Time-Dependent Flare Models with MALI

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Abstract. Time variations of Hα line-profile intensities produced by electron beams are presented. We show first results of time-dependent simulations of the chromospheric response to a 1 s monoenergetic electron beam. A 1-D hydrodynamic code together with a particle representation of the beam have been used to calculate the atmospheric evolution. The time-dependent radiative-transfer problem has been solved for the resulting atmosphere by the MALI approach, using a Crank-Nicholson semi-implicit scheme. Non-thermal collisional rates have been included in linearized equations of statistical equilibrium.

1. Introduction

It is generally believed that the energy of solar flares is released in the solar corona, then transported by accelerated energetic particles downwards into the transition region and chromosphere. The particles deposit their energy into the ambient plasma mainly via Coulomb collisions, resulting in a rapid heating, accompanied by violent dynamic phenomena in the initially quiet atmosphere.

The aim of our work is to investigate the time-evolution of Hα line-profiles during the impulsive phase of solar flares. Our simulations of the atmospheric response to the heating are split into two independent steps. The flare-plasma evolution, together with particle propagation and thermalization of their energy, is treated by a hybrid hydrodynamic code. Its results are then used as inputs to a code solving the time-dependent non-LTE radiative-transfer problem.

2. Hybrid Hydrodynamic Code

The hybrid hydrodynamic code (Varady 2002) consists of a hydrodynamic and a particle part. The time-evolution of the atmosphere is described by the standard system of 1-D hydrodynamic equations, completed by an equation of state in the one-fluid approximation. Ionization of hydrogen has been approximated by the modified Saha equation (Brown 1973), and radiative losses have been estimated according to the models of Rosner, Tucker, & Vaiana (1978). The particle part of the code simulates interaction of accelerated particle beams with the ambient atmosphere (Bai 1982; Karlický & Hénoux 1992). The deposit of beam energy into the ambient neutrals and electrons is calculated following the approach of Emslie (1978). The energy deposited into electrons is used as a flare-heating term in the energy equation of the hydrodynamic code. The energy deposit into
the neutrals, together with the time-evolution of temperature and total-hydrogen number-density are the inputs into the radiative transfer code.

3. Radiative transfer

We have solved the time-dependent radiative-transfer problem for a 3-level plus continuum atomic model of hydrogen. The time-evolution of the atmosphere’s structure was prescribed by the hydrodynamic calculations. Time-dependent equations of statistical equilibrium (ESE) were preconditioned using a diagonal approximate-lambda-operator in the Multilevel Accelerated Lambda Iteration method - MALI (Rybicki & Hummer 1991). According to Nejezchleba (1998), velocities of the order of 10 km s\(^{-1}\) cause only minor changes in the level populations \(n_i\). Thus we restrict ourselves to only a static problem where the ESE take the form

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

(1)

with \(n_c\) and \(n_e\) denoting the proton and electron density respectively. The total rates \(P_{ij}\) are sums of radiative \(R_{ij}\) and collisional \(C_{ij}\) rates. The \(R_{ij}\) have been preconditioned in the framework of the MALI method. Excitation and ionization by particles in the beam have been taken into account via non-thermal collisional rates \(C_{ij}^\text{nt}\), which are directly proportional to the energy \(E_H\) deposited into hydrogen. We have adopted the approach of Fang, Hénoux, & Gan (1993) and included the non-thermal collisional rates from the ground level of hydrogen as follows:

\[
C_{1c}^\text{nt} = 1.73 \times 10^{10} \frac{E_H}{n_1} \quad C_{12}^\text{nt} = 2.94 \times 10^{10} \frac{E_H}{n_1} \quad C_{13}^\text{nt} = 5.35 \times 10^{9} \frac{E_H}{n_1} .
\]  

(2)

Using the non-thermal rates specified above, the total rates \(P_{ij}\) from the ground level are

\[
P_{ij} = R_{ij} + C_{ij} + C_{ij}^\text{nt} .
\]  

(3)

The set (1) of ESE is completed by equations of particle and charge conservation

\[
\sum n_j + n_c = n_H \quad n_e = n_c + Q n_H .
\]  

(4)

Here \(n_H\) corresponds to the total hydrogen density and \(Q = 1.4\) represents the contribution to the electron density from non-hydrogenic elements.

3.1. Numerical methods

A semi-implicit difference scheme has been used on the system (1) of ESE

\[
F_i^{t+1} = \alpha \Delta t f_i^{t+1} - n_i^{t+1} + (1 - \alpha) \Delta t f_i^t + n_i^t = 0 .
\]  

(5)

The parameter \(\alpha (0 \leq \alpha \leq 1)\) determines the degree of implicitness of the algorithm, \(\Delta t\) is the timestep, and the upper index denotes values corresponding to the two successive time-levels.
Because the electron density $n_e$ is unknown, the preconditioned ESE are non-linear because of the terms containing $n_e$. Thus, the system of semi-implicit equations (5) together with the conservation conditions (4) is linearized with respect to all level populations, including protons $n_c$ and the electron density, and solved using a Newton-Raphson iteration technique (Heinzel 1995).

$$F_{i}^{t+1} = F_{i}^{t+1} \left( n^\dagger \right) + \sum_{j}^{NL} \left( \frac{\partial F_{i}^{t+1}}{\partial n_{j}} \right)_{n^t} \delta n_{j} + \left( \frac{\partial F_{i}^{t+1}}{\partial n_{c}} \right)_{n^t} \delta n_{c} + \left( \frac{\partial F_{i}^{t+1}}{\partial n_{e}} \right)_{n^t} \delta n_{e} = 0$$

Using eq. (5), the final linearized time-dependent ESE system (1) and conservation conditions (4) is

$$\left( -\alpha \Delta t f_{i}^{t+1} \left( n^\dagger \right) + \left( n_{i}^{t+1} \right)^{\dagger} - (1 - \alpha) \Delta t f_{i}^{t} - n_{i}^{t} = \right.$$}

$$\left[ \alpha \Delta t \sum_{j}^{NL} \left( \frac{\partial f_{i}^{t+1}}{\partial n_{j}} \right)_{n^t} - \delta_{ij} \right] \delta n_{j} + \alpha \Delta t \left( \frac{\partial f_{i}^{t+1}}{\partial n_{c}} \right)_{n^t} \delta n_{c} + \alpha \Delta t \left( \frac{\partial f_{i}^{t+1}}{\partial n_{e}} \right)_{n^t} \delta n_{e} \right.$$}

$$Q \sum_{j}^{NL} \delta n_{j} + (1 + Q) \delta n_{c} - \delta n_{e} = n_{c}^{\dagger} - (1 + Q) n_{c}^{\dagger} - Q \sum_{j}^{NL} n_{j}^{\dagger} \right.$$}

$$\sum_{j}^{NL} \delta n_{j} + \delta n_{c} = n_{H} - \sum_{j}^{NL} n_{j}^{\dagger} - n_{c}^{\dagger} .$$

$NL$ is the number of bound levels, and $\dagger$ denotes values from the previous iteration at the time level $t + 1$. Having evaluated the corrections $\delta n$, new populations and electron density are then obtained as

$$n = n^\dagger + \delta n .$$

The iteration scheme described above is performed for each timestep until maximum relative changes in the level-populations and electron-density are less than a prescribed value (typically $10^{-3}$). After convergence is reached, which is usually within several iterations, the synthetic spectrum is calculated. The converged populations are then used as starting values for the next timestep.

4. First Results

We have simulated the chromospheric response to a 1 s monoenergetic beam of electrons created above the atmosphere with a kinetic energy 30 keV, and an energy-flux of $2.5 \times 10^{10}$ erg cm$^{-2}$ s$^{-1}$ at the point of injection. The energy flux has the form of a sinusoidal pulse of 1 s duration. At time $t = 0$ s the initial atmospheric temperature- and density-structure is that of the VAL C model atmosphere (Vernazza, Avrett, & Loeser 1981). The resulting time-evolution of the total hydrogen density, temperature and energy-deposition into hydrogen have been used as inputs to the calculation of the time-variation of H$\alpha$ line.
profiles. The timestep $\Delta t$ of the radiative transfer code has been set to 0.001 s. Figure 1 displays the time-evolution of the H$\alpha$ profile and the temperature in the part of the atmosphere where the profile of H$\alpha$ line is calculated. The figure shows that during a time-interval of 1 s, the H$\alpha$ line evolves from a quiet chromospheric shape to one typical of a flare. The non-thermal rates influence mainly the core of the line where they cause a small dip at $t \sim 0.1$ s.

5. Conclusions

Our results show that time variations of H$\alpha$ line intensities are mainly caused by the time-evolution of the temperature structure of the atmosphere. For simplicity, velocity fields were not considered in the radiative-transfer code. We plan to include both advection and line-profile anisotropy in future work. The hybrid hydrodynamic code is also capable of computing time-variations of the hard X-ray flux from a thick-target model.

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References

Varady, M. 2002, PhD Thesis, Charles University, Prague
8. SPECIAL TOPICS IN RADIATIVE TRANSFER