Supplementary material for manuscript "Quantum hydrodynamics for plasmas– quo vadis?"

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This supplement contains additional information on 1. the stability of dust particles in a quantum degenerate plasma and 2. representative examples of QHD articles.

1 Dust grain destruction mechanism under dense quantum plasma conditions

The most important destruction mechanisms of a dust particle (if it would exist) in a quantum plasma are due to the fluxes of ions and electrons to the surface of the grain and include (i) melting and evaporation of the dust material due to heating, (ii) sputtering of the dust material, and (iii) field emission of ions from the dust particle. [We do not consider dust material sublimation, which is too slow for our consideration, even though it becomes relevant on astrophysical time scales [1]].

Mechanism (i) takes place when the cooling of a dust particle by neutral atoms, radiation, thermal emission of electrons and ions is unable to stabilize the dust material temperature. On the other hand, mechanisms (ii) and (iii), are important at high energies of ions colliding with the dust particle surface [2, 3]. In the context of this paper, "high temperature" means that the ion (atom) temperature exceeds the melting temperature of the dust particle, $T_i > T_m$. At high temperatures and low plasma density ($n_e \sim 10^{12} - 10^{14}$ cm^{-3}), the investigation of a micron size dust particle evolution in the plasma of tokamak fusion devices showed that the life time of a dust particle, τ, ranges from $\tau \sim 10^{-4}$ s to $\tau \sim 0.1$ s, depending on the initial size of the grain [3, 4]. Comparing this to quantum plasmas of similar temperature but much higher densities, $\gtrsim 10^{23}$ cm^{-3}, the dust particle life time would be much shorter, because the energy flux to the surface of a dust particle, which is proportional to n_e, is larger billions times.

At lower temperatures and densities in the range of 10^{23} cm^{-3} and 10^{24} cm^{-3}, calculations based on the model of Ref. [3] that takes into account all important heating and cooling mechanisms as well as sputtering, yields $\tau \ll 1$ s. For example, at $T = 10$ K, for a micron sized dust particle [relevant dust materials are tungsten, graphite, and silicates], $\tau < 1$ ns, whereas at 1000 K, $\tau \lesssim 0.1$ ns. At still higher temperature and fixed density, τ is obviously even shorter, as dust destruction becomes more efficient with increase of temperature. Therefore, we conclude that dense astrophysical objects, such as the dense atmosphere of a neutron star, is not a candidate for a "quantum dusty plasma".

1.1 Surface temperature of a dust particle in a quantum plasma

Let us now discuss in more detail why a dust particle cannot survive in plasmas with densities, $n_e > 10^{23}$ cm^{-3} which is required to achieve quantum degeneracy of free electrons (condition I. in the main paper). Recall that the dust particle surface temperature is stabilized most effectively via cooling by neutral atoms, and by radiative energy loss [5, 6]. At these densities which are close to the Mott transition or beyond, the degree of ionization approaches one, and the cooling by neutral atoms is not relevant. For the dust surface temperature to be stabilized, the heat flux to the grain surface due to energy deposition of collected ions and electrons and their recombination, Γ_H, should equal the energy loss flux due to radiation, Γ_R. The former is approximated as $\Gamma_H \approx J_0 k_B T_e(2 + \phi_s + I/k_B T_e)$, where I is the ionization energy, and the plasma flux is approximated in OML, $J_0 \simeq \sqrt{8\pi} a_D^2 n_e v_{T_e} \exp(-\phi_s)$, e.g. Ref. [5]. The radiation flux is treated as black body radiation, $\Gamma_R \approx 4\pi a_D^2 \sigma \left(T_s^4 - \zeta T_e^4\right)$, where σ is the Stefan-Boltzmann constant and $\zeta > 1$ is a correction due to a positive shift of the radiation frequency in a plasma, $\omega^2 = c^2k^2 + \omega_p^2$, cf. Ref. [7]. Assuming stability of the surface temperature, we find:

$$T_s^4 \gtrsim n_e T_e^{3/2} \frac{k_B^{3/2}}{\sqrt{2\pi m_e}\sigma} e^{-\phi_s}(2 + \phi_s + I/T_e) + \zeta T_e^4, \tag{S1}$$

where $\left(\frac{k_B^{3/2}}{\sqrt{2\pi m_e}\sigma}\right)^{1/4} \simeq 2.5 \times 10^{-2}$ (in CGS units).

Using Eq. (S1) with $\phi_s \sim 1$ and $k_BT_e \gtrsim I$, we find that radiation is unable to prevent dust particle melting as $T_s > \left(10^{16} \times T_e^{3/2} + T_e^4\right)^{1/4}$, at $n_e \gtrsim 10^{23}$ cm^{-3}. Indeed, even if we minimize thermal effects by assuming an unrealistically low plasma temperature, $T_e = 1$ K, we find that $T_s > 10^4 \times T_e^{3/8} \simeq 10^4$ K and, at the considered high densities, the dust particle surface temperature is well above the melting temperature of all known materials. At a more realistic plasma temperature, $T \sim 10^4$ K, we find that $T_s > 10^5$ K. Therefore, at these high densities, melting of the dust particle is unavoidable. Melting, in turn, facilitates evaporation of atoms, sputtering, and field emission from the surface and rapid destruction of the dust particle. Indeed, the heat flux per dust particle atom, Γ_H/N, exceeds the binding energy of the surface atoms, E_D, which is in the range of a few eV, and one easily finds that a micron sized dust particle of the considered materials will loose every single atom within less than 1 ns.

To summarize, we conclude that dust particles cannot survive in dense plasmas with $n_e \gtrsim 10^{23}$ cm^{-3}. In particular, a dust particle would not be stable in the atmosphere of neutron stars or the interior of white dwarfs. This conclusion is also backed by the independent analysis of the quantum pressure of degenerate electrons that destroys micrometer and nanometer size particles, cf. Sec. V.C of the main text.

1.2 Surface potential of a dust particle in a quantum plasma

Here we show that, if a dust particle would exist in a quantum plasma, its dimensionless surface potential would be on the order of unity. In dense quantum plasmas (see Fig. 2 in the main manuscript), the diameter of a micro- or nano-particle is much larger than the characteristic plasma length scales such as the mean interelectronic distance and the screening length (Thomas-Fermi screening length). Therefore, the flux (total current) of electrons and ions through a closed spherical surface of radius r around a dust particle can be computed using the drift-diffusion (extended Mermin) approximation:

$$J_{i(e)} = 4\pi r^2 \left(\pm Z_{i(e)}|e|\mu_{i(e)} n_{i(e)} E - Z_{i(e)}|e| D_{i(e)} \frac{\partial n_{i(e)}}{\partial r}\right), \tag{S2}$$

where the upper and lower signs correspond to the flux of ions and electrons, respectively. In Eq. (S2), $\mu_{i(e)}$ denotes the mobility, $D_{i(e)}$ the diffusion coefficient, Z_i the charge number of an ion, and $Z_e = 1$. For classical ions, Einstein's relation applies: $D_i = \mu_i k_B T_i/(|Z_i e|)$. For quantum electrons, the analogue of the classical Einstein relation is more complicated, e.g. [8, 9]. In the case of strong degeneracy, $\theta_e \ll 1$, one can use $D_e \simeq (2/8)(E_F\mu_e/|e|)$, cf. Ref. [9]. In a stationary state ($\partial n_{i(e)}/\partial t = 0$), the total flux $J_{i(e)}$ is constant. Assuming that all electrons and ions colliding with the dust particle surface are absorbed (recombine), we have the boundary condition $n_{i(e)}(r = a_d) = 0$. From this and, taking $E = \frac{Z_d e}{r^2}$ in the vicinity of the dust particle, we find the solution of Eq. (S2):

$$n_{i(e)}(r) = \pm \frac{J_{i(e)}}{4\pi Z_d e^2 \mu_{i(e)} Z_{i(e)}} \left[1 - \exp\left\{\pm \frac{Z_d|e|\mu_{i(e)}}{D_{i(e)}}\left(\frac{1}{a_d} - \frac{1}{r}\right)\right\}\right]. \tag{S3}$$

Using the second set of boundary conditions, $Z_i n_i(r \to \infty) = n_e(r \to \infty) = n_0$, for the total flux, we find from Eq. (S3):

$$J_{i(e)} = \frac{\pm 4\pi Z_d e^2 \mu_{i(e)} n_0}{1 - \exp\left\{\pm \frac{Z_d|e|\mu_{i(e)}}{D_{i(e)} a_d}\right\}}. \tag{S4}$$

The non-linear equation for the dust particle charge follows from Eq. (S4) recalling that, in a steady state, the total current of electrons is equal to that of ions. For the quantum plasma with classical ions and degenerate electrons, $E_F \gg k_B T_{e(i)}$, we derive the charge number of the dust particle:

$$Z_d \simeq -\frac{a_d}{|e|}\frac{D_e}{\mu_e} \ln\left(\frac{\mu_e}{\mu_i} + 1\right), \tag{S5}$$

from which we find for $\phi_s = -Z_d e^2/a_D E_{Fe}$:

$$\phi_s \simeq \frac{|e|}{E_F}\frac{D_e}{\mu_e} \ln\left(\frac{\mu_e}{\mu_i} + 1\right). \tag{S6}$$

For $Z_i = 1$ ($Z_i = 10$), assuming $\frac{\mu_e}{\mu_i} \simeq \frac{m_e}{m_i}$, and taking $D_e \simeq (2/8)(E_F\mu_e/|e|)$ [9], we obtain $\phi_s \simeq 1.9$ ($\phi_s \simeq 2.5$), in agreement with the discussion in Sec. V.A. in the main manuscript. Note that, for classical electrons, $D_e = \mu_e k_B T_e/|e|$, and Eq. (S5) reproduces the result for a low temperature classical plasma with $T_e \gg T_i$ [10].

2 Examples

In the following we consider a few representative examples of QHD papers for quantum plasmas.

2.1 The paper of Ali and Shukla, Ref. [11]

In the very first paper on "quantum dusty plasmas" Ali and Shukla considered the one-dimensional problem of a zero-temperature mixture of three ideal Fermi gases of electrons (e), ions (i) and dust particles (d) with the Fermi temperatures $k_B T_{Fj} = E_{Fj}$ and mean densities n_{j0}, where $j = e,\ i,\ d$. Electrons and ions were considered inertialess, obeying the following linearized momentum equations:

$$0 = \mp e\frac{\partial \phi}{\partial x} - \frac{2k_B T_{Fi(e)}}{n_{i(e)0}}\frac{\partial n_{i(e)1}}{\partial x} + \frac{\hbar^2}{4m_{i(e)}n_{i(e)0}}\frac{\partial^3 n_{i(e)1}}{\partial x^3}, \tag{S7}$$

where the upper (lower) sign is for ions (electrons). In Eq. (S7), $n_{i(e)1}$ denotes a small ion (electron) density perturbation, and ϕ stands for the mean electrostatic potential. The negatively charged dust particles are described by the continuity equation and the linearized momentum equation,

$$m_d\left(\frac{\partial}{\partial t} + \nu_d\right)u_d = Z_d e\frac{\partial \phi}{\partial x} - \frac{2k_B T_{Fd}}{n_{d0}}\frac{\partial n_{d1}}{\partial x} + \frac{\hbar^2}{4m_d n_{d0}}\frac{\partial^3 n_{d1}}{\partial x^3}, \tag{S8}$$

where $n_{d1} \ll n_{d0}$ is the perturbation of the dust particles density, and ν_d is the dust-neutral collision frequency. The last terms on the right hand sides of Eqs. (S7) and (S8) are due to the Bohm potential, cf. Sec. III of the main text.

Solving Eqs. (S7) and (S8), together with the relevant continuity equations, the dispersion relation of the quantum dust acoustic wave was obtained [11]:

$$\omega(k) = -i\frac{\nu_d}{2} \pm \left[-\frac{\nu_d^2}{4} + k^2 V_{Fd}^2(1+\gamma_d) + \frac{k^2 C_{Dq}^2(1+\gamma_i)}{1+\sigma}\right]^{1/2}, \tag{S9}$$

where $\sigma = n_{e0}T_{Fi}\left(1+\gamma_i\right)/n_{i0}T_{Fe}(1+\gamma_e)$, $C_{Dq} = Z_d(2k_B T_{Fi}n_{d0}/m_d n_{i0})^{1/2}$, $\gamma_j = \hbar^2 k^2/8m_j k_B T_{Fj}$, and $V_{Fd}^2 = 2k_B T_{Fd}/m_d$. For the collisionless case, $\nu_d = 0$, Eq. (S9) simplifies to

$$\omega(k) = k\left[V_{Fd}^2(1+\gamma_d) + \frac{C_{Dq}^2(1+\gamma_i)}{1+\sigma}\right]^{1/2}. \tag{S10}$$

The classical dust acoustic wave is recovered if the Bohm potential is neglected ($\gamma_j \to 0$) and T_{Fj} is replaced by the temperature T_j. On the basis of Eqs. (S9) and (S10), the authors concluded that the dust acoustic wave in a "quantum dusty plasma" significantly differs from that in a classical dusty plasma. Without discussing the validity of their results the authors came to the conclusion that they "can be helpful for diagnostics of charged dust impurities in microelectronics".

However, it remains completely open what the considered model has in common with materials or devices that are being used in microelectronics and whether the computed dust acoustic mode can occur at all in these systems. In fact, as we have shown in Sec. V.C of the main text, elementary considerations lead to the conclusion that the dust acoustic mode (S9) does not exist in a quantum plasma.

A further example is discussed in the next section. We note in passing that the original QHD equations (S7, S8) are incorrect: in the low-frequency regime the Bohm term has to be multiplied by a factor 1/9 [12, 13], and also the Fermi pressure term is incorrect, cf. Sec. III.F of the main text.

2.2 The example of reference [14]

The authors of this reference considered a slightly more realistic [compared to Sec. 2.1] case of QDP where the dust particles are non-degenerate whereas electrons and ions are treated as a zero-temperature Fermi gases. After analyzing linear dust acoustic waves, the authors turn to nonlinear excitations such as solitons. Applying standard methods they derive a Korteweg de Vries equation, for low-amplitude dust acoustic solitons, and a Sagdeev potential, for high amplitude solitons, in analogy to classical dusty plasmas. The analysis appears to be formally correct and carefully done, and the soliton properties are systematically studied by varying the QDP parameters in a broad range. Examples from that article for two cases of QDP (using the terminology of the authors) – "semiconductor quantum wells" and "white dwarfs, magnet stars etc." – are reproduced in table 1.

Parameter	"Semiconductor quantum well"	"white dwarfs, magnet stars, etc."
n_{e0} [cm^{-3}]	$5 \cdot 10^{16}$	$2 \cdot 10^{27}$
T_{Fe} [K]	5.74	$6.71 \cdot 10^{7}$
T_{Fi} [K]	10^{-4}	2946
n_{d0} [cm^{-3}]	10^{11}	$1.9 \cdot 10^{21}$
m_d [m_i]	10^{12}	?
Z_{d0}	10^{3}	10^{3}
soliton amplitude [V]	$-3.93 \cdot 10^{-15}$	$-2.14 \cdot 10^{-8}$
soliton width [Å]	0.807	0.0136

Table 1: "Quantum dusty plasma" parameters used by and dust acoustic soliton parameters obtained in Ref. [14]. The amplitude of the electrostatic pulse is given in volts.

Let us critically analyze the validity of these parameters. First, for the semiconductor case (second column), the authors write that they "adopt a set of parameters of relevance to semiconductor quantum wells" [citation from pp. 9-10]. Instead of consulting a primary source on semiconductor physics, they refer to another reference on QDP, Ref. [15]. However, already elementary knowledge in semiconductor physics, cf. Sec. IV A. in the main manuscript, raises serious questions and concerns about the chosen parameters: at low temperature the density of free electrons (in the conduction band) is typically small. So how is this density produced and what is its lifetime against recombination? What are the ions in a semiconductor quantum well to which the given Fermi temperature refers to? By comparing the Fermi temperatures of electrons and ions one concludes that the mass of the ions equals $57,400\ m_e$. So, what material do the authors consider? However, there is no "gas of ions" inside a semiconductor and no Fermi gas in particular. Ions form the host lattice but they are essentially immobile and, at typical temperatures, far from quantum degeneracy. Further, the authors do not present a value for the temperature of the semiconductor. Their Fermi gas analysis is only formally correct if the temperature is well below the Fermi temperature. This means they have to suppose that the ion temperature is on the order of or below 10^{-5} K. How can such a situation be realized in a real semiconductor?

As the second example (third column), the authors use the "typical set" of parameters for "white dwarfs, magnet stars, etc." [citing from p. 10]. One may wonder how such diverse systems can have "typical" parameters (besides, it is not even explained what a "magnet star" is). And indeed, their choice is again not based on a primary source, but on another QDP reference, Ref. [16]. While the electron density is in the range of white dwarf parameters [cf. Fig. 2 in the main manuscript], the ion data raise questions. Even though the authors omit information about the ion species, from the ratio of the Fermi temperatures, one can conclude that the ions, probably, refer to carbon. However, treating the ions as a Fermi gas, as the authors do, requires elementary tests for the system to be physical. Are these C^{6+} ions? Ions of what carbon isotope? In fact, the most common isotope ^{12}C is a boson for which the present considerations are wrong. The ^{13}C nucleus, on the other hand, is a fermion but its natural abundance (on Earth) is about one percent. This means that the analysis of fermionic plasma properties has to be revised. Finally, as in the case of the semiconductor example, thermal effects are ignored which means that the temperature is implied to be much less than the ion Fermi temperature, i.e. $T \lesssim 1000K$. Such low temperatures are not expected to exist in the core of white dwarf stars to which the given electron density refers to. So both quantum plasma examples that have been discussed in Ref. [14] are internally inconsistent and have nothing to do with reality, even without considering an additional dust component. An analysis based on such examples will never have the chance to be taken serious by the semiconductor or astrophysics communities or even to contribute new knowledge in these fields.

Let us now turn to the dust component, cf. table 1. The authors assume that the plasma of a white dwarf star contains dust particles of a density that exceeds 10^{21} cm^{-3}. There is no explanation given how a system of dust particles that have a mean interparticle distance of 5 Å each and acommodate 1000 elementary charges, can exist and what the particle radius would be. These elementary considerations did not even involve the questions of stability of dust particles in a quantum plasma that were analyzed in Sec. 1 and in Sec. V C. in the main manuscript. The situation is even more critical for the semiconductor example. A dust particle with a charge number $Z_d = 1000$ has (in a dusty plasma) a radius of about $a_D \sim 1\ \mu m$ whereas the given density corresponds to a mean distance between neighboring dust particles of 1.3 μm. Finally, the authors suggest that one can insert into a cube of solid semiconductor material of side length 1cm a total of 10^{11} of these dust particles. Before that one would need to remove the host semiconductor material to make room for the dust particles. Finally, let us consider the parameters of the dust acoustic solitons that are presented in the bottom lines of Tab. 1. Even if one would assume that the presented QDP exists, the prediction of a soliton amplitude on the order of 10^{-15} V (10^{-8} V) makes the results irrelevant for a semiconductor (white dwarf), compared to other fields existing in these systems. Moreover, by predicting a soliton width of less than 1 Å implies that QHD can resolve subatomic length scales which is impossible as was shown in Sec. V.F of the main text.

To conclude this brief discussion of Ref. [14] we quote from the abstract of that paper: "Our results aim at elucidating the characteristics of electrostatic excitations in dust-contaminated dense plasmas, e.g., in metallic electronic devices, and also arguably in supernova environments, where charged dust defects may occur in the quantum plasma regime." This claim is re-iterated in the concluding paragraph, even though the authors only consider (fictiteous) semiconductors and compact dwarf stars in their paper, but nowhere they consider parameters of metallic electronic devices or supernovas.

2.3 Application of QHD to semiconductors. The example of Ref. [17]

Aside from the QDP topic, there are serious more general problems with many of the QHD-based quantum plasma papers. As discussed in the introduction and in Sec. V of the main manuscript, and illustrated on the examples above, it has become common in QHD-based quantum plasmas paper to "extend" their results to other systems, in particular, semiconductors. Let us consider a typical recent example that is not related to "quantum dust" but to solitons. The article is entitled "The effects of geometrical configurations on the head collision on nonlinear solitary pulses in a quantum semiconductor plasma: A case study on GaAs semiconductor" and is by EL-Shamy, Gohman, Alqahtani, and AlFaify, Ref. [17]. The authors start by citing some quantum plasma papers to motivate their research. They also cite experimental papers from semiconductor physics where the observation of solitons and acoustic pulses was reported, e.g. [18, 19]. The authors of Ref. [17] then formulate coupled QHD equations for electrons and holes for the one-dimensional (1D) and isotropic 2D and 3D cases, including an exchange-correlation potential V_{xc} according to Manfredi *et al.* [20].

The equations are cast into dimensionless form, and nonlinear solutions are derived using the standard Poincare-Lighthill-Kuo technique. The authors then investigate the collision of two planar and nonplanar solitary pulses, in particular the dependence of the phase shift on the electron density and on V_{xc}. For the numerical analysis they use the effective masses of electrons and holes, $m_e^* = 0.047 m_e g$, $m_h^* = 0.4 m_e g$ (g is not defined) and the background dielectric function $\epsilon = 12.8$ for GaAs. The authors also present results for GaN, for which no material parameters are given, and conclude their paper with the statement (quote) "...we believe that the present results may help in gaining a deep understanding of the dynamic behavior of nonlinear dark pulses that propagate in quantum semiconductor plasmas."

Unfortunately, Ref. [17] does not allow to gain any understanding of semiconductor plasmas. The results in the figures (in dimensionless units or without labels at all), make it practically impossible to assess how realistic the obtained soliton parameters are. Even though the authors underline in the introduction the experimental observation of solitons in semiconductors, they do not perform a comparison of their results with the experiments. In fact, a quick look at the experimental papers reveals that the reported solitons are caused by completely different physics: they are related to lattice effects (strain pulses) [18, 19] and have nothing to do with plasma effects. Of course, it is not excluded from the beginning that there could be solitons of charged particles in the present electron-hole plasma. However, it is the responsibility of the authors to prove that their results are not only a mathematically correct solution but are also of practical relevance: in particular they would need to verify that dissipation effects between the carriers and with the lattice (which they neglect) do not destroy the solitons and that the electron-hole populations live long enough before recombining [cf. Sec. IV A.] so that the solitons can form at all. Unfortunately, no validity analysis is presented in Ref. [17]. As a consequence, the presented results have to be regarded as irrelevant for real semiconductors.

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