANSFER

The input to the non–LTE radiative transfer code are the time evolution of temperature, density and energy deposit into hydrogen atoms along field lines. These quantities are calculated with a timestep \( \Delta t = 10^{-3} \) s. The hydrogen atom was approximated by a 3–level plus continuum model. In order to obtain the level populations, the time dependent system of ESE was solved

\[
\frac{\partial n_i}{\partial t} = \sum_{i \neq j} (n_j P_{ji} - n_i P_{ij}) \equiv f_i(n),
\]

\( n = (n_1, n_2, n_3, n_p, n_e) \), where \( n_1, n_2, n_3 \) are the populations of the discrete levels, \( n_p \) and \( n_e \) are respectively number densities of protons and electrons. The last two quantities are different due to the contribution of electrons from non–hydrogenic elements. \( P_{ij} \) are generally sums of the radiative \( R_{ij} \) and collisional \( C_{ij} \) rates. The non–thermal collisional rates \( C_{ij}^{nt} \) have been included only for the transitions from the first level. Considering the three level model of hydrogen atom according to Fang et al. (1993) the rates are

\[
C_{1e}^{nt} = 1.73 \times 10^{10} \frac{E_H}{n_1}
\]
Using the non-thermal rates specified above, the total rates for the ground level are $P_{ij} = R_{ij} + C_{ij} + C_{ij}^{*}$. The system of ESE has been solved using a semi-implicit scheme

$$P_{ij}^{t+1} = \alpha f_{ij}^{t+1} \Delta t - n_{ij}^{t+1} + (1 - \alpha) f_{ij}^{t} \Delta t + n_{ij}^{t} = 0,$$

where $\alpha \in (0; 1)$ determines the implicitness of the algorithm, $\Delta t$ is the timestep and the upper index denotes values corresponding to the two subsequent timesteps. The ESE have been linearised with respect to densities $n$ and solved using the Newton-Raphson iteration technique. When calculating the evolution of the Hα line profile, the velocities in the atmosphere were neglected. This simplification can be acknowledged considering the velocities in the flaring atmosphere and the results of Nejezchleba (1997) that velocities around 10 km s$^{-1}$ do not play any important role in ESE.

The resulting time evolution of the Hα line profile (for the first second) is shown in Figure 4. The profile evolves during 1 s from a quiet chromosphere shape to a typical flare shape mainly due to evolution of temperature in the atmosphere. The non-thermal processes slightly influence the line profile at the very beginning of the simulation, when the electron beam starts to interact with the chromospheric plasma ($t \sim 0.1$ s), by causing a small dip in the line core. However, the direct influence of non-thermal processes on the shape and intensity of Hα line seems to be minor in this particular simulation.

4. CONCLUSIONS

We present our first attempt to calculate the evolution of the Hα line profile at the flare onset, after the start of interaction of a pulse of high energy electron beam with plasma in the solar chromosphere. Despite the fact that the method of calculation was not fully consistent because there was no feedback between the hybrid and non-LTE radiative transfer codes, e.g. the radiative losses in the optically thick regions were estimated by simple analytic formulas instead of consistently calculated by the non-LTE radiative transfer code, the time evolution of the Hα profile represents typical observations. We found that the time variations of Hα line intensity are mainly due to the time evolution of the temperature profile in the atmosphere. Also the influence of the high energy electron beam on the Hα profile evolution is recognizable as a dip in the line profile at the beginning of the energy deposition.

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