PRAMANA — journal of physics © Indian Academy of Sciences Vol. 55, Nos 5 & 6 Nov. & Dec. 2000 pp. 843–848

Basic physics of colloidal plasmas

C B DWIVEDI
Plasma Physics Division, Institute of Advanced Study in Science and Technology, Khanapara, Guwahati 781 022, India

Abstract. Colloidal plasma is a distinct class of the impure plasmas with multispecies ionic composition. The distinction lies in the phase distribution of the impurity-ion species. The ability to tailor the electrostatic interactions between these colloidal particles provides a fertile ground for scientists to investigate the fundamental aspects of the Coulomb phase transition behavior. The present contribution will review the basic physics of the charging mechanism of the colloidal particles as well as the physics of the collective normal mode behavior of the general multi-ion species plasmas. Emphasis will be laid on the clarification of the prevailing confusing ideas about distinct qualities of the various acoustic modes, which are likely to exist in colloidal plasmas as well as in normal multi-ion species plasmas. Introductory ideas about the proposed physical models for the Coulomb phase transition in colloidal plasma will also be discussed.

Keywords. Colloidal plasma; acoustic waves; acoustic turbulence; dust grain charging; Coulomb correlation; Coulomb phase transition.

PACS Nos 82.70D; 52.25V; 52.35; 52.35F

1. Introduction

During last one decade or so vigorous research activities have been launched to characterize the dust-plasma interaction process with main focus on collective behavior of dusty plasma [1]. The motivation behind such activities was derived by Voyager-1 and 2 observations of Saturnian ring system which revealed a number of interesting phenomena like spokes and braid formation [2,3]. The term 'dusty plasma' seems to be coined in the late eighties [1]. In fact, different types of photometric observations in about mid thirties [4] revealed that the dark holes observed in milky way by William Herschel (about 150 years ago) were the regions of heavy obscuration by cosmic dust. Micro-particles are naturally produced in plasma aided manufacturing like surface processing in plasma medium [5] and produce undesirable effects. Particles in sputtering and etching plasmas used for semiconductor device production have been studied extensively since the earliest paper appeared in 1985 [6]. Selwyn and co-workers [7] reported the formation of dust clouds near the driven electrode by use of video laser scanning. Moreover, many workers for solid particles termed as the dust grains or grains reported the experimental demonstration even earlier. The gaseous plasma containing dust suspensions was commonly known as colloidal plasma [8]. The first experimental realization of colloidal plasma in laboratory was claimed by James and Vermeulen in 1968 [9] by various electrostatic, mechanical and acoustic means. However, Sheehan *et al* [10] were the first to develop a formal dust dispersal device and conduct preliminary observations to understand dust-plasma interaction processes in laboratory experiments. They were the first to report the presence of very low frequency (VLF) noise in dust contaminated plasma. Here the VLF means the spectrum well below the ion oscillation frequency (LF) of the background electron-ion plasma in which the dust grains are embedded. In this talk we include a topical review to clarify the controversial viewpoints about the classification of various kinds of plasmas and associated spectrum of collective plasma dynamics on basic physical grounds of the dust-plasma interaction process with highlights about different physical models of Coulomb phase transition [11].

2. Dust-plasma interaction processes

Depending on the charging mechanism to produce the impurity ions, the impure plasmas could be classified into two different categories viz. normal impure or multi ion species plasma and the colloidal plasma [12]. To avoid confusion about nomenclature of the colloidal plasma versus dusty plasma the author opines that 'dusty plasma' is a misnomer and historically correct and scientifically more suitable nomenclature should be 'colloidal plasma'. The distinguishing qualities of the colloidal plasma include two-phase (solid and gaseous) distribution of the plasma constituents and surface charging process of finite size impurity ions with dynamical variation of Coulomb charge on these impurity ions. To avoid ambiguity in different nomenclatures of impurity ions of finite size, these should be classified as the dust grainlike impurity ions (DGLII) [12]. Most of the earlier works were confined to estimate potential distribution around solid surface [13]. In the absence of surface emissions, the grains acquire negative charge. This is to clarify that the dust grains or simply grains will appear in the text to represent DGLII in short form. In a simple case of spherically symmetric grains under isolated dust grain approximation, the basic charging equation can be written as

$$\frac{\mathrm{d}Q_I}{\mathrm{d}t} = I_e + I_i. \tag{1}$$

Here, d/d$t = (\partial/\partial t + v_I \cdot \nabla)$ denotes for total time derivative. Subscript I represent the notation for impurity ions in general. For normal impurity ions of atomic/molecular size the charging equation becomes redundant. I_e and I_i denote for the parent electron and ion currents collected by the dust grain surface. Under static approximation of the dust grains, the expressions for electron and ion currents are given as [13];

$$I_e = -\pi a^2 e \left[\frac{8\kappa_B T_e}{\pi m_e}\right]^{1/2} n_e \exp\left[\frac{e}{\kappa_B T_e}(\varphi_f - v_p)\right], \tag{2}$$

$$I_i = \pi a^2 e Z_i \left[\frac{8\kappa_B T_e}{\pi m_i}\right]^{1/2} n_i \left[1 - \frac{e}{\kappa_B T_i}(\varphi_f - v_p)\right]. \tag{3}$$

Here φ_f and v_p denote for the grain surface floating potential and ambient plasma potential respectively, n_e and n_i represent the gaseous electron and ion components. At equilibrium, the plasma currents add up to zero and yield the steady state floating potential φ_{f0} of the embedded dust grains. Goertz and Ip [14] were the first to address the capacitance charging model to calculate the Coulomb charge on the dust grainlike impurity ions as; $Q_{I0} = C\phi_{f0}$, where C is the capacitance of the dust grainlike impurity ions, which can be expressed as

$$C \approx a\left(1 + \frac{a}{\lambda_{\mathrm{D}}}\right). \tag{4}$$

Here 'a' is the size of the dust grains, λ_{D}, the plasma Debye length and the correction a/λ_{D} arises due to proximity of the other grains in gaseous plasma environment. Recently few experiments have been conducted to describe the dust grain charging [15]. Here we comment that no theoretical effort has been made to derive the dust grain charging equation when the ambient magnetic field is present and violates the straight orbit approximation of the plasma particle dynamics. The next important aspects of the dust-plasma interaction have concern with the effects of the dust grains on the plasma dielectric function and in turn the dispersion characteristics of the collective plasma dynamics [1]. In addition to these effects some new degrees of VLF oscillations are expected to arise.

3. Collective dynamics in colloidal plasmas

The potential of non-neutral plasma background seems to have random distribution in the form of background fluctuations to provide stochastic force [16] to maintain Brownian like thermal motion. However, global quasi-neutrality holds good. Let us consider the case of negative impurity ions to illustrate authors viewpoint regarding LF and VLF oscillations in impure plasma. Ignoring grain size and mass distributions as well as grain charge fluctuation, the rescaling of the characteristic space and time for LF dynamics can be easily estimated to show that

$$\lambda_{De} = \sqrt{\varepsilon_n}\,\lambda_{Di}, \quad \tau = \tau_i\left[1 + \left(1 - \frac{1}{\varepsilon_n}\right) Z_I \frac{m_i}{m_I}\right]^{-1/2},$$

where

$$\lambda_{Di} = \frac{T_e}{4\pi n_{i0} e^2}, \quad \tau_i = \omega_{pi}^{-1} \quad \text{and} \quad \varepsilon_n = \frac{q_i n_{i0}}{e n_{e0}}.$$

Using equilibrium quasi-neutrality for impure plasmas in general ε_n could be correlated with impurity ion parameter p as $\varepsilon_n = (1+p)^{-1}$ for positive impurity ions and $\varepsilon_n = (1-p)^{-1}$ for negative impurity ions. Here $p = |Z_I(n_{I0}/n_{i0})|$, $Z_I = |Q_I/q_i|$. Now in limiting cases for cold ion model, the scaling of phase velocity v_P of LF acoustic oscillations in non-neutral electron-ion plasma can be derived as:

Case 1: When $\varepsilon_n \to 1, \lambda_{De} \to \lambda_{Di}, \tau \to \tau_i$ then $v_P \to c_s, c_s = \sqrt{T_e/m_i}$.

This represents the fluid branch of the usual LF ion acoustic wave (IAW) in quasi-neutral pure plasma. This can be treated as a reference scale.

Case 2: When $\varepsilon_n \to \infty (\varepsilon_n \ll m_i/m_e), \lambda_{De} \to \sqrt{\varepsilon_n}\lambda_{Di}, \tau \to \tau_i[1 + Z_I(m_i/m_I)]^{-1/2}$ and $v_P \to \sqrt{\varepsilon_n} c_s[1 + Z_I(m_i/m_I)]^{+1/2}$.

This branch represents the modified branch of the usual low frequency IAW. For DGLII $(m_I \to \infty)$ this branch can be observable with $v_P \to \sqrt{\varepsilon_n} c_s$. However, in the case of normal negative ions, this branch can be observed only when significant amount of these impurities are present. Let us consider more details about these branches in the context of warm ion model with general local dispersion relation as given below

$$1 + \frac{1}{k^2\lambda_{De}^2} - \frac{\omega_{pi}^2}{\omega^2 - k^2 v_{ti}^2} - \frac{\omega_{pI}^2}{\omega^2 - k^2 v_{tI}^2} = 0. \tag{5}$$

If we adopt the notation of '$+$' for parent ions (i) and '$-$' for impurity ions (I), the above dispersion relation becomes equivalent to the fluid dispersion relation as derived by Angelo *et al* [17] in 1966 for normal negative ion contamination. For long wavelength approximation, the above dispersion relation can be rearranged to yield,

$$1 - Z_I \frac{k^2 c_s^2}{1-p} \left[\frac{1}{\omega^2 - k^2 v_{ti}^2} + Z_i \frac{m_i}{m_I} p \frac{1}{\omega^2 - k^2 v_{tI}^2} \right] = 0. \tag{6}$$

Now the nature of different acoustic modes can be described under following limiting cases of p.

Case 1*a*: When $p \to 0$ [static response of impurity ions]

$$\omega^2 \approx ZIk^2 c_s^2 + k^2 v_{tI}^2. \tag{7}$$

For isothermal case $(T_e \sim T_i \sim T_I)$ this behaves as a kinetic branch of the usual low frequency IAW with heavy Landau damping. For non-isothermal case $(T_e \gg T_i, T_I)$ this reduces to $\omega^2 \approx Z_I k^2 c_s^2$ which is the fluid branch of the usual IAW. Angelo *et al* [17] have termed it as the 'slow mode'.

Case 1*b*: When $p \to 0$ [dynamic response of the impurity ions]. This is obvious to note that in this limiting case, the dynamical response of the impurity ions can be realised only if $\omega \approx k v_{tI}$ (see eq. (6)). This is the kinetic branch of the impurity driven acoustic mode and falls within kinetic regime.

Case 2*a*: When $p \to 1$ [under cold ion approximation].

$$\omega^2 \approx Z_I \frac{k^2 c_s^2}{1-p} \left(1 + Z_I \frac{m_i}{m_I}\right) = \varepsilon_n \left(1 + Z_I \frac{m_i}{m_I}\right) k^2 c_s^2. \tag{8}$$

In the case of DGLII $(m_I \to \infty)$, this reduces to the modified branch of the usual low frequency IAW in non-neutral electron-ion plasma observable in colloidal plasma within wide range parameter domain of p or ε_n. This is the mode which has been termed as 'fast mode' by Angelo *et al* [17] in the case of negative ion plasma and dust-ion acoustic wave by Shukla and Silin in dusty plasma [18]. However, the author [18] opines that it is more appropriate to call it as the modified-ion acoustic wave on the basis of electrodynamical response of plasma species participating in wave propagation.

Case 2*b*: When $p \to 1$ [hot ions]

$$\omega^2 = k^2 \frac{(T_I + Z_I T_i)}{m_I + Z_I m_i} = k^2 c_{\text{seff}}^2. \tag{9}$$

Case 2*c*: When $p \to 1$ [under hot and cold ion approximation with impurity ions to be cold], $\omega^2 \approx Z_I \frac{T_i}{m_I}$.

This is a distinct class of fluid branch of the impurity ion driven acoustic mode with v_{te}, $v_{ti} \gg v_P \gg v_{tI}$. Of course this branch can not exist for $p = 1$ in normal impure plasmas until and unless the hot and cold ion masses differ by orders of magnitude. For comparable masses this branch is found to occur for hot and cold ion distributions under restrictive conditions for their population densities as reported by Dwivedi *et al* first time in 1989 [19]. In colloidal plasmas hot and cold ion model is very well satisfied for wide range parameter domain of p. Under steady state electron approximation following dispersion relation can be deduced;

$$\omega^2 \approx Z_I p \frac{T_i}{m_I} \quad \text{for} \quad k\lambda_{Di} < 1. \tag{10}$$

This mode referred to as the so-called acoustic mode has been already reported in scientific literature [12]. This is to emphasize that the grain charge fluctuation causes damping [20,21] and growth [12] of plasma modes.

4. Coulomb phase transition (CPT)

The ability to tailor the interactive forces between Coulomb colloidal particles offers a fertile ground for scientists to understand fundamental aspects of phase transition behavior and crystal growth dynamics. In fact, the self-consistent disorder-order transition of colloidal particles occurs when the particle correlation force effect becomes significantly large. The basic question before theoretical plasma physicists is to understand the origin of attractive interaction potential to hold grains in order. The author and collaborator have proposed a phenomenological model approach to understand the phase transition behavior in terms of the collective plasma dynamics [22]. This is based on the proposition that correlation potential relaxes by nonlinear driving of collective plasma mode (say acoustic wave) to form a random collection of the nonlinear wave grains (like soliton, double layer etc.) with positive polarity. Subsequently thermodynamical interaction of these virtual grains with real negative dust grains may allow disorder-order transition to take place depending on the Coulomb correlation strength between virtual and real grains. On this paradigm of collective excitations the role of plasma sheath could be visualized as a source to form dense dust clouds with significant Coulomb correlation effect near the plasma-sheath boundary through levitation process due to interplay between gravito-electrostatic forces [22]. Sheath–sheath interaction between randomly moving grains in non-neutral plasma background could prove more useful for final comment on viable choice over all proposed models.

In conclusion colloidal plasma is a complicated system and hence more intensive study is needed for various aspects of physical and technological interest.

References

[1] U de Angeles, R Bingham and V S Tsytovich, *J. Plasma Phys.* **38**, 543 (1989)
[2] K Avinash and A Sen, *Phys. Lett.* **A194**, 241 (1994)

[3] B A Smith *et al*, *Science* **212**, 163 (1982)
[4] A Mendis and M Rosenberg, *Ann. Rev. Astrophys.* **32**, 419 (1994)
[5] G S Selwyn, J E Heidenreich and K L Haller, *Appl. Phys. Lett.* **57**, 1876 (1990)
[6] R M Roth, K G Spears, G D Stein and G Wong, *Appl. Phys. Lett.* **46**, 253 (1985)
[7] G S Selwyn, J Singh and R S Bennett, *J. Vac. Sci. Technol.* **A7**, 2758 (1989)
[8] M S Sodha and S Guha, in *Advances in plasma phyiscs* edited by A Simon and W B Thompson (Wiley, New York, 1971) vol. 4
[9] C R James and F Vermeulen, *Can. J. Phys.* **46**, 855 (1968)
[10] D P Sheehan, M Carrillo and W Heidbrink, *Rev. Sci. Instrum.* **61**, 387 (1990)
[11] V E Fortov *et al*, *J. Exptl. Theor. Phys.* **87**, 1087 (1998) and references therein
[12] C B Dwivedi, *Phys. Plasmas* **6**, 31 (1999)
[13] E C Whipple, T G Northorp and D A Mendis, *J. Geophys. Res.* **90**, 7405 (1985)
[14] C K Goertz and W H Ip, *Geophys. Res. Lett.* **11**, 349 (1984)
[15] R C Hazelton and E J Yadlowsky, *IEEE Trans. Plasma Sci.* **22**, 91 (1994)
[16] J T Mendonca, P K Shukla, A M Martins and R Guerra, *Phys. Plasmas* **4**, 674 (1997)
[17] N D' Angelo, S V Goeller and T Ohe, *Phys. Fluids* **9**, 1605 (1966)
[18] P K Shukla and V P Silin, *Phys. Scr.* **45**, 504 (1992)
C B Dwivedi, *Phys. Plasmas* **4**, 3427 (1997)
[19] C B Dwivedi, R S Tiwari, V K Sayal and S R Sharma, *J. Plasma Phys.* **41**, 219 (1989)
[20] R K Varma, P K Shukla and V Krishan, *Phys. Rev.* **E47**, 750 (1993)
[21] M R Jana, A Sen and P K Kaw, *Phys. Rev.* **E48**, 3930 (1993)
[22] K Rajkhowa, C B Dwivedi and S Bujarbarua, *Pramana – J. Phys.* **52**, 293 (1999)