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A possible mechanism for the Hα broad wings emission of Ellerman bombs

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Abstract. In this paper, the non-thermal emission of Lyα, Lyβ and Hα lines generated through charge exchange by protons accelerated in the low chromosphere and moving with a small pitch angle around an horizontal magnetic field has been computed. Computations have been done for observations made at the center of the solar disk, i.e. in a situation where the solar magnetic field is perpendicular to the line of sight, for non zero pitch angles. In such conditions, the photons emitted through charge exchange are Doppler shifted symmetrically in both wings of the lines. The Hα far line wing intensities increase significantly, making possible to reproduce the characteristics of the spectra of Ellerman bombs. Thus it is proposed that a proton beam accelerated in the low chromosphere, and losing its energy there, is a viable candidate for explaining the observed EB spectra.

Key words: line: profiles – radiation mechanisms: non-thermal – Sun: chromosphere

1. Introduction

Ellerman bombs (EBs) or moustaches are known as fine structures with a typical 10 min lifetime and a size of $\sim$ 1 arc sec characterized by Balmer line profiles with broad wings (about 10Å half width in Hα) and deep central absorption (e.g. Severny 1956, 1959; Engvold & Maltby 1968; Bruzek 1972; Kitai 1983; Rust & Kell 1992). Several mechanisms to explain the broad emission profiles of EBs have been proposed. Engvold & Maltby (1968) discussed two mechanisms: One is random macroscopic motions, the other is scattering due to electrons in a heated atmosphere. Severny (1968) suggested incoherent scattering in an expanding opaque layer. Canfield & Athay (1974) showed the possibility to explain the observed broad Hα by assuming it was emitted in a heated and condensed atmosphere. Kitai (1983) made non-LTE computations and indicated that a heated (ΔT=1500 K) and condensed (ρ/ρ_0=5) layer in the lower chromosphere could produce a broad Hα profile of EB. All mechanisms proposed so far to explain the broad profiles are based on thermal models.

However, linear polarization of hydrogen line emission in EBs was reported by many authors (Severny & Khokhlova 1958; Babin & Koval 1986, 1987; Firstova 1986). Firstova (1986) suggested that the excitation of hydrogen atoms by a flux of energetic electrons or by heat conduction may be responsible for the observed polarization. Recently, Firstova et al. (1997) observed that Hα line in EBs was linearly polarized in the tangential direction, which could be interpreted as resulting from the bombardment of the solar atmosphere by beams of very energetic particles moving vertically.

Ding, Hénoux and Fang (1997) explored recently the possibility that the Hα line profiles of EBs could be due to the effect of energetic particles bombarding the solar atmosphere, i.e. moving vertically. Their non-LTE computations, with non-thermal excitation and ionization included, showed that the characteristics of EB Hα line profiles can be qualitatively reproduced in two cases: (1) high energy particles ($\geq$ 60 keV electrons or $\geq$ 3 MeV protons) being injected high in the solar atmosphere; (2) less energetic particles with a lower injection site (in middle chromosphere or deeper). However, except near the solar limb, the computed intensity at Hα far line wings does not seem to be large enough to explain the observations.

On the other hand, several authors indicated that, by proton-hydrogen charge exchange, proton beam bombardment could produce Doppler shifted emission in Balmer lines and hence could enhance hydrogen line wings (Orral & Zirker 1976; Canfield & Cheng 1985). Using more recent atomic data and refined atmospheric models, Fang et al.(1995) confirmed their results and indicated that this effect will be obvious only at the beginning of solar flares. Recently, Zhao et al.(1997) (ZFH) computed the hydrogen line profiles caused by an oblique incident proton beam through proton-hydrogen charge exchange. They showed that the asymmetry and the intensity of the non-thermal emission profiles strongly depend on the beam incident pitch angle α and on the angle θ between the directions of the magnetic field and of the line of sight: when $\alpha + \theta \geq 90°$, blue shifted emission is present, and the line even becomes symmetrical when $\theta = 90°$.

All computations of Hα line profiles based on charge exchange emission, given so far, indicate that for energetic protons accelerated in the corona and moving vertically around a vertical magnetic field, the Hα line non-thermal emission is too

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Send offprint requests to: J.-C. Hénoux small to be detectable. In fact EBs are not seen in Hα line center, so they must originate from the chromosphere. Therefore, in this paper we propose proton-hydrogen charge exchange, due to a proton beam moving around a horizontal magnetic field in the chromosphere, to be at the origin of the EBs Hα line profiles. Sect. 2 gives computational results, followed by a discussion and by conclusions in Sect. 3.

2. A possible mechanism for emission in the Hα far line wings

The rôle of the magnetic field in the formation of moustaches is still unclear. Kitai and Muller(1983) suggested that moustaches originate in elementary flux tubes. On the othe hand, Rust(1968) and Rust and Keil(1992) pointed out that Ebs are located at places where magnetic features of one polarity meet opposite polarity features. The location of Ebs at the interface between regions of opposite magnetic polarity suggest that they are associated with the presence of horizontal magnetic fields. Diver et al.(1996) proposed the Kelvin-Helmotz instability resulting from a laminar flow along a horizontal magnetic field as the origin of Ebs. It is also possible that magnetic reconnection between horizontal and non-aligned magnetic fields does occur in the lower atmosphere (Li et al.1997). If this is true, energetic protons accelerated there would propagate horizontally in opposite directions.

2.1. Proton-hydrogen charge exchange

When an proton beam precipitates into a neutral hydrogen atmosphere, a beam proton H_b^+ may capture an electron from a target hydrogen atom, H_t, becoming a superthermal one, $H_{j,b}$, excited to level j :

$$H_b^+ + H_t \leftrightarrow \; H_{j,b} + H^+. \tag{1}$$

The line intensity enhancement in a transition from upper level j to lower level i is $I_{ji}(\Delta\lambda) = hC/\lambda_{ij}\Phi_{ji}(\Delta\lambda)$ where the photon emission rate is (ZFH):

$$\Phi_{ji}(\Delta\lambda) = \frac{1}{4\pi^2}\frac{c}{\lambda}\int_0^\infty\int_{E_{min}}^{E_{max}}\sqrt{\frac{m}{2E}}A_{ji}\,n_j$$

$$\left[\sin^2\theta\sin^2\alpha - (\cos\alpha\cos\theta - \Delta\lambda\frac{c}{\lambda}\sqrt{\frac{m}{2E}})^2\right]^{-1/2} ds\,dE, \tag{2}$$

where C is the speed of light, A_{ji} is the spontaneous radiative transition probability from level j to level i, n_j the number density of non-thermal protons of energy E excited to the level j in (E,s)-phase space, s is the distance along the trajectory of the protons of pitch angle α. The parameters E_{min} and E_{max} are dependent on the geometry and are given in ZFH. m and E are respectively the mass and the energy of a proton; θ is the angle between the line of sight and the magnetic field direction.

In order to get a line profile symmetrical around $\Delta\lambda = 0$, θ must be equal to $\pi/2$. In that case, the maximum amplitude $\Delta\lambda_M$ of the Doppler shift associated with the variation of the component along the line of sight of the velocity of a recombined hydrogen atom is given by:

$$\Delta\lambda_M = 2\frac{\lambda}{C}\sqrt{\frac{2E}{m}}\sin\alpha, \tag{3}$$

Since θ is related to the heliocentric angle $\theta^\star$ and to the angle between the magnetic field direction and the plane defined by the line of sight and the local solar vertical, ψ, by $\cos\theta = \cos\psi\sin\theta^\star$, this imposes to assume that the particles are moving around an horizontal magnetic field, either at disk center ($\theta^\star = 0$) with any orientation, or at the limb, perpendicular in that case to the line of sight ($\psi = \pi/2$). The Doppler shift is then given by $\Delta\lambda_M$ = 607 Å $\sin\alpha\sqrt{E_{MeV}}$.

2.2. Non-thermal emission

Three bound levels plus an ionized state were used to represent the hydrogen atom. The same procedure as in ZFH was used to compute the number density n_j.

The computations were restrained to the hydrogen Hα emission line profile at the center of the solar disk, assuming that the proton beam was accelerated in the lower chromosphere at a column mass m_0. At the site of acceleration, the energy distribution of the flux, $F(E_0,0)$, of energetic protons of energy E_0 was represented by a power law, $F(E_0,0) \propto \; E_0^{-\delta}$, above an energy cut-off E_c. After crossing an horizontal distance s, with column number density N, the energy distribution of the proton beam flux is given by (ZFH):

$$F(E,s) = (\delta\; - 2)\mathcal{F}_1\; E_c^{\delta-2}E(E^2 + E_N^2)^{-(\delta+1)/2}, \tag{4}$$

where $\mathcal{F}_1$ is the total energy flux above the low energy cutoff E_c. E_N is the energy needed for a proton to cross a distance s, corresponding to a column number density N such that $E_N = 2\gamma KN/\mu_0$, with K=2 πe^4, $\mu_0 = \cos\alpha, \gamma = m_p/m_e[x\Lambda + (1-x)\Lambda^{'}]$; x is the ionization degree. As x is very small ($\sim 10^{-5} - 10^{-6}$) in the lower chromosphere, $\gamma \simeq \Lambda^{'} m_p/m_e$, where $\Lambda^{'}$ represents the effect of inelastic collisions on neutral hydrogen atoms. We took $\Lambda^{'} \simeq 5$, typical value for a proton with an energy of 1 MeV.

By using Eqs. (2) and (3), for different values of $\mathcal{F}_1$, E_c and δ, the intensity enhancements in Lyα, Lyβ and Hα lines have been computed. A fixed hydrogen density, N_H, equal to 1×10^{15} cm $^{-3}$, and an ionization degree $x = 10^{-5}$, were used. For very weak ionization, changing x does not influence significantly the results.

Fig. 1 gives the computed non-thermal emission profiles of the Lyα, Lyβ and Hα lines for different values of the total input energy flux $\mathcal{F}_1$. The intensity plotted in this figure, as well as in Figs. 2 and 3, is not the intensity at the solar surface but rather the energy emitted per steradiant, per second and per Å by a horizontal beam of protons of Sect. 1 cm^2. It cannot be compared directly to the quiet sun intensity. However, Figs. 1, 2 and 3 give the wavelength dependence of the hydrogen emission lines and show that intensities comparable to the quiet sun intensity can be reached by assuming a vertical extension

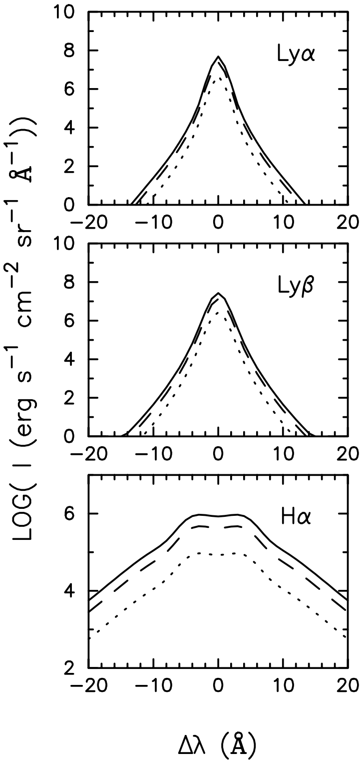

Fig. 1. Computed non-thermal emission profiles of the Lyα, Lyβ and Hα lines, at disk center ($\theta = \pi/2$), for a total input energy flux $\mathcal{F}_\infty$ = 1 $\times 10^{12}$ (solid line), 5 $\times$ 10^{11} (dashed line) and 1 $\times 10^{11}$ (dotted line) erg cm^{-2} s^{-1} above a low energy cut-off E_c = 300 KeV and a power index δ = 5 for the quiet-Sun model C (Vernazza et al. 1981). In all cases the pitch angle α is taken to be 5°

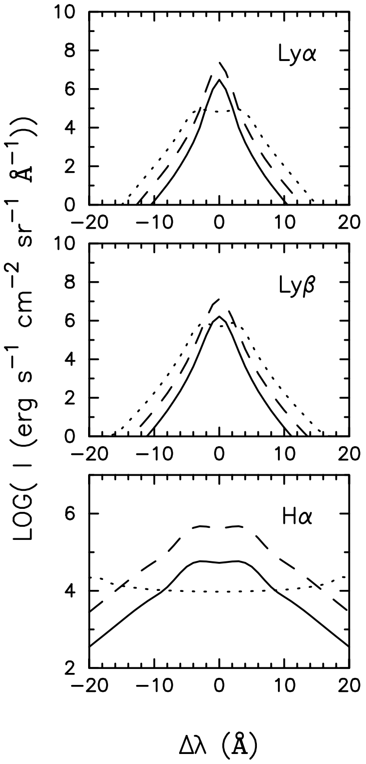

Fig. 2. E_c-dependence of the non-thermal emission profiles of the Lyα, Lyβ and Hα lines for E_c = 150 keV (solid line), 300 keV (dashed line) and 600 keV (dotted line) and for the values $\mathcal{F}_1$ = 5 $\times$ 10^{11} erg cm^{-2} s^{-1}, δ = 5, $\theta = \pi/2$ and α = 5°

of the moustaches of a few ten of km. The intensities of the Lyα and Lyβ line wings may increase by two to three orders of magnitude relatively to the quiet-Sun line profile intensities (see ZFH), while the intensity of the central part ($\sim \pm$ 5 Å) of the Hα line also increases and reaches about 10 $\sim$20 % of the quiet-Sun continuum. This is quite different to the case where a proton beam bombards the chromosphere from the corona producing a non-thermal Hα emission three or four orders of magnitude weaker than the continuum background (see ZFH). The reason is simply that the proton beam loses all its energy locally in the chromosphere (see Fang et al., 1995).

Fig. 2 shows the E_c-dependence of the non-thermal profiles for $\mathcal{F}_1$ = 5 $\times$ 10^{11} erg cm^{-2} s^{-1}, δ = 5 and α = 5°. An interesting point to be noticed is that the highest intensity corresponds to E_c = 300 KeV. When E_c increases, the non-thermal emission decreases. This is probably due to the non linear variation of the charge-exchange cross section with the particle energies, and to the fact that the superthermal hydrogen atoms with higher energy produce non-thermal emission at wavelengths further away from the line center, so that the profile becomes broader and flatter.

Fig. 3 gives the δ-dependence of the non-thermal emission profiles for the parameter values $\mathcal{F}_1$ = 5 $\times$ 10^{11} erg cm^{-2} s^{-1}, E_c = 300 keV and α = 10°. It is worth to notice that the line wing intensities decrease with increasing values of δ, while the intensities in the line center part increase. This is due to the fixed value of $\mathcal{F}_1$, so that the number density of protons with lower energy is higher than that of protons with higher energy when δ increases. Another point that should be mentioned is that with α increasing, the line intensity decreases. This is especially obvious for the Hα line.

2.3. *Transfer of Hα radiation, net excess Hα emission*

The non-thermal Hα photons emitted in the low chromosphere will be absorbed by the ambient atmosphere. The non-thermal Hα emission line profile resulting from photon propagation through the atmosphere has been computed. Considering that the intensity of the non-thermal emission is at most only about 10–20 % of the background continuum emitted deeper in the atmosphere, we assumed simply that the atmosphere was playing only an absorbing role. Thus, the emerging emission is given by

$$I_e(\Delta\lambda) = I(\Delta\lambda)e^{-\tau(\Delta\lambda)}, \tag{5}$$

where $\tau(\Delta\lambda)$ is the opacity of the upper atmosphere at a distance $\Delta\lambda$ from Hα line center. It was computed from the quiet-Sun model C (Vernazza et al. 1981) used as basic model representative of the solar atmosphere including the non-thermal excitation and ionization caused by the proton beam (see Hénoux et al.

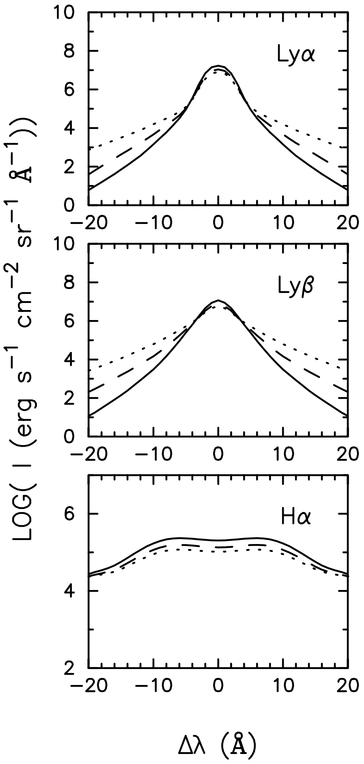

Fig. 3. δ-dependence of the non-thermal emission profiles for δ = 5 (solid line), 4 (dashed line) and 3 (dotted line). The values of the parameters are the same as in Fig. 2, but α = 10°

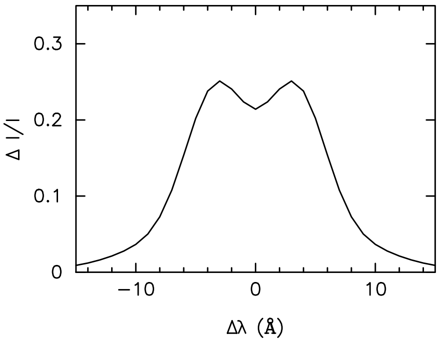

Fig. 4. Computed Hα excess profile for the case of $\mathcal{F}_1$ =5 × 10^{11} erg cm^{-2} s^{-1}, E_c = 300 keV, δ = 5 $\theta = \pi/2$ and α = 5°. Convolution with a line profile with a macro-velocity of 10 km s^{-1} is made.

1993). Fig. 4 gives the computed Hα excess profile, $I_e(\Delta\lambda)/I_c$, where I_c is the background continuum emission, for the case of $\mathcal{F}_1$ = 5 × 10^{11} erg cm^{-2} s^{-1}, E_c = 300 keV, δ = 5 and α = 5°. This profile is convolved with a Doppler profile with a macro-velocity. It can be seen that only near the line center (∼ ±1 Å), there is an obvious absorption. It is favourable to the reproduction of the observed Hα line profiles of EBs, because, as indicated by many authors, the latter just have a strong central reversal.

3. Discussion and conclusion

We have computed the non-thermal Lyα, Lyβ and Hα line emission produced by charge exchange in the case of propagation in the low chromosphere of energetic protons having a small pitch angle around a horizontal magnetic field. The magnetic field is supposed to be perpendicular to the line of sight. Compared to the quiet-Sun spectra, not only the line intensities increase significantly, but also the lines become very broad, especially for Hα. This scenario can be used to explain the very broad Hα line wings of EBs. If we take into account the non-thermal excitation and ionization and also the heating of the atmosphere caused by the energetic particles (see Ding et al. 1997), then the characteristics of the EB spectra can be at least qualitatively understood. Moreover, due to the high density in the low chromosphere, protons lose their energy in a short distance. For instance, when N_H= 1 × 10^{15} cm^{-3}, 1 MeV protons lose their energy through collisions with ambient particles in a distance of about 4 km. In that case the size of the EBS is defined by the size of the reconnection region. It should also be mentioned that the results of our computation practically do not depend on the model of the atmosphere, which changes only the absorption near the line center, provided the hydrogen density and the ionization degree are kept constant.

In summary:

1. Proton-hydrogen charge exchange is a viable mechanism to explain the broad Hα line and the nearly symmetrical wings observed in the spectra of EBs by protons accelerated in the lower chromosphere and propagating along a horizontal magnetic field perpendicular to the line of sight.

2. If the spectral line emission of EBs is produced by a proton beam located in the lower chromosphere, then the intensities of Lyα and Lyβ line wings should increase by 2-3 orders of magnitude above that of the quiet-Sun intensity, providing a possible diagnostic tool for the mechanism of EBs. In order to get such intensities, the beam must have a section of about 10 km^2. The associated energy carried by the beam over 10 mn, for a energy flux $\mathcal{F}_1$ = 5 × 10^{11} erg cm^{-2} s^{-1} would be of 3 10^{25} erg. That is four order of magnitude less than a small flare.

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