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Anomalous dust temperature in dusty plasma experiments

K. Avinash [a,1], R.L. Merlino [b], P.K. Shukla [c,d,*]

[a] Centre for Space Plasma and Aeronomic Research, University of Alabama, Huntsville, AL 35899, USA
[b] Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA
[c] RUB International Chair, International Center for Advanced Studies in Physical Sciences, Faculty of Physics and Astronomy, Ruhr University Bochum, 44780 Bochum, Germany
[d] Department of Mechanical and Aerospace Engineering, University of California, San Diego, La Jolla, CA 92093, USA

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ABSTRACT

Dust heating in dusty plasmas due to thermal electric field fluctuations and dust acoustic waves is examined. It is shown that dust particles acquire large random motion in fluctuating electric fields (within dust cloud) of background plasma causing dust electrostatic pressure P_E [K. Avinash, Phys. Plasmas 13 (2006) 012109] and corresponding large temperature T_E. Due to quadratic dependence on q_d and high dust charge ($\sim 10^3$–$10^4 e$), T_E is much bigger than the dust kinetic temperature T_d and is in the range of 10–300 eV for typical experimental numbers. Using global energy constraints dust heating due to dust acoustic waves is examined. It is shown that dust acoustic waves are potentially capable of heating dust to high temperatures in the range of a few hundreds of eV.

A number of recent experiments in dusty plasmas have revealed anomalously high dust temperature in the range of 10–300 eV at low neutral gas pressures [1–10]. These observations have been confirmed by independent stereoscopic particle image velocimetry techniques where random dust motion corresponding to such high temperature has been seen [4,7,8,10].

Some of these experiments showed high dust temperature without significant wave activity [1,2,4,8,10] while other experiments, in which the dust acoustic (DA) waves [11] were present, the agreement with the theoretical dispersion relation required the assumption of dust temperatures in the range of tens to hundreds of eV [3,5–7]. In this context, the experiment by Fisher and Thomas [8] is particularly noteworthy where dust temperature was measured in dust clouds with DA waves and in stable clouds without DA waves or any other type of non-thermal fluctuations. It was observed that the dust temperature was high without DA waves ($\leqslant 600$ eV) and significantly higher with DA waves (~ 800 eV) showing the heating of dust both with and without DA waves. Winske et al. [12] performed a one-dimensional electrostatic particle simulation of DA waves driven by drifting ions and showed that both the ions and dust were heated by the DA waves. Joyce et al. [13] performed numerical simulations using the dynamically shielded dust (DSD) code that included the effects of the two-stream (ions-dust) instability in a dusty plasma and dust-neutral collisions. Their numerical results showed that the dust temperature increased with decreasing neutral pressure. Recently, Merlino [14] has shown that DA wave is driven unstable by ion-dust streaming instability in DC and RF discharges over a wide range of plasma and dust conditions. These arguments support the possibility of dust heating via DA waves driven by the ion-dust streaming instability.

In this Letter we examine the possibility of dust heating due to thermal electric field fluctuations and DA waves. In the first part of our calculation, described below, we show that heating due to thermal electric field fluctuations is sufficient to account for the high dust temperature observed in stable dust clouds without DA waves or any other type of non-thermal fluctuations. In the second part of our calculation, we examine the possibility of dust heating due to DA waves using global energy constraints. These arguments show that the DA waves are also potentially capable of heating dust to high temperatures.

1. Dust heating due to thermal electric field fluctuations

Dust heating due to thermal electric field fluctuations arises as follows. Electrostatic fields within dust clouds in dusty plasma experiments fluctuate due to equilibrium thermal fluctuations in the background plasma. Dust particles acquire random motion in these fluctuating fields causing dust electrostatic (ES) pressure P_E [15–19] and corresponding temperature which is much bigger than the

* Corresponding author at: RUB International Chair, International Center for Advanced Studies in Physical Sciences, Faculty of Physics and Astronomy, Ruhr University Bochum, 44780 Bochum, Germany
E-mail address: profshukla@yahoo.de (P.K. Shukla).
[1] Permanent address: Department of Physics and Astrophysics, University of Delhi, Delhi 110007, India.

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dust kinetic pressure and temperature. This is a simple thermodynamic effect related to thermal electric field fluctuations and the following estimate shows that it is enough to account for the high dust temperature. The typical mean screened potential in the dust cloud formed in RF and glow discharges where the screening is predominantly due to cooler ions is on the order of $\psi \approx T_i/q$. In these fluctuating fields a dust particle with charge q_d acquires a mean kinetic energy $\sim q_d\psi \sim Z_d T_i$. At low neutral gas pressure where the frictional drag dust-neutral collision is weak, a good fraction of this energy is retained, in which case the average dust kinetic energies are $\sim Z_d T_i \sim 30$–300 eV for $T_i \sim 0.03$ eV and $Z_d \sim 10^3$–10^4. The large dust kinetic energies are essentially due to the large value of the dust charge.

In the following we calculate this effect rigorously. We begin by considering a group of N_d discrete point dust particles each carrying a negative charge q_d dispersed within a neutralizing, statistically averaged (uncorrelated) plasma background of temperature T and volume V. The plasma contains N_e electrons, N_i ions such that there is overall quasi neutrality in V i.e. $q_d N_d = q(N_i - N_e)$. The dust particle cloud is confined locally in a volume V_d $(V_d < V)$ within the plasma by a suitable configuration of external fields and forces. Let the temperature of dust particles be denoted by T_d. The cloud and the plasma are considered to be stable (without DA waves or any other type of non-thermal fluctuations). This system is similar to the one considered earlier [19,20] except that now dust particles are also assumed to have finite temperature.

We begin by calculating the entropy of the background plasma which, apart from plasma thermal contributions, contains extra contributions due to electric fields of the background plasma. Since the background plasma is assumed to be ideal, the entropy S is given by the Thomas Fermi expression for the ideal gas

$$S = \frac{5}{2}(N_e + N_i) - \sum_\alpha \int n_\alpha(r)\left[\ln n_\alpha \Lambda_\alpha^3\right] dr,$$
$$\Lambda_\alpha^3 = \left(\frac{h^2}{2\pi m_\alpha T}\right)^{3/2}, \quad \alpha = i, e, \tag{1}$$

where n_α is the local number density of α-th species. In thermal equilibrium, the electron and ion densities are given by Boltzmann relations $n_e = c_e e^{q\psi/T}$, $n_i = c_i e^{-q\psi/T}$ where ψ is the potential of the electrostatic field which is localized within V_d and is zero away from it where there no dust particles and ion and electron densities are equal given by $c_e = c_i = n_0$. We assume $q\psi/T < 1$ in which case Boltzmann relations can be linearized to give electron and ion densities as $n_i = n_0(1 - q\psi/T)$ and $n_e = n_0(1 + q\psi/T)$. Substituting these relations in Eq. (1) and retaining terms of order ψ^2 gives [21]

$$S = \frac{5}{2}N - \sum_\alpha N_\alpha\left(\ln n_0 \Lambda_\alpha^3\right) - \frac{\varepsilon_0 \kappa_d^2}{2}\int_{V_d} \psi^2\, d^3r, \tag{2}$$

where $\kappa_d^2 = 1/\lambda_d^2 = (\varepsilon_0 T/q^2 n)^{-1}$, n is the average plasma density given by $n = 2n_0 = N/V$, $N = N_e + N_i$ and λ_d is the linearized Debye length. In Eq. (2), the last term gives the contributions due to the fluctuating ES fields of background plasma within the dust cloud. We will show that it is this term which is responsible for the large dust temperatures observed in stable dust clouds. To calculate this term we need to evaluate ψ which is given by the usual superposition of the shielded Yukawa potential of N_d discrete dust particles

$$\psi = -\frac{q_d}{4\pi\varepsilon_0}\sum_j^{N_d} \frac{\exp(-\kappa_d|r - r_j|)}{|r - r_j|}. \tag{3}$$

Substituting ψ from Eq. (3) in the last term in Eq. (2) we get

$$\frac{\varepsilon_0\kappa_d^2}{2}\int \psi^2\, d^3r = \frac{\varepsilon_0\kappa_d^2}{2}\left(\frac{q_d}{4\pi\varepsilon_0}\right)^2 \int \sum_i \frac{\exp(-\kappa_d|r - r_i|)}{|r - r_i|} \times \sum_j \frac{\exp(-\kappa_d|r - r_j|)}{|r - r_j|}\, d^3r. \tag{4}$$

In Eq. (4), the integrals can be performed term by term in spherical polar coordinates to give [20]

$$\sum_i\sum_j \int \frac{\exp(-\kappa_d|r - r_i|)}{|r - r_i|}\frac{\exp(-\kappa_d|r - r_j|)}{|r - r_j|}\, d^3r = \frac{2\pi N_d}{\kappa_d} + \frac{2\pi}{\kappa_d}\sum_i\sum_j{}' \exp\left(-\kappa_d|r_i - r_j|\right). \tag{5}$$

Substituting Eqs. (4) and (5) in Eq. (2) we finally get the total entropy of the plasma as

$$S = \frac{5}{2}N - \sum_\alpha N_\alpha\left(\ln n_0\Lambda_\alpha^3\right) - \frac{q_d^2\kappa_d N_d}{16\pi\varepsilon_0 T} - \frac{q_d^2\kappa_d}{16\pi\varepsilon_0 T}\sum_i\sum_j{}' \exp\left(-\kappa_d|r_i - r_j|\right). \tag{6}$$

Dust clouds in Refs. [4–10] are usually in the weakly coupled gaseous state. In this limit the correlation effect which scale as $(q_d^2/T_d a)\exp(-a/\lambda_d)$ are negligible ($a = \sqrt[1/3]{3/4\pi n_d}$ is the mean distance between dust particles) and the dust can be smeared out into a smooth fluid with density $n_d = N_d/V_d$. In this limit $q_d \to 0$ however $N_d q_d$ remains finite. Hence the third term in Eq. (6) goes to zero while the double summations is evaluated by converting it into integration by replacing $\sum_i\sum_j = n_d N_d \int_{V_d} \cdots dV_d$. Performing the integration and substituting it in Eq. (6) finally gives the entropy as

$$S = \frac{5}{2}N - \sum_\alpha N_\alpha\left(\ln n_0\Lambda_\alpha^3\right) - \frac{q_d^2 N_d^2}{2\varepsilon_0\kappa_d^2 T V_d}. \tag{7}$$

The calculation can now be completed by calculating the Helmholtz's free energy F of the whole system (plasma and dust) defined as $F = U - TS - T_d S_d$ where U is the internal energy of the system and S_d is the entropy of the dust. It should be noted that the last term in Eqs. (2) and (7) depends on the dust volume V_d and hence there are extra contributions of electrostatic origin from this term to dust pressure over the usual thermal contributions. The internal energy U of the system is given by

$$U = \frac{3}{2}NT + \frac{3}{2}N_d T_d + \frac{1}{2}\int \rho\psi\, d^3r - \frac{q_d^2}{8\pi\varepsilon_0}\sum_{j=1}^{N_d}\int \frac{\delta(r - r_j)}{|r - r_j|}\, dr, \tag{8}$$

where the first two terms represents the thermal energies of the plasma and the dust, the third term gives the total electrostatic energy while the last term removes the infinite self energy of discrete dust particles formally contained in the second term.

In order to calculate U in the gaseous limit we note that the total ES field within V_d can expressed as the sum of the mean field and that due to correlations i.e. $\psi = \langle\psi\rangle + \psi_c$. Now, in the ideal limit, $\psi_c \to 0$, the last term is not required, while the second term is zero because $\int \rho\langle\psi\rangle\, d^3r = \langle\psi\rangle \int \rho\, d^3r = 0$, therefore $U = 3/2(NT + N_d T_d)$ [19,20]. The entropy of ideal dust particles is given by $S_d = 5/2N_d - N_d(\ln n_d\Lambda_d^3)$. Substituting expressions for U,

S and S_d in F we obtain the total dust pressure P_D through the thermodynamic relation

$$P_D = -\frac{\partial F}{\partial V_d}\bigg|_{T,T_d} = P_d + P_E = \frac{N_d T_d}{V_d} + \frac{q_d^2 N_d^2 T}{2q^2 n V_d^2}. \tag{9}$$

In Eq. (9), the second term is the dust ES pressure P_E in the fluid limit which has been discussed earlier [15–20]. This pressure is due to the background plasma entropy and corresponds to an extra dust random kinetic energy density that is acquired when dust particles are accelerated in plasma electric fields within the dust cloud (which fluctuate due to the plasma temperature) within V_d. The extra random kinetic energy per particle is equivalent to a dust temperature of electrostatic origin denoted by T_E. These considerations allows us to express $P_D = n_d T_D$, where T_D is the total dust temperature given by

$$T_D = T_d + T_E, \quad T_E = \frac{q_d^2 n_d}{2q^2 n} T. \tag{10}$$

Another interesting interpretation of the temperature T_E is that it is the average electrostatic energy per dust particle i.e. $T_E = q_d\langle\psi\rangle/2$. This can be seen by noting that from quasi neutrality condition $\langle\psi\rangle = q_d n_d T/q^2 n$ (the factor of half occurs because the ES field ψ is the self consistent field due to all the dust particles). It should be noted both T_d and T_E are state variable of the system and hence are physical quantities which can be measured in experiments. The scaling $P_E, T_E \propto q_d^2$ is noteworthy.

In case of unequal electron and ion temperatures $T_e \gg T_i$ usually encountered in RF and glow dusty plasma discharges, the electric fields are determined by the ion temperature. In this case $T \to T_i$ in Eq. (10) and with $T_d \approx T_i$, $T_D \approx (1 + pZ_d/2)T_i$ where $q_d/q = Z_d$ while $p = Z_d n_d/n$ is the Havnes parameter. Since $T_E \propto Z_d^2$ and $Z_d \sim 10^3$–10^4, T_E is much larger than T_d. For $T_i \approx 0.03$ eV, $T_D \sim T_E$ is in the range of 10–300 eV. For example in Auburn experiments [6], $p \sim 0.8$ and $Z_d \sim 3000$, $T_D \sim 36$ eV. In microgravity experiment on the other hand, $p \sim 0.4$ and $Z_d \sim 2 \times 10^3$ and hence $T_D \sim 10$ eV [22]. While in Refs. [1,2] which were first experiments to report large dust temperatures with bigger dust particles (~ 5 μm), $Z_d \sim 3 \times 10^4$ and $p \sim 0.5$, T_D can be as large as ~ 250 eV. Interestingly, in this Letter the dust temperature was also calculated theoretically by solving the corresponding Langvin's equation with experimentally measured fluctuating electric fields measured upstream of the dust particle layer. However these were found to be too weak to account for the experimentally observed large dust temperatures. Hence Quinn and Goree surmised that it is fluctuations originating elsewhere, most probably within the dust layer itself, which are responsible for large dust temperatures [2]. Their surmise is indeed confirmed by our explanation here which shows that it is the acceleration in the plasma electric fields around dust particles located *within* V_d which is responsible for large random dust kinetic energy.

The dependence of dust temperature T_D on q_d and n_d for typical plasma and dust parameters are shown in Figs. 1 and 2. For constant plasma temperature T and dust charge, the total dust pressure P_D satisfies the ES isothermal equation of state $P_D \approx P_E \propto n_d^2$ [19] or equivalently $T_D \approx T_E \propto n_d$. Next we briefly discuss effect of dust–dust correlations which are important in the high dust density. In this regime the total dust pressure P_D is given by the equation of state [20]

$$P_D = n_d(T_d + T_E) - \frac{\partial}{\partial V_d}\left(\frac{q_d^2}{8\pi\varepsilon_0}\sum_i\sum_j \frac{\exp(-\kappa_d|r_i - r_j|)}{|r_i - r_j|} - \frac{q_d^2 N_d^2 T}{2q^2 n V_d}\right)\bigg|_T + T_d \frac{\partial S_{dc}}{\partial V_d}\bigg|_{T_d}, \tag{11}$$

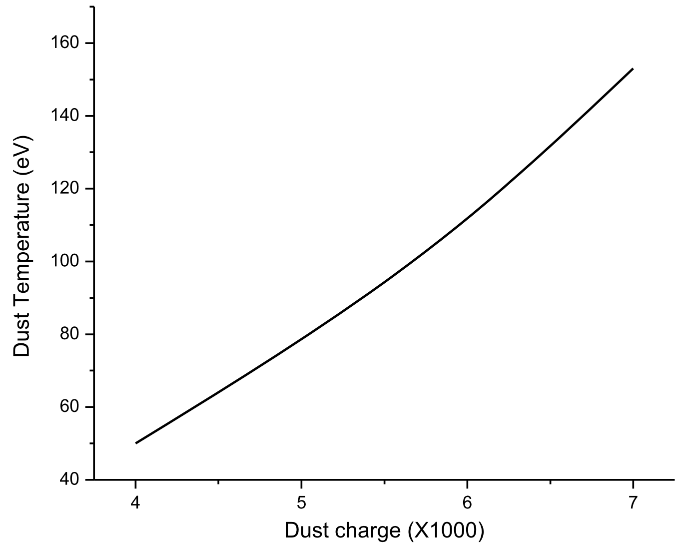

Fig. 1. Dust temperature T_D as a function of dust charge Z_d (in units of electronic charge q) for constant dust and plasma density ($n_d = 10^4$ cm^{-3}, $n = 5 \times 10^7$ cm^{-3}) and constant ion temperature ($T_i = 0.03$ eV).

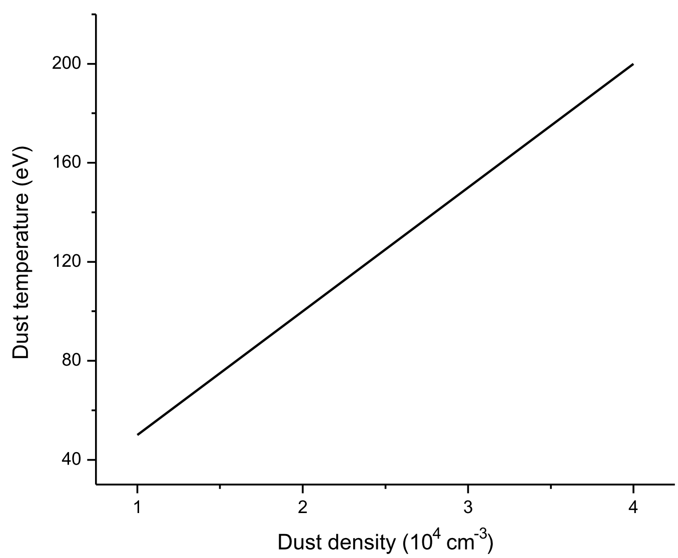

Fig. 2. Dust temperature T_D as a function of dust density n_d for constant dust charge ($Z_d = 4000$), plasma density ($n = 5 \times 10^7$ cm^{-3}) and ion temperature ($T_i = 0.03$ eV).

where we have included contributions to dust entropy from correlations in the last term. From this expression we see that while dust pressure has contributions from the dust correlations at higher dust densities there are no contributions to the dust temperature T_D which is still given by entropic contributions in the first term and corresponds to actual random motion of the dust. In this regime it is thus questionable to express P_D as the product $(n_d T_d^{\text{eff}})$ where T_d^{eff} is some effective dust temperature [23]. Next we discuss dust heating due to DA waves.

2. Dust heating by dust acoustic waves

Spontaneously excited dust acoustic waves in dc discharge dusty plasmas have often been observed. The excitation mechanism is due to an ion-dust streaming instability [14]. The electric fields associated with the discharge currents typically produce ion drifts on the order of the ion thermal speed which are sufficient to produce the DA waves. It was also shown [24] that if the discharge current was reduced below a critical value, the DA waves were quenched. The quenching of the DA waves was accompanied by the remarkable effect that the general characteristics of the dusty plasma changed from a gaseous/liquid-like state to a more quiescent, ordered state in which individual dust particles could be discerned [24]. This observation suggested that the DA waves were energizing the particles leading to a high dust temperature.

The possibility that dust particles can be heated by dust acoustic waves can be seen from the following argument in which the DA wave energy density W_{DA}, is compared to the thermal energy density of the dust, $W_{\mathrm{thd}} = n_d T_d$. For DA waves, the particle energy density is much larger than the energy density in the wave electric field, so that

$$W_{\mathrm{DA}} = \frac{1}{2} m_d n_d u_{d1}^2, \tag{12}$$

where u_{d1} is the perturbed velocity of the dust in the DA wave. Using the equation of continuity the dust velocity can be related to the wave amplitude as

$$u_{d1} = \frac{\omega}{\kappa}\left(\frac{n_{d1}}{n_d}\right) = C_{\mathrm{DA}}\left(\frac{n_{d1}}{n_d}\right), \tag{13}$$

where n_{d1}/n_d is the DA wave amplitude, and C_{DA} is the dust acoustic speed. Combining the last three expressions, we arrive at an upper bound on the dust temperature

$$T_d \leqslant \frac{1}{2} m_d C_{\mathrm{DA}}^2 \left(\frac{n_{d1}}{n_d}\right)^2. \tag{14}$$

The point here is to see if there is sufficient energy in the DA waves to heat the dust. For typical dc discharge dusty plasmas with 1 micron dust particles, $m_d \sim 10^{-14}$ kg, $C_{\mathrm{DA}} \sim 10$ cm/s, and $\sim n_{d1}/n_d \sim 0.5$, we find that $T_d \sim 100$ eV. Thus the considerations of the global energy constraints given here indicate that DA waves, when present, can also provide a viable dust heating mechanism.

We have thus shown that both, the thermal electric field fluctuations as well as DA waves are capable of heating dust to high temperatures in the range of a few hundreds of eV. In stable dust clouds, thermal electric field fluctuations heat the dust to within a few hundreds of eV. When DA waves are present, they further heat dust to still higher temperatures in excess of a few hundreds of eV as observed in experiments and simulations [8,12,13]. The dispersion relation of DA wave in short and long wave number regimes with P_D from equation of state in Eq. (11) will be reported in future.

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