PAPER

Ultracold ions wake in dusty plasmas

Sita Sundar and Zhandos A Moldabekov

1 Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai—600036, India
2 Institute for Experimental and Theoretical Physics, Al-Farabi Kazakh National University, 71 Al-Farabi str., 050040 Almaty, Kazakhstan
3 Institute of Applied Sciences and IT, 40-48 Shashkin Str., 050038 Almaty, Kazakhstan

E-mail: sitaucsd@gmail.com

Keywords: complex plasmas, cryogenic dusty plasmas, wakefield, open non-Hamiltonian system, anistropic forces

Abstract

Motivated by the recent experimental realization of ultracold dusty plasma (2019 Sci. Rep. 9 3261), we present the results of particle-in-cell simulation with Monte-Carlo-collisions for wake behind a dust particle due to focusing of ions at superfluid helium temperature (~2 K). Dynamical screening (wakefield) defines structural and dynamical properties of charged dust particles in plasmas such as phase transition, crystal formation, vibration modes (waves) etc. Here, we delineate in detail the dependence of wake strength on the streaming velocity of ions and on the ion-neutral charge exchange collision frequency (neutrals density) in the ultracold dusty plasma. Lowering the temperature to ultracold level leads to a wake pattern behind a dust particle that completely differs from the wake at normal conditions. For wide range of parameters, most remarkable features of the wakefield are (i) the formation of wake pattern with two maxima split in transverse to ion flow direction in the downstream area, (ii) pronounced inverse V shape of the wakefield closely resembling the wake in quark-gluon plasma and dense quantum plasma (warm dense matter), and (iii) the inter-dust attraction region in transverse direction. The latter shows that molecule-like interaction between dust particles is realized in ultracold dusty plasmas. These observations show a fundamental difference of ultracold dusty plasma physics from well studied complex plasmas at normal conditions.

1. Introduction

Plasmas containing micro and nano-sized dust particles are referred to as the dusty (complex) plasmas [1, 2]. Dust particles of different shapes and sizes are formed in an ionized medium in the laboratory and astrophysical environments. Over the last two decades, dusty (complex) plasmas have grown from its infancy to a mature field with developed theoretical and modeling tools which provide very good agreement with the experiment and have predictable capability. Dusty plasmas are actively investigated in various discharges, where gas temperature is usually about 300 K (further denoted as normal temperature (condition)) [3]. In the quest for new phenomena, dusty plasma experiments are routinely performed in micro-gravity conditions on board international space station [4–7]. In fact, dusty plasmas manifest many interdisciplinary research problems and can be realized in a broad range of parameters (e.g. see [8–13]). The extension of dusty plasma parameter range to cryogenic conditions has been performed in [14–16]. The experiment at ultracold temperatures of superfluid helium in dusty plasma has also recently been reported in [17]. This established a novel connection of dusty plasmas to a new research field named—‘ultracold dusty plasmas’.

It is a well known fact that charged dust particle dynamics is defined by the screening features of the grain charge. In most of the experiments, dust particles are in stationary non-equilibrium plasma environment with streaming of plasma particles. This leads to the deviation of the actual charge screening from the results of equilibrium plasma description. Therefore, the understanding of the dynamical screening (wakefield) in complex plasmas is highly important for qualitative and quantitative description of dust particles dynamics. Previous studies of wakefield in dusty plasmas are limited to the case with neutral particles at normal condition.
At normal temperature, wake observation in dusty plasmas has been discussed in great detail [18–21] in the presence and absence of external electric and magnetic fields [22–25] and collisions [18, 26].

Clearly, to explain dust particles dynamics in ultracold dusty plasmas, the investigation of wake phenomena is of utmost importance. Previous cryogenic dusty plasma works have been restricted to the investigation of opportunity of crystal formation or dense dust structure formation, and the exploration of wake aspect and related inter-grain interaction mediated by plasmas is missing. To this end, in this paper we report the results of detailed research of wake in ultracold dusty plasmas with gas and ion temperature at ~2 K. It appears that wakefield in ultracold dusty plasmas has a number of new features compared to that at normal condition.

We report the results on the wake formation due to one grain in ultra-cold dusty plasmas in section 3, after the description of the simulation method and plasma parameters in section 2. In section 4, we present the main conclusions of the present work and possible future directions.

2. Numerical details and plasma parameters

Numerical simulations are performed with 'DUSTRz' particle-in-cell with Monte-Carlo-collisions (PIC-MCC) hybrid code in cylindrical coordinate [20, 21]. In the present work, we have restricted the distribution to the Maxwellian and Shifted Maxwellian cases for the stationary and drifting ions respectively. Simulation parameters chosen for the investigation are as follows:

(i) Electron temperature $T_e = 3$ eV, ion and neutral (He) temperature $T_i = T_n = 0.00017$ eV (which is equivalent to 2 K), $T_e/T_n \sim 1.7647 \times 10^4$, plasma density $n_i = n_i = 10^8$ cm$^{-3}$, neutrals density (pressure) is in the range from $n_n = 10^{11}$ cm$^{-3}$ to $n_n = 10^{16}$ cm$^{-3}$, the Debye length due to electrons $\lambda_{De} = 1286.9 \mu$m, the Debye length due to ions $\lambda_{D} = 9.68 \mu$m, and the ion charge number $Z_i = 1$. The calculation of coupling parameter of ions gives us a value of $\Gamma_i = 0.6 < 1$, where $\Gamma$ being the mean inter-ionic distance. This corresponds to the regime of weak coupling. It is known that plasma in the weak coupling regime is well described by the mean-field approximation on which the PIC approach is based.

(ii) Helium (He) molecular species is kept at a collision frequency which shares a relation with collision cross-section through $\nu_{in} = \sigma_{in} n_i n_n$ where $\sigma_{in}$ is the collision cross-section. The collision cross-section has been taken to be equal to $\sigma_{in} = 2.79 \times 10^{-15}$ cm$^2$ [15].

(iii) Grains are of cylindrical shape and its radii is chosen to be the same as its length. The dust particle radius is taken to be $a_d = 5 \mu$m. Due to reduced screening length, the grain radius is of the order of the ion screening length in the cryogenic dusty plasmas, i.e. $\lambda_D/a_d = 1.936$ and $\lambda_{De}/a_d = 257.382$.

(iv) Ion streaming velocity encompasses the subsonic, sonic, and supersonic regimes. The Mach number is defined as the ratio of the streaming velocity and thermal velocity of ions and is considered in the range $M_{th} = 0 - 15$.

(v) The initial grain charge chosen in the present work is $\sim 250 e$, which is commensurate with experimental observations [14] and the self-consistent charging of the grain takes place with time evolution.

Electrons and ions keep depositing on the grain and the shielding develops concurrently. Ions are injected from the walls with the velocity consistent with the ambient distribution. Poisson equation is solved at every 10 time steps to get steady state for Poisson solver and large time-steps ($\sim 1000$) to get good particle statistics. Interval for scattering is chosen to be 100 time steps. Grid size of the simulation domain has been chosen to be $257 \times 1025$ in conformity with the Poisson solver. Leapfrog push has been used to get the position and velocity co-ordinates in six-dimensions. The code facilitates the explicit calculation of electric field and potential due to the grain and plasmas. CGS unit has been followed throughout the paper for all the parameters except temperature which is in eV.

3. Simulation results

The cases wherein the source giving rise to the wave moves at a speed higher than the wave itself, in general, one observe wakes. This wake feature is a much discussed phenomena in neutral fluids in general and dusty plasmas in particular. In dusty plasmas under normal conditions, ions streaming past an isolated grain focus behind the grain and give rise to wakefield. It has routinely been a common analytical as well as numerical observation in dusty plasmas [26–29]. A detailed description of these wakes delineating the grain-plasma dynamics under cryogenic environment is presented here.
3.1. Dependence on the ion streaming speed

Relation of the wake potential with variation in ion flow is illustrated in figure 1 (top row). We see that ion streaming speed influences the wake features significantly. As expected, there is no ion focusing for grain in stationary ion case ($M_{th} = 0$). As we increase the ion streaming speed, ion focusing behind grain starts building up at $M_{th} = 5 – 10$ and eventually results in a very strong ion focus. We observe inverse V shape pattern of the wake field similar to the one observed in simulations for quark-gluon plasma and dense quantum plasma wakes (e.g. see [30–32]). Additionally, at $M_{th} = 5$ and $M_{th} = 10$ (see figures 1(c) and (d)), in transverse to ion flux direction the wakefield develops the region characterized by the attraction between dust particles. Furthermore, from figure 1 (top row) we clearly see the formation of the wake pattern with two maxima split in transverse to ion flow direction in downstream area. This is a distinct feature of the wake of ultracold complex plasmas as compared to the dusty plasmas at normal conditions, and other many-particle systems such as quark-gluon plasmas and quantum plasmas (warm dense matter). At normal condition with ion and neutral temperature $\sim 300$ K, the wakefield of a dust particle can have maxima and minima with separation along ion flow direction.

In figure 1 (bottom row), we show corresponding ion density contour in the wake. The density contour for the considered streaming speeds ($M_{th} = 0–10$), shows that there is no separate ion focusing region behind the dust particle. The ion flow leads to the continuous deformation of the screening cloud (i.e. without breaking it to aggregated parts) making it more elongated along flow direction without significant shrinking in transverse direction (see figures 1(f)–(h)). Though the inverse V shape of the wake potential is similar to the one observed in quark-gluon plasmas and warm dense matter [30–32], the profile of wake density is quite different. An important aspect is that even in the equilibrium case, $M_{th} = 0$, one can see from figure 1(e) that the plasma polarization around dust particles is not spherically uniform. Correspondingly, the screened potential at $M_{th} = 0$ (see figure 1(a)) also slightly deviates from the spherical symmetry. The reasons for that are, firstly, the cylindrical shape of the grain (which has already been mentioned in section 2), and, secondly, the fact that the Debye screening length is comparable with the dust particle size.

To explore further the dust particle potential in transverse direction, in figure 2(a), is shown the wake potential transverse to flow at the grain location $z = 0$ and in figure 2(b), the same at the maxima of the twin peak location. The wake has strongly inverted V shape which protrudes the region of attraction of another dust particles in transverse direction at $z = 0$ and in downstream region. From figure 2(a) one can observe that at $M_{th} = 5$ and 10 the wakefield results in the interaction that resembles molecular-like interaction with repulsion.

Figure 1. Figure showing the variation of wake potential and spatial density contour with change in ion streaming speed for $M_{th} = 0$, $M_{th} = 1$, $M_{th} = 5$, and $M_{th} = 10$ at cryogenic temperatures.

In figure 2 (bottom row), we show the variation of wake potential and spatial density contour with change in ion streaming speed for $M_{th} = 0$, $M_{th} = 1$, $M_{th} = 5$, and $M_{th} = 10$ at cryogenic temperatures.
at short distances and attraction at intermediate distances. As one may anticipate, for the case of stationary ions with $M_{th} = 0$, there is a region of attraction around the grain.

From figure 2(b) we see that enhanced ion concentration around the grain results in twin peak in downstream area. These peaks are not located along z axis unlike at normal condition [23], but are separate in transverse to the ion flow direction. At $M_{th} = 5$ and 10, the peak on the both sides of the grain appears. This observation of twin peak is a unique feature of wakefield in ultracold dusty plasmas compared to the wakefield properties discussed in previous works for room temperature plasmas [18, 23, 32] and other types of plasmas wherein one does not observe any such twin peak behind the grain. Hence, it can be envisaged that this twin peak provides an extra handle which can be tweaked to facilitate an attractive intergrain interaction under ultracold dusty plasma conditions.

3.2. Dependence on the neutral density
To maneuver the wake behind grain at ultracold superfluid He temperatures, we investigated the dependence of wake characteristics on the density of neutrals in the system. Neutral density in the simulation depicts the pressure also and a variation in density signifies a variation in ion-neutral charge exchange (BGK type) collisions. In the simulation, ion-neutral charge exchange collision frequency is linearly proportional to the neutral density (see definition of $\nu_{in}$ in section 2(ii)). Dependence of wake potential and density contour on the variation in neutral density (increasing from $10^{13}$ to $10^{16}$ cm$^{-3}$ with intermediate values $10^{14}$ and $10^{15}$ cm$^{-3}$) is illustrated in the top and bottom subplots of figure 3 respectively.

It can be seen from figure 3 that with increase in the neutral density from $10^{13}$ to $10^{15}$ cm$^{-3}$, no significant change in either wake potential or density is visible. As we increase the neutral density (which in turn means a linear corresponding increase in collision frequency as well) beyond $10^{15}$ cm$^{-3}$ (4 Pa), non-monotonic spatial distribution of the wakefield gets strongly suppressed at $10^{16}$ cm$^{-3}$ (which corresponds to 40 Pa). Correspondingly, from the bottom panel of figure 3 we see that the ion focusing behind grain starts depleting with increase in neutral particles density (gas pressure). Compared to the lower values of neutral density, at $10^{16}$ cm$^{-3}$ (40 Pa), the wake density shrinks along the flow direction and, in contrast, widens in transverse to ion flow direction. Apparently, neutral density range also plays a crucial role in wake formation.

Figure 4 illustrates the twin peaks at (a) the center of the grain location ($z = 0$) and (b) at the location of the twin peak itself ($z = z_{max}$) for varying neutral density (which also implies change in neutral pressure or ion-neutral charge exchange collisions). So, as we increase the neutral pressure, the twin peaks do not show much variation until it changes to very high pressure corresponding to a neutral density of $10^{16}$ cm$^{-3}$. At this higher pressure, at the location of the grain, there is no twin peak while at the twin peak location itself, twin peak is observable but with very small amplitude. So, it implies we have a very wide range of pressure within which we can envisage molecular-like attraction due to twin peak in the transverse to flow direction downstream grain unless it exceeds a value mentioned above.

Figure 2. Figure showing the potential transverse to flow (a) at the the center of the grain ($z = 0$) and (b) at the maxima of the twin peak location ($z = z_{max}$) for $M_{th} = 0, 1, 5, 10$ at cryogenic temperatures.
4. Discussions and conclusions

We presented here the first numerical observation of wake for an isolated grain in stationary and streaming ions at ultracold temperature conditions. The low ion temperature has unavoidable consequences on the grain-plasma dynamics. It significantly reduces the screening length and grain charge eventually changing the overall dynamics. Wake feature, which has been found to be one of the crucial parameters under normal discharges, gives rise to the self organization and crystal formation. It is known that large electron-neutral temperature ratio results in strong ion focusing behind grain which in turn modifies inter-grain forces mediated by streaming ions and manifest attributes quite different from the one for stationary plasma case. In the experiment by Boltnev et al[17] on ultracold dusty plasmas, the electron-neutral temperature ratio is about...
$T_v/T_i = 10^4$. Naturally, significant difference in the wake pattern from that at normal conditions (where $T_v/T_i = 100$) can be expected and, indeed, it is confirmed by numerical simulation.

Ion focusing behind grain in ultracold complex plasmas has inverse V shape wake in contrast to that observed at room temperatures for defined set of parameters. The point to be mentioned here is that the inverse V shaped wake potential discussed here has been observed in quark-gluon plasmas and warm dense matter also though the detailed mechanism of formation of wake in the two cases may differ significantly. The distinction of the ultracold plasma wake also lies in the fact that it exhibits twin peak in the transverse to flow direction in the downstream region. Another remarkable feature is that at $M_{th} > 1$ the molecule-like interaction between grains appear with repulsion at close distances $r < 5\lambda_D \approx 10a_d$ and attraction at $r > 5\lambda_D \approx 10a_d$.

Dusty plasmas have been attracting significant attention for about two decades because of possibility of experimental investigation at the level of individual dust particles of processes similar to that in classical liquids and solids. However, in contrast to molecular-like interaction usually occurring in liquids and solids, Yukawa type repulsive interaction between grains at normal condition has hindered the full scale usage of such an analogy. The presented results show that this restriction can be mitigated by going to ultracold dusty plasma domain, which can lead to an interdisciplinary exploration. On the other hand, there is an important question ‘What can we learn from electromagnetic plasmas about the quark-gluon plasma?’ [33], which is motivated by challenges of quark-gluon plasma diagnostics. Probably, within complex plasmas, ultracold dusty plasmas can be the best candidate for being a toy model allowing experimental study of the physical processes similar to that in various other non-ideal many-particle systems such as classical liquids, warm dense matter, and even quark-gluon plasmas. We must mention that in a number of works (e.g. see [34–37]) the attraction between like charged grains in transverse to ion flow direction has been predicted in dusty plasmas at normal condition considering the solution of the linearized kinetic and fluid equations. However, this prediction was not confirmed so far neither by experiment nor by more accurate PIC or molecular dynamics simulations.

The Lennard-Jones type potential around moving color charge in the quark-gluon plasma appears in transverse to flow direction and in downstream region [38]. This was explained by observing induced density distribution which shows that due to plasma stream the screening cloud becomes more prolonged in the perpendicular direction as well as along the z-direction. Similarly, the inverse V shaped pattern in ultra cold dusty plasmas can be attributed to the wide shape in the transverse direction of the deformed screening cloud in the downstream region (compare figure 1(f) with figure 1(h)). This can be interpreted being as the result of a strong ion-dust particle coupling which is able to effectively keep ions scattered from upstream region in the transverse to ion flux area (additionally to the downstream region).

We note that at normal conditions (with $T_i \approx 300$ K) with V shaped wake in complex plasmas, the attraction in down stream was interpreted using multipole expansion. In the latter case the negatively charged dust particle together with the screening ion cloud creates a dipole type field (see illustration in figure 5(a)) [39]. This leads to a model of a point-like ion wake charge (see figure 5(a)) which was successfully used in simulations and allowed for a detailed investigation as well as a deeper understanding of various phenomena [39–42]. By analogy, based on wake picture in ultra cold dusty plasmas (see figures 1(c) and (d)), we suggest the model of two point-like ion wake charges as illustrated in figure 5(b) (‘water molecule-like’), which can generate the inverse V shape and attraction in transverse direction.

Investigation at different values of neutral density showed that aforementioned peculiar properties of the wake in ultracold dusty plasmas are suppressed at $P > 10$ Pa due to ion-neutral collisions. Therefore, we

![Figure 5. Figure illustrating the pattern of the potential for two different configurations: (a) with one point-like ion wake charge and (b) with two point-like ion wake charges.](image-url)
conclude that due to inverse V shape of the wake in ultracold dusty plasmas at $M_{th} > 1$ and $P < 10$ Pa manifestation of new and fascinating phenomena like twin wake potential peak and molecular-like interaction is envisaged. The latter potentially can explain helical filament like structure observed in the experiment by Boltnev et al [17]. In future, experimental observation of forces in the transverse direction and along ion flow direction might confirm the observations presented herein. For example, at normal conditions with $T_i \approx 300K$, linear response result (based on kinetic equation) for the wake potential of a single grain was confirmed in the experiment by considering interaction of two dust particles [43]. Similarly, experimental study for ultra cold dusty plasma may reveal molecular-like interaction.

Acknowledgments

SS acknowledges the hospitality of IIT Madras India. This work was supported by the DRDO project via project no. ASE1718144DROASAM. Zh Moldabekov thanks the funding from the Ministry of Education and Science of the Republic of Kazakhstan via the grant BR05236730 ‘Investigation of fundamental problems of Phys. Plasmas and plasma-like media’ (2020). Numerical simulations were performed at HPC cluster of Indian Institute of Technology Madras India.

ORCID iDs

Sita Sundar https://orcid.org/0000-0002-5934-4858
Zhandos A Moldabekov https://orcid.org/0000-0002-9725-9208

References

[1] Piel A and Melzer A 2001 Dynamical processes in complex plasmas Phys. Plasmas. Control. Fusion 44 R1–26
[2] Melzer A and Goree J 2008 6 Fundamentals of Dusty Plasmas (Weinheim: Wiley)
[3] Bonitz M, Becker K and Lopez J 2014 HTE Atomic, Optical and Plasma Physics (Springer Series on Atomic, Optical, and Plasma Physics vol 82) (Heidelberg: Springer)
[4] Fortov V et al 2005 The project ‘Plasmakristall-4’—a new stage in investigations of dusty plasmas under microgravity conditions: first results and future plans Plasma Phys. Control. Fusion 47 B537–49
[5] Kretschmer M et al 2005 Force field inside the void in complex plasmas under microgravity conditions Phys. Rev. E 71 056401
[6] Ramazanov T S et al 2016 Experimental investigations of strongly coupled Coulomb systems of diamagnetic dust particles in a magnetic trap under microgravity conditions Europhys. Lett. 116 65001
[7] D’yachkov L G et al 2018 Structure of a Coulomb cusp in the magnetic trap under microgravity conditions Contrib. Plasma Phys. 58 940–5
[8] Bonitz M, Henning C and Block D 2010 Complex plasmas: a laboratory for strong correlations Rep. Prog. Phys. 73 066501
[9] Bonitz M, Moldabekov Z A and Ramazanov T S 2019 Quantum hydrodynamics for plasmas—Quo vadis? Phys. Plasmas 26 090601
[10] Jaiswal S, Hall T, LeBlanc S, Mukherjee R and Thomas E 2017 Effect of magnetic field on the phase transition in a dusty plasma Phys. Plasmas 24 113703
[11] Veeresh B M, Das A and Sen A 2005 Rayleigh–Taylor instability driven nonlinear vortices in dusty plasmas Phys. Plasmas 12 044506
[12] Kaw P K, Nishikawa K and Sato N 2002 Rotation in collisional strongly coupled dusty plasmas in a magnetic field Phys. Plasmas 9 387–90
[13] Kaw P and Singh R 1997 Collisional instabilities in a dusty plasma with recombination and ion-drift effects Phys. Rev. Lett. 79 423–6
[14] Antipov S N et al 2007 Dust structures in cryogenic gas discharges Phys. Plasmas 14 090701
[15] Antipov S N et al 2008 Charge and structures of dust particles in a gas discharge at cryogenic temperatures J. Exp. Theor. Phys. 106 830
[16] Fortov V E, Vasilyev L M, Vetchinin S P, Zimnukhov V S, Nefedov A P and Polyanov D N 2002 Plasma-dust structures at cryogenic temperatures Dokl. Phys. 47 21–4
[17] Boltnev R E, Vasiliev M M, Konorov E A and Petrov O F 2019 Formation of solid helical filaments at temperatures of superfluid helium as self-organization phenomena in ultracold dusty plasma Sci. Rep. 9 3261
[18] Sundar S, Kähler H, Joost J P, Ludwig P and Bonitz M 2017 Impact of collisions on the dust wake potential with Maxwellian and non-Maxwellian ions Phys. Plasmas 24 102130
[19] Kähler H 2015 Ion-dust streaming instability with non-Maxwellian ions Phys. Plasmas 22 073703
[20] Sundar S and Moldabekov Z A 2019 Plasma–grain interaction mediated by streaming non-Maxwellian ions Phys Rev. E 99 063202
[21] Lampe M and Joyce G 2015 Grain-grain interaction in stationary dusty plasma Phys. Plasmas 22 023704
[22] Carstensen J, Greiner F and Piel A 2012 Ion-wake-mediated particle interaction in a magnetized plasma flow Phys. Rev. Lett. 109 135001
[23] Ludwig P et al 2017 Non-Maxwellian and magnetic field effects in complex plasma wakes Eur. Phys. J. D 72 82
[24] Sundar S 2018 Wake effects of a stationary charged grain in streaming magnetized ions Phys. Rev. E 98 023206
[25] Joost J P, Ludwig P, Kähler H, Arran C and Bonitz M 2015 Screened Coulomb potential in a flowing magnetized plasma Plasma Phys. Control. Fusion 57 052004
[26] Hutchinson I H 2012 Intergrain forces in low-Mach-number plasma wakes Phys Rev. E 85 066409
[27] Miloch W J, Jung H, Darian D, Greiner F, Mortensen M and Piel A 2018 Dynamic ion shadows behind finite-sized objects in collisionless magnetized plasma flows New J. Phys. 20 073027
[28] Haakonsen C B and Hutchinson I H 2015 The electron forewake: Shadowing and drift-energization as flowing magnetized plasma encounters an obstacle Phys. Plasmas 22 102103
[29] Ludwig P, Miloch W J, Kähler H and Bonitz M 2012 On the wake structure in streaming complex plasmas New J. Phys. 14 053016
[30] Moldabekov Z, Ludwig P, Bonitz M and Ramazanov T 2015 Ion potential in warm dense matter: Wake effects due to streaming degenerate electrons Phys. Rev. E 91 023102
[31] Mandal M and Roy P 2013 Wake potential in collisional anisotropic quark-gluon plasma Phys. Rev. D 88 074013
[32] Moldabekov Z A, Ludwig P, Joost J P, Bonitz M and Ramazanov T S 2015 Dynamical screening and wake effects in classical, quantum, and ultrarelativistic plasmas Contrib. Plasma Phys. 55 186–91
[33] Thoma M H 2009 What can we learn from electromagnetic plasmas about the quark–gluon plasma J. Phys. A: Math. Theor. 42 214004
[34] Kompaneets R, Morfill G E and Ivlev A V 2016 Interparticle attraction in 2D complex plasmas Phys. Rev. Lett. 116 125001
[35] de Angelis U, Regnoli G and Ratynskaia S 2010 Long-range attraction of negatively charged dust particles in weakly ionized dense dust clouds Phys. Plasmas 17 043702
[36] Bingham R and Tsytovich V N 2001 New mechanism of dust growth and gravitation-like instabilities in astrophysical plasmas Astron. Astrophys. 376 L43–7
[37] Ramazanov T S, Moldabekov Z A and Gabdullin M T 2016 Multipole expansion in plasmas: effective interaction potentials between compound particles Phys. Rev. E 93 033204
[38] Chakraborty P, Mustafa M G and Thoma M H 2006 Wakes in the quark–gluon plasma Phys. Rev. D 74 094002
[39] Morfill G E and Ivlev A V 2009 Complex plasmas: an interdisciplinary research field Rev. Mod. Phys. 81 1353–404
[40] Ivlev A V, Bartnick J, Heinen M, Du C R, Nosenko V and Löwen H 2015 Statistical mechanics where newton’s third law is broken Phys. Rev. X 5 011035
[41] Laut I, Räth C, Zhdanov S K, Nosenko V, Morfill G E and Thomas H M 2017 Wake-mediated propulsion of an upstream particle in two-dimensional plasma crystals Phys. Rev. Lett. 118 075002
[42] Ivlev A V, Thoma M H, Räth C, Joyce G and Morfill G E 2011 Complex plasmas in external fields: the role of non-Hamiltonian interactions Phys. Rev. Lett. 106 155001
[43] Kompaneets R, Konopka U, Ivlev A V, Tsytovich V and Morfill G 2007 Potential around a charged dust particle in a collisional sheath Phys. Plasmas 14 052108