The role of non-thermal electrons in the hydrogen and calcium lines of stellar flares

M. D. Ding and C. Fang

Department of Astronomy, Nanjing University, Nanjing 210093, China

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ABSTRACT

There is observational evidence showing that stellar and solar flares occur in a similar circumstance, although the former are usually much more energetic. It is expected that the bombardment by high energy electrons is one of the chief heating processes of the flaring atmosphere. In this paper we study how a precipitating electron beam can influence the line profiles of Lyα, Hα, Ca II K and λ8542. We use a model atmosphere of a dMe star and make non-LTE computations taking into account the non-thermal collisional rates due to the electron beam. The results show that the four lines can be enhanced to different extents. The relative enhancement increases with increasing formation height of the lines. Varying the energy flux of the electron beam has different effects on the four lines. The wings of Lyα and Hα become increasingly broad with the beam flux; change of the Ca II K and λ8542 lines, however, is most significant in the line centre. Varying the electron energy (i.e., the low-energy cut-off for a power law beam) has a great influence on the Lyα line, but little on the Hα and Ca II lines. An electron beam of higher energy precipitates deeper, thus producing less enhancement of the Lyα line. The Lyα/Hα flux ratio is thus sensitive to the electron energy.

Key words: line: profiles – stars: activity – stars: atmospheres – stars: flare – stars: late-type.

1 INTRODUCTION

Stellar flares have been frequently detected in both broad band photometry and in spectral lines. A large stellar flare can be several orders of magnitude more energetic than its solar analogy. During a stellar flare, the continuum emission in UV and visible bands is significantly enhanced and is usually characterised by a blue colour (e.g. Pagano et al. 1997); on the other hand, spectral lines show an increased net emission, with a magnitude varying from line to line (e.g. Catalano & Frasca 1994; Montes et al. 1996); lines show asymmetries and macroscopic velocity fields of several hundreds of km s$^{-1}$ possibly exist (e.g. Houdebine et al. 1993; Gunn et al. 1994; Montes et al. 1999), implying that the flaring atmosphere is very dynamic.

A detailed comparison between stellar and solar flares was made by Haisch, Strong & Rodonò (1991). Despite the big difference in magnitude and scale, stellar and solar flares still show many similar features in the enhancement of lines and continua, implying further that the basic heating processes and emission mechanisms are similar in these two phenomena. It is widely accepted that a solar flare occurs through the reconnection of magnetic fields, which releases a large amount of thermal energy and results in the acceleration of charged particles. Accelerated particles then precipitate downwards to heat the lower atmosphere, leading to a dynamic evolution of the atmosphere (chromospheric evaporation and condensation). Although there is no direct information on spatially resolved magnetic activity on stars like that observed on the Sun, some observations still show evidence that a stellar flare may result from the interaction between an old magnetic structure and a new emerging flux (Catalano & Frasca 1994). Simon, Linsky & Schiffer (1980) proposed a speculative scenario of major long-lived RS CVn flares in which the component stars have very large corotating flux tubes, which occasionally interact. Recently, Rubenstein & Schaefer (2000) proposed that superflares, which are newly detected on F–G main-sequence stars by Schaefer, King & Deliyannis (2000), are caused by magnetic reconnection between fields of the primary star and a close-in planet. In these cases, the basic flare mechanism is also magnetic reconnection.

Therefore, we can postulate that the eruption of a stellar flare involves the acceleration of charged particles which then bombard the lower atmosphere. This process not only provides direct heating through Coulomb collisions, producing the bulk mass motions as revealed in the observed spectra (e.g. Houdebine et al. 1993), but also yields non-thermal
collisional excitation and ionization of the ambient atoms. The latter increases the source function and thus enhances the line and continuum emission. This issue is important in the spectroscopy and, in particular, the atmospheric modelling of stellar flares. It is then desirable to have a quantitative assessment of the non-thermal effects on both the line and continuum emission. Numerical computations including the non-thermal effects have been done mostly for solar flares (e.g. Fang, Hénoux & Gan 1993; Hénoux, Fang & Gan 1995; Ding & Fang 1997; Ding & Schleschter 1997; Ding 1999; Fang, Hénoux & Ding 2000). Recently, Ding & Fang (2000) studied the role of non-thermal electrons in the optical continuum of stellar flares. They found that an electron beam with a large energy flux can produce a $U$-band brightening and a $U - B$ colour that are roughly comparable with the observed values of a typical large flare. This work investigates how the non-thermal electrons influence the lines of hydrogen (H I, Lyα and Hα) and the lines of ionized calcium (Ca II K and λ8542) which are frequently used in the spectroscopy of stellar atmospheres (e.g. Hawley & Pettersen 1991; Panagi, Byrne & Houdebine 1991; Houdebine & Doyle 1994a, 1994b; Houdebine & Stempels 1997).

2 COMPUTATIONAL METHOD

When an electron beam precipitates downwards from the corona, the beam electrons collide elastically with the ambient electrons and protons, leading to a direct heating of the plasma; meanwhile, the beam electrons collide inelastically with the ambient atoms and produce a non-thermal excitation and ionization of the atoms. As in Ding & Fang (2000), we first evaluate the rate of energy deposition corresponding to the latter process, which reads

$$\Phi = \frac{1}{2}(1 - \xi)n_H \lambda K(2 - \delta) \frac{F_1}{E_1^2} \left( \frac{N}{N_1} \right) \int_0^{\xi} \frac{u^2}{1 - u} \frac{du}{\cos \theta}.$$  \hspace{2cm} (1)

where $\xi$ is the ionization degree of the ambient plasma, $K = 2\pi e^4$, $\lambda$ the Coulomb logarithm for inelastic collisions. We assume a power law flux spectrum for the electron beam, characterised by a power index, $\delta$, a low-energy cut-off, $E_1$, and a total energy flux, $F_1$. $N$ is the column density and $N_1$ is the depth penetrated by electrons of an energy $E_1$, which is expressed as

$$N_1 = \frac{\mu_0 E_1^2}{(2 + \beta/2) \pi K},$$  \hspace{2cm} (2)

where $\mu_0$ is the cosine of the initial pitch angle, taken to be unity here. The expression for $\beta$ and $\gamma$ can be found in Emslie (1978). Moreover, in equation (1),

$$u_1 = \begin{cases} 1, & N > N_1, \\ N/N_1, & N < N_1. \end{cases}$$  \hspace{2cm} (3)

We adopt an atomic model of four bound levels plus continuum for hydrogen and a model of five bound levels plus continuum for ionized calcium. The non-thermal excitation and ionization rates are computed as

$$C_{ij}^{\beta} \simeq a_{ij} \Phi/n_1,$$  \hspace{2cm} (4)

where $n_1$ is the hydrogen ground level population. The coefficients $a_{ij}$ are taken from Fang et al. (1993): in cgs units, $a_{12} = 2.94 \times 10^{10}$, $a_{13} = 5.35 \times 10^9$, $a_{14} = 1.91 \times 10^8$ and $a_{15} = 1.73 \times 10^{10}$ for H; $a_{14} = 2.38 \times 10^{10}$, $a_{15} = 4.25 \times 10^{10}$ and $a_{16} = 4.69 \times 10^{10}$ for Ca II. The above formulae for non-thermal collisional rates are derived empirically using the collisional cross-sections for various transitions (Fang et al. 1993). It is very convenient to include these rates into the computation of model atmospheres.

We do non-LTE computations using a method similar to that described in Gan & Fang (1987) and Fang et al. (1993). The general procedure is as follows. Given a model atmosphere and a prescribed electron beam, we solve iteratively the equations of hydrostatic equilibrium, particle conservation, radiative transfer and statistical equilibrium, including the non-thermal collisional rates ($C_{ij}^{\beta}$), for both H and Ca II. After the computations reach convergence, we then calculate the line source function and the opacity, and finally the line profile as

$$F_\lambda = 2\pi \int_0^1 I_\lambda(\mu) \mu d\mu = 2\pi \int_0^1 d\mu \int_0^\infty S_\lambda e^{-\tau_\lambda/\mu} d\tau_\lambda.$$  \hspace{2cm} (5)

Broadening mechanisms include radiative damping, the Doppler effect and the Stark effect. Note that for all the lines involved, we assume complete frequency redistribution (CRD), while the effect of partial frequency redistribution (PRD) may be important for some lines (e.g. Lyα and Ca II K). However, CRD is still a reasonable assumption in the present investigation since our main purpose is to show the effect of non-thermal electron beams, not to reproduce exactly the observed line profiles.

3 INFLUENCE OF ELECTRON BEAMS ON THE LINE EMISSION

Many authors have investigated how the spectral lines, including the H I Lyα and Hα, and the Ca II K and λ8542 lines, change with the modifications of atmospheric models of, for example, late-type stars (e.g. Linsky et al. 1979; Houdebine & Doyle 1994a, 1994b; Houdebine, Doyle, & Koscielecki 1995; Houdebine & Stempels 1997; Short & Doyle 1997, 1998; Mauas 2000). These lines are shown to be good diagnostics of the atmospheric conditions in the late-type stars. Generally speaking, the Ca II K line, in particular, the K1 minimum, can be used to determine the temperature structure around the temperature minimum region; emission in the hydrogen Balmer lines (Hα etc.) is related to the temperature and temperature gradient in the chromosphere; the Lyα flux relies sensitively on the position of the transition region, i.e., the coronal pressure. However, we will show below that the presence of a non-thermal electron beam in a flare star can also change these spectral features without modifying the atmospheric model. Therefore, in order to construct reliable semi-empirical models or make proper spectral diagnostics for these flare stars, we need first to study quantitatively the effect of non-thermal electrons on the above-mentioned lines.

3.1 Effect of varying the beam flux

As in Ding & Fang (2000), we adopt the semi-empirical model of the dMe star, AD Leo, proposed by Mauas & Falchi (1994), as the base model, and then introduce an
3.2 Effect of varying the electron energy

To check the effect of non-thermal electrons of different energies, we have also computed the line spectra for electron beams with a fixed energy flux but different low-energy cut-offs. The line profiles and the net integrated fluxes are plotted in Figs. 2 and 3 respectively. Fig. 2 shows that, varying $E_1$ does not alter obviously the profiles of Hα, Ca II K and λ8542. However, it has a great influence on the Lyα profile, namely, increasing $E_1$ reduces the non-thermal effects on the line intensities. This result is not surprising. As the Lyα line is formed in the very upper chromosphere, electrons of a higher energy penetrate deeper and thus leave less energy in upper layers to excite the hydrogen atoms.

In the above computations, the electron beam is assumed to originate in the corona, i.e., at the top of the model atmosphere. If the beam originates in a lower layer, its effect could become more significant for lines formed in the lower atmosphere. Such a scenario has been proposed to be a possible origin of a flare-like phenomenon on the Sun, Ellerman bombs (Ding, Hénoux & Fang 1998).

3.3 Discussion

To illustrate the different behaviours of the four lines in response to the electron beam, we plot in Fig. 5 the height distribution of the line source function in different cases of formation heights, spanning a range from the upper photosphere or lower chromosphere to the upper chromosphere. So the results are compatible with the general picture that the electron beam precipitates downwards from the corona.

We note that the negative value of $\Delta F$ for Lyα in weak beam cases is due to a reduction of emission in the inner part of the line, as described above.
Figure 3. Line profiles of Lyα, Hα, Ca ii K and λ8542 computed from a model atmosphere of the dMe star AD Leo (Mauas & Falchi 1994), considering the effect of a precipitating non-thermal electron beam. Different line styles show the effect of varying the low-energy cut-off, \( E_1 \), of the beam: 20 (dotted line), 60 (dashed line) and 100 (solid line) keV. In all cases, the energy flux, \( J_1 \), is \( 10^{12} \) erg cm\(^{-2}\) s\(^{-1}\), and the power index, \( \delta \), is 3.

Figure 4. Net integrated fluxes of Lyα, Hα, Ca ii K and λ8542 against the low-energy cut-off of the electron beam. In all cases, the energy flux, \( J_1 \), is \( 10^{12} \) erg cm\(^{-2}\) s\(^{-1}\), and the power index, \( \delta \), is 3.

Figure 5. Height distribution of the source function of the four lines in the atmosphere of AD Leo in the presence of an electron beam. The line styles have the same meaning as in Fig. 1.

beam fluxes. It shows that the beam can make the source function of Lyα greatly increased in a broad region from the chromosphere to the photosphere. This can be understood that the hydrogen ground level is depopulated while the excited levels are overpopulated with respect to the beam-free case. Accordingly, the Lyα wings are significantly enhanced. In the very upper layers, however, the source function of Lyα could be slightly reduced, which results in a decrease of the line centre intensity in some cases (see Fig. 6). Similar results have been obtained for the Lyα line in solar flares (Hénoux et al. 1995). The source function of Hα is also increased but less significantly than Lyα. Note that the Stark effect, due to an enhanced electron density, plays an important role in the broadening of the Hα line. Fig. 6 displays the height distribution of the electron density, which is shown to be raised by up to three orders of magnitude in the chromosphere, highlighting the non-thermal ionization effect of the beam.

The increase of the source function of hydrogen lines in photospheric layers is mainly caused by a backwarming effect, i.e., the enhanced radiation from the chromosphere, while the direct penetration of non-thermal electrons has less effect. In contrast, the source function of the Ca ii lines is mainly increased in the chromosphere; it is still coupled to the local Planck function in the photosphere. In addition, the Ca ii lines are less affected by the Stark effect. Therefore, the enhancement of these lines is most apparent in the line centre, as shown in Fig. 1.

The quantitative results of line and continuum enhancement due to an electron beam are certainly model-dependent. In all the above computations, we have assumed a cool background atmosphere. In fact, the model atmosphere should change with the activity level of the star, especially when flare occurs. A model of the flaring state of AD Leo, for example, was proposed by Mauas & Falchi (1996).
Compared with the model in the quiescent state, a flare model has a higher temperature in the chromosphere and even in the photosphere, and a lower position of the transition region (a higher coronal pressure). This model itself can produce an enhanced line emission. However, a higher coronal mass in the flaring atmosphere would consume a part of the electron energy, so that the effect of the electron beam is less significant than in the case of a quiescent atmosphere. The real situation might be a combination of the effects of a heated atmosphere and a non-thermal electron beam.

In addition to the line flux, we find that the Lyα/Hα flux ratio is in positive dependence on the electron beam flux, but, apparently, in negative dependence on the low-energy cut-off. In the case of $F_1 = 10^{12}$ erg cm$^{-2}$ s$^{-1}$, $E_1 = 20$ keV and $\delta = 3$, the ratio amounts to $\sim 6$. Therefore, it seems that an electron beam can produce most spectral features that are usually ascribed to a modification of the model atmosphere. As long as the electron beam exists during the flaring process, its effect should be taken into account in order to properly construct the semi-empirical models, otherwise the chromospheric temperature will be overestimated.

4 CONCLUSIONS

There is observational evidence showing that a stellar flare may occur in a similar circumstance to the eruption of a solar flare. A common flare scenario is the reconnection of magnetic fields. Although a stellar flare, in particular, the flares in late-type stars, can be several orders of magnitude more energetic than a solar flare, their emission features, in both lines and continua, still share many similarities. It can be postulated that the flaring process in a star also involves the acceleration of energetic particles (protons or electrons), carrying most energy to heat the lower atmosphere.

We study in this paper how a precipitating electron beam can influence the line profiles of Lyα, Hα, Ca II K and λ8542. We make non-LTE computations taking into account the non-thermal collisional rates due to the electron beam. The results show that the four lines can be enhanced to different extents. The relative enhancement increases with increasing formation height of the lines. Varying the energy flux of the electron beam has different effects on the four lines. The wings of Lyα and Hα become increasingly broad with the beam flux; change of the Ca II K and λ8542 lines, however, is most significant in the line centre. Varying the electron energy (i.e., the low-energy cut-off for a power law beam) has a great influence on the Lyα line, but little on the Hα and Ca II lines. An electron beam of higher energy precipitates deeper, thus producing less enhancement of the Lyα line. The Lyα/Hα flux ratio is thus sensitive to the electron energy. Together with our computations for the continuum emission (Ding & Fang 2000), these results provide a diagnostic tool for the non-thermal processes in stellar flares.

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