INFLUENCE OF ELECTRON BEAM PULSES ON Hα LINE FORMATION

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Abstract. In this contribution we present results of our simulations focused on determination of spectroscopic signs of the presence of non-thermal electrons in the formation region of Hα using three mutually communicating codes. The originally autonomous and highly specialised codes model three simultaneously acting processes in flares: the precipitation and energy dissipation of the non-thermal power-law electron beams in the solar atmosphere, the hydrodynamic response of the atmosphere to the energy deposited by the beams, and the radiative transfer in chromosphere and photosphere which determines the hydrogen line profiles and their time evolution. The results show possible existence of a new diagnostic method on presence of electron beams in the formation region 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 particle beams in the flare energy transport and deposition. According to the ‘standard flare model’ Sturrock (1968), Kopp and Pneumann (1976), the flare energy is released during reconnection of magnetic fields in the corona and as a consequence of this process high energy particle 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 heating of these layers results in expansion of 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 and Fisher, 1994) and by radiative hydrodynamics models (Abbett and Hawley, 1999) using analytic formulae 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 – TPC (Karlický, 1990; Varady, 2002), the 1–D hydrodynamic code – HDC (Varady, 2002) and time dependent 1–D non–LTE code – TDNLTEC calculating the time dependent radiative transfer (Kašparová, 2004). The codes have been partially integrated to enable modelling of hydrodynamic and radiative process in flares more consistently.

The results are obtained for power–law electron beam pulses precipitating originally hydrostatic atmosphere given by VAL C model (Vernazza et al., 1981). The beam energy flux \( \mathcal{F} \) is time modulated. A sinus–like pulse with duration 1 s is generated. The energy flux reaches its maximum at \( t = 0.5 \) s, \( \mathcal{F}_{\text{max}} = 10^{11} \) erg cm\(^{-2}\) s\(^{-1}\) and the lower and upper energy cutoffs are \( E_l = 30 \) keV and \( E_u = 100 \) keV. The simulations are carried out for two power–law indices \( \delta = 3 \) and \( \delta = 5 \).

2. Methods

2.1. Electron beam precipitation

The energy losses of non–thermal electrons of the kinetic energy \( E \) and velocity \( v \) caused by Coulomb collisions in a partly ionised hydrogen target due to electron and neutral (hydrogen) components of solar plasma per unit time can be approximated by the following formulae given by Emslie (1978)

\[
\left( \frac{dE}{dt} \right)_{ee} = - \frac{2\pi e^4}{E} \Lambda(x + \varepsilon) n_H v, \quad \left( \frac{dE}{dt} \right)_{en} = - \frac{2\pi e^4}{E} \Lambda' (1 - x) n_H v, \tag{1}
\]

\[ 
\]
Figure 1: Top panels: The total energy deposit (thick lines) and the energy deposit into neutral hydrogen (thin lines) for $F_{\text{max}}$. Dashed lines correspond to the initial atmosphere ($t = 0$ s), solid lines correspond to the already heated atmosphere ($t = 0.5$ s). Bottom panels: The temperature at $t = 0$ s (solid line), $t = 0.25$ s (dashed line), and $t = 0.5$ s (dash-dot line). The left and right panels correspond to $\delta = 3$ and $\delta = 5$.

where $n_H = n_p + n_n$ is the number density of equivalent hydrogen atoms, $n_p$ and $n_n$ are the proton and neutral hydrogen number densities, $x \equiv n_p/n_H$ is the hydrogen ionisation and $\varepsilon = 1.4 \times 10^{-4}$ accounts for the contribution of the non-hydrogenic atoms to the plasma electron density. $\Lambda$ and $\Lambda'$ are the Coulomb logarithms. The scattering of the beam due to Coulomb collisions is taken into account using Monte–Carlo method (Bai, 1982).

The TPC implements these relations and follows motion of statistically important number of test particles representing electrons. In each time-step of the simulation the positions, energies and pitch angles of the particles are followed (Varady, 2002).

2.2. HYDRODYNAMICS

The state and time evolution of originally hydrostatic plasma along magnetic field–lines is calculated using the HDC. The time evolution of the sys-
tem is initiated by the energy deposited by the beam, which corresponds to the beam energy losses. The main processes that determine plasma evolution in flare loops are: convection and conduction (both in 1-D approximation assuming low β plasma), radiative losses, and the flare heating, i.e. the beam energy losses calculated by the TCP. The hydrodynamics of the plasma in the flare loops can be described by the following system of 1-D hydrodynamic (HD) equations

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

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

\[
\frac{\partial U}{\partial t} + \frac{\partial}{\partial s} (U v_s) = -\frac{\partial}{\partial s} (v_s P) - \frac{\partial}{\partial s} F_c - \mathcal{R} + \mathcal{S},
\]

where \( s \) and \( v_s \) are the position and velocity of plasma along the field–lines and \( \rho \) is the plasma density. The gas pressure \( P \) and total plasma energy \( U \) are

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

where \( T \) is the temperature and \( \gamma \) is the ratio of specific heats. The hydrogen ionisation \( x \) is calculated using a modified Saha equation (Brown, 1973). The source terms on the right hand sides of the system of equations are: \( F_g \) the tangent component of the gravity force to the field–lines, \( F_c \) the heat flux, calculated using the Spitzer’s classical formula, \( \mathcal{R} \) the radiative losses and \( \mathcal{S} \) includes all kinds of heating, i.e. mainly the flare heating and quiet heating assuring the stability of the initial unperturbed atmosphere. The radiative losses are calculated according to Rosner et al. (1978) for the optically thin regions and according to Peres et al. (1982) for the optically thick regions. The latter are expressed using an analytic fit of the radiative losses of the VAL C atmosphere.

The set of HD equations (2) is solved using the time step splitting method (Oran et al., 1987). The convection is computed using the LCPFCT algorithm (Boris et al., 1993) and the conduction is calculated using the Crank-Nicholson algorithm.
2.3. Non–LTE radiative transfer

From the time evolution of the temperature $T$, density $n_H$ and energy deposit into neutral hydrogen $E_H$ calculated by the HDC and TPC, the radiative transfer for hydrogen in the chromosphere and photosphere along the magnetic field–lines (1–D plan–parallel approximation) is solved by the TDNLTEC. 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)

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

(4)

where the advection term is neglected due to the small plasma velocities under $10$ km s$^{-1}$ (Nejezchleba, 1998). $P_{ij}$ are given by the sum of the thermal collisional rates $C_{ij}$ and radiative rates $R_{ij}$. The excitation and ionisation of hydrogen by the non–thermal electrons from the beam is included using the non–thermal collisional rates $C_{ij}^{nt}$. We use the approach of Fang et al. (1993) and take into account only the rates from the ground level. $C_{ij}^{nt}$ are directly proportional to $E_H$

$$C_{1e}^{nt} = 1.73 \times 10^{10} \frac{E_H}{n_1}, \quad C_{12}^{nt} = 2.94 \times 10^{10} \frac{E_H}{n_1}, \quad C_{13}^{nt} = 5.35 \times 10^9 \frac{E_H}{n_1}$$

(5)

and $P_{ij}$ are modified as

$$P_{ij} = R_{ij} + C_{ij} + C_{ij}^{nt}.$$ 

(6)

The system of ESE (4) is closed by the equations of charge and particle number conservation

$$n_e = n_p + \varepsilon n_H, \quad \sum n_i + n_p = n_H,$$

(7)

where $n_e$ is the electron density. The system of ESE together with the equation of radiative transfer is solved using the MALI - Multilevel Accelerated Lambda Iterations – method (Rybicki and Hummer, 1991). Because the electron density is not known in advance, the system of ESE (4) is non-linear due to products of $n_i$ and $n_e$. Therefore the ESE and conservation equations (7) are linearised with respect to $n_i$ and $n_e$. The complete system of equations is then solved using the Crank–Nicholson algorithm and Newton–Raphson iterative scheme (Heinzel, 1995; Kašparová, 2004).
Figure 2: The time evolution of the Hα line profile (top panels) and ratio of intensities $I_{nt}/I$ (bottom panels) with and without taking into account $C_{ij}^n$ during the first second of the evolution. The left and right panels correspond to $\delta = 3$ and $\delta = 5$.

2.4. Communication among individual codes

The TPC and HDC are fully integrated, so the beam of test particles interacts with the atmosphere which changes in time due to the previously deposited energy. In this respect the energy deposit fully reflects the changes of the solar plasma density, temperature and ionisation. The hydrogen ionisation is here calculated using an analytic formula (Brown, 1973), i.e. it is inconsistent with the values given by the TDLTEC. The individual codes communicate as follows. First, the HDC reads the profiles of the initial hydrostatic atmosphere, i.e. the functions $T(s)$, $n_H(s)$, and $x(s)$. In the next step the TPC is initiated and the test particles start to propagate through the atmosphere. The calculated beam energy losses are passed to the HDC and new $T(s, t_i)$, $n_H(s, t_i)$, $x(s, t_i)$, and $v(s, t_i)$ at the time $t_i$ are computed. This scheme is repeated throughout the calculation of the atmosphere evolution. The resulting time evolution of $T(s, t)$, $n_H(s, t)$, and $\mathcal{E}_H(s, t)$ are...
used as the input to the TDNLTEC which calculates the corresponding non–LTE hydrogen ionisation and hydrogen line profiles in a separate run.

3. Results of Simulations

The typical profiles of the energy deposit into the plasma of solar atmosphere and into the neutral hydrogen component for $\delta = 3$ and $\delta = 5$ are shown in the upper panels of Figure 1. In the case of the flatter spectrum ($\delta = 3$), the maximum of the energy deposit is lower than for the steeper spectrum ($\delta = 5$) and more energy is deposited into the deeper layers. The energy deposit into neutral hydrogen for the initial atmosphere is higher and distributed over a broader region than for the already heated atmosphere. This is caused by the lower temperature and therefore higher density of neutral hydrogen in the initial atmosphere as compared to the heated atmosphere where the hydrogen is fully ionised above $\sim 1600$ km.

The heating of the atmosphere during the 1 s pulse of the beam propagation affects mainly the temperature structure, the density changes by a factor of 20\%, and the plasma velocities in the region relevant to the H\alpha line formation are lower than 10 km s$^{-1}$. Bottom panels of Figure 1 show an abrupt increase of the temperature for the times $t = 0.25$ s and $t = 0.5$ s even by an order of magnitude in the latter time in comparison with the initial state ($t = 0$ s). As expected from the profiles of the energy deposit for different $\delta$, higher $\delta$ results in higher temperature in the upper part of the atmosphere while the lower $\delta$ is the deeper layers of the atmosphere are affected by the heating.

The evolution of the H\alpha line and the influence of non–thermal collisional rates on its intensity during the first second of heating is shown in Figure 2. The profile of the H\alpha line evolves from a typical absorption profile corresponding to the quiet solar atmosphere to a typical flare profile with broad emission wings. The shape of the line is influenced both by the temperature structure of the atmosphere and by the non–thermal collisional rates. When the first beam electrons reach the H\alpha line core formation region, the non–thermal collisional rates cause a decrease of the line core intensity by a factor of $\sim 70\%$. The duration of the intensity decrease is $\sim 0.15$ s and it is followed by an approximately equally deep and long decrease of the intensity again in the line core which is now caused by the increase of the temperature in the region of the line formation, i.e. by the thermal
collisional rates. The total duration of this significant decrease of intensity is 0.3 s. This effect is shown in Figure 3 where the time evolution of the line core intensity integrated over a typical Hα filter with a half–width 0.7 Å is compared for two cases: with and without including $C_{1j}^{nl}$ into ESE. However, it must be pointed out that the characteristics of the intensity decrease will probably depend on the structure of the initial atmosphere. Later, at $t \geq 0.5$ s, $C_{1j}^{nl}$ contribute to the broadening and to the increase of the intensity in the line wings. This behaviour is more pronounced for the beams with flatter spectra which affect deeper regions of the atmosphere where the line wings are formed.

4. Discussions and Conclusions

We have presented the numerical simulations of the chromospheric response to the electron beam heating and shown that beam electrons significantly affect the evolution of the Hα line intensities. Despite the fact that the simulations were not fully self-consistent because there was no feedback between the hydrodynamic and radiative transfer codes concerning the electron density and optically thick losses, i.e. they were calculated by approximate formulae, the time evolution of the Hα line profile represents typical ob-
servations. We propose to use the decrease of the \( \text{H} \alpha \) line core intensity as shown in Figure 3 for diagnostics of the presence of the electron beams. If this result is observationally confirmed, a new method of the determination of the electron beams impact positions in the chromosphere could be obtained by the means of an analysis of high temporal and spatial resolution series of \( \text{H} \alpha \) images acquired before and at the beginning of a flare.

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References

UTJECAJ ELEKTRONSKIH SNOPOVA NA STVARANJE Hα LINIJE

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Izlaganje sa znanstvenog skupa

Sažetak. Prikazuju se rezultati simulacije određivanja spektroskopskih značajki prisustva netermičkih elektrona u području stvaranja Hα linije koristeći tri međusobno komunicirajuća koda. Ti izvorno autonomni i vrlo specijalizirani kodovi modeliraju tri istodobno djelotvorna procesa u bljeskovima: prikupljanje i disipaciju energije netermičkih elektronskih snopova u Sunčevoj atmosferi, hidrodinamički osadiv atmosfere na energiju pohranjenu u snopovima i radijativni transfer u kromosferi i fotosferi koji određuje profile vodikovih linija i njihov vremenski razvoj. Rezultati ukazuju na mogućnost nove dijagnostičke metode za otkrivanje snopova elektrona u području nastanka Hα linije.

Ključne riječi: Sunčevi bljeskovi - snopovi elektrona - Hα linija