**Hα LINE IN SOLAR ATMOSPHERE HEATED BY PARTICLE BEAMS**

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**ABSTRACT**

Electron and proton beams propagating through the solar atmosphere cause its heating and also modify atomic level populations via collisional processes. Using the approach of NLTE radiative hydrodynamics, we show the influence of the electron beams on the Hα line profile in numerical simulations of the electron beam heating of the solar atmosphere. Hydrodynamics of the heated atmosphere, the beam propagation and the return current generation are briefly discussed. We focus mainly on the effects of the non-thermal collisional rates and the return current on the Hα spectral line profile. Based on our results, we speculate on a diagnostic method for determination of the electron beam presence in the formation regions of the Hα line.

Key words: solar flares; electron beams; Hα line.

1. INTRODUCTION

Most of the contemporary models of solar flares assign a fundamental role to the high energy electron beams in the flare energy transport. According to the 'standard flare model' of Sturrock (1968) and Kopp & Pneumann (1976), the flare energy is released during reconnection of magnetic fields in the corona and as a consequence of this process the high energy beams are generated. The beams are then guided along the magnetic field lines, also towards the deeper and denser layers of the solar atmosphere, where their energy is dissipated and transformed mainly into the thermal energy of plasma in the transition region and chromosphere. The propagation of electron beams is inevitably connected with the so-called return current (RC) which is formed by background electrons to balance the huge electron currents associated with the beam (van den Oord, 1990). RC is driven by electric field which also contributes to the beam energy dissipation and thus to the atmosphere heating.

The heating results in expansion of the chromospheric and transition region plasma into the corona. Besides the heating, the beams also influence atomic level populations of ambient plasma via collisional excitation and ionisation. Their influence on spectral line profiles was previously studied both for static atmospheres (e.g. Fang et al., 1993; Hawley & Fisher, 1994) and by radiative hydrodynamic models (Abbett & Hawley, 1999; Alred et al., 2005) using analytic formulas for the beam energy dissipation.

In this paper we concentrate on beam pulses of a short duration. We model the beam propagation and energy deposition by a test particle approach consistently with the hydrodynamics of the atmosphere and focus on the signatures of the beams in the hydrogen spectral line profiles. The numerical code consists of three originally autonomous codes: the test particle code (Karlícký, 1990; Varady, 2002), the 1–D hydrodynamic code (Varady, 2002) and time dependent 1–D NLTE radiative transfer code (Kašparová, 2004). The codes have been partially integrated to enable more consistent modelling of hydrodynamic and radiative process in flares.

In Sect. 2, we describe our approach and methods we use to model hydrodynamic and radiative response of solar atmosphere plasma to the heating by the power-law electron beams. Section 3 presents the influence of the non-thermal collisional rates and the return current on the hydrogen ionisation and the Hα line intensity. In Conclusions a new diagnostics method of the electron beam presence is suggested.

2. METHODS

2.1. Hydrodynamics and beam propagation

We assume low-$\beta$ plasma confined along semicircular magnetic field lines with initial profiles of temperature $T$, hydrogen density $n_{\text{HI}}$, and ionisation $x$ in the photo-

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spherosphere and chromosphere corresponding to the VAL C atmosphere (Vernazza et al. 1981). The state and time evolution of originally hydrostatic plasma along magnetic field lines is described by 1-D hydrodynamic equations in one fluid approximation

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

\[
\frac{\partial \rho v_s}{\partial t} + \frac{\partial}{\partial s}(\rho v_s^2 + P_e - F_g) = 0
\]

where \(s\) and \(v_s\) are the position and velocity of plasma along the field lines, \(\rho\) is the plasma density and \(P\) is the total pressure including the turbulent pressure. The gas pressure \(P_{gas}\) and the total energy \(E\) are

\[
P_{gas} = n_H (1 + x + \varepsilon) k_B T, \quad E = \frac{P_{gas}}{\gamma - 1} + \frac{1}{2} \rho v_s^2,
\]

where \(\gamma\) is the ratio of specific heats and \(\varepsilon\) represents contribution to the electron density \(n_e\) by non-hydrogenic elements (Heinzel & Karlicky, 1992). The hydrogen ionisation \(x\) is calculated by the NLTE radiative transfer code, see section 2.2. The source terms in r.h.s. of Eq. 1 are: \(F_g\) the tangential component of the gravity force to the field lines, \(F_e\) the heat flux, calculated using the Spitzer’s classical formula, \(\Delta E_p\) the change of the potential energy, \(R\) the radiative losses calculated according to Rosner et al. (1978) for the optically thin regions and according to Peres et al. (1982) for the optically thick regions, and \(S\) includes all kinds of heating, i.e. mainly the flare heating and quiet heating assuring the stability of the initial unperturbed atmosphere.

The flare heating is given by the beam energy deposit into the atmosphere calculated by the particle code for the instant properties of the atmosphere. The code takes into account Coulomb collisions with neutrals and electrons (Emslie, 1978), electron scattering (Bai, 1982), and optionally the return current (Varady et al., this issue).

Fig. 1 shows the beam energy deposits and the temperature structure corresponding to power-law electron beam heating of a sinus-like pulse of 1 s duration: maximum energy flux \(F = 10^{10}\) erg cm\(^{-2}\) s\(^{-1}\) with a time modulation

\[
F(t) = F_0 \frac{1 - \cos(2\pi t)}{2},
\]

power-law index \(\delta = 7\), the low-energy cutoff \(E_1 = 30\) keV, and high-energy cutoff \(E_2 = 100\) keV.

2.2. Radiative transfer

NLTE radiative transfer for hydrogen is calculated in the lower part of the loop (1-D plane parallel geometry) simultaneously with the hydrodynamics of the atmosphere and the beam propagation using the instant values of \(T\), \(n_H\) and the energy deposit to hydrogen \(E_{H}\). The hydrogen atom is approximated by a three level + continuum atomic model. The level populations \(n_i\) are determined by the solution of the time dependent system of the equations of statistical equilibrium (ESE)

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

where the advection term is neglected due to the small plasma velocities below 10 km s\(^{-1}\) (Nejezchleba, 1998). The transition rates \(P_{ij}\) are given as a sum of the thermal collisional rates \(C_{ij}\) and radiative rates \(R_{ij}\). The excitation and ionisation of hydrogen by the beam electrons (i.e. non-thermal electrons) are included using the non-thermal collisional rates \(C_{ij}^{nt}\) given by expressions of Fang et al. (1993).

\[
C_{ij}^{nt} = k_{ij} \frac{E_{H}}{n_1}
\]

with

\[
P_{ij} = R_{ij} + C_{ij} + C_{ij}^{nt}.
\]
The ESE system (Eq. 3) together with the charge and number conservation equations

\[ n_e(t) = n_p(t) + \varepsilon n_H(t) \quad n_H(t) = \sum n_x(t) \]

are linearised with respect to \( n_x \) and \( n_H \) and solved in the formalism of multilevel accelerated Lambda iterations (Kašparová et al., 2003).

2.3. Communication among individual codes

The particle and hydrodynamic codes are fully integrated, therefore the beam of test particles interacts with the atmosphere which changes in time due to the previously deposited energy. NLTE hydrogen ionisation is calculated self-consistently for each time step for instant \( T \) and \( n_H \) given by the hydrodynamic code. Optically thick radiative losses are approximated by analytic expressions.

3. RADIATIVE RESPONSE TO THE BEAM HEATING

The heating of the atmosphere by the power-law electron beams results in a rapid increase of temperature, ionisation, and the H\( \alpha \) line intensity. The NLTE ionisation lags behind the time evolution of the temperature and thus behind the ionisation approximated by the modified Saha equation (Brown, 1973). This effect, as shown by Heinzel & Karlícký (1992) and Carlsson & Stein (2002), is due to the long relaxation for recombination and illustrates the necessity of using the time-dependent ESE (Eq. 3), see Fig. 2.

3.1. The non-thermal collisional rates

The ionisation can be affected also by the \( C_{ij}^{\text{nt}} \) at heights \( \lesssim 1000 \text{ km} \) mainly for low beam energy flux \( F \) when temperature increase itself does not completely ionise the plasma, see Figs. 1 and 2.

The non-thermal collisional rates influence the H\( \alpha \) line profile as well. At the very beginning of the beam propagation, \( C_{ij}^{\text{nt}} \) causes a decrease in the H\( \alpha \) line centre intensities by a factor of 2, see Fig. 3 (left). This decrease precedes by \( \sim 0.1 \text{ s} \) a lower decrease caused by the temperature evolution. Later on, \( C_{ij}^{\text{nt}} \) enhances wing intensities (at \( \sim \Delta \lambda = 1 \text{ Å} \)), which are more pronounced for lower values of \( \delta \) and higher energy flux \( F \), see Fig. 3 (right). Such dips have been already reported by Heinzel (1991).

3.2. The return current

Effects of the return current were included in its macroscopic approximation for the case of \( \alpha = 0.1 \), for details see the contribution in this issue by Varady et al. RC causes an increase in the H\( \alpha \) line intensity at \( \sim 0.5 \text{ s} \) (see Fig. 4), which is the result of the higher total energy deposit and subsequent temperature increase at \( \sim 2000 \text{ km} \), see Fig. 3 (top) in Varady et al. (this issue). The decrease in the H\( \alpha \) line centre intensity due to \( C_{ij}^{\text{nt}} \) is again present, see Fig. 4 (left). Therefore, we suggest that such a decrease can be considered as a signature of electron beam heating of the atmosphere in the region of the H\( \alpha \) line formation.

4. CONCLUSIONS

Electron beam heating of solar atmosphere significantly affects the evolution of the H\( \alpha \) line intensities on a time scale of the beam heating. The H\( \alpha \) intensities are influenced not only by the temperature structure but also by the non-thermal collisional rates and the return current. We propose to use the decrease of the H\( \alpha \) line core intensity as shown in Fig. 3 and 4 for diagnostics of the presence of the electron beams. Such a decrease will be probably correlated with time history of hard X-ray emission and positions of hard X-ray sources. If this result is observationally confirmed, a new method of the determination of the electron beams impact positions in the chromosphere could be established.
Figure 3. Hα intensities for $F = 10^{11}$ erg cm$^{-2}$ s$^{-1}$ at $\Delta \lambda = 0$ Å (left) and $\Delta \lambda = 1$ Å (right). Blue lines correspond to $\delta = 3$, red lines to $\delta = 7$, solid lines show the profiles with $\text{C}^{\text{IV}}$, dashed lines show the profiles without $\text{C}^{\text{IV}}$. Intensities are scaled to the intensity at $t = 0$ s. RC is not included.

Figure 4. Hα intensities for $\delta = 3$ and $F = 10^{10}$ erg cm$^{-2}$ s$^{-1}$ at $\Delta \lambda = 0$ Å (left) and $\Delta \lambda = 1$ Å (right). Blue lines correspond to the profiles without RC, green lines to the profiles with RC, solid lines show the profiles with included $\text{C}^{\text{IV}}$, dashed lines show the profiles without $\text{C}^{\text{IV}}$. Intensities are scaled to the intensity at $t = 0$ s.

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