EXCITATION OF ELECTROSTATIC WAVES IN A FLARING PLASMA

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Abstract

Solar flare events release in explosive manner an enormous amount of the stored magnetic field energy (typically 10^{20} J) in the corona. The process of magnetic reconnection is believed to be responsible for this to happen. Soft X-ray images show hot high speed plasma streams that are ejected from the reconnection site. During their propagation through the surrounding coronal plasma, electrostatic fluctuations may arise. Here, we study the conditions for excitation of such electrostatic waves which may later on interact with the electrons and lead to their energization and acceleration.

1 Introduction

During solar flares the stored energy in the magnetic field is suddenly released and transfered into plasma heating, mass motions (e.g. jets and/or coronal mass ejections), energetic particles (electrons, protons, and heavy ions), and electromagnetic radiation (from radio up to γ-rays), see e.g. in Heyvaerts [1981]. If two magnetic field lines with opposite directions come close to each other in the corona, because of their photospheric footpoint motion, a process known as magnetic reconnection takes place. The tension due to the strong curvature of the reconnected magnetic field lines is shooting the plasma away from the reconnection site. This leads to the establishment of (sometimes oppositely directed) jets of hot plasma (see Figure 1).

As already discussed by Yokoyama and Shibata [1995] magnetic reconnection is the most probable mechanism leading to the generation of the solar X-ray jets. For instance, such jets are really seen in soft X-ray images from *Yohkoh*, as presented in Shibata et al. [1994].

Aurass et al. [1994] reported on correlated type III and U radio bursts with plasma jets in the corona by a common analysis of radio and soft X-ray data. Type III and U radio bursts are considered to be the radio signatures of electron beams traveling along open and closed magnetic field lines, respectively (see e.g. Suzuki and Dulk [1985] for

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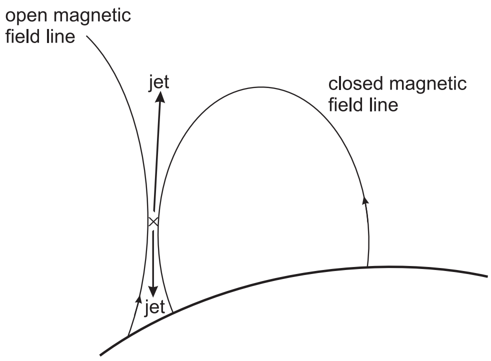

Figure 1: Sketch of the magnetic field configuration possibly leading to formation of jets in the solar corona.

a review). Thus, it was noticed for the first time that accelerated electrons originate above a site where a soft X-ray jet was present. A further evidence for the production of nonthermal electrons associated with soft X-ray jets was given by Pick et al. [1994], Kundu et al. [1995] and Raulin et al. [1996]. In general a good association (temporal and spatial) was found between metric type III bursts and soft X-ray jets.

The interaction of a hot neutral plasma stream (jet) with the surrounding background plasma is studied here in terms of the multi-fluid approach. This interaction gives rise to the excitation of electrostatic fluctuations and due to these wave-like disturbances electrons can be energized up to relativistic velocities. The multi-fluid equations and the employed normalizations are introduced in Section 2. The linear wave analysis is performed in Section 3. In Section 4 the conditions for excitation of electrostatic fluctuations are presented. The movement of a test electron in an oscillatory electrostatic field is investigated in Section 5. The results are discussed in Section 6.

2 Basic equations

In order to study the interaction of a hot neutral plasma stream (jet) with the surrounding background plasma a multi-fluid approach (Krall and Trivelpiece [1986]) is employed:

$$\frac{\partial N_j}{\partial t} + \nabla \cdot (N_j \mathbf{V}_j) = 0 \tag{1}$$

$$m_j N_j \left(\frac{\partial \mathbf{V}_j}{\partial t} + \mathbf{V}_j \cdot \nabla \mathbf{V}_j \right) = -\nabla p_j + q_j N_j \mathbf{E} \tag{2}$$

$$p_j = p_{j0} \left(\frac{N_j}{N_{j0}} \right)^{\gamma_j} \tag{3}$$

$$\nabla \cdot \mathbf{E} = \frac{1}{\varepsilon_0} \sum q_j N_j \tag{4}$$

with $p_{j0} = N_{j0} k_{\mathrm{B}} T_j$, k_{B}, Boltzmann constant and ε_0, permittivity of vacuum. Here, all kinds of particles j with the charge q_j and mass m_j are considered as different fluids, that interact with each other by the electromagnetic forces. A standard notation has been used for the plasma parameters: N_j is the particle number density, $\mathbf{V}_j$ is the flow velocity, p_j is the pressure, and T_j is the temperature for each kind of particles. The fluid equations are closed by the assumption of an equation of state in terms of an ideal gas for each particle kind, Eq. (3). The parameter ν_j gives the portion of the undisturbed number density N_{j0} of the particle component j to the total one N_0, i.e. $\nu_j = N_{j0}/N_0$. γ_j is the ratio of the specific heats of each kind of particles. Note, that bold typed quantities must be considered as vector-like ones.

All quantities are normalized to the characteristic parameters of the plasma:

$$t' = t/\omega_{\rm pe}^{-1}, \;\; x' = x/\lambda_{\rm De}, \;\; V_j' = V_j/V_{\rm th,e}, \;\; N_j' = N_j/(\nu_j N_0), \;\; Q_j = q_j/e, \;\; \phi = \varphi/\frac{k_{\rm B}T_{\rm e}}{e},$$

($\omega_{\rm pe} = (e^2\, N_0/(\varepsilon_0 m_{\rm e}))^{1/2}$, electron plasma frequency; $\lambda_{\rm De} = V_{\rm th,e}/\omega_{\rm pe}$, Debye length; $V_{\rm th,e}$, thermal electron velocity; e, elementary charge; $T_{\rm e}$, electron temperature). φ denotes the electrostatic potential. Here, all the left sided values are normalized ones. Henceforth, while working only with normalized values, we omit the primes.

Since the plasma stream is considered to move along the magnetic field, the Lorentz force can be neglected as already done in Eq. (2). In addition, only electrostatic fields are considered, so that the Poisson equation is used for describing the field $\mathbf{E}$ in Eq. (4). Furthermore it is justified to reduce the equations only to one spatial dimension (i.e. $\nabla \to \partial/\partial x$), i.e. the lateral extension of the jet is neglected. Finally the set of the basic equations (1) – (4) is reduced to the following dimensionless form:

$$\frac{\partial N_j}{\partial t} + \frac{\partial (N_j V_j)}{\partial x} = 0 \tag{5}$$

$$\frac{\partial V_j}{\partial t} + V_j \frac{\partial V_j}{\partial x} = -\frac{\gamma_j}{\gamma_j - 1} \frac{V_{\rm th,j}^2}{V_{\rm th,e}^2} \frac{\partial N_j^{(\gamma_j-1)}}{\partial x} - Q_j \frac{\mu_{\rm e}}{\mu_j} \frac{\partial \phi}{\partial x} \tag{6}$$

$$\frac{\partial^2 \phi}{\partial x^2} = -\sum Q_j N_j \nu_j \tag{7}$$

with $\mu_j = m_j/m_{\rm p}$ ($m_{\rm p}$, proton mass), and $\mu_{\rm e} = m_{\rm e}/m_{\rm p} = 1/1837$ ($m_{\rm e}$, electron mass). $V_{{\rm th},j} = k_{\rm B}T_j/m_j$ denotes the thermal velocity for each plasma component.

3 Linear wave analysis

In order to perform a linear wave analysis the set of Eqs. (5), (6), and (7) is linearized with respect to the quantities n_j and v_j according to $N_j = N_{j0} + n_j$ and $V_j = V_{j0} + v_j$, and with ϕ being already a perturbed value. Also we assume that all varying quantities are depending on x and t by $\propto \exp[i(kx - \omega t)]$ and $\gamma_j \to 1$ (isothermal case). After some standard procedure we arrive at the general dispersion relation for electrostatic wave propagation in this special plasma configuration

$$k^2 - \sum \frac{\mu_{\rm e}}{\mu_j} \frac{Q_j^2\, \nu_j}{(V_{\rm ph} - V_{j0})^2 - V_{{\rm th},j}^2/V_{\rm th,e}^2} = 0, \tag{8}$$

where the phase velocity is denoted by $V_{\rm ph} = \omega/k$ (ω, frequency and k, wave number).

Both the jet and the background plasma are comprised by electrons and protons, denoted with subscripts e and i, correspondingly. Since we intend to study the interaction of the jet with the background plasma, relation (8) is reduced to a case of a four-component plasma. For the background plasma the following parameters are chosen

$$\begin{aligned} V^{\rm b}_{\rm th,e} &= (k_{\rm B}T^{\rm b}/m_{\rm e})^{1/2}, & V^{\rm b}_{\rm th,i} &= \mu_{\rm e}^{1/2}V^{\rm b}_{\rm th,e} \\ V^{\rm b}_{\rm e0} &= V^{\rm b}_{\rm i0} = 0, & T^{\rm b}_{\rm e} &= T^{\rm b}_{\rm i} = T^{\rm b} \quad \text{and} \\ N^{\rm b}_{\rm e0} &= N^{\rm b}_{\rm i0} = (1-\nu)N_0, \end{aligned}$$

whereas the parameters of the flaring plasma (jet) are given by

$$\begin{aligned} V^{\rm jet}_{\rm th,e} &= \theta^{1/2}V^{\rm b}_{\rm th,e}, & V^{\rm jet}_{\rm th,i} &= (\mu_{\rm e}\theta)^{1/2}V^{\rm b}_{\rm th,e}, \\ V^{\rm jet}_{\rm e0} &= V^{\rm jet}_{\rm i0} = V_0, & T^{\rm jet}_{\rm e} &= T^{\rm jet}_{\rm i} = T^{\rm jet} = \theta T^{\rm b} \quad \text{and} \\ N^{\rm jet}_{\rm e0} &= N^{\rm jet}_{\rm i0} = \nu N_0. \end{aligned}$$

Here, θ denotes the ratio between the jet temperature $T^{\rm jet}$ to the background one $T^{\rm b}$, i.e. $\theta = T^{\rm jet}/T^{\rm b}$. Note, that the temperature of the electrons is assumed to be equal to the temperature of the protons in the background and jet plasmas. With the so-chosen plasma parameters, Eq. (8) for the normalized dispersion relation becomes

$$k^2 - \left[\frac{\mu_{\rm e}(1-\nu)}{V_{\rm ph}^2 - \mu_{\rm e}} + \frac{1-\nu}{V_{\rm ph}^2 - 1} + \frac{\mu_{\rm e}\,\nu}{(V_{\rm ph}-V_0)^2 - \theta\,\mu_{\rm e}} + \frac{\nu}{(V_{\rm ph}-V_0)^2 - \theta}\right] = 0. \qquad (9)$$

Thus, the problem can be described completely by three parameters: ν, θ, and V_0. In general, Eq. (9) can be transformed into a polynomial of the 8-th order leading to eight different modes (roots). The resulting modes are presented in Figures 2 and 3 for $\nu = 0.3$, $\theta = 1.0$, and $V_0 = 0.0518$ as a special choice for illustration.

Figure 2 shows nearly symmetrical distribution of the wave modes, with a slight displacement into the positive area of the $\omega - k$ plane due to the non-zero initial flow velocity. In addition, the low frequency modes (i.e. $\omega \ll 1$) are separately plotted in Figure 3 for the same set of parameters. In this Figure one can see that the two modes coincide for $k < 1.8$ indicating to two complex roots of Eq. (9), i.e. to an instability. Thus, the interaction of the jet with the background plasma gives rise to an electrostatic instability.

4 Electrostatic instability

The properties of the electrostatic instability will depend on the choice of the parameters ν, θ, and V_0. The rough evaluation of Eq. (9) reveals that for $\nu = 0.3$ and $\theta = 1$ instability occurs either for $V_0 > 2.5$ or $0.04 < V_0 < 0.07$. The chosen values for ν, θ and V_0 are in correspondence with the observed jet properties, see Shimojo et al. [1998]. Remind that V_0 is the jet speed normalized to the thermal electron speed, which is greater than 3900 km s^{-1} for typical coronal temperatures $T > 10^6$ K.

Since the speeds of the jets are essentially smaller than 3900 km s^{-1}, as presented in the work of Shimojo [1999], it is only necessary to look for the instability in the case $0.04 < V_0 < 0.07$ for the flow speeds. In general, the growth rate $\gamma = \mathrm{Im}(\omega)$ is depending on the wave number k and the three parameters ν, θ, and V_0. A 3D-plot of the instability region, i.e. $\gamma = \gamma(k, V_0)$ is given for $\nu = 0.3$ and $\theta = 1$ in Figure 4. The instability range is diminishing, i.e. $\gamma \to 0$, for extremely long wavelengths ($k \to 0$). From this overall 3D-plot could be noticed that the region of instability, i.e. $\gamma > 0$, is not restricted with respect to k but is confined within a relatively small jet speed range. For further illustrations, Figures 5 and 6 present some 2-D cuts of Figure 4 in the γ–k and γ–V_0 plane. The solid curve on both figures represents the found maximum value for the growth rate, i.e. $\gamma_{\max} = 0.0024$ is positioned at $k = 1.06$ and $V_0 = 0.0518$.

5 Movement of electrons in oscillatory electrostatic field

In order to study the effect of the oscillatory electrostatic field excited by the presently discussed instability on the electrons, the motion of an electron as a test particle in such a wave field is considered now. Then, the equations of motion are given by

$$\frac{dp}{dt} = -eE = e\frac{\partial \varphi}{\partial x}, \qquad v = \frac{dx}{dt} \tag{10}$$

and in normalized quantities by

$$\frac{1}{\beta_{\mathrm{th}}} \cdot \frac{1}{(1-\beta^2)^{3/2}} \cdot \frac{d\beta}{dt} = \frac{\partial \phi}{\partial x}, \qquad \frac{dx}{dt} = \frac{\beta}{\beta_{\mathrm{th}}} \tag{11}$$

with $p = m_e v/(1-\beta^2)^{1/2}$, $\beta = v/c$, $\beta_{\mathrm{th}} = V_{\mathrm{th,e}}/c$ (v, velocity of the test particle and c, velocity of light). Additionally $\phi = \phi_0\, e^{\gamma t} \cos[k\, x(t) - \omega\, t]$ is adopted for the spatial-temporal behaviour of the electrostatic potential. At the thermal level the amplitude of the electrostatic (ion-acoustic) fluctuations is assumed to be $k_{\mathrm{B}}T$, i.e. $\phi_0 = 1$. The

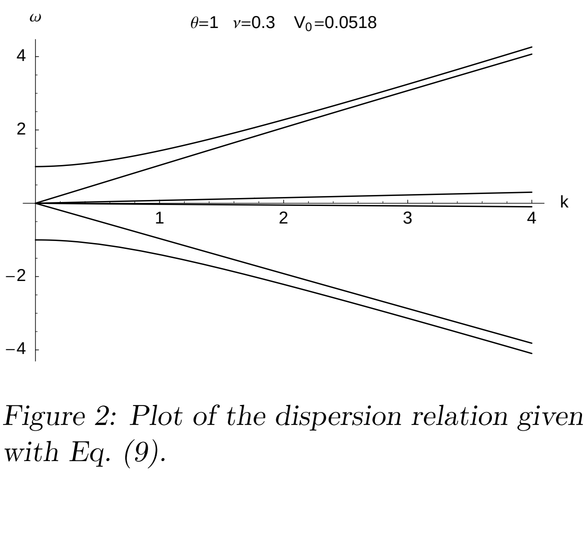

Figure 2: Plot of the dispersion relation given with Eq. (9).

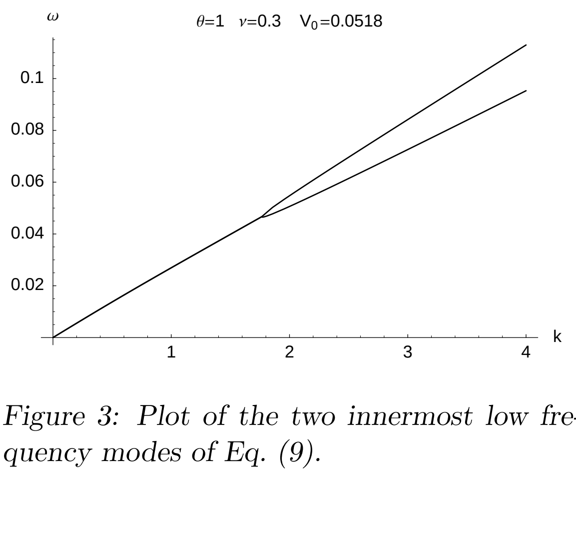

Figure 3: Plot of the two innermost low frequency modes of Eq. (9).

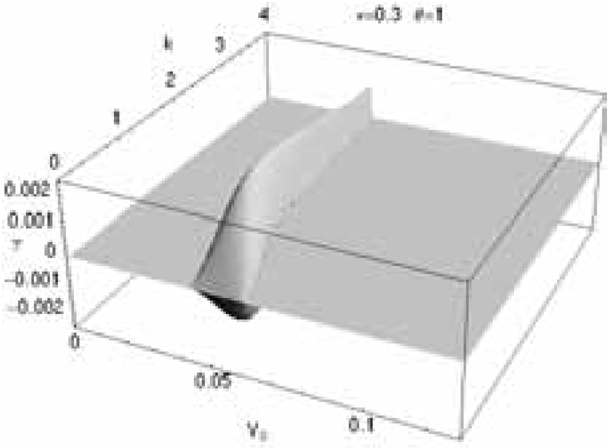

Figure 4: Plot of the 3D instability range, i.e. $\gamma = \gamma(k, V_0)$, for ν = 0.3 and θ = 1.

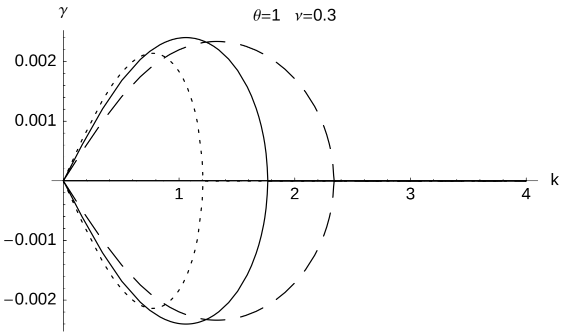

Figure 5: Plot of $\gamma(k)$ for: $V_0 = 0.050$ (dashed curve), $V_0 = 0.0518$ (solid) and $V_0 = 0.055$ (dotted).

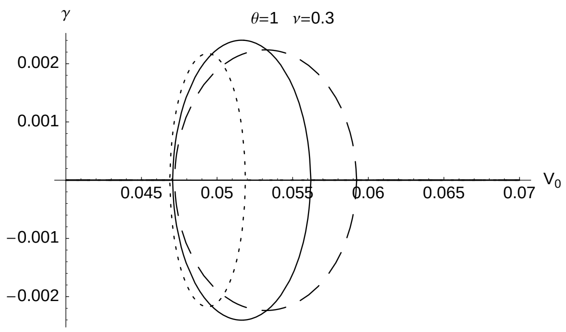

Figure 6: Plot of $\gamma(V_0)$ for: $k = 0.75$ (dashed curve), $k = 1.06$ (solid) and $k = 1.75$ (dotted).

normalized equations of motion are numerically solved for the mode with a maximum growth rate (with $k = 1.06$, $\gamma = 0.0024$, and $\mathrm{Re}(\omega) = 0.0285$), because it is the most dominant one during the appearance of the instability. In order to consider the electron as a test particle, it must be collisionless with respect to Coulomb collisions. This is justified if its initial velocity $v_0 \geq 4V_{\mathrm{th,e}}$ or $\beta_0(= v_0/c) \geq 0.0613$ ($V_{\mathrm{th,e}} = 4600\ \mathrm{km\,s^{-1}}$ for a typical coronal temperature of 1.4×10^6 K), see Estel and Mann (1999). Thus, the initial conditions are $x(t = 0) = 0$ and $\dot{x}(t = 0) = 4$ in the sense of normalized quantities. A zoomed part of the resulted movement in the x–t-plane is presented in Figure 7.

Initially the electron is homogeneously moving with some constant velocity. Since the amplitude of the electrostatic field is increasing with the time, its influence on the particle motion will become essential after the time

$$t = \frac{1}{\gamma} \cdot \ln\left(\frac{W}{k_{\mathrm{B}}T} \cdot \frac{1}{\phi_0}\right), \tag{12}$$

that is reached when the kinetic energy of the particle, $W/(k_{\mathrm{B}}T) = \beta_{\mathrm{th}}^{-2}[(1-\beta^2)^{-1/2} - 1]$, becomes similar to the electrostatic field energy, $\phi_0\, e^{\gamma t}$. Or after $t = 867$ (for $W/(k_{\mathrm{B}}T) = 8$ corresponding to $v_0 = 4V_{\mathrm{th,e}}$), the electrostatic fluctuations lead to a trapping of the electron (regarded as a test particle) within the wave field as seen in Figure 7. During this trapping, the electron is moving with the slowly propagating wave and gains energy, e. g. up to $100\,k_B T$ within a period of $2200/\omega_{pe}$, from the electrostatic wave field (as shown on Figure 8). For a coronal temperature of 1.4×10^6 K, and for $\omega_{pe} = 2\pi\,300$ MHz and $k_B T = 120$ keV, we obtain an energy gain for the electron of 12 keV within a period of 1.26×10^{-6} s. The value of 300 MHz is chosen here for the electron plasma frequency, since radio signatures of flaring processes usually appear around this frequency range.

6 Discussion

During magnetic reconnection, considered to be the basic process of solar flares, jets of hot plasma are ejected from the reconnection site into the surrounding coronal plasma. The interactions of such jets with the background coronal plasma lead to the excitation of electrostatic fluctuations/waves due to an instability if the jet speed is about $0.05\,V_{th,e}$ (i.e. the jet should have a speed of about 230 km s^{-1} for $V_{th,e} = 4600$ km s^{-1}). Such values are typical ones for jets as observed in the soft X-ray images by *Yohkoh* (Shimojo et al. [1998]). If these fluctuations act on supra-thermal electrons, the latter are trapped within the wave (Fig. 7) and gain energy (Fig. 8). Thus, the kinetic energy of the jet is transfered by this instability towards the electrons. This represents a collisionless energization or heating of the electrons, a process that was observed in the hard X-ray emission by *RHESSI* spacecraft during flares. Due to this energy loss of the jet it is slowed down. Since its initial speed (≈ 230 km s^{-1}) is well above the sound speed of 140 km s^{-1} in the corona, this process can lead to the formation of a slow shock, see Priest [1982].

Since the instability only appears in a small range of the jet speed (Fig. 4), the enhanced level of electrostatic fluctuations are localized in a small region in the corona. Consequently, if the energized electrons leave the region of instability, a part of them can escape with a high velocity along a magnetic field line. This could lead to either solar type III or U radio bursts during the propagation of the electrons along open and closed magnetic field lines (Fig. 1). Note, that type III burst electrons have typical velocities of 52 000 km s^{-1} (i. e. 8 keV) [Mann and Klassen, 2002]. Figure 8 shows that an electron can be accelerated up to such energies within a so-exited electrostatic wave field.

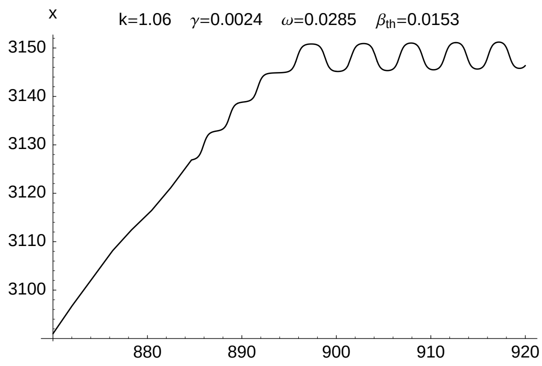

Figure 7: Movement of a test electron.

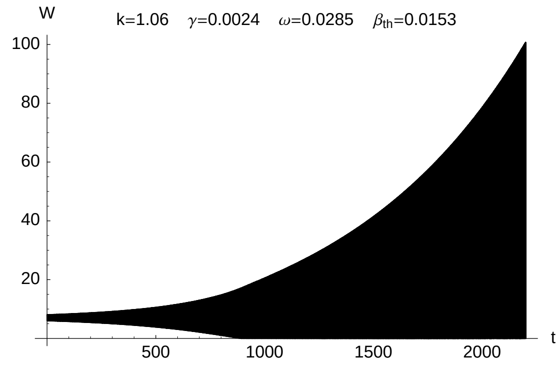

Figure 8: Energy gain of the test electron.

In summary, the interaction of a jet expelled from the reconnection site with the surrounding plasma leads both to collisionless heating (energization) and acceleration of electrons (the exciting agent of type III/U radio bursts) in the solar corona. Of course, the so-energized electrons act back towards its exciter finally leading to a switch off of the instability (see e. g. Muschietti et al. [1995]). But this nonlinear process is beyond the scope of this brief communication.

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