36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, O-4.043 (2009)

On the charge fluctuation effects in plasma expansion

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Abstract

The ionization source model is considered to investigate plasma expansion into vacuum in the presence of highly charged dust particles. Due to the attachment (emission) of ions and electrons at (from) the dust surface, source and sink terms as well as momentum transfers are included in fluid equations. Based on the self-similar transformation a one dimensional numerical solution is conducted using, as a first approximation, Boltzmann assumption for the current calculation. The model is improved by dust potential self-consistent calculation. The expanding profiles are found to be changed when the fluctuation is considered. The relevancy of this investigation to comet tail expansion is pointed out.

Introduction

The presence of highly charged dust particles in a plasma of ions and electrons has been found to change the plasma characteristics. Moreover, new physical phenomena were associated to dust particles properties such as the dust ions-acoustic wave. For stationary dust grains, the wave phase velocity is larger than the ion acoustic velocity[1]. One of the dust important characteristics is the charge fluctuation that is inherent to a momentum transfers between dust particles and electrons or ions[2]. The latter was found to be responsible of the existence of an acceleration front during dusty plasma expansion[3]. The plasma expansion is a consequence of the combination of two effects, the thermal pressure at the plasma source and the ambipolar electric filed induced by charge separation at the expanding front, light weighted species leave first the plasma bulk region. Solving expansion problem is subject to obtain the equation of the moving front that is not an easy task for free expansion. The self-similar approach presents a good alternative to this problem however, the solution obtained using this formalism is an asymptotic one that gives the behavior for long time [4].

Modeling

The fully ionized plasma is composed of positively charged ions and cold electrons in the presence of stationary dust particles of negative charge $q = -Ze$ and density n. The fluid equations that govern the one dimensional plasma expansion are,

$$\frac{\partial n_j}{\partial t} + \frac{\partial (n_j v_j)}{\partial x} = -a_j n_j n, \tag{1}$$

$$\frac{\partial v_j}{\partial t} + v_j \frac{\partial v_j}{\partial x} = -\frac{q}{m_j}\frac{\partial \phi}{\partial x} - \frac{1}{m_j n_j}\frac{\partial p_j}{\partial x} - a_j n v_j, \tag{2}$$

where $j = e$(electrons), i(ions) and $n_j,\ v_j, m_j, q_j$ are respectively the density, velocity, mass and the charge of the species j. The pressure is considered for an isothermal situation i.e., $p_j = n_j T_j$. Due to the presence of massive spherical dust grains the main charging process is by particles collection. The electrons reach first the dust surface to give a negative potential to the dust surface. After, the ions are attached while electrons are repeled till a critical value of the surface potential where the opposite phenomenon occurs. Such effect leads to the fluctuation of the dust charge governed by the following equation,

$$\frac{\partial q}{\partial t} = e(a_i n_i - a_e n_e) \tag{3}$$

The currents coefficient are obtained using the orbit motion limited theory (OML) which gives the correct calculations under a restrictive conditions that concern the plasma parameters[5].

$$a_e = \pi r_o^2 \sqrt{\frac{8T_i}{\pi m_e}}\, n_e\, exp\left(-e^2 Z/(r_o T_e)\right), \tag{4}$$

$$a_i = \pi r_0^2 \sqrt{\frac{8T_i}{\pi m_i}}\, n_i\ \left(1 + e^2 Z/(r_o T_i)\right), \tag{5}$$

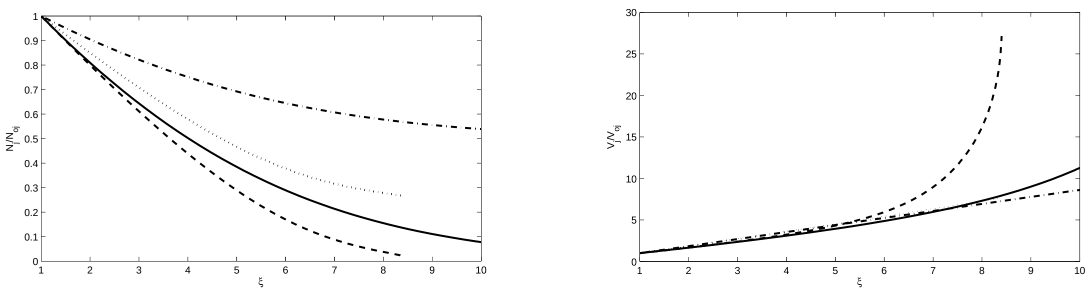
where $T_e(T_i)$ is the electrons (ions) temperature. The set of Eqs(1-3) is closed by the quasi-neutral condition:

$$n_i = n_e + Zn, \tag{6}$$

using the following ansätz:
$\xi = r/c_{ds}t \quad n_j = \frac{n_{io}N_j(\xi)}{\omega_{pd}t}, \quad V(\xi) = v/c_{ds}, \quad \Phi(\xi) = e\phi/T_i,$
where, $\omega_{pd}^2 = \frac{4\pi n_{io} e^2}{m_d}$ and $c_{ds}^2 = T_i/m_d$, the set of differential equations (1-6) is transformed to an ordinary one.

Halley's comet plasma expansion

Numerical investigation is conducted for a plasma outside the ionopause of Halley's comet. The presence of neutral atoms is neglected and the dust density is sufficiently small to assume stationary dust particles in the time scale corresponding to the ions motion. The dust charge ranges between 20 and 10^4 of the elementary charge[6]. The electron temperature is estimated to be equal to 1 eV and the spherical dust are of radius $a = 1\ \mu m$. To compare, we choose two



(a) (b)

Figure 1: Normalized densities (a) and normalized velocities (b) vs the similar variable corresponding to electrons (—) and ions $(---)$ for $Z_1 = 10^4$ and with $Z_2 = 5000$ it is $(\cdot - \cdot)$ for electrons and $(\dots)$ for ions.

different values of the dust charge $Z_1 = 10^4$ and $Z_2 = Z_1/2$ and dust density $N = 10^{-5} \times N_i(1)$, $N_i(1)$ is the ions density when the expansion starts. The normalized electrons and ions densities are plotted in Fig.1a where we found the usual profile of plasma expansion that corresponds to density depletion. However, due to the presence of negatively charged dust we note two main differences. The value of the limited self-similar parameter changes when the dust charge changes. This limited value is higher when the dust charge increases. At the first stage the expansion can be associated to the gas pressure close to the plasma source region. Far away from the source this can not be true, the electrostatic potential starts to be of significant contribution. As a consequence, the electrons are accelerated due to the presence of negatively dust charge (Fig.1b) while the ions are attracted, their velocities increase slowly due to momentum transfer during the attachment process. Thus, the end of expansion in Figs.1 does not correspond to the density vanishes, as expected. The figures indicate only the limits of the self-similar solution, beyond this limit the charge separation effect is more important and the self-similar approach can not be used.

It is important to note that the electrons and ions temperature play also an important role. For higher electron temperature, the particles overcome the potential barrier and the attachment on the negatively charged dust surface can occur. In Figure (2), the potential decreasing is slower as the dust charge increases. The electrostatic potential, resulting from the starting of the charge separation, is not important when the charge of the dust is higher. The ions attachment leads to reduce the electron motion towards the expanding front. Increasing the dust charge cause the depletion of electrons that are not attracted by the ions motion during the charging processes.

To conclude , we have shown that the presence of charged stationary dust particles can modify

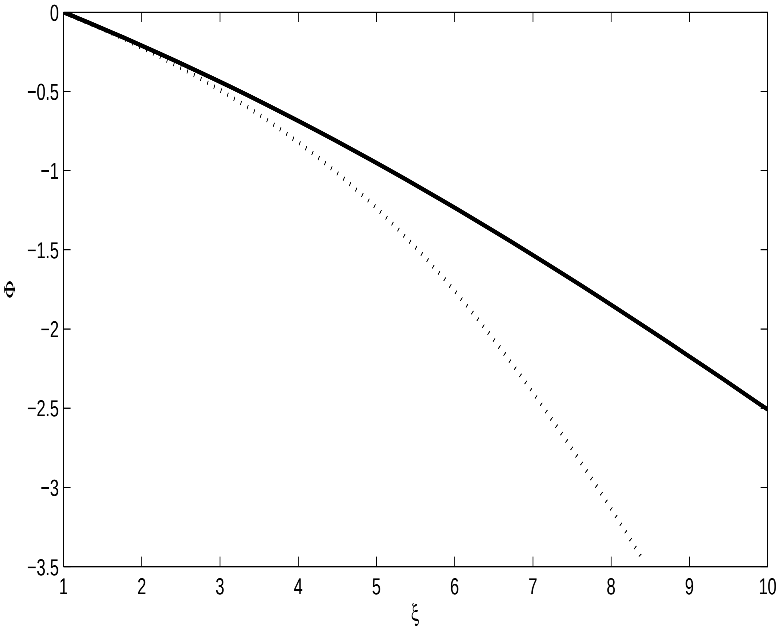


Figure 2: Electrostatic potential vs ξ. Solid line corresponds to $Z_1 = 10^4$ and the dotted one for $Z_2 = 5000$.

the plasma expansion. The self similar solution provides that the expanding profile depends on the dust charge. The ions and electrons motion are accelerated or decelerated due to the attachment or emission of particles on or from the dust surface.

References

[1] P. K. Shukla and A. A. Mamun, Introduction to Dusty Plasma Physics, IoP Publishing, Bristol 2002

[2] F. Verheest and S. R. Pillay, Phys. Plasmas 15, 013703 (2008).

[3] M. Djebli, S. Bahamida and R. Annou, Phys. Plasmas 9, 4107(2002).

[4] Ch. Sack an H. Schamel, Phys. Rep. 156, 311(1987).

[5] A. L. Alexandrov, I. V. Schweigert and F. M. Peeters, New Journal of Physics 10 (2008) 093025.

[6] D. A. Mendis, Plasma Source Sci. Technol. 11, A219(2002).