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Multi-ion plasma expansion in the presence of suprathermal electrons

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Abstract

The self similar expansion of a two-ion plasma is investigated via a multi-fluid model. Our aim is to elucidate the effect of secondary ions on the plasma expansion front, in combination with energetic (suprathermal) electrons in the background. Considering an analytically tractable situation (namely, assuming secondary ions to represent a minority population), and adopting a kappa-type distribution function for the suprathermal electrons, it is shown that energetic electron contribute to acceleration of the expansion front and to an increase in the associated electric field.

Introduction. Plasma expansion into vacuum has received growing interest in recent years, in particular due to its relevance with experiments on ultraintense laser pulse interaction with solid targets [1], and with applications of high energy ion beams, e.g. for ion acceleration [2] and laser-assisted fast ignition scenaria for fusion [3] among others. Plasma expansion mechanisms are also involved in experimental low-temperature plasmas [4] and in plasmas for medical applications (e.g. cancer therapy) [5].

Recent studies have considered the role of secondary ions (rather than electrons) in ultrafast collisional plasma heating by electrostatic shocks [6]. Since multi-ion configurations appear to be ubiquitous in laser-plasm interactions [7], this is expected to be an area of growing interest in the years to come. Furthermore, the generation of energetic (suprathermal) electrons during laser-plasma interactions is a known phenomenon [8]; its effect on expanding plasmas has been investigated in simple electron-ion configurations [9], but never in multispecies plasmas, to the best of our knowledge. Inspired by an earlier study of two-ion expanding plasma [10], this paper is dedicated to an investigation of the dynamics of expanding plasma in a two-ion configuration, in the presence of energetic (suprathermal) electrons.

Theoretical model. We consider a planar plasma slab consisting of electrons (absolute charge e, mass m_e) and two different (positive) ion populations. The two ion species are characterized by their respective mass m_j, charge $q_j = z_j e$ and temperature $T_{j,0}$, as well as their equilibrium density $n_{j,0}$, respectively (for $j = 1,2$). The plasma is assumed to be quasineutral, hence, the electron number density inside the slab equals $n_{e,0} = \sum z_j n_{j,0}$ at equilibrium.

At $t = t_0$, the plasma is assumed to occupy the negative semi-axis (for $x < 0$), while vacuum is assumed to occupy the positive semi-axis (for $x > 0$); here x is the distance measured from the plasma slab. The dynamics of the ions (at time $t > t_0$) can be described by the model:

$$\frac{\partial n_j}{\partial t} + \frac{\partial}{\partial x}(n_j u_j) = 0,$$

$$m_j n_j \left(\frac{\partial u_j}{\partial t} + u_j \frac{\partial u_j}{\partial x} \right) = z_j e n_j E - \frac{\partial P_j}{\partial x},$$

$$E = -\frac{T_e}{e n_e} \frac{\partial n_e}{\partial x}, \tag{1}$$

$$\frac{\partial P_j}{\partial x} = \frac{3T_{j,0}}{n_{j,0}^2} n_j^2 \frac{\partial n_j}{\partial x}, \tag{2}$$

where indices $j = 1, 2$ denote the ion fluid(s) 1 and 2, respectively, and P_j is the ion thermal pressure. The electrons are described by the *"kappa"* distribution [11] $n_e = n_{e,0} \left(1 - \frac{e\Phi}{T_e(\kappa - \frac{3}{2})} \right)^{-\kappa + \frac{1}{2}}$, where Φ is the electrostatic potential, viz. $E = -\partial\Phi/\partial x$, and T_e denotes electron temperature. The system is closed by the neutrality condition (plasma approximation): $n_e = z_1 n_1 + z_2 n_2$.

Self-similar expansion scheme. Assuming that all dependent variables are functions of the similarity parameter $\xi = X/T$, the system of Eqs. (1)-(4) take the form:

$$(V_1 - \xi) N_1' + N_1 V_1' = 0$$

$$(V_1 - \xi) V_1' = -\alpha_1 N_1 N_1' - \left(\frac{a}{b}\right) \left(1 - \frac{\phi}{a} \right) \left[\ln(N_1 + Z N_2) \right]',$$

$$(V_2 - \xi) N_2' + N_2 V_2' = 0$$

$$(V_2 - \xi) V_2' = -\alpha_2 N_2 N_2' - \gamma \left(\frac{a}{b}\right) \left(1 - \frac{\phi}{a} \right) \left[\ln(N_1 + Z N_2) \right]', \tag{3}$$

where prime denotes differentiation with respect to ξ, X and T are the space coordinate and the time, respectively. The following dimensionless variables have been defined: $T = (t - t_0)/t_0$, $X = x/(c_s t_0)$, $N_j = n_j/n_{10}$, $V_j = u_j/c_s$, $\phi = e\Phi/T_e$, in addition to the characteristic (sound) speed scale $c_s = (z_1 T_e/m_1)^{1/2}$. Furthermore, the following dimensionless parameters are defined: $Z = z_2/z_1$, $\gamma = (q_2/m_2)/(q_1/m_1) = z_2 m_1/(z_1 m_2)$, $\alpha_j = \frac{3}{z_1} \frac{T_{j,0}}{T_e} \frac{n_{10}^2}{n_{j,0}^2} \frac{m_1}{m_j}$; note the kappa df related parameters $a = \kappa - 3/2$ and $b = \kappa - 1/2$. As boundary condition, we require that there should exist a point ξ_0 such that $V_1(\xi_0) = 0$, $V_2(\xi_0) = 0$, $N_1(\xi_0) = 1$, $N_2(\xi_0) = N_{20}$. Interestingly, it turns out in the analysis that $\xi_0 = (a/b)^{1/2} = [(2\kappa - 3)/(2\kappa - 1)]^{1/2}$, which is essentially the sound speed in non-Maxwellian plasmas within the kappa-distribution approach [11, 12].

Single-ion fluid limit. In the single- ($N_2 = V_2 = 0$) cold- ($\alpha_1 = 0$) ion case, Eqs. (3) become

$$(V_1 - \xi) \frac{N_1'}{N_1} + V_1' = 0 \qquad \text{and} \qquad \frac{a}{b} \left(1 - \frac{\phi}{a} \right) \frac{N_1'}{N_1} + (V_1 - \xi) V_1' = 0. \tag{4}$$

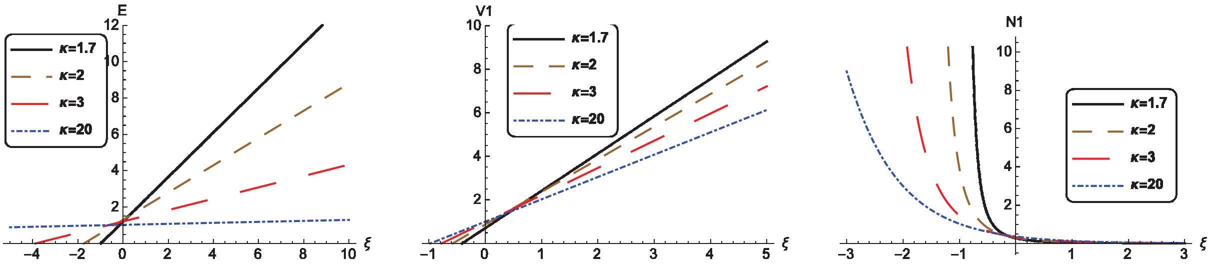

Figure 1: Single (cold) ion fluid model: the state variables (top to bottom: electrostatic potential, electric field, ion fluid speed and density) are depicted versus ξ, following (5).

One can derive a self-similar solution for the system under the assumption of charge quasi-neutrality, for the potential, the ion fluid speed, and for the ion density. The set of analytical expressions for the state variables thus obtained read:

$$\phi^{(ss)} = \frac{-1}{(1-2b)^2}\left[b(\xi-\xi_0)\left(2\sqrt{\frac{a}{b}}(2b-1)+\xi-\xi_0\right)\right],$$

$$V_1 = \xi + \sqrt{\frac{a}{b}\left(1-\frac{\phi^{(ss)}}{a}\right)} \qquad \text{and} \qquad N_1 = \left(1-\frac{\phi^{(ss)}}{a}\right)^{-b}. \tag{5}$$

The results are plotted in Fig. 1. As expected [11], large values of κ recover the known Maxwellian result [10, 13, 14]. Retaining the thermal pressure term in Eqs. (3), the algebra is substantially more complicated, but a closed expression for all state variable can still be obtained analytically. The results are shown in Figs. 2 and 3.

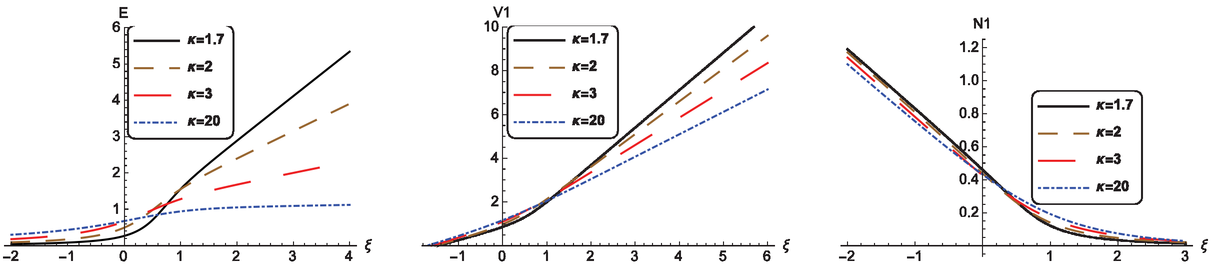

Figure 2: Single (warm) ion fluid model: the effect of superthermality is shown. The state variables (top to bottom: electrostatic potential, electric field, ion fluid speed and density) are depicted versus ξ. We have considered $\alpha_1 = 2$, as an indicative value.

Two-ion model: the role of minority ions. We now turn to the two-fluid problem described by Eqs. (3) above (wherein the thermal pressure is now retained), in an attempt to find similarity solutions for the full two species case (assuming $\alpha_1, \alpha_2 \neq 0$). The result is shown in Fig.4.

Conclusion. The expanding plasma front appears to be effectively accelerated by the energetic electrons (i.e. for lower values of the superthermality index κ), as intuitively expected. For infinite κ, the Maxwellian limit is recovered.

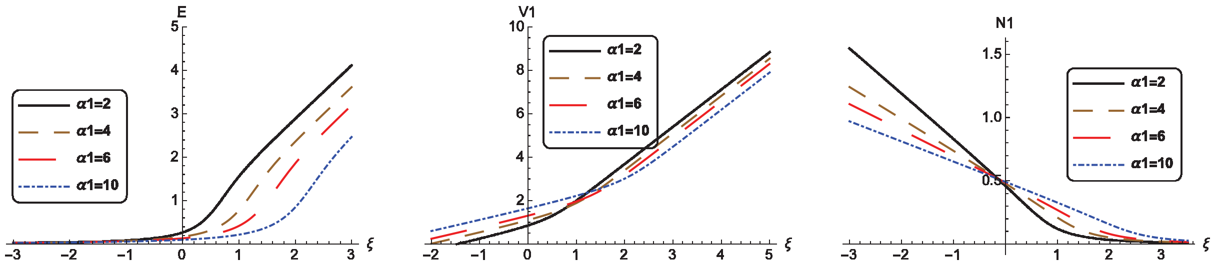

Figure 3: Single (warm) ion fluid model: the effect of thermal pressure is shown. The state variables (top to bottom: electrostatic potential, electric field, ion fluid speed and density) are depicted versus ξ. We have considered $\kappa = 1.7$, to emphasize electron superthermality.

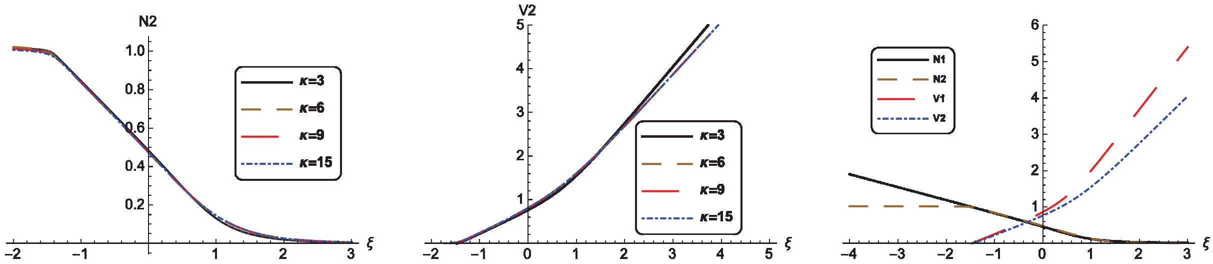

Figure 4: Minority ions (N_2) in a two-ion plasma (for $\alpha_1 = \alpha_2 = 2, \gamma = 1/3$): the effect of superthermality is shown on the secondary ion population. Population N_1 is still given in Fig. 3.

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