EXPANSION OF HOT PLASMA WITH KAPPA DISTRIBUTION INTO COLD PLASMA

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ABSTRACT

The X-ray emission of coronal flare sources can be explained considering the kappa electron distribution. Motivated by this fact, we study the problem of how hot plasma with the kappa distribution of electrons is confined in these sources. For comparison, we analyze the same problem but with the Maxwellian distribution. We use a 3-D particle-in-cell code, which is large in one direction and thus effectively only one-dimensional, but describing all electromagnetic effects. In the case with the Maxwellian distribution, and in agreement with the previous studies, we show a formation of the double layer at the hot-cold transition region that suppresses the flux of hot electrons from hot plasma into the cold one. In the case with the kappa distribution, contrary to the Maxwellian case, we found that there are several fronts with the double layers in the hot-cold transition region. It is caused by a more extended tail in the kappa case than in the Maxwellian one. The electrons from the extended tail freely escape from the hot plasma into a cold one. They form a beam which generates the return current and also Langmuir turbulence, where at some locations Langmuir waves are accumulated. At these locations owing to the ponderomotive force, Langmuir waves generate density depressions, where the double layers with the thermal fronts, suppressing the hot electron flux, are formed. We also show how protons are accelerated in these processes. Finally, we compared the kappa and Maxwellian cases and discussed how these processes could be observed.

Keywords: Plasmas – Sun: flares – waves – methods: numerical
1. INTRODUCTION

In solar flares, there are very hot plasma sources at some locations, e.g., the loop-top (Kolomazňský & Karlický 2007) or above-loop-top (Masuda et al. 1994; Krucker et al. 2007, 2010) sources that exist for a longer time than the transit time of hot electrons in these sources. We note that the above-loop-top sources can be described as the plasmoids located in the rising magnetic rope (Karlický et al. 2020) or secondary ropes formed in the current sheet below the rising rope by the plasmoid instability (Loureiro et al. 2007; Bárt et al. 2011). In both the loop-top and above-loop-top sources, the hot plasma is naturally confined in the direction perpendicular to the magnetic field lines of the magnetic loop or ropes (loops with the helical magnetic field and electric current). However, the question arises how the hot plasma is trapped in the direction parallel to the magnetic field lines. In the papers by Brown et al. (1979); Arber & Melnikov (2009); Karlický (2015), it was proposed that it could be caused by the so-called thermal conduction front. Such thermal fronts have also been proposed in the interpretation of some observed features in solar flares (Fárník et al. 1983; Rust et al. 1985; Mandrini et al. 1996).

The problem of hot plasma confinement was also studied in the papers by Li et al. (2012, 2013, 2014); Roberg-Clark et al. (2018); Guo (2019); Sun et al. (2019), where the authors, using particle-in-cell (PIC) simulations, presented details of the heat flux suppression at the contact region between hot and cold plasmas. Li et al. (2012, 2013, 2014) showed that at the beginning of the hot plasma expansion into a cold one, the hot electrons, escaping from the hot plasma region, trigger the return current, which is unstable due to the electron-ion streaming (Buneman) instability. During this process, the double layer with the electric potential jump is formed. The double layer grows over time and supports a significant drop in temperature and hence reduces heat flux between the hot and cold regions. Furthermore, Roberg-Clark et al. (2018) studied this process in dependence on the plasma beta parameter. They recognized two regimes of this process: a) the regime with the double layer for low values of the plasma beta parameter, and b) the regime with the whistlers for the high beta parameter. Note that in all these studies, Maxwellian or bi-Maxwellian distributions of particles were considered.

In the paper by Kašparová & Karlický (2009), based on fitting of the X-ray spectra of the coronal flare sources, it was shown that electrons in these sources can be described by the kappa distributions. This finding was confirmed in the paper by Oka et al. (2013); Effenberger et al. (2017); Battaglia et al. (2019). The Kappa distribution in flaring regions is also theoretically supported. Ryu et al. (2007) showed using nonlinear Vlasov and Particle-in-cell simulations that Langmuir turbulence leads to formation of kappa velocity distribution. Yoon (2011, 2012a,b) in the series of papers also analytically calculated that the kappa distribution can be rigorous steady-state solution of the Langmuir turbulence. However, in our case, the flare coronal sources (plasmoids) are transient phenomena, where the distribution is generated by the acceleration processes in the current sheet, where the plasmoids are formed. In the present paper, we try to answer how the hot plasma with the kappa distribution of electrons is confined in these coronal sources.

For these reasons, we study an expansion of the hot plasma with the kappa electron distribution into the cold one. For the hot plasma we consider an isotropic distribution function because no information about a possible anisotropy. We choose ratio between mean speed of hot electrons and thermal velocity of cold ones as $v_{he}/v_{ce} = \sqrt{10}$. Such a study is made, according to our knowledge, for the first time. We use a 3-dimensional electromagnetic particle-in-cell (PIC) code, which is large in one direction and short in other directions. Firstly, for comparison with the previous studies, we analyze the case, where both hot and cold plasmas have the Maxwellian distributions (in the following, we call this case as Maxwell model). Then, we study the case with the hot plasma with the electron kappa distribution expanding into the cold Maxwellian one (Kappa model). Finally, the results of both Kappa and Maxwell model are compared and discussed.

The paper is organized as follows. In Section 2, we describe our numerical PIC model. The results are in Section 3 and discussion and conclusions in Section 4.

2. NUMERICAL MODEL

We use a 3-dimensional electromagnetic PIC code TRISTAN (Buneman & Storey 1985; Matsumoto & Omura 1993; Karlický & Bárt 2008) with multi-core Message Passing Interface (MPI) parallelization in domains. The simulation box in $x$-, $y$- and $z$-directions is $49152\Delta \times 8\Delta \times 8\Delta$, where $\Delta = 1$ is the grid size. Thereby, the simulation is effectively one-dimensional, but describing all electromagnetic effects. The simulation box in $x$-direction is divided into two parts: the “left” part with hot plasma and the “right” part with colder plasma for $x < 0$ and $x > 0$, respectively, where $x = 0$ ($x$ is in units $\Delta$) corresponds to the position of $25000\Delta$ in the numerical box. The length of the “left” part is more than a half of the whole simula-
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In order to study an expansion for a sufficiently long time.

The simulation time step is $\omega_{pe} t = 0.0125$. The electron cyclotron frequency is $\omega_{ce} = 0.1 \omega_{pe}$. The magnetic field is along $x$-direction. We consider the hydrogen (electron-proton) plasma. The initial electron density is the same as the proton density, i.e., $n_0 = 100$. The proton-electron mass ratio is chosen $m_i/m_e = 100$ to speed-up studied processes.

We use the periodic boundary conditions in $y$- and $z$-directions. In the $x$-direction, the mirror boundary conditions are applied. However, at the “right” boundary of the simulation box, the particles that have their velocities five times greater than the thermal speed of the cold plasma are not reflected, but removed. The electrons coming from the hot plasma part that are removed on the right boundary are much less numerous than those in the cold plasma. Although the removing of these electrons does not guarantee charge neutralization on the right boundary, these electrons make only a very localized effect close to the right boundary. They are far away from the space of studied processes. In comparison with simulations with all periodic boundaries, computations with these boundaries extend the effective size of the simulation box with the same computational demands.

In the initial state, the hot plasma is located at positions at $x < 0$ and cold plasma is at $x > 100$. The transition between the hot and cold plasmas is at $x = 100$. The hot plasma consists of electrons with the kappa distribution

$$f_k(v) = \frac{n_0}{2\pi(2\kappa v_{he}^2)^{3/2}} \frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)\Gamma(3/2)} \left(1 + \frac{v^2}{2\kappa v_{he}^2}\right)^{-(\kappa+1)}$$

where $\kappa$ is the spectral index, $\Gamma(x)$ is the Gamma function, $v_{he} = \sqrt{\kappa(\kappa-3)/2} k_B T_{he}/(\kappa m_e)$ is the mean speed of hot electrons, and $k_B$ is the Boltzmann constant. In the simulation, we apply $\kappa = 2$ to emphasize the effects of kappa distribution. We note that the end of tail of the distribution function ($v > 12 v_{he}$) is not fully covered due to the finite number of particles. Effectively, the resulting distribution is more similar to regularized kappa distribution (Scherer et al. 2017) with $\alpha \lesssim 0.08$. Also note, that $\kappa \approx 2$ was observed during the early and impulsive phases of the solar flare (Dziřičáková et al. 2018).

The protons in a hot plasma and electrons and protons in cold plasma have Maxwellian velocity distribution function with corresponding thermal velocities $v_{hi}, v_{ce}$, and $v_{ci}$. The Maxwell velocity distribution function is defined as

$$f_M(v) = \frac{1}{(2\pi v_{\alpha}^2)^{3/2}} e^{-v^2/2v_{\alpha}^2},$$

where $v_{\alpha} = \sqrt{k_B T_{\alpha}/m_\alpha}$ means the thermal velocity of the particle $\alpha$ with mass $m_\alpha$. The ratio of the characteristic velocity of the hot plasma and the thermal velocity of the cold plasma is $v_{he}/v_{ce} = v_{hi}/v_{ci} = \sqrt{10}$. The thermal velocity of the cold component is $v_{ce} = 0.006488 c$, where $c$ is the light speed. That corresponds to the temperature of cold electrons and protons 250 kK, hot protons 2.5 MK and hot electrons 10 MK. These temperatures correspond to those in solar flares. The transition between the hot and cold plasmas is implemented separately for each species. The protons have Maxwellian distribution in both parts. We implemented a linear transition in temperature. The implementation of transition from kappa velocity distribution to Maxwellian is not trivial without generating deformed velocity distribution. We implemented the transition in both characteristic velocity and $\kappa$ index. The square of the velocity $v^2$ is scaling linearly from $v_{he}^2$ to $v_{ci}^2$. The $\kappa$ index is scaling from $\kappa = 2$ to $\kappa = \infty$ (Maxwell distribution). We implemented the linear scaling of its reciprocal value $1/\kappa$ in the interval $1/2 - 1/\infty = 0.5 - 0$. The Debye length $\lambda_c = v_{ce}/\omega_{pe}$ is $0.260 \Delta$ for the cold part. The hot electron Debye length $\lambda_h = v_{he}/\omega_{pe} \sqrt{(2\kappa - 3)/(2\kappa - 1)}$ equals to $0.474 \Delta$. The plasma beta parameter, $\beta = 4(\omega_{pe} v_{hi}/\omega_{ce} c)^2$, is $\beta = 2.1 \times 10^{-3}$ for cold part and $\beta = 2.1 \times 10^{-2}$ for hot part.

The time of presence of hot electrons in our numerical box can be estimated as $2L/v_{tail} \approx 6.6 \times 10^5$ time steps $= 8250 \omega_{pe} t$, where the length of the hot part is $L = 25000 \Delta$. $v_{tail} = 0.15 c$ is the typical speed of the generated electrons in the tail of the distribution function if we take into account that the numerical particle density is limited by a finite number of numerical particles. The factor of 2 corresponds to the propagation of hot tail electrons in the simulation box. One group of hot tail electrons propagates directly to the right direction. Other hot tail electrons have the initial velocity to the left direction, and then they are reflected to the right by the left mirror boundary, thereby also contributing to the electron flux at the hot-cold transition region. On the other hand, our simulations last for $3 \times 10^5$ time steps $= 3750 \omega_{pe} t$. Thus, at the end of our simulations, approximately half of all hot tail electrons still remain in the hot part of the simulation box. If we assume the plasma density at the thermal front in the flare loop as $n_e = 10^{10} \text{ cm}^{-3}$ (Aschwanden & Benz 1997), then the simulation time corresponds to $4.2 \mu s$.

For comparison, we also performed a simulation that has all parameters the same, except it contains hot electrons with Maxwellian velocity distribution. The ratios $v_{he}/v_{ce} = v_{hi}/v_{ci} = \sqrt{10}$ remains same. The hot electron Debye length is $0.82 \Delta$. The simulation with
the kappa distribution of hot particles we designate as “Kappa model”, and the simulation with the Maxwellian distributions only as “Maxwell model”.

3. RESULTS

3.1. Maxwell model

Figure 1 shows an evolution of the electron temperature, electron particle density, and electric potential energy. These quantities are taken along $x$– axis and always averaged in $y$– and $z$– directions. The temperature of species $\alpha$ is computed as $T_{\alpha} k_B = m_{\alpha} \langle (v_{\alpha} - \langle v_{\alpha} \rangle)^2 \rangle$, where the mean value is computed over all particles inside a grid cell. The temperature and density are normalized to the initial hot plasma temperature and the initial density $n_0$, respectively. The electric potential is expressed here and in the following as the potential energy normalized to the mean initial kinetic energy of hot electrons $E_{k,h} = \frac{1}{2} m_e v_{he}^2$ and set to zero at $x = 1000$. It is also smoothed along time interval $18.6 \omega_{pe} t$ (1500 time steps).

As seen in Figure 1a, at the hot-cold plasma transition region and starting from the initial time, the temperature of the hot plasma decreases, and that of the cold plasma increases. It is owing to a free-streaming of hot plasma electrons into the cold plasma. It is associated with a decrease of the electron plasma density in the hot plasma part ($x < 0$) and density increase in the cold plasma part ($x > 0$) (Figure 1b). Simultaneously, at the location close to $x \sim 0$, the electric potential jump is formed and drifting with the velocity $8 \times 10^{-4} c$ to the region with $x < 0$ (Figure 1c). This velocity agrees to the local ion-acoustic speed. The potential jump corresponds to the sharp decrease in the electron temperature profiles as shown in Figure 2, which indicates a suppression of the hot electron flux from the hot plasma part into the colder one.

To see more details about these processes, we show the electron velocity $v_x$ distribution together with the electric potential at three times $\omega_{pe} t = 500, 1500, \text{ and } 2500$ in Figure 3. As seen here, in all these times, the electrons from the hot plasma region are streaming with the positive velocities to the cold plasma region. At time $500 \omega_{pe} t$ and for $x < 70$ the maximum of the distribution is shifted to the negative value $v_x = -0.015 c$, thus forming the return current, which compensates the current of streaming hot electrons. Namely, the total electric current needs to be close to zero. In accordance with the description of these processes in Li et al. (2012), the return current generates the ion-acoustic waves by the Buneman instability. At positions $x > 70$, the distribution is disturbed, even multi-peaked. The electric

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Maxwell model: (a) Evolution of the electron temperature $T_e$ normalized to the initial hot plasma temperature $T_h$. (b) Evolution of the electron density $n_e$ normalized to the initial particle density $n_0$. (c) Electric potential.}
\end{figure}
potential at this time is waved, but not still forming a significant jump.

It happens in later time. At $1500 \omega_{pe}$, the thermal front is fully developed, and the electric potential has a form, which is typical for the double-layer (DL). The DL restrains all electrons with kinetic energy lower than $\approx 0.8 E_{k,h}$ on its left side. The electrons with higher velocity pass, and their kinetic energy is decreased by the potential jump (cooling). The electrons flying from right to left are not confined, and they gain some energy passing the DL (heating).

In the following times, the DL evolves. For example, at $2500 \omega_{pe}$ it is partly deformed. Especially its left part, where the potential is varying and forming potential wells. Concurrently, the hot electrons are not so strongly confined. They can escape more easily from the left plasma part thereby reinforcing the return current.

Furthermore, in Figure 4 we show the proton velocity $v_x$ distribution at $3000 \omega_{pe} t$, i.e., when the DL is slightly dissipated. The hot protons that were in the initial state in the hot plasma region form a beam in $x = 350 - 800$ and have the velocity $v_x > 0.0025 c$. The potential jump corresponding to the DL is at $x = -40$. On the right side of the DL, the protons that are flying to the left towards the DL are reflected back to the right. The protons that flying from the left to right pass the DL, and thus, they support the proton beam. In the system, there are also small DLs at $x \sim 50$, and $x \sim 320$. The potential increases between them. These DLs influence the proton distribution.

In summary: The results of our Maxwell model are similar to those shown in the papers by Li et al. (2012); Sun et al. (2019). Some small differences are owing to that all our distributions are taken as isotropic and in the hot plasma part there are hot protons. The results from this section will be used for comparison with those in the Kappa model below.
3.2. Kappa model

The evolution of the electron temperature, plasma density, and electric potential in Kappa model is shown in Figure 5. Contrary to the Maxwell model, the Kappa model shows a multi-front solution. Firstly, not very distinctive front (Front 1) is formed at $x \sim -50$ and $x \sim 50$ (Figure 5a). The other fronts are formed on the right side of it in a disturbed plasma in the cold plasma region. At 1000 $\omega_{pe}t$ and $x \sim 500$ a new distinct front is formed (Front 2). Its temperature is increasing until 2000 $\omega_{pe}t$ when it reaches a maximum. Then, it slowly dissipates. Shortly after a formation of this front, the new front (Front 3) is generated at $x \sim 900$. From the beginning, the front is weak, but at times after 3000 $\omega_{pe}t$, its temperature raises.

Shortly after the start of the simulation, density waves are created. Because the plasma conserves the electric neutrality, almost the same waves are created in the proton and electron density. The waves are reinforced during the evolution, and their edges mutually intersect. The most distinct density depressions are connected with Front 1, Front 2, and Front 3 (Figure 5b). Between these main density depressions, there are feeble ones that gradually appear and dissipate.

At the location of Front 1, there is only some potential well, not the DL as in Maxwell model. On the other hand, a strong DL appears at 1000 $\omega_{pe}t$ and $x = 485$ in connection with Front 2. Its potential jump is about $e\phi = 6E_{k,h}$. In the time interval 2500–3000 $\omega_{pe}t$, this DL is disintegrating. The hot electrons and cold protons, that have been detained by this DL, escape. Since 3000 $\omega_{pe}t$, the DL reinforces at the position of Front 3.

Figure 6 presents a detailed view of temperate profiles at four times. At time 800 $\omega_{pe}t$ the temperature creates transition between the hot and cold parts of the model as caused by a free-streaming electrons from hot to cold plasma. The first, but transient, enhancements are in $x \sim 50$, $x \sim 250$, and $x \sim 400$. Only the enhancement at $x \sim 50$ (corresponding to Front 1) sustains, and it is slowly moving to the left. At 2000 $\omega_{pe}t$, the highest temperature enhancement is at the location of Front 2. Front 3 is here illustrated by the temperature enhancement at 3000 $\omega_{pe}$. In comparison with the thermal front in the Maxwell model, expressed as the one-side temperature step, Front 2 and 3 can be better described as temperature enhancements. Their temperatures are lower at both front sides. On the left side the temperatures has a much smoother decrease than on the right side.

Detailed view on the electron temperature evolution of Front 2 and 3, as well as the electric field energy density is shown in Figure 7. The temperature enhancements are located at the regions where the density depressions are; see the red contours in Figure 7c,d. The left edge of Front 2 moves to the left with the velocity $1 \times 10^{-3}$c, i.e., with the velocity close to local ion-acoustic speed until 2000 $\omega_{pe}t$. Then, the front becomes disturbed, and its left edge is smoothed. The right edge is sharper for the whole time, but its position changes more rapidly. After the time 2500 $\omega_{pe}t$, a motion of the temperature enhancement turns from the left direction to the right one. Front 3 moves all the time to the left more slowly than Front 2 because it is surrounded by a colder plasma. Its velocity is about $-6 \times 10^{-4}$c and the surrounding plasma ion-acoustic speed is $7 \times 10^{-4}$c.

The electric field energy in Figure 7c,d is the energy of the electrostatic waves. As seen here, there are electrostatic waves at space around Front 2 and 3 everywhere till 500–1000 $\omega_{pe}t$ when they are absorbed. Then, the electrostatic waves appear at the edges of the density depressions, where the gradient of the density is nonzero. They are on the left edge of Front 2 and the right edge of Front 3. Moreover, they also appear when fronts dis-
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Figure 5. Kappa model: (a) Evolution of the electron temperature $T_e$ normalized to the initial hot plasma temperature $T_h$. (b) Evolution of the electron density $n_e$ normalized to the initial particle density $n_0$. (c) Electric potential. Compare with Figure 1.

Figure 6. Kappa model: Electron temperature profiles at four times. The temperature is normalized to the initial temperature of the hot plasma component. Compare with Figure 2.

During the front evolution, the Langmuir wave packets Vladimirov et al. (1995)) are generated. Individual Langmuir wave packets are denoted by blue arrows in Figure 7. They are identified as local electric field enhancements. They propagate to the left and right from the fronts and have lower speed than the ion-acoustic speed. For example, the solitons escaping from the Front 3 to the left at $1700 \omega_{pe}t$ have their velocity about $-9 \times 10^{-3}c$, while the characteristic thermal velocity is $2.3 \times 10^{-2}c$. In our case, the solitons travel distance up to $300 \Delta (1150 \lambda_d)$ and some of them live longer than $500 \omega_{pe}t$.

Profiles of the temperature, density, electric potential and electric field energy density for Front 2, at the time of the fully developed front at $\omega_{pe}t = 2000$ are shown in Figure 8. The electron temperature peak and the electron and proton density depressions are located at the same position, where the electric potential steeply decreases (location of DL). The enhanced proton temperature is shifted a little bit to the right; very steep on the left side, while on the right side a decrease is much smoother. See that the maximum of the proton temperature is higher than that of electrons. The highest peak in the electric energy density is at $x = 480$ where the densities are enhanced and temperatures have depressions.

Figure 9 shows the evolution of the electron velocity distribution $v_x$ for Front 2. At time $\omega_{pe}t = 750$ and in the position $x = 480$, a disturbance is formed. Here the return current (the maximum of the distribution function is at negative velocities) increases and the Langmuir turbulence is formed at $1000 \omega_{pe}t$. At this
position also the potential jump (DL) increases until 2350 $\omega_{pe}t$ when it is about $6E_{k,h}$. The velocity distribution on the left side from DL has two maxima in this time. The maximum at $v_x = 0$ corresponds to electrons of the background plasma. The stronger and more narrow maximum ($v_x = -0.05c$) is a product of DL that accelerates the electrons flying from the right of the DL. At this time, on the right side of DL, the distribution is violated by the beam ($v_x = 0.025c$ in the position $x \sim 450 - 460$) through the beam-plasma instability forming Langmuir turbulence also on the right side of DL. After this time, the DL dissipates. The return current decreases and variations of the distribution together with the electric potential diminish.

The evolution of the proton velocity $v_x$ distribution is shown in Figure 10. First, a disturbance in the velocity distribution can be seen at $\omega_{pe}t = 1850$ and in $x \sim 500$. The protons that pass the DL from the left to right side are accelerated and gain a high positive velocity. The protons on the right side of DL and having the negative velocity are confined on the right side of the DL. Both groups of protons interact through the beam-beam instability, and their large velocity difference determines high proton temperatures on the right side of DL (compare the distribution function with Figure 4 in the same location). The proton electrostatic turbulence evolves in the position $x = 400 - 700$ (Figure 10b) and deforms the DL. A new DL is created at $x = 875$. At 3725 $\omega_{pe}t$, the turbulence calms down, potential smooths, and the released proton beam passes towards Front 3.

The electron velocity ($v_x$) distribution functions computed at different times for the Maxwell and Kappa models are in Figure 11. The distributions were computed on the right side of the DL, i.e., in the space inter-

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**Figure 7.** Kappa model: Detailed view on the temperature evolution of Front 2 (a) and Front 3 (b) and the corresponding electric field energy ((c) and (d)). The electric field energy density is normalized to the kinetic energy of hot electrons $E_{k,h}$. It is overlaid by contours of the electron density with $0.7n_0$ (red line). Selected individual Langmuir wave packets are denoted by blue arrows.
Figure 8. Kappa model: Comparison of temperatures, densities, electrical potential, and electric field energy density for Front 2 at $\omega_{pe}t = 2000$, when the front is fully developed. Blue: Electron density, Green: Electron temperature, Magenta: Electric potential energy, Red: Proton temperature, Cyan: Proton density, Black: Electric field energy.
Figure 9. Kappa model: The electron velocity $v_x$ distribution along $x-$ axis for Front 2 in the selected times from the front creation to its dissipation. The electric potential at corresponding times is overlaid (magenta line).
Figure 10. Kappa model: Proton velocity $v_x$ distribution along $x$ axis for Front 2 and 3 and for three selected times $\omega_{pe} t = 1850, 2975, \text{ and } 3750$. The electric potential is overlaid (magenta line). (a) The distribution at time when DL in Front 2 is formed. (b) DL of Front 2 is dissipating and generating the proton beam with the velocity $v_x \approx 0.006c$ and at locations $x = 720 – 850$. At this time DL ($x = 900$) of Front 3 starts its formation. (c) Proton beam from Front 2 disturbs the DL of Front 3. Compare with Figure 4.
When the DL diminishes at the end of the simulation, the hot electron distribution (red line) arises to the initial kappa distribution (dashed line). This means that with the disappearance of DL the particle flux is without any reduction by the DL.

4. DISCUSSION AND CONCLUSIONS

Motivated by the results of Kašparová & Karlický (2009); Oka et al. (2013) that the X-ray emission of flare coronal sources can be explained by the kappa electron distribution, we studied processes of the plasma confinement in these coronal sources. The numerical results by Ryu et al. (2007) and analytical solutions by Yoon (2011, 2012a,b) also indicate that the kappa distribution is natural solution of Langmuir turbulence created in the flare region. We studied an expansion of the hot plasma to cold one using a particle-in-cell code in two models: a) Maxwell model with the Maxwellian distributions in both hot and cold plasmas, and b) Kappa model with the kappa electron velocity distribution of the hot plasma; others plasma components have the Maxwellian distributions. Based on observations and in order to emphasize the kappa case effects, we take $\kappa = 2$.

We compared the results of our Maxwell model with those presented in the papers by Li et al. (2012); Sun et al. (2019). The results are very similar despite of some small differences that are owing to a partly different setup: a) we used the numerical system divided into two parts with the hot and cold plasma that differs to the system with the cold-hot-cold parts in the mentioned papers, b) we considered hot protons in the hot plasma part, and c) we used the isotropic particle distributions. Therefore, we do not expect a principal difference in the results of our Kappa model and that with the bi-kappa distribution anisotropy.

The main result of our study follows from a comparison of the results obtained in Kappa and Maxwell models. We found that contrary to the Maxwell model, where one more or less stable thermal front with DL is formed, in the Kappa model, we recognized a series of thermal fronts associated with DLs. The differences between the Maxwell and Kappa model are not caused by different pressures of the hot plasmas, but by the nature of the velocity distribution of the hot plasma interacting with the DL.

Now, let us summarize our results in more detail:

At the very beginning of the hot-cold plasma interaction, the electrons and protons from both plasmas are mixing. The hot electrons from the tail of the distribution of hot plasma that are flying to the right form an electron beam that generates the return current and electrostatic waves.

The electron beam that is formed from the distribution tail of the kappa distribution contains more electrons than in the case of the Maxwell model. Therefore, the electrostatic waves are stronger in the Kappa case. While in the Maxwell model, these electrostatic waves generate only weak ion-acoustic waves by the non-linear processes, the stronger electrostatic (Langmuir) waves in the Kappa model are accumulated at some locations in
the cold plasma region, and by the ponderomotive force, they generate the plasma density depressions. This process is known as the collapse of Langmuir waves (Zakharov 1972). These density depressions are then a location for the formation of the thermal fronts with DL. We found that the maxima of the electrostatic wave energy are at locations of Front 2 and 3, and the maximum in Front 2 is higher than that in Front 3.

The front in the Maxwell model and Front 1 in the Kappa model are connected with a significant jump in the electron temperature. There is a DL at the front in the Maxwell model, but no significant DL at Front 1 in Kappa model. However, at Front 2 in the Kappa model, there is a DL that has a higher potential jump than in the Maxwell model. It is because the tail of the kappa distribution contains more electrons than Maxwell distribution. The potential jump in the Maxwell model is about $e\phi = 0.8 E_{k,h}$ (86 eV) which is in agreement with Li et al. (2012, 2014). The potential jump in the Kappa model is higher; its maximum is about $e\phi = 6 E_{k,h}$ (645 eV).

Front 2 and 3 in the Kappa model can be described more likely as temperature enhancements, not like the thermal front in the Maxwell model. From both sides, they are separated by the plasma with a lower plasma temperature. These temperature enhancements are connected with DLs and density depressions. The proton temperature enhancement is located on the right side of DL.

The process of the thermal front formation can be described as follows. First, the hot electron beam from the tail of hot electron distribution generates the return current and electrostatic waves. Because the return current is unstable by the Buneman instability, it generates density waves that are progenitors for the thermal fronts. Then the electron flow creates a potential jump with a density depression. As the density depression increases, the potential jump increases, and the double layer with its typical particle flows is generated.

The thermal front formation process occurs independently on the hot-cold transition width because the electrons from the hot plasma always have higher velocities than those from the colder plasma and thus overtake them and form the electron beam. A moment of the beam formation is then the start of the thermal front formation.

On the other hand, the process of the thermal front dissipation seems to be connected with the two-stream proton instability (Langmuir turbulence) at the right side of DL. As the instability reduces the DL jump, the electron flux increases. In the Maxwell model, the instability is weak and the DL can be reinforced almost in the instability location. However, in the Kappa model, the instability is strong enough to suppress the DL reinforcement. The DL is formed in more distant and colder parts of the model. Both formation and dissipation DL processes can be repeated until there is a source of the hot plasma.

We can estimate the dissipation time of thermal fronts. Let us suppose that the width of the density depression is $d = 20\Delta$. The depression is created by the both electrons and protons. During the front dissipation both these elements step by step fill the density depression. Because the filling time by protons is longer than that by electrons and also due to the charge neutrality, in the estimation, we consider only protons. The proton filling time is about $d/v_{ci} \approx 770\omega_{pe}t$, where $v_{ci} = 6.488 \times 10^{-4} c$ is the cold proton thermal speed. This time agrees with the dissipation of Front 2 in the time interval $2500 - 3300\omega_{pe}t$.

All fronts in the Maxwell and Kappa cases move with the ion-acoustic speed. The Front 2 moves to the left with velocity $1 \times 10^{-3} c$ until 2000 $\omega_{pe}t$. Then, during the front dissipation, the motion direction changes by the electron flow to the right. Front 3 has constant velocity $-6 \times 10^{-4} c$.

During the evolution of fronts with the DL, the Langmuir wave packets and maybe even solitons appear (Figure 7). It is due to that the electrostatic energy density of Langmuir waves $W$ exceeded the local thermal energy density,

$$W > \frac{n k_B T}{N} \left( \frac{m_e}{m_i} \right)^{1/2}$$

where $N$ is the number of particles in Debye’s sphere (Zakharov et al. 1975; Goldman 1984), $k$ is the wave vector. If we assume that the typical soliton wave vector $k$ is independent on the ion mass, the increase of ratio $m_i/m_e$ to natural values results in decreasing of the strong Langmuir turbulence threshold on right side of Equation 3. Therefore, for natural values of $m_i/m_e$ it is expected to have more generated solitons than in our case. Also, the dissipation should be more difficult.

We analyzed the electron velocity distributions just on the right side of DL for the Maxwell model and Kappa model. In both cases the distributions are asymmetric owing to the expansion of hot plasma electrons into the region with cold electrons. We found that during an existence of the DL the distribution on the right side of the DL, formed mainly by the hot electrons propagating through DL, is lower than the initial distribution of hot electrons in the hot plasma region. It indicates a reduction of the hot particle (or heat) flux through DL.

Our simulations show that in the expansion of the hot plasma into a cold one, in the both Kappa and Maxwell
models, electrostatic and ion-acoustic waves are generated. Considering a coalescence of these waves into the electromagnetic waves, described processes can be detected in the solar radio emission. We propose that the electrons from the hot-plasma distribution tail can generate some type III-like bursts. On the other hand, owing to a motion of the thermal front, some slowly drifting bursts can be observed in the dynamic radio spectra.

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