The grain charging and the dust acoustic wave instability

Ram K. Varma

Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India

(Received 6 November 2000; accepted 27 March 2001)

The stability of the steady charging state of the assembly of dust grains in a plasma is analyzed using, besides the equations of continuity and momentum balance, also the equations of thermal energy balance with the grain charging terms for both the electron and ion species. The grain charging terms account for the energy exchange between the dust grains and the electron and ion fluids. The grains are taken to be immobile for the purpose of this analysis. Two limiting cases are analyzed: (i) \( f = 4\pi n_d \lambda_D^2 a \ll 1 \) and (ii) \( f \gg 1 \) \( (n_d \text{ is the dust number density, } \lambda_D \text{ plasma Debye length, and } a \text{, the grain radius}). The steady grain charge state is found to be stable in the case \( f \ll 1 \), so that the steady state grain charge \( q_o \) is unaffected. On the other hand, in the limit \( f \gg 1 \), the state is found to be unstable provided \( \gamma_q = q_o e / a T_e < \frac{1}{2} (T_e - T_i) / T_e \). Next, by letting the grain charges be mobile, so that the perturbation of dust number density is nonzero, we examine the stability of the dust-acoustic wave (DAW). The DAW is found to be unstable, also in the \( f \gg 1 \) case, while stable in the \( f \ll 1 \). The instability of the DAW also implies a concomitant grain charge growth, which would again be of a coherent nature.


I. INTRODUCTION

The study of dusty plasmas has grown rapidly over the last decade. The main motivation for their study has come from their ubiquitous occurrence in space and astrophysical environments, and their potential importance in understanding a variety of related physical phenomena. A large number of entirely new physical processes have been discovered both theoretically and experimentally which are characteristically related to the charged dust grains in the plasma. These are very low frequency phenomena characteristic of the large mass \( m_d \) of dust particles, typically \( m_d > 10^8 - 10^{12} m_p \) \( (m_p \text{ = proton mass}). The dust plasma frequency is thus \( Z(m_d / m_p)^{1/2} \) times smaller than ion-plasma frequency where \( Z \) is the dust charge number. There has also been discovered the dust analogue of the ion-acoustic wave, christened as the “dust acoustic wave” \( ^{1-1} \) whose existence has been verified experimentally. \( ^2 \) A number of investigations continue to explore the already known plasma phenomena with the inclusion of dust charges. This extends the range of plasma processes to ultra low frequencies.

On the application front, a number of observed phenomena relating to Saturn’s rings, such as the “spokes” and the “braided” structure have been attempted to be explained in terms of dust plasma physics. \( ^{3,4} \) The role of dust plasmas in star formation is also being actively pursued. \( ^5 \) There also exist dust envelopes around a number of star types, such as the carbon stars, WC8 and WC9, where dust is continuously produced around 30% of the former ones and 85% of all the known later ones. Clearly, these situations present sites of potential applications of dust plasma physics, which have yet to be explored.

The key physical process that leads to the generation of a dust plasma is the acquisition of charges by the dust grains. The inclusion of the charging dynamics of the dust grains in the analysis of any dust plasma dynamical process is what distinguishes it as a truly dust plasma process as against simply as a multicomponent plasma albeit with a considerable larger mass. This was first pointed out by Varma et al. \( ^6 \)

When dust is introduced into a plasma, its grains get charged negatively as a result of the predominant electron flows to them. The positive ions also flow to them until an equilibrium negative charge is attained by the grains, when the electron current flow balances the ion current flow. This is expressed by the equation

\[ q = I_e + I_i = 0, \]  (1)

where \( I_e \) and \( I_i \) are the well known expressions used in the probe theory: \( ^7 \)

\[ I_e = -\pi a^2 e n_e \left( \frac{8 T_e}{\pi m_e} \right)^{1/2} e^{\Phi / T_e}, \]

\[ I_i = \pi a^2 e n_i \left( \frac{8 T_i}{\pi m_i} \right)^{1/2} [1 - e^{\Phi / T_i}], \]  (2)

In expression (2), \( a \) represents the grain radius, \( T_e \) and \( T_i \) electron and ion temperatures, \( m_e \) and \( m_i \) electron and ion masses, while \( \Phi \) represents the surface grain potential relative to the plasma potential. Quite clearly, the electron thermal energy is used up in charging the grains as the work is done in charging the negatively charged grains, while the energy is released as ion current flows to the grains. The energy may be returned to the plasma in the form of secondary electrons.

It may be pointed out that the charging process via the probe theory described above may be described as “incoherent,” because the grains acquire charges individually and independently of each other because of the electron and ion...