Proton versus electron heating in solar flares

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Abstract

Proton and electron heating of a flaring atmosphere is compared in a kinetic approach for the particles ejected from a non-neutral reconnecting current sheet (RCS) located above the top of reconnected flaring loops in a two-ribbon flare. Two kinds of high-energy particles are considered: particles accelerated by a super-Dreicer electric field and those ejected from the reconnection region as neutral outflows, or separatrix jets. The beam electrons are assumed to deposit their energy in Coulomb collisions and Ohmic heating of the ambient plasma particles by the electric field induced by the precipitating beams. The protons are assumed to deposit their energy in generation of kinetic Alfvén waves (KAWs), which, in turn, dissipate due to Cherenkov resonant scattering on the ambient plasma electrons. The beam electrons are found to provide a fast (within a few tenth of a second) heating of the atmosphere that is well spread in depth from the corona to the lower chromosphere. The protons are shown to precipitate to the lower atmosphere much slower (up to few seconds for beam and up to 10–20 s for slow jets). Slow jet protons provide heating of the two compact regions: the first located at the top of a flaring loop just below the RCS, and the second one appearing at the transition region (TR) and upper chromosphere; fast beam protons deposit their energy in the TR and chromosphere only.

Keywords: Solar flares-particle beams; Sun; Flares; Particle acceleration; Proton kinetics; Electron kinetics; Atmosphere heating

1. Introduction

The hard X-ray observations of solar flares revealed high-temperature sources located above the top of the flaring loop in addition to two or more footpoint sources (Masuda et al., 1995; Somov and Kosugi, 1997; Lin et al., 2003). These sources indicate that the primary magnetic reconnection energy release occurs above this site in the corona (see Somov and Kosugi, 1997; Priest and Forbes, 2002; Somov et al., 2002). The electrons accelerated to high energies either by super-Dreicer electric field or by stochastic acceleration on plasma waves or shocks are assumed to carry this energy to deeper atmospheric levels. The accepted thick target models of energy transport (Syrovatskii and Shmeleva, 1972; Brown, 1973) suggest that electron beams and plasma waves are the most important energy transport mechanisms that provide prompt heating of the atmosphere and its resulting microwave (MW), hard and soft X-ray (HXR and SXR) emission often observed in solar flares (Benz et al., 1994; Masuda et al., 1995; Benz, 2002).

However, the estimations of the overall energy budget of HXR emission show that a pure electron beam does not contain energy enough to provide all the observed flare signatures (i.e. radiation, shock waves or CMEs) (see e.g., McClymont and Canfield, 1984; Emslie et al., 1996). On the other hand, the observations of γ-ray line intensities indicate that the energy carried by accelerated protons can be significantly higher than those of the accelerated electrons (Share and Murphy, 1995; Ramaty et al., 1995). High energy protons are also...
shown to deliver to lower atmospheric layers much higher (up to 80%) energy conserved in the HXR flux in the assumption that this proton energy is converted into the energy of the ambient plasma electrons, which are dragged electrostatically by protons and produce the observed HXR (Karlicky et al., 2000). Although the signatures of proton precipitation are rather difficult to detect directly unless they are accelerated to very high energies producing γ-rays (Share and Murphy, 1995; Vilmer et al., 2003).

In addition, a local helioseismic response associated with the solar flare (a ‘solar quake’) (Kosovichev and Zharkova, 1998) revealed some additional constraints on the timing and energy balance from this response in the photosphere. For instance, the onset time of the ‘quake ripples’ does not show a delay of a few minutes expected from a travel time towards the photosphere of the shock developed as a hydrodynamic response to the beam electron injection used in the interpretation of 1 min cadence dopplergrams. Also it was found that neither the shock nor the electron beam itself carry the momentum flux sufficient for generation of the observed helioseismic response (Kosovichev and Zharkova, 1998; Zharkova and Kosovichev, 2002). Hence, it is logical to assume that there are some alternative sources delivering such a momentum to the photosphere within a very short (under 1 min) timescale that can be proton or neutralised beams.

For the estimation of energy and momentum fluxes carried by protons and electrons and their heating effects, one needs to revise the scenarios, in which the energy is delivered to the lower atmosphere. This can be a very challenging task keeping in mind a variety of different proposed mechanisms of particle acceleration in an reconnecting current sheet (RCS) (see e.g., Benz, 2002). However, since magnetic reconnection is well accepted to be a source of flaring energy (Somov, 2000; Priest and Forbes, 2002), so we can consider an RCS as a primary acceleration point generating high energy electron and proton beams (Martens and Young, 1990; Litvinenko et al., 1993; Zharkova and Gordovskyy, 2004), and fast outflows of neutral plasma in separatrix jets (Priest, 1990; Strachan and Priest, 1994; Voitenko, 1998; Voitenko and Goossens, 2002). The recent results on the full or partial separation of these high energy protons and electrons at ejection from the RCS (Zharkova and Gordovskyy, 2004) allowed to suggest a dependence of proton and electron precipitation on the magnetic field topology in a reconnecting region.

In order to simplify the problem, we assume that both types of particles, beams and neutral jets, are injected from an RCS into a flaring atmosphere and not further accelerated by waves or shocks. These particles then precipitate downwards to the photosphere and heat a flaring atmosphere. Since accelerated protons and electrons will either belong to beams or to neutral jets we consider separately their precipitation and the effect on the atmosphere taking into account either particle–particle (electrons) or wave–particle (protons) interactions with the ambient plasma.

Electron beam precipitation was intensively investigated in a kinetic approach that resulted in rather detailed models of electron precipitation in Coulomb collisions (Syrovatskii and Shmeleva, 1972; Brown, 1973), plus a converging magnetic field and the induced electric field (see Zharkova and Gordovskyy, 2005b, and references therein). The kinetic approach applied to electron beam precipitation in collisions with the ambient plasma particles (ions, electrons and neutral) with anisotropic scattering with either deceleration or acceleration of precipitating electrons by the self-induced electric field followed by the Ohmic heating of the ambient plasma electrons explains rather well a broken power law of the resulting HXR spectra (Zharkova and Gordovskyy, 2005b). This approach can be also used for the calculations of the atmosphere heating by beam electrons.

Heating of flaring atmospheres by proton beams was investigated in pure collisional approach in a number of papers which concluded that these beams deposit too little energy to account for observed radiative signatures (see e.g., Emslie and Brown, 1985; Tamres et al., 1986). However, proton beams are also shown to be subject to wave–particle interaction with the ambient plasma due to the possible generation of kinetic alfven waves (KAWs, hereafter) (Voitenko, 1996). KAWs, in turn, can cause plasma heating owing to Cherenkov resonant scattering on ambient plasma electrons (Voitenko and Goossens, 2000). This can be another efficient mechanism of proton energy losses in addition to Coulomb collisions.

A description of the RCS model with the two types of accelerated particles (beams and neutral jets) is presented in Section 2. Particle acceleration in an RCS by electric field and as separatrix jets is considered in Section 2.1 and the electron and proton precipitation models are presented in Section 2.2. Results are discussed in Section 3 with the RCS adopted parameters summarised in Section 3.1. Both types of particle distributions presented in Section 3.3 and their timescales compared in Section 3.4. The conclusions are drawn in Section 4.

2. Description of the model

2.1. The particle acceleration model

2.1.1. The model reconnecting current sheet

We adopt a model RCS located above the top of the loop arcade in a two-ribbon flare. For simplicity, let us consider a 2D vertical slice of this arcade (Fig. 1(a)) with a reconnection occurring in the 2D RCS based on a Petschek-type model (see e.g., Priest and Forbes, 2002)
The considered model RCS consists of two regions: the inner region, where the electric current is not zero and where the magnetic diffusion occurs and the outer region without electric current, where slow outflow shocks appear.

The particles of the ambient coronal plasma passing through the inner region are assumed to be accelerated by a super-Dreicer electric field (Zharkova and Gordovskyy, 2004, 2005a) and the bulk of particles in the outer region are ejected as a neutral plasma outflows, or separatrix jets (Strachan and Priest, 1994). Hence, there are the four kinds of accelerated particles injected into a flaring loop from the reconnection region: protons and electrons accelerated by super-Dreicer field ('fast' particles) and protons and electrons accelerated as separatrix jets ('slow' particles).

After ejection from the RCS particles are assumed to precipitate downward to the footpoints (FP) in the photosphere while losing their energy in particle–particle or wave–particle interaction with the ambient plasma. We evaluate the energy deposited by these particles into the ambient plasma and the momentum fluxes carried by protons and electrons to the bottom of the considered 2D vertical slice.

2.1.2. Particle acceleration by a super-Dreicer electric field

We use the simulations of the acceleration by electric field in a 2D model of RCS with a non-zero longitudinal component of magnetic field parallel to a separator ('guiding field' thereafter) (Zharkova and Gordovskyy, 2004). According to these results, the accelerated protons and electrons are ejected from the RCS separately into the opposite loop-legs. The energy spectra of accelerated particles (Zharkova and Gordovskyy, 2005a) are found to be a power-law at the energies higher than a lower energy cut-off, which is about ~1 keV for electrons and ~8–12 keV for protons. The indices of energy spectra were found to be 1.5–1.8 for protons and 1.8–2.2 for electrons.

2.1.3. Particle acceleration as separatrix jets

The existence of fast neutral plasma outflows near the slow MHD shocks in the Petschek-like reconnection was suggested by Priest (1990) and Strachan and Priest (1994). The main difference between the classical outflow and separatrix jets is that separatrix jets are ejected within a small angle to the magnetic field lines, while the classical outflow is assumed to be perpendicular to them. Hence, in the collisionless reconnection model of a hot current sheet, the separatrix jets are the plasma (and heat) outflows along the field lines.

The energy spectra of jet particles have Maxwellian dispersion with the maxima at \( \frac{1}{2}m_p V_{sj}^2 \), shifted to the separatrix jet velocity \( V_{sj} \). Since the latter is much higher (\( \sim V_A = 2 \times 10^6 \text{ cm/s} \)) than the Maxwellian velocity dispersion (\( \sim 10^7 \text{ cm/s} \) for the coronal temperature of \( 10^6 \) K), one can assume that all the separatrix jet particles have the same velocity \( V_{sj} \). This, in turn, allows us to consider the separatrix jets as monoenergetic electron and proton flows. If the reconnected outflows are super-hot (with the temperature greater than 30–40 MK), then, of course, this assumption is not valid, and the MHD approach is not applicable (see e.g., Somov, 2000).
2.1.4. Estimations of the parameters in an RCS

In order to evaluate the accelerated particle parameters in the adopted reconnection model, let us consider the flux conservation equations for outer (1) and inner (2) regions, the energy conservation equation (3) and the Ampere law equations for inner (4) and outer (5) regions. For consistency this set has to be completed by the expressions for velocities of protons $V_p$ and electrons $V_e$ accelerated by a super-D reconnection field. Although these particles have a wide range of velocity spectra, for the current estimations the average magnitudes (at lower energy cutoffs) can be taken as per formula (6) and (7) (see Zharkova and Gordovskyy, 2004). Hence, the set of equations can be written as follows:

\[ (A - L) V_{in} = (a - l) V_{sj}, \]  
\[ LV_{in} = HV_p, \]  
\[ \frac{B_0^2}{4\pi} AV_{in} = \frac{1}{2} n_0 m_p V_p^3 l + \frac{1}{2} n_0 m_p V_{sj}^3 (a - l), \]  
\[ \frac{B_0}{l} = e n_0 (V_p + V_e), \]  
\[ E_0 = \frac{V_{in}}{c} B_0, \]  
\[ V_p \approx \frac{e c}{B_0} E_0, \]  
\[ V_e \approx \frac{e}{m_e} l B_{lon}. \]

Here $B_0$, $B_t$, and $B_{lon}$ the tangential (changing the sign), transversal and longitudinal (guiding) magnetic field components, respectively, $E_0$ is the electric field in the inner region, $A$ is the length of the outer region, $n_0$ is the plasma density, $V_{in}$ is the inflow velocity. These values are assumed to be taken from the reconnection models (see Section 3.1). Hence, the solution of this set provides us with the electric field $E_0$, thickness $l$ and width $L$ of the inner region, the thickness $a$ of the outer region and the velocity $V_{sj}$ (separatrix jet velocity) of the neutral plasma outflow, respectively.

2.1.5. Energy fluxes

Using these estimations one can evaluate the energy fluxes carried by the electron and proton beams at the ejection from the RCS assuming that all the ejected particles are distributed uniformly in the loop cross-section in Fig. 1(a). Then, the energy flux carried by the accelerated particles in a flux-tube is described by formula:

\[ F_{p/e} = \frac{m}{2} V_{p/e}^3 n_{p/e} \approx \frac{m}{2} \frac{V_{p/e}^2 V_{p/e} n_{p/e}}{e} = \frac{m}{2} \frac{V_{p/e}^2 V_{in} n_0 L}{d}, \]

where $d$ is a thickness of the 2D slice (see Fig. 1(a)) where the beam precipitates. By the model definition, its size is much smaller than the loop leg thickness, since only a small part of the magnetic field lines enters the reconnection region at each given time.

The similar estimations can be made for the separatrix jet particles by substituting the outer region size $A$ instead of $L$ and the jet outflow velocity $V_{sj}$ instead of $V_{el/p}$.

2.1.6. Momentums carried by the particles

The momentum flux carried by any beam can be calculated from its distribution function as follows:

\[ M(x) = 2K \int f(x, E) E dE. \]  

The distribution function is normalised on the beam density $N(x)$ at given depth $x$ as follows:

\[ N(x) = K \int f(x, E) dE, \]

where $K$ is the scaling factor (see Section 2.5 in Zharkova and Gordovskyy, 2005b).

2.2. Proton and electron precipitation model

2.2.1. Electron kinetics in a flaring loop

During their precipitation electrons are assumed to lose energy in Coulomb collisions with the particles of the ambient plasma and in Ohmic heating of the ambient plasma electrons by the self-induced electric field. The effect of the latter is double-folded and includes a deceleration of the precipitating electrons, which are scattered in collisions into positive pitch angles, and acceleration of the ambient plasma electrons and the precipitating electrons that are scattered into the negative pitch angles.

Hence, the kinetics of electron beams in a flaring loop can be considered in the terms of Fokker–Planck kinetic equation (see e.g., Somov, 2000) taking into account the effects above of the induced electric field and anisotropic pitch angle scattering (Zharkova and Gordovskyy, 2005b) that naturally explains the broken power law HXR photon spectra often observed in solar flares. The same kinetic simulations are applied to calculate the flaring atmosphere heating by precipitating electrons with their parameters obtained from the accepted acceleration model (Section 2.1.2).

2.3. Proton kinetics in a flaring loop

The main channel of the proton energy losses in a flaring loop is assumed to be the excitation of proton beam-driven KAWs (Voitenko, 1996, 1998). The advantage of the KAWs is that their instability has lower thresholds than other plasma wave modes and they deposit their energy into the ambient plasma due to Landau or collisional electron damping within a short timescale.

The KAWs can be excited if some part of the proton beam velocity spectra meets the following conditions:
\[ \frac{df}{dV}_{F_s V_A} > 0, \]  
(10)

i.e. if there is a positive inclination of the spectra at velocities greater than the local Alfvén velocity. Using this simple condition one can calculate proton beam spectra for every depth at the flaring loop assuming that the KAWs excitation leads to flattening of the velocity spectra with positive slopes with respect to the condition of a proton flux conservation.

The generated KAWs effectively interact with ambient plasma owing to the Cherenkov resonance with thermal electrons. This results in the relaxation of KAWs and in the subsequent ambient plasma heating (Voitenko, 1998; Voitenko and Goossens, 2000). The heating rate can be deduced from the proton beam energy spectra as the gradient of a beam energy flux.

3. Results and discussion

3.1. Estimated parameters of the acceleration model

The parameters of the reconnection region as well as the average velocities of accelerated particles are estimated from a solution of the set of Eqs. (1)–(7).

Assuming that the magnetic field components are \( B_0 = 100 \) G, \( B_{tr} = 1 \) G, \( B_{bon} = 1 \) G, the width of the outer region is \( A = 10^7 \) cm, the density and velocity of the inflowing plasma are \( n_0 = 10^9 \) cm\(^{-3}\) and \( V_{in} = 10^7 \) cm/s, respectively, the sought values are as follows: the electric field is \( E_0 = 10 \) V/cm, the average velocities of protons and electrons accelerated by super-Dreicer field are \( V_p = 3 \times 10^6 \) cm/s (\( \approx 5 V_A \)), \( V_e \approx 10^{10} \) cm/s (\( \approx 17V_A \)), respectively, the width and thickness of the diffusion region are \( L = 6 \times 10^6 \) cm and \( l \approx 3 \times 10^2 \) cm, respectively. The thickness of the outer region is \( a = 1.5 \times 10^5 \) cm, and the separatrix jet velocity is \( V_{sj} \approx 8 \times 10^8 \) cm/s (\( \approx 1.3V_A \)).

3.2. Estimated energy and momentum fluxes

Let us evaluate the energy and momentum fluxes carried by each kind of particle species using the Eqs. (8),(9) (Sections 2.1.5 and 2.1.6) and the estimations made in Section 3.1. For this purpose one needs to have a thickness \( d \) of elementary flux-tube, where the particles precipitate. There are two regions: the inner one (size \( L \times l \)) where ‘fast’ protons are accelerated and the outer one (size \( A \times a \)) where ‘slow’ protons are accelerated. For the sake of simplicity, let us assume that particles accelerated in the inner region precipitate in the fluxtube with thickness \( l \), while particles accelerated in the outer region precipitate in the fluxtube with thickness \( a \). Then the particle densities, energy and fluxes calculated for the considered kinds of particles are shown in Table 1.

It can be seen that the energy flux (\( \approx 4 \times 10^{14} \) erg/cm\(^2\)/s) is carried by the separatrix jet protons (‘slow protons’ hereafter). At the same time, the protons accelerated by electric field (or ‘fast protons’) carry the energy flux of \( \approx 2.3 \times 10^{13} \) erg/cm\(^2\)/s being 60 times higher than for the slow protons. Then for a flare area of \( 10^{17} \) cm\(^2\) (for ‘fast’ particles) and \( 5 \times 10^{19} \) cm\(^{-2}\) (for ‘slow’ particles) gives a power of \( \approx 10^{31} \) erg/s and for a flare duration of 10 s gives a total energy deposited by these protons up to \( 10^{32} \) erg. This is comparable with the energy of a moderate flare.

The electrons accelerated by electric field (‘fast electrons’) carry much less energy than protons (\( F_e \approx 2 \times 10^{14} \) erg/cm\(^2\)/s at area of \( 10^{17} \) cm\(^2\)) that results in the deposited energy of about \( 10^{29} \) erg. However, this kind of particles is important because of its high (sub-relativistic) propagation velocity. Finally, electrons of the separatrix jets (or ‘slow electrons’) have very low velocities, thus, carry a very small energy flux and can be simply neglected. Hence, only three kinds of high-energy particles will be considered for the atmosphere heating: ‘fast’ electrons, ‘fast’ and ‘slow’ protons.

The momentum flux \( M(x) \) from a reconnection region is carried mainly by protons (both ‘fast’ and ‘slow’ ones) (see Table 1). The ‘fast’ protons accelerated by a super-Dreicer electric field carry the momentum flux of \( \approx 1.5 \times 10^9 \) g/cm/s\(^2\) into the area of \( 10^{17} \) cm\(^2\), while the separatrix jet protons carry about \( 1 \times 10^3 \) g/cm/s\(^2\) into the area of \( 5 \times 10^{17} \) cm\(^2\). Hence, for the flare duration 10 s, the ‘fast’ protons that precipitate into a small flaring area deliver to the photosphere the momentum of about \( 10^{22} \) g/cm/s. The ‘slow’ protons precipitate into the area by factor 500 larger than the ‘fast protons’ and deliver a momentum about \( 5 \times 10^{23} \) g/cm/s. These estimation can be considered as a lower limit of the momenta carried by protons since their ejection time can be longer than the 10 s accepted.

Hence, the estimated momentum carried by ‘slow’ protons is about \( \approx 5 \times 10^{23} \) g/cm/s and by ‘fast’ protons is about \( \approx 10^{22} \) g/cm/s that is in a reasonable agreement with the magnitude reported from the helioseismic response (Kosovichev and Zharkova, 1998). These proton beams can be good candidates for the interpretation of the energy and temporal constraints induced by the ‘solar quake’.

At the same time the total energy carried by considered populations of accelerated particles appears to be

<table>
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<th>Table 1</th>
<th>The energy and momentum fluxes carried by ‘slow’ and ‘fast’ components of the proton and electron beams</th>
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<td></td>
<td>‘Fast beam’</td>
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<td></td>
<td>Electrons</td>
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<tr>
<td>Energy flux, erg/cm(^2)/s</td>
<td>( 1.8 \times 10^{11} )</td>
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<td>Momentum flux, g/cm/s(^2)</td>
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about $10^{30}$–$10^{31}$ erg, that corresponds to the energy of moderate flare.

Therefore, both kinds of protons can bring a substantial momentum to the lower atmosphere unlike the electrons that lose their energy almost completely at the lower chromosphere level.

### 3.3. The distribution functions

For the three kinds of beams considered distribution functions are calculated from the injection site (at $3 \times 10^{17}$ cm$^{-2}$ in the column density scale or at 35 Mm in a linear height scale) to the photosphere ($4 \times 10^{23}$ cm$^{-2}$ or 0.5 Mm).

#### 3.3.1. The electron beam distribution function

The precipitation of an electron beam ejected from an RCS with the initial power law energy distribution with spectral index $\gamma = 2.1$ and initial energy flux $1.5 \times 10^6$ erg/cm$^2$/s (see Zharkova and Gordovskyy (2005a) and Section 3.2) was simulated using the approach by Zharkova and Gordovskyy (2005b) (see Section 2.2.1).

With beam precipitation into deeper layers the electron energy spectrum becomes harder and its lower energy cut-off shifts to lower energies due to energy losses. In addition, the beam loses its directivity owing to pitch-angle diffusion. The beam almost disappears at the photospheric depth corresponding to the column density about $3 \times 10^{22}$ cm$^{-2}$.

#### 3.3.2. The proton distribution functions

##### 3.3.2.1. ‘Slow’ protons of separatrix jets. As it was discussed in Section 2.1.3, the initial spectrum of the ‘slow’ protons can be simplified to nearly a monoenergetic one. This monoenergetic jet of protons with velocity higher than the local Alfvén velocity relaxes on the ambient plasma parameters and is about $10^7$–$10^8$ cm for the plasma conditions in the corona.

The velocity $V_A$ depends on the ambient plasma parameters and is about $10^7$–$10^8$ cm for the plasma conditions in the corona.

Hence, at the depth $x$ the slow proton distribution function can be defined as follows:

$$f_s(V_A(x), V) = \frac{2n_s V_{sj}}{V^2_{sj} - V^2_A} \left[ \theta(V - V_A) - \theta(V - V_{sj}) \right],$$

where $n_s$ is the initial particle density in a separatrix jet.

There are the two regions where ‘slow’ proton beams reveal fast changes of the distribution function with depth: just below the reconnection site where the velocities of ejected ‘slow’ protons $V_{sj}$ are higher than the local Alfvén velocity $V_A$ and in the TR and chromosphere owing to a fast decrease of the local Alfvén velocity with the increasing density.

##### 3.3.2.2. ‘Fast’ protons accelerated by super-Dreicer field. The initial energy spectrum of ‘fast’ protons is power law with the spectral index of 1.5 (Zharkova and Gordovskyy, 2005a) (see Section 2.1.2) and the initial beam energy flux is $\sim 10^{13}$ erg/cm$^2$/s (Section 3.2). The numerical calculations show that at all depths the proton beam distribution function $F$ can be described in two parts: the constant one $F(V) = \text{const}$ between $V_A$ and some $V_{cr}(x)$, and the power-law one at $V V_{cr}$ (Fig. 2).

The velocity $V_{cr}$ that separates the ‘flattened’ part of the spectra from the power-law one is equal to the lower energy cut-off at the injection point and it gradually increases with the decrease with depth of the local Alfvén velocity. It can be seen, that the distribution functions of a ‘fast’ proton beam remains constant in the corona, but changes rapidly in the TR and chromosphere resembling those for the ‘slow’ protons.

### 3.4. Depth distributions of the heating rate

A heating function (heating rate) $S(x)$ is defined as the energy deposition per unit volume per unit time and it can be derived as a depth gradient of the beam energy flux as follows:

$$S(x) = -\frac{dF(x)}{dx},$$

where the energy flux can be calculated from the distribution function $f(x, E)$:

$$F(x) = \sqrt{\frac{2}{m}} K \int f(x, E) E^{1.5} \, dE.$$
3.4.1. Heating by electrons

The electron heating function (Fig. 3) was deduced using the distribution functions above (see Section 3.3.1). Electrons are seen to deposit their energy nearly uniformly through the whole atmosphere depth from the reconnection site to the chromosphere. The maximum heating rate of about $10^{-1}$ erg/cm$^3$/s appears at the height of about 20 Mm in the upper layers of the corona.

3.4.2. Heating by protons

3.4.2.1. ‘Slow’ protons near the reconnection site. In the case of heating by KAWs, the heating function can be expressed as a derivative of the KAWs energy flux:

$$S_1(x,t) = -\frac{\partial F_{\text{W}}(x,t)}{\partial x}.$$ 

For a quasi-steady regime one can use the following expression:

$$S_1(x) = \frac{F_{\text{W}0}}{l_{rx}} \exp\left(-\frac{x}{l_{rx}}\right). \quad (12)$$

Here $F_{\text{W}0}$ is the initial energy flux of ‘slow’ protons, $l_{rx} \approx 10^5-10^6$ cm is the KAWs dissipation distance (Voitenko, 1998).

3.4.2.2. ‘Slow’ protons in the TR and chromosphere. The heating function of a ‘slow’ proton beam in TR and chromosphere can be derived from its distribution function as follows:

$$S_2(z) = \frac{\partial P_H(z)}{\partial z} = -\frac{1}{2} n_b m_p V_b V_{A2}(z) \frac{\partial V_{A2}(z)}{\partial z}. \quad (13)$$

The ‘slow’ protons’ energy deposition is calculated using the Alfven velocity profile taken from Nakariakov et al. (2000). The ‘slow’ protons’ energy deposition rate is shown in Fig. 3 (solid line). It can be seen that the heating rate is non-zero only at the height below 5 Mm, where the local Alfven speed decreases.

3.4.2.3. ‘Fast’ protons below the RCS. The heating rates of ‘fast’ protons are calculated from the numerical solution for its distribution function (Fig. 2). At acceleration in an RCS the fast protons gain high energies resulting in velocities much higher than the local Alfven speed (Zharkova and Gordovskyy, 2005a). In the accepted model proton energy distributions are power laws, so they do not have a positive derivative in their spectra. Hence, they cannot generate KAWs during their propagation in the region below the RCS. Although, this can be changed if the pitch-angle distribution of protons at ejection is considered, that is out of the scope of the present research.

3.4.2.4. ‘Fast’ protons in the TR and chromosphere. The ‘fast’ protons with the distributions from Fig. 2 are found to deposit their energy only at the levels where the local Alfven velocity $V_A$ becomes lower than the minimum velocity in the initial ‘fast’ proton spectrum $V_{\text{min}}$, where $E_{\text{low}}$ is a lower energy cut-off of ‘fast’ proton energy spectrum (see Section 3.3.2). Therefore, the ‘fast’ protons heat only the lower atmosphere below the height of 4.5 Mm.

The resulting depth distributions of heating rates for the both ‘fast’ and ‘slow’ proton beams are shown in the Fig. 3. In comparison with the electron heating (see Sec. 3.4.1 and Fig. 3), the heating by protons is very localized in the two compact regions. The magnitude of the protons heating rate is about 10–100 erg/cm$^3$/s.

3.5. The characteristic timescales of particle precipitation

The characteristic timescales of beam propagation throughout a whole atmosphere length of $10^9$ cm are summarized in Table 2. The ‘fast’ electron beam precipitates with the average velocity of $10^{10}$ cm/s ($27 V_A$) (see Section 3.1). Assuming that a loop length is about $10^9$ cm, the characteristic precipitation time for beam electrons is about 0.1 s.

The ‘fast’ protons propagate about five times slower ($5.5 V_A$) (see Section 3.1). For the same loop length the precipitation time for ‘fast’ protons is about 1 s. At the

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<td>The velocities and precipitation timescales of different beam populations</td>
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<tr>
<td>'Fast' electrons</td>
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<td>Velocity, $10^8$ cm/s</td>
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<td>Precipitation time, s</td>
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Fig. 3. Energy deposition function for ‘fast’ electrons and ‘slow’ and ‘fast’ protons. The ‘slow’ proton beam (solid line) is injected with particle velocity of $5 \times 10^8$ cm/s and energy flux of $4 \times 10^{11}$ erg/cm$^2$/s. The ‘fast’ proton beam (dashed line) is injected from the RCS with a power-law spectral index $\gamma = 1.5$ and energy flux $2 \times 10^{12}$ erg/cm$^2$/s. The electrons (dot-dashed line) are injected from the RCS with power-law spectral index $\gamma = 2.1$ and energy flux $2 \times 10^{11}$ erg/cm$^2$/s.
same time, the precipitation timescale for ‘slow’ protons is up to few seconds.

The differences in the precipitation timescales can result in the different times for electron and proton beams to deposit their energy into the precipitating atmospheres. Keeping in mind that the ‘fast’ protons and electrons accelerated in an RCS with a strong longitudinal field can be ejected into the opposite loop legs, this can also lead to the difference in spectral signatures of their emission from different footpoints. Since protons are likely to induce Alfvén waves then the ambient plasma electrons are likely to be accelerated by these waves (Pryadko and Petrosian, 1997) leading to a production of MW and HXR emission from the flaring loop footpoints. However, this emission is to be produced by thermal electrons and with some temporal delay allowed by the proton precipitation and wave generation times while in the electron leg the emission is produced by power law electron beams within a short timescale immediately after their ejection. The quantitative implications of magnetic field topology on the timescale and spectral signatures produced by these beams precipitation will be discussed in a forthcoming paper.

4. Conclusions

In the present paper we considered particle acceleration in a non-neutral RCS occurring above the loop top in the corona and their precipitation downwards to the photosphere. The particles are assumed to be accelerated to high velocities either by a super-Dreicer electric field or as MHD plasma outflows, or separatrix jets. During their precipitation electrons are assumed to lose their energy owing to Coulomb collisions and Ohmic heating of the ambient plasma. Protons are supposed to lose energy in the excitation of kinetic Alfvén waves and the Cherenkov scattering on these waves. The resulting energy deposition as well as energy and momentum fluxes carried by different kinds of particles are evaluated. Basically, there are the three types of heating occurring in a flaring atmosphere:

(a) A comparably weak \((\sim 10^{-1} \text{erg/cm}^{3}/\text{s})\) heating caused by fast electron beams ejected from the RCS. This heating is nearly uniform from the reconnection site in the corona to the column depth of \(\sim 10^{22} \text{cm}^{-2}\) in the photosphere.

(b) A strong heating \((\sim 100 \text{erg/cm}^{2}/\text{s})\) occurring at the top of the loop just below the reconnection site caused by the protons of ‘slow beams’ accelerated as the separatrix jets. This heating occurs as the relaxation of the initially monoenergetic protons to a step-like energy distributions because of these velocities have a positive slope and have magnitudes higher than the local Alfvén ones.

(c) A strong heating of the TR and chromosphere caused by both the ‘fast’ and ‘slow’ protons owing to a sharp decrease of the local Alfvén speed in the TR and chromosphere.

The temporal variations of the atmosphere heating can be also described by the associated features:

(a) The characteristic time of a weak uniform heating caused by the electron beam precipitation is about 0.1 s that is a likely time lag between the start of a reconnection and the appearance of non-thermal HXR and MW emission from the footpoint sources without their further (stochastic) acceleration.

(b) The heating of the region below the reconnection site, starts immediately after the ejection of ‘slow’ proton from an RCS.

(c) The time lag between the start of the reconnection and the heating possibly, observed as a result of the proton precipitation to footpoints in the lower atmosphere is about 1–10 s. In order to observe it, one requires to have the energisation of the ambient plasma electrons, or stochastic acceleration, either by waves or by electrostatic dragging by protons that will again result in thermal SXR/HXR and MW emission in the footpoints.

(d) If an RCS magnetic topology leads to asymmetry in accelerated particle trajectories resulting in the separation of ‘fast’ protons from electrons (see Zharkova and Gordovskyy, 2004), then the plasma heating by protons will appear only in one of the flaring loop footpoints leading to HXR and MW emission produced by the ambient plasma thermal electrons electrostatically dragged by protons.

‘Fast’ and ‘slow’ protons are found to carry the momentum flux of about \(10^{2}–10^{4} \text{g/cm}^{2}/\text{s}^{2}\) just below the RCS and it decreases to \(\sim \times 10^{2} \text{g/cm}^{2}/\text{s}^{2}\) at the lower chromosphere level. Protons can bring a substantial part of their energy to the lower atmosphere, comparable to those observed in the ‘solar quakes’ (Kosovichev and Zharkova, 1998), while the electrons lose their energy almost completely at the lower chromosphere level (see Table 1).

Therefore, similarly to many other results (see e.g., Benz, 2002, and references therein) electron beams within a short timescale deliver their energy nearly evenly to a flaring atmosphere from the corona to chromosphere that can naturally explain fast appearances of HXR and MW emission. At the same time, the precipitation of high-energy proton beams can provide much higher energy deposited either in the region just below a reconnecting current sheet or in the dense chromosphere. This energy is deposited in Alfvén waves that dissipate in Cherenkov’s
resonance scattering causing a substantial plasma heating that can also lead to enhancement of HXR and MW emission. The protons can also account for the observed timing and momentum measured from the helioseismic response associated with the solar flare (Kosovichev and Zharkova, 1998). Taking into account that electrons and protons can be injected into the opposite legs of reconnecting loops (Zharkova and Gordovskyy, 2004) these heating mechanisms can be the keys to the explanation of temporal and spectral differences in HXR and MW emission observed from the opposite footpoints of the same flaring loop. However, further precipitation of fully or partially separated proton and electron beams after ejection from the RCSs with different magnetic field configurations requires further investigation of their neutralisation and stability in a flaring atmosphere that will be considered in the forthcoming paper.

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References