Hα with Heating by Particle Beams

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Abstract. Using 1D NLTE radiative hydrodynamics we model the influence of the particle beams on the Hα line profile treating the beam propagation and the atmosphere evolution self-consistently. We focus on the influence of the non-thermal collisional rates and the return current. Based on our results, we propose a diagnostic method for determination of the particle beam presence in the formation regions of the Hα line.

1. Introduction

Some of the flare models assign a fundamental role to the high energy particle beams in the flare energy transport. As the beams interact with the ambient plasma, their energy is dissipated and transformed mainly into the thermal energy of the transition region and chromosphere plasma. Several models studied electron and proton beams as heating agents (e.g., Mariska et al. 1989; Emstie et al. 1998) as well as their influence on spectral line profiles (e.g., Allred et al. 2005). The propagation of electron beams is inevitably connected with the so-called return current (RC, van den Oord 1990) which also contributes to the beam energy dissipation. Besides the heating, the beams influence atomic level populations of the ambient plasma via collisional excitation and ionization. The work presented here concentrates on these two effects which are commonly neglected in the flare modeling and assesses their importance on the formation of Hα line in solar flares.

2. Model

The beam propagation and energy deposition is modelled by a test particle approach consistently with the hydrodynamics of the atmosphere and NLTE radiative transfer in the transition region, chromosphere, and photosphere. Details of the model and the methods used are described in Kašparová et al. (2005).

We study the response of quiet Sun atmosphere (VAL C from Vernazza et al. 1981) to beam pulses of short duration, 1 s with sinus-like time modulation, and power-law energy spectrum with δ = 3.

3. Hydrodynamics and Beam Propagation

The model takes into account Coulomb collisions of the beam with ambient neutrals and electrons, scattering of beam electrons, and optionally RC for the
case of an electron beam (return current is a factor of $E_e/E_p$ lower for protons carrying the same power as electrons (Brown et al. 1990) and is neglected). The return current is included in a runaway approximation assuming $\alpha = 0.1$, i.e. 10% of ambient electrons carry RC. For details and other approximations of RC in solar atmosphere conditions see Varady et al. (2005, 2007).

Figure 1 shows that RC significantly increases the energy deposit of electron beams at heights $> 1500$ km leading to corresponding increase of the tempera-
Figure 2. Time evolution of the H\(\alpha\) line center (left column) and wing (right column) intensities. Top: electron beam for \(F = 10^{10} \text{erg cm}^{-2}\text{s}^{-1}\) and \(\delta = 3\) with and without RC. Bottom: proton beam for \(F = 10^{12} \text{erg cm}^{-2}\text{s}^{-1}\), \(\delta = 3\), and \(E_1 = 5, 20 \text{ MeV}\). The solid curves refer to cases with \(C_{\text{nt}}\) included, dashed lines to cases without \(C_{\text{nt}}\).

The atmospheric response to proton beams was modelled for two different values of the low-energy cutoff \(E_1 = 5, 20 \text{ MeV}\). Note that deka-MeV protons produce approximately the same amount of hard X-rays as deka-keV electrons (Emslie & Brown 1985). Figure 1 illustrates that proton beams deposit their energy into deeper layers than electron beams (Emslie et al. 1996). The energy deposit of proton beams with lower value of \(E_1\) peaks at higher atmospheric layers and is larger at heights above in comparison with a proton beam of \(E_1 = 20 \text{ MeV}\). Consequently, the temperature at these layers is substantially increased.

4. H\(\alpha\) Line Profiles

The hydrogen level populations are affected also by non-thermal collisional ionization and excitation. The corresponding rates \(C_{\text{nt}}\) are directly proportional to the beam’s energy deposit on hydrogen (see Fang et al. 1993 for electron beams, and Hénoux et al. 1993 for proton beams). Their influence on the temporal evolution of the H\(\alpha\) profile was studied for electron beams by Heinzel (1991); Kasparová et al. (2005). Here, we describe in detail their effect for proton beams.
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Figure 3. Hα contribution function $CF$ for an electron beam. RC and $C^{\text{mt}}$ were included. Solid curve: energy deposit on hydrogen.

and the influence of RC for electron beams. The temporal evolution of the Hα line-center ($\Delta \lambda = 0 \, \text{Å}$) and wing ($\Delta \lambda = 1 \, \text{Å}$) intensities are shown in Fig. 2. As discussed in Heinzel (1991) and Kašparová et al. (2005) for the case of electron beams, $C^{\text{mt}}$ cause a decrease of the line-center intensity at the very start of the beam propagation and enhance the wing intensity later on (mainly for fluxes $\gtrsim 10^{11}$ erg cm$^{-2}$ s$^{-1}$). The line behaviour can be understood in terms of contribution functions $CF$ to the outgoing intensity given by $I_\lambda = \int CF_\lambda \, dz$, where $z$ is the height.

Figure 3 shows the evolution of Hα $CF$ for the case of an electron beam with RC and $C^{\text{mt}}$ included. A decrease of the line center intensity is caused by an increase of opacity due to $C^{\text{mt}}$ (see $CF$ at 0.2 s). Later on, a new region of wing formation occurs at the layers where the energy deposit peaks (see $CF$ at 0.4 s). Such a layer is not formed if $C^{\text{mt}}$ are not considered. Since RC causes heating of the top parts of the atmosphere, it is responsible for the increase
Figure 4. Comparison of Hα contribution function $CF$ for proton beams with $E_1 = 5$ MeV (first column) and $E_1 = 20$ MeV (second column). $C^{int}$ were included.
of the line center intensity at 0.4 s (see Fig. 2) forming in a narrow region at \( \sim 2000 \, \text{km} \) (see Fig. 3).

The situation for a proton beam is shown in Fig. 4. In the case of \( E_1 = 20 \, \text{MeV} \), the beam energy is deposited in regions where the line wings are formed. If \( C^\text{int} \) are included, they cause increase of opacity which leads to a drop of both the wing and the line-center intensities (see \( CF \) at 0.2 s). Later on, a new wing region occurs. Neglecting \( C^\text{int} \), the line intensity does almost not change because the temperature structure is not significantly affected by the beam propagation.

However, for a proton beam of \( E_1 = 5 \, \text{MeV} \), the temperature increase is large enough to form a new region of the line center intensity, as in the case of RC for an electron beam. Also, the energy deposit is large enough to create a new layer of strong wing intensity (see \( CF \) at 0.4 and 1.1 s and Fig. 2). The second peak of the line center intensity at about 1.1 s is due to broadening of the formation region. Similarly to the electron beams, the line wings are not changed if \( C^\text{int} \) are not considered.

5. Conclusions

The \( \text{H}_\alpha \) line is influenced by temperature structure resulting from the beam propagation and return current as well as the non-thermal collisional rates. We propose to use the decrease of \( \text{H}_\alpha \) line-center intensity as diagnostic indicating the presence of particle beams. We also predict that proton beams with deka-MeV low-energy cutoffs produce only decrease of the \( \text{H}_\alpha \) in comparison with quiet-sun intensities.

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References

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