MODELLING OF OPTICAL EMISSION IN SOLAR FLARES

M. VARADY\textsuperscript{1,2}, J. KAŠPAROVÁ\textsuperscript{2}, P. HEINZEL\textsuperscript{2}, M. KARLICKÝ\textsuperscript{2} and Z. MORAVEC\textsuperscript{1}

\textsuperscript{1}Physics Department, Faculty of Science, J.E. Purkinje University, České mládeže 8, CZ 400 96 Ústí nad Labem, Czech Republic
\textsuperscript{2}Astronomical Institute v.v.i., Fričova 298, 251 65 Ondřejov, Czech Republic

Abstract. We present recent progress achieved by our group in the field of flare optical emission modelling. We concentrate on two problems. Firstly, on the possibility of modelling of the time evolution of several Balmer line profiles calculated for real electron fluxes obtained from the hard X-ray observations of a particular flare with the prospect to compare the theoretical results with the observed data for the corresponding flare. Secondly, we discuss the influence of the non-thermal electrons in the line emitting region on the formation and time evolution of Balmer hydrogen line profiles.

Key words: Solar flares - modelling - Balmer lines

1. Introduction

In the standard solar flare model Sturrock (1968), the energy of magnetic fields in the solar atmosphere is converted during the magnetic reconnection process into the kinetic energy of particle beams, which transport the energy released in the course of reconnection downwards to the transition region, chromosphere and possibly photosphere. Here, due to the high density of local plasma, their kinetic energy is thermalized, and the corresponding regions in the solar atmosphere are rapidly heated. Consequently, the atmosphere hydrodynamically responds and dramatic changes of temperature, ionization, density and velocities occur through the flaring atmosphere. The manifestations of the flare processes can be observed in basically all bands of the electromagnetic spectrum.

Due to the complexity of solar flares, it is obvious that computer modelling plays an important role in testing, whether the general picture of how individual mechanisms in flares work is correct and what are the details and observable consequences of individual flare processes, if any. This effort should lead to comparison of individual observed flares with their computer models and to development of new diagnostic methods applicable to the observational data.
There have been many attempts to address this challenging problem, starting from the 1-D models describing the evolution of flare plasma especially in the coronal part of flare loops due to a prescribed, artificial, intense flare heating located mainly in the transition region and chromosphere (Nagai, 1980; Cheng et al., 1983; Pallavicini et al., 1983; Peres and Reale, 1993; etc.). Another class of models differs by using a more realistic flare heating due to the thermalization of high energy electron beams with power law spectra (Somov et al., 1981; MacNeice et al., 1984; Mariska et al., 1989). The models have been used to explain the origin of the strong soft–X ray emission observed from flares, plasma transport within the flare loops and formation, and time dependence of intensities of some intense flare EUV and XUV lines (e.g. Pallavicini et al., 1983).

Due to the complexity of simultaneous treatment of non–LTE radiative transfer and hydrodynamics (radiative hydrodynamics), only a few models (Canfield et al., 1983; Fisher et al., 1985) and recently also (Abbett and Hawley, 1999; Allred et al., 2005; Varady et al., 2005; Kašparová et al., 2007) included also, at least partially, calculations of the optically thick flare emission from the flaring chromosphere and photosphere. One of the possible outputs of models of this kind are the theoretical time evolutions of the profiles and intensities of selected optically thick lines (e.g. hydrogen lines, K and H calcium lines, etc). As many of the optically thick lines lie within the optical band, they can be easily studied by the ground based instruments and therefore they can present a rich source of information on the flare processes.

2. Scope of the Model

We concentrate on the modelling of formation of optically thick hydrogen spectral lines Hα and Hβ in flares by the means of numerical radiative hydrodynamics. In this context we address two principal problems:

1. Can we compute the theoretical time evolution of the above mentioned hydrogen line intensities for a specific flare, using the corresponding electron beam parameters (i.e. the time dependent energy flux $F(t)$ and power law index $\delta$) obtained from e.g. RHESSI hard X–ray spectra? Can we model long enough time evolution ($\sim$ 10 s) in order to compare the theoretical results with observations?

2. What is the influence of presence of non-thermal particles in the formation region of hydrogen lines? Do the non–thermal particles influence the line...
profiles and line intensities in an observable way? Can there be identified some new diagnostic methods on the presence of non–thermal particles in the line emitting region?

2.1. **Physics and Methods**

The model covers physics of three important classes of processes which have been identified in flares:

1. Propagation of charged, high–energy particle beams with power–law spectra through the solar atmosphere plasma from the corona to the transition region and chromosphere and their thermalization due to the Coulomb collisions with the ambient plasma electrons and neutrals (Emslie, 1978). For the electron beams we have optionally included the effect of the return current (RC) on the electron beam flare heating function in the approximation assuming that only 10% of background electrons carry the RC (for details see Varady and Karlický (2007)). The RC effects for proton beams are unimportant due to the low electron proton mass ratio.

2. The hydrodynamic response of solar plasma corresponding to the thermalized beam energy. The flaring plasma is confined by the magnetic field in the closed configuration of the flare loop. The gas dynamic includes effects of gravity, heat conduction along field lines, and radiative losses (Varady et al., 2002).

3. The radiative transfer and time dependent non–LTE ionization of hydrogen in the photosphere and chromosphere using a simplified either three or five level plus continuum approximation of hydrogen atom (Kašparová et al., 2003). The effect of plasma velocities on the hydrogen line formation is neglected in this model.

The individual classes of flare processes are modelled using three fully integrated computer codes and each code models one class of processes identified above. A test particle code (TPC) simulates the propagation, scattering, and energy losses (optionally also due to RC) of a non–thermal particle beam in the solar atmosphere using test particle approach (Bai, 1982; Karlický, 1990; Varady et al., 2002; Varady and Karlický, 2007). The time dependent parameters of the synthetic electron beam (energy flux \(F(t)\) and power–law index \(\delta\)) are among the free parameters of the model. The 1-D gas dynamics is treated using the explicit
LCPFCT solver (Oran and Boris, 1987), the Crank–Nicolson algorithm for heat transfer and the time step splitting technique to couple the individual source terms of the energy equation with hydrodynamics (Varady et al., 2002). The energy losses of the electron beam are taken as flare heating (i.e. as an input) by the gas dynamic part of the code. On the other hand, the propagating synthetic electron beam interacts with the atmosphere evolving according to the flare heating. The initial atmosphere is hydrostatic and its temperature and density profiles in the photosphere and chromosphere correspond to the VAL C atmosphere (Vernazza et al., 1981). Finally, a non–LTE radiative transfer code takes the temperature, density, and beam energy deposit profiles obtained by the 1-D gas dynamic code and TPC to calculate the non–LTE hydrogen ionization within the adopted model of the hydrogen atom. The resulting hydrogen ionization then enters the hydrodynamic part of the code and at the same time it is used to calculate the time evolution of selected hydrogen line profiles (Kášparová et al., 2003).

3. Results

3.1. Modelling of Hydrogen Line Profiles in Flares

In order to test the ability of the code to carry out long simulations and to calculate the time evolution of Hα and Hβ line profiles in a 5–level plus continuum hydrogen atom for at least 10 s with realistic input data derived from observations, we took the energy flux time profile and a mean value of the power–law index $\delta = 3$ obtained by Rudawy (2007), for the 07-03-1993 flare observed by Yohkoh HXT. Then, we produced a corresponding synthetic electron beam and we let it to interact with the VAL C atmosphere extended to the corona, confined by the magnetic field within a single flare loop. A grid of models obtained by scaling the beam energy flux by a constant factor showed that the original energy flux obtained by Rudawy (2007) is too high and the simulation gives unrealistically high temperatures in the corona and the code crashes. This behaviour can be explained by combination of following factors: poor knowledge of the beam cross–sectional area leads to very inaccurate values of the beam energy flux per square unit; there is no information on the real initial state of the preflare atmosphere, especially on its initial density profile which determines its thermal capacity a therefore also strongly influences the response to the flare heating; it is not known if the beam energy during the hard X–ray event is deposited into a single flare thread (loop) despite of proceeding reconnection in the corona. The scaling of the beam energy
MODELLING OF OPTICAL EMISSION IN SOLAR FLARES

Figure 1: Top: First 15 s of time evolution of Hα (left panel) and Hβ (right panel) line intensities in the line centre (solid line) and the line wings (dashed line). The broken linear function identical in both graphs shows the corresponding electron beam energy flux. Bottom: First 15 s of evolution of Hα (left panel) and Hβ (right panel) line profiles.

flux therefore seems to be an inevitable consequence of poor knowledge of the initial parameters of the model and detailed mechanism of the energy deposition into the flare loop arcade.

The results for the maximum energy flux $F = 5 \times 10^{10}$ erg cm$^{-2}$ s$^{-1}$ are shown in Figure 1. The maximum flux corresponds to the unit value of the relative flux in Figure 1. The time lag of the intensities behind the flux can be almost completely explained by the travelling time of the electron beam from the corona to the chromosphere, so the positions of the intensity peaks in both lines correspond quite well with the peak positions of the electron flux. On the other hand rapid
and deep decreases of the electron flux are followed by a much more moderate decrease of intensity fluxes.

3.2. Influence of Electron and Proton Beams on the Hα Line

For an electron beam and a 3–level plus continuum hydrogen atom model we carried out four simulations: flare heating with and without RC; radiative transfer with and without non–thermal collisional rates. The time profile of the beam en-
ergy flux was a sinus-like modulated pulse of 1 s duration with the maximum flux $F = 10^{10}$ erg cm$^{-2}$ s$^{-1}$. The non-thermal electron spectrum was a power-law with $\delta = 3$ and low-energy cutoff $E_1 = 30$ keV. As we are interested only in the effects of the RC and the non-thermal collisional rates, we calculated only 3 s of time evolution. The results show (see two upper panels in Figure 2) that both RC and the non-thermal collisional rates influence the time evolution of the intensity especially in the line centre. It is due to the fact that RC increases the energy deposit in the upper chromosphere roughly of an order. Non-thermal collisional rates which are directly proportional to the beam energy deposit on hydrogen are responsible for the decrease of line intensities at the very beginning of the beam propagation. The details of the H$\alpha$ line formation in the presence of RC and/or the non-thermal rates are discussed in Kašparová et al. (2007).

The influence of proton beams is shown in the lower panel of Figure 2. In this case, the effect strongly depends on the value of the low-energy cutoff. Deka-MeV protons (which produce the same hard X-ray spectrum as deka-keV electrons) cause mainly decrease of intensity. However, neglecting the non-thermal rates, the line intensities are almost not changed. On the other hand, protons beams of $E_1 = 5$ MeV deposit their energy in higher parts of the atmosphere, thus heat them which consequently leads to the increase of line emission. Similarly to electron beams, the non-thermal rates are responsible for the drop of line intensities. More details about the influence of proton beams can be found in Kašparová et al. (2007).

4. Conclusions

We have shown that using an appropriate scaling factor to the beam energy flux we are able to calculate more than a 10 s long time evolution of H$\alpha$ and H$\beta$ line profiles, i.e. long enough evolution to be compared with observations. The results demonstrate a good correlation of H$\alpha$ and H$\beta$ intensity peaks with the peaks of the electron flux. In the frame of a 3-level plus continuum model of hydrogen we show that both RC and non-thermal collisional rates can significantly influence H$\alpha$ line profiles.

Acknowledgements

The work was supported by the grants 205/07/1100, 205/04/0358, 205/06/P135, and 1ET 400720409 of the Grant Agency of the Czech Republic.
References