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Letter to the Editor

Collisional excitation and ionization of hydrogen by return current in solar flares

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Abstract. First a problem of the transport of electron beams with high energy fluxes into the cold chromosphere during the flare is presented. Then it is shown that the problem might be solved by the return current formed by superthermal (runaway) electrons. In such a case the return current electrons could influence hydrogen excitations and ionizations. Therefore, we computed collisional rates of such a return current and compared them with those of the thermal plasma and of a monoenergetic (10 keV) electron beam with the energy flux $F_\mathrm{E} = 10^{12}$ erg cm^{-2} s^{-1} penetrating into the flare atmosphere described by the F1 model (Machado et al. 1980). We show that in this situation the return current collisional rates can be dominant for some transitions.

Key words. Sun: flares – plasmas – atomic processes

1. Introduction

There is an increasing interest in the role of superthermal particles, especially electrons in the chromospheric line formation and polarization (Fang et al. 1993; Hénoux & Vogt 1998; Kašparová & Heinzel 2002). Electron beam fluxes up to 10^{12} erg cm^{-2} s^{-1} penetrating into the chromosphere during the solar flares are considered. But as it will be shown in the following the *transport* of such high energy fluxes is a complex problem which requires further analysis. As a solution of this problem, the return current formed by superthermal (runaway) electrons is proposed. To confirm the existence of such a return current, its diagnostic aspects, related to collisional rates of hydrogen excitations and ionizations, are studied.

2. Return current problem

It is known that the electrons accelerated during the impulsive phase of flares bombard dense chromospheric layers of the flare atmosphere. These electron beams represent huge electric currents which have to be neutralized by the return current (Hoyng et al. 1978; van den Oord 1990). If the return current is formed by background plasma electrons then it generates the electric field $\mathcal{E}$ according to the Ohm law $\mathcal{E} = \eta j$, where η is the plasma resistivity and j is the electric current density. Such an electric field is then a cause of beam deceleration which can be very efficient, especially in cold chromospheric layers. Namely, if we characterize the deceleration due to the return current losses by the stopping distance s as $s = v_\mathrm{B}^2/2a$, where v_B is the beam velocity and $a = e\mathcal{E}/m_\mathrm{e}$ is the deceleration due to the return current losses, then we can express this distance as

$$s = \frac{m_\mathrm{e}^2 v_\mathrm{B}^4}{4e^2\eta F_\mathrm{E}} = \frac{m_\mathrm{e}^2 v_\mathrm{B}^4}{4e^2 \times 10^{-6}\, T^{-3/2} F_\mathrm{E}}, \qquad (1)$$

where e is the electron charge, T is the plasma temperature, m_e is the electron mass, F_E is the beam energy flux, and the relation for

$$\eta = m_\mathrm{e}/(n_\mathrm{e}\, e^2\, \tau) = 13.7\, \Lambda\, m_\mathrm{e}/(e^2\, T^{3/2}) = 10^{-6}\, T^{-3/2} \qquad (2)$$

was used (Melrose 1980; Priest 1982). n_e is the electron density, τ the collisional time of background electrons, and Λ the Coulomb logarithm. Thus, for a chromospheric temperature $T = 20\,000$ K and a typical beam energy of $E = 10$ keV (beam velocity is $v_\mathrm{B} = 5.93 \times 10^9$ cm s^{-1}) we can write

$$s\,(\mathrm{cm}) = 3.14 \times 10^{15}/F_\mathrm{E}\,(\mathrm{erg\,cm^{-2}\,s^{-1}}). \qquad (3)$$

It gives stopping distances of 31.4 m for the beam energy flux $F_\mathrm{E} = 10^{12}$ erg cm^{-2} s^{-1} and $s = 31.4$ km for $F_\mathrm{E} = 10^9$ erg cm^{-2} s^{-1}.

This result shows the problem. In the above described scenario the beam fluxes above $F_\mathrm{E} = 10^9$ erg cm^{-2} s^{-1} cannot penetrate into the sufficient depth (tens to hundreds kilometers) of the cold chromosphere and thus influence the Hα line formation.

Partly, this problem can be solved by the presence of proton beam fluxes, which neutralize the electric current of the electron beam. It is probable that in solar flares proton beams accompany electron beams, but the problem is that the neutralizing proton beam (for $n_\mathrm{Bp} \sim n_\mathrm{Be}$, where n_Bp and n_Be are the proton and electron beam densities; in the following n_B will be used for the electron beam density only) need to be accelerated

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to the same speed as the electron one. It needs a special acceleration process and moreover this proton beam carries much more energy (m_p/m_e times) than the electron one.

In such a situation it looks that the only possible way how to transport high energy electron fluxes into sufficient depths of the cold chromosphere is the neutralization of the beam electron current by the return current formed by a group of electrons with velocities well above the thermal plasma velocity (their collisional losses with the background plasma are strongly reduced) moving in backward direction. This type of the return current is similar to that presented in the paper by Rowland & Vlahos (1985). The source of these electrons can be: a) runaway electrons from the chromospheric plasma; b) backscattered beam electrons (Karlický 1993) or beam electrons reflected in the magnetic mirror (Karlický & Hénoux 1993) expected at footpoints of flare loops. The amount of the runaway electrons N_r can be estimated as (Norman & Smith 1978):

$$\frac{N_r}{n_e} = \frac{1}{2} \exp\left[-\frac{1}{2}\left[\left(\frac{\mathcal{E}_D}{\mathcal{E}}\right)^{1/2} - \frac{\mathcal{E}}{\mathcal{E}_D}\right]^2\right], \quad (4)$$

where $\mathcal{E}_D$ is the Dreicer electric field which during the collision time τ accelerates the electron from zero velocity to the thermal one v_{Te}, i.e. $\mathcal{E}_D = m_e\, v_{Te}/(e\tau)$. The relation (4) shows that for $\mathcal{E}/\mathcal{E}_D > 0.25$, 10% of the background plasma electrons are runaway electrons which can be accelerated without any collisional losses.

The electron beam penetrating into the cold chromosphere generates the electric field which can be estimated as follows:

$$\frac{\mathcal{E}}{\mathcal{E}_D} = \frac{\eta\, j_B}{m_e\, v_{Te}/(e\tau)} = \frac{n_B\, v_B}{n_e\, v_{Te}} = \frac{n_e\, v_{RC}^{ne}}{n_e\, v_{Te}} = \frac{v_{RC}^{ne}}{v_{Te}}, \quad (5)$$

where v_{RC}^{ne} denotes velocity of return current formed by all background electrons. The relations (4) and (5) show that for sufficiently high return current velocities of all background plasma electrons, i.e. for high energy fluxes of electron beams, a sufficient number of runaway electrons can be generated for the following formation of the (runaway) return current.

We propose that these runaway electrons (and also the backscattered and mirrored beam electrons) are preferentially accelerated in the return current electric field and thus form the return current of high velocity electrons. Their velocities should be above the runaway velocity limit. Their upper velocity limit can be up to the beam velocity, especially for backscattered electrons as shown by Karlický (1993). When these electrons form the return current, which neutralizes the beam current, then the electric field drops down to values keeping the total current more or less close to zero.

Such a hypothetical return current enables the transport of high energy fluxes into the cold chromosphere. Otherwise, these fluxes are suddenly stopped and they strongly heat the uppermost chromospheric layers. In such a case the hydrogen line formation cannot be directly influenced by these electron beams.

On the other hand, if such a hypothetical return current exists then it should influence the collisional rates for chromospheric line and continuum transitions, and possibly could affect the line intensities and polarization (see also Karlický & Hénoux 2002; Hénoux & Karlický 2003). This diagnostic aspect is studied in the following chapter.

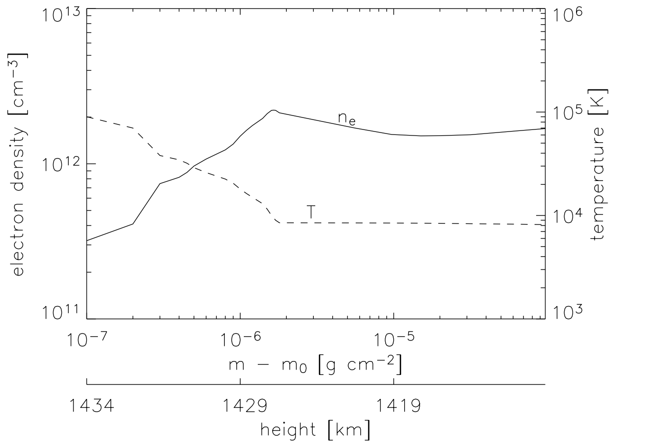

Fig. 1. Temperature T and electron density n_e profiles in the upper part of the F1 solar flare atmosphere.

3. Non-thermal excitation and ionization by Return Current

For our study the F1 model of the flare atmosphere was chosen, which we hereafter refer to as F1 atmosphere (Machado et al. 1980; Avrett et al. 1986). The temperature T and electron density n_e profiles of the upper part of this atmosphere where beams of assumed parameters propagate, are shown in Fig. 1.

We consider a monoenergetic electron beam of velocity v_B and density n_B, the return current will satisfy the flux conservation equation of the form

$$n_B\, v_B = n_{RC}\, v_{RC} = \alpha\, n_e\, v_{RC}, \quad (6)$$

where n_{RC} and v_{RC} are the density and velocity of the return-current electrons, respectively, and α expresses the ratio of densities of return current electrons to those of the background plasma. As can be seen from Fig. 2, the ratio v_{RC}^{ne}/v_{Te} in the F1 chromosphere, for the electron beam flux $F_E = 10^{12}$ erg cm^{-2} s^{-1}, is well above 0.25. Thus according to the relations (4) and (5), the number of runaway electrons is sufficient for a formation of the runaway return current with $\alpha = 0.1$ (10% of all background electrons).

To evaluate non-thermal collisional rates due to return current C_{RC}^{nt} and electron beam C_{B}^{nt}, we use the H I excitation and ionization cross-sections retrieved from the Atomic and Molecular Data Information System (AMDIS)[1]. We are particularly interested in low-energy regions which correspond to monoenergetic return-current energies. An example of cross sections for excitation 2 → 3 (from the atomic level 2 to 3), σ_{23}, and for ionization 1 → c (from the ground atomic level), σ_{1c}, is shown in Fig. 3. Note that the theoretical as well as experimental determination of cross sections is most difficult and thus rather uncertain at low energies, while for high-energy tails one can use the Born approximation (this is the regime of beams themselves).

[1] AMDIS http://www-amdis.iaea.org/

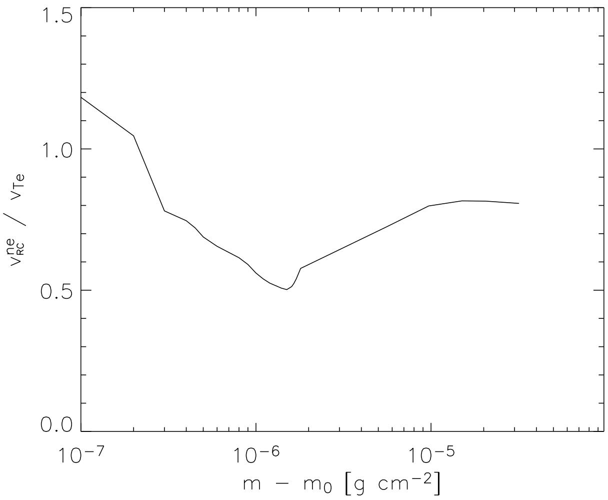

Fig. 2. Ratio of the return current drift (for all background plasma electrons) and thermal plasma velocities in the solar flare atmosphere F1 for a monoenergetic (10 keV) beam with the energy flux F_{E} = 10^{12} erg cm^{-2} s^{-1}. The ending point of the profile corresponds to the stopping depth of the beam.

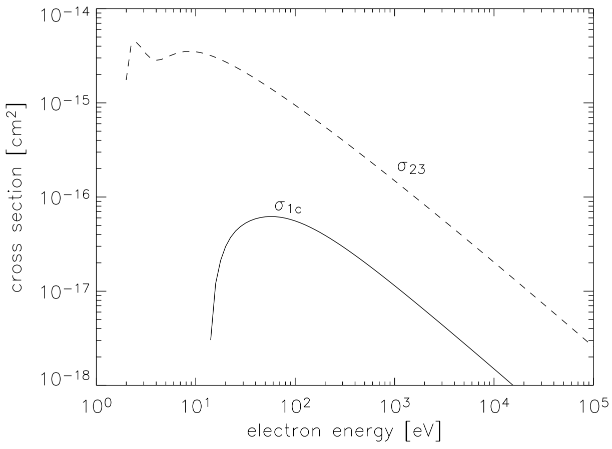

Fig. 3. H I excitation σ_{23} (dashes) and ionization $\sigma_{1\mathrm{c}}$ (solid line) cross sections. Data taken from AMDIS database.

Using these cross sections, we have computed the non-thermal collisional rates for 5-level plus continuum atomic model of hydrogen along the whole trajectory of the beam up to its stopping depth as follows

$$C_{\mathrm{RC}}^{\mathrm{nt}} = \alpha\, n_{\mathrm{e}}\, v_{\mathrm{RC}}\, \sigma_{\mathrm{ij}}(E_{\mathrm{RC}}) \qquad C_{\mathrm{B}}^{\mathrm{nt}} = n_{\mathrm{B}}\, v_{\mathrm{B}}\, \sigma_{\mathrm{ij}}(E_{\mathrm{B}}). \quad (7)$$

E_{RC} denotes energy of return current electrons which is according to Eq. (6) equal to

$$E_{\mathrm{RC}} = \frac{1}{2} m_{\mathrm{e}}\, v_{\mathrm{RC}}^2 = \frac{1}{2} m_{\mathrm{e}} \left(\frac{n_{\mathrm{B}} v_{\mathrm{B}}}{\alpha n_{\mathrm{e}}} \right)^2 . \quad (8)$$

We considered here only the effect of a mean value of the return current velocity, we neglected here the velocity distribution of electrons in the return current. Energy of beam electrons E_{B} along the beam trajectory is evaluated using the relations derived by Emslie (1978). The formulae of Fang et al. (1993) for non-thermal beam rates $C_{\mathrm{B}}^{\mathrm{nt}}$ are not used here, rather we compute these rates in the same way as the return-current ones. This makes their mutual comparison more consistent. Further, we assume that all background plasma electrons have the Maxwellian velocity distribution $f_{\mathrm{T}}(v)$ leading to classical thermal collisional rates

$$C = n_{\mathrm{e}} \int_{v_0}^{\infty} \sigma(v) v f_{\mathrm{T}}(v) \mathrm{d}v, \quad (9)$$

where we have also used the cross-sections from the AMDIS database. The depth variations of 4 chosen collisional rates representing their general behaviour are show in Fig. 4.

4. Discussion

We showed here a role of the return-current in transport of electron beams with high energy fluxes to a relatively cold chromosphere. It looks that the only way how to transport them is through a formation of the return current having electron velocities well above the thermal velocity of the chromospheric plasma. If this is the case then such a return current affects excitations and ionizations of hydrogen. The computations indicate that these non-thermal collisional rates may be important and may outweigh other collisonal rates at some depths of the flare atmosphere. In particular, the non-thermal return current rates dominate both thermal and non-thermal beam rates for the transitions from the first (ground) level almost along the whole trajectory of the beam. As regards the higher levels, only collisional rates from the second level and collisional ionisation of the third level could be influenced by the return current, other transitions are unaffected. The non-thermal beam rates are found to be negligible for all transitions from excited levels. These results are promising for a potential diagnostics of the return current formed by superthermal electrons.

In order to calculate an influence of the return-current collisional rates on spectral line intensities, one has to solve the full non-LTE transfer problem for a given flare atmosphere and this is out of scope of this letter. However, one can make an approximate estimate of the expected diagnostics potential. As an example we can consider the Balmer line Hα and the resonance Lyman line Lα within a three-level model atom. If we can demonstrate that the spontaneous emission in these lines dominates the collisional de-excitations, we can roughly say that the emissivity in Lα and Hα will be roughly proportional to the rates of collisional excitations shown in Fig. 4. For this we have computed all collisional de-excitation rates, using the formulae given in Jefferies (1968) which apply for non-thermal (beam and return current) processes. In Lα, the total de-excitation rate by collisions is around 10^4 s^{-1} for the F1 atmosphere, while $A_{21} = 4.7 \times 10^8$ s^{-1}. For the Hα line being the subordinate line the situation is more complex, but the collisional depopulation rate is still well below the spontaneous rate $A_{32} = 4.41 \times 10^7$ s^{-1} (note that from the 3rd level also the Lβ arises and with $A_{31} = 5.58 \times 10^7$ s^{-1} it will behave similarly as Hα). Therefore, if we see that the levels 2 and 3 are populated at certain depths much more by the return current than by beam or thermal electrons, then the emissivity at those depths should be also accordingly higher. This is further supported by two other results: (i) in Kašparová & Heinzel (2002), when beams are enough strong they also dominate the

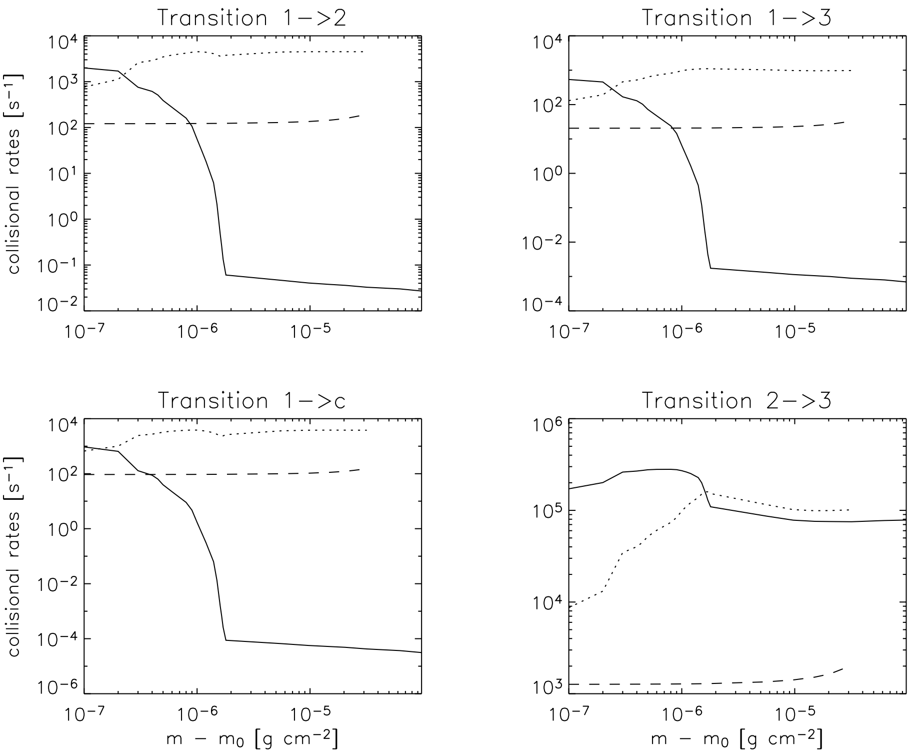

Fig. 4. Comparison of non-thermal collisional return current rates $C^{\rm nt}_{\rm RC}$ (dots), beam rates $C^{\rm nt}_{\rm B}$ (dashes), and thermal collisional rates C (solid line) for transitions $1 \rightarrow 2$, $1 \rightarrow 3$, $1 \rightarrow c$, and $2 \rightarrow 3$ in the case of a monoenergetic electron beam of energy 10 keV and flux 10^{12} erg cm^{-2} s^{-1}. Temperature and electron density structure is that of model F1 (see Fig. 1).

Hα emission (mainly in the wings), and (ii) Hénoux & Karlický (2003) have shown how the return current collisonal excitation leads to proportional production of linearly-polarized Hα photons. In summary, we expect that the return current collisional excitation will significantly enhance the line radiation and we plan to make quantitative non-LTE calculations in a next paper.

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