From plasma crystals and helical structures towards inorganic living matter

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From plasma crystals and helical structures towards inorganic living matter

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Abstract. Complex plasmas may naturally self-organize themselves into stable interacting helical structures that exhibit features normally attributed to organic living matter. The self-organization is based on non-trivial physical mechanisms of plasma interactions involving over-screening of plasma polarization. As a result, each helical string composed of solid microparticles is topologically and dynamically controlled by plasma fluxes leading to particle charging and over-screening, the latter providing attraction even among helical strings of the same charge sign. These interacting complex structures exhibit thermodynamic and evolutionary features thought to be peculiar only to living matter such as bifurcations that serve as 'memory marks', self-duplication, metabolic rates in a thermodynamically open system, and non-Hamiltonian dynamics. We examine the salient features of this new complex 'state of soft matter' in light of the autonomy, evolution, progenity and autopoiesis principles used to define life. It is concluded that complex self-organized plasma structures exhibit all the necessary properties to qualify them as candidates for inorganic living matter that may exist in space provided certain conditions allow them to evolve naturally.

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Contents

1. Introduction

A universal definition of life [1] relates it to autonomy and open-ended evolution [2], i.e. to autonomous systems with open-ended evolution/self-organization capacities. Thus a number of features follow: some energy transduction apparatus (to ensure energy current/flow); a permeable active boundary (membrane); two types of functionally interdependent macromolecular components (catalysts and records)—in order to articulate a 'genotype–phenotype' decoupling allowing for an open-ended increase in the complexity of the individual agents (individual and 'collective' evolution) [3]. The energy transduction system is necessary to 'feed' the structure; the boundary as well as a property called 'autopoiesis' (which is a fundamental complementarity between the structure and function [4, 5]) are necessary to sustain organized states of dissipative structures stable for a long period of time. To maintain a living organic state, it is also necessary to process nutrients into the required biochemical tools and structures through metabolism which in mathematical terms can be seen as a mapping f that transforms one metabolic configuration into another (and is invertible) $f(f) = f$; i.e. it is a function that acts on an instance of itself to produce another instance of itself [6, 7]. Finally, memory and reproduction of organic life are based on the properties of DNA which are negatively charged macromolecules exhibiting an important property of replication [8].

Self-organization of any structure needs energy sources and sinks in order to decrease the entropy locally. Dissipation usually serves as a sink, while external sources (such as radiation of the Sun for organic life) provide the energy input. Furthermore, memory and reproduction are necessary for a self-organizing dissipative structure to form a 'living material'. The well known problem in explaining the origin of life is that the complexity of living creatures is so high that the time necessary to form the simplest organic living structure is too large compared to the age of the Earth. Similarly, the age of the Universe is also not sufficient for organic life to be created in a distant environment (similar to that on the Earth) and then transferred to the Earth.

Can faster evolution rates be achieved for non-organic structures, in particular, in space consisting mostly of plasmas and dust grains, i.e. of natural components spread almost everywhere in the Universe? If yes, then the question to address is: are the above necessary requirements of self-organization into a kind of a 'living creature' present in plasmas containing macro-particles such as dust grains? Here, we discuss new aspects of the physics of dust self-organization that can proceed very fast and present an explanation of the grain condensation into highly organized structures first observed as plasma crystals in [9, 10]. We stress that, previously, important features of these structures were not clearly related to their peculiar physics such as plasma fluxes on to grain surfaces, sharp structural boundaries, and
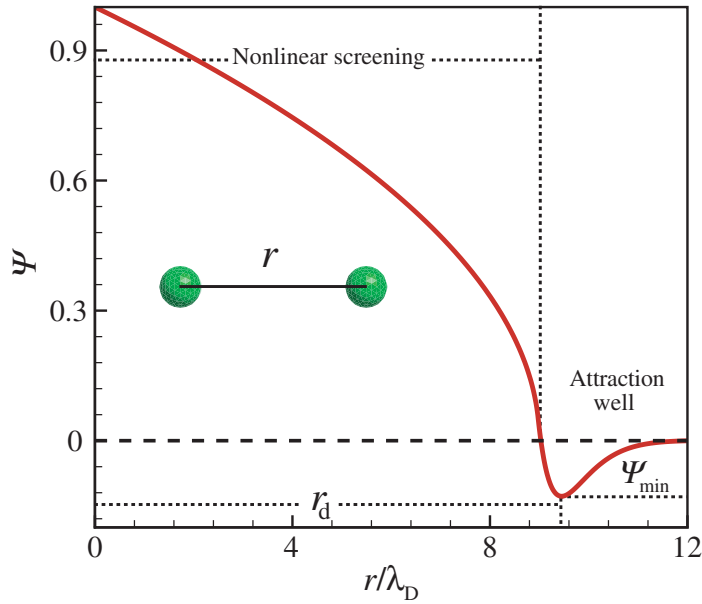
Figure 1. Sketch of the screening factor ψ of the grain interaction potential. The grain interaction energy V can be described in units of pure (not screened) Coulomb interactions of grains $V = \psi(Z_d^2 e^2/r)$ as a function of the distance between the grains in units of the linear Debye screening length. The distance r_d displays the position of the minimum of the attraction well and has a typical experimental value of $200\,\mu$m [9, 10]. This corresponds to the inter-grain distances observed during the phase transition to the plasma crystal state. The value of $|\psi_{min}|$ varies between 10^{-2} and 10^{-4} for different models and different experiments. This value is in accordance with the ratio of the interaction at the minimum of the potential well and the maximum interaction energy corresponding to $\psi = 1$, respectively. The value of coupling constant $\Gamma = 1/|\psi_{min}|$ ranges from 10^2 up to 10^4 in accordance with observations.

bifurcations in particle arrangements that can serve as memory marks and help reproduction. The plasma fluxes strongly influence interactions of dust particles, sustain the boundaries, and realize the energy transduction. We discuss experiments which indicate the natural existence of the memory marks in helical dust structures, similar to DNA, and natural mechanisms of the helical dust structure reproduction.

2. Plasma over-screening and plasma fluxes

An important feature of inorganic structures is the presence of 'memory marks' existing as 'rigid marks' in common crystal systems. In contrast, observations of crystals formed by dust in a plasma (plasma crystals) [9, 10] demonstrate no rigid marks because of unusual properties of plasma crystals such as large coupling constant, low temperature of phase transition, and large separation of grains. These puzzling properties can be resolved by employing the over-screening of grain fields, the effect that was clearly realized only recently. The over-screening appears in the presence of plasma fluxes on to the grain surfaces [11]–[13]. As a result, an attraction well appears as indicated schematically in figure 1. This potential well is usually shallow and

located at a distance much larger than the Debye screening length λ_D (an example shown in figure 1 uses parameters typical for plasma crystal experiments [9, 10]). A shallow potential well explains the large coupling constant as well as the low temperature of phase transitions. By extracting the pure Coulomb potential of interaction and introducing the screening factor ψ, the grain interaction potential is $V = Z_d^2 e^2 \psi / r$ (Z_d is the grain charge in units of electron charge $-e$). Due to over-screening, the value of ψ changes its sign at large distances as indicated in figure 1. At the potential well minimum, the screening factor ψ_{min} is negative. The value $|\psi_{min}|$ determines the temperature of the associated phase transition T_d and also characterizes the distance $r_d = r_d(|\psi_{min}|)$ of the well minimum (in the simplest case, $r_d \approx 1/\sqrt{|\psi_{min}|}$). If condensation of grains (or grain pairing) occurs, the grains will be localized at the minimum of the attraction well, r_d. The corresponding criterion can be expressed through the coupling constant Γ (which is the ratio of the potential energy of the grain interaction to their kinetic energy) as $\Gamma > \Gamma_{cr} \equiv Z_d^2 e^2 / r_d T_d = 1/|\psi_{min}|$. Thus, $|\psi_{min}|$ determines values of the inter-grain distance, the temperature of transition, and the coupling constant. For a shallow attractive well, $|\psi_{min}| \ll 1$ and $\Gamma \gg 1$. This qualitatively explains thelarge value of Γ observed in experiments. The model predicts Γ_{cr} to be of the order of the difference between the maximum grain interaction and the temperature of transition (about 3–4 orders of magnitude). As a result, the concept of plasma over-screening agrees well [12, 13] with major experimental observations [9, 10]. It also applies for description of dust helical structures and leads to the possibility of unusual 'memory marks' impossible in common crystals.

We have performed molecular dynamics simulations to demonstrate that a random distribution of grains, interacting via the potential shown in figure 1 with a shallow attractive well $|\psi_{min}| \approx 10^{-3}$ and experiencing background friction and stochastic kicks, forms spherical grain crystals. In figure 2, we show results of these simulations. Application of this model is of double importance. Firstly, we resolve the problems of laboratory observations, and secondly, we predict the possible existence of large plasma poly-crystals in space—a new state of matter which is unexplored so far. Here, an important point for space applications is that the attraction potential well is shallow and therefore even weak dissipation can cause the grain capture in the well.

Physically, the attraction appears due to the electrostatic self-energy of grains, supported by plasma fluxes continuously absorbed by the grains. The fluxes are necessary to sustain the grain charges and appear almost immediately as soon as a particle is embedded in the plasma. The self-energy of grains is much larger than their kinetic and potential energies so that its (even small) changes can strongly influence grain interactions. It was first shown in [11] that for a fixed source of plasma fluxes, the electrostatic energy of two grains decreases when they approach each other. As the self-energy is supported by continuous plasma fluxes, work has to be done to maintain them and this can almost compensate the associated changes of self-energy. Nevertheless, a full compensation does not occur if the distance between the grains is large. At present it is understood [12, 13] that this phenomenon is a general feature of grain interactions in a plasma. The fluxes on grains depend on the electrostatic polarization charges of the grains and the polarization charges depend on the fluxes and create an accumulation of excess plasma charges between the grains. These plasma charges exhibit the sign opposite to that of likely charged interacting grains and therefore cause the attraction. *The appearance of grain attraction is a general phenomenon which converts the grain containing matter into a new unusual state.*
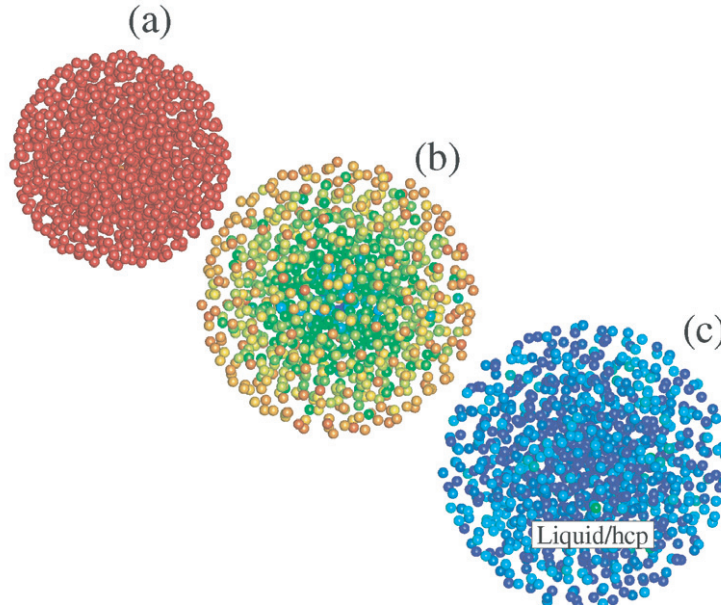
Figure 2. Molecular dynamics simulations of dusty cloud evolution. The figure shows snapshots of the velocity field and grain positions: (a) corresponds to the initial state ($t = 0$) of the cloud, (b) $t = 0.3$ s and (c) $t = 3$ s, respectively. The velocity magnitude is color-coded. It rises from blue to red by a factor of five. Initially, $10^3 \mu$ m-size grains were distributed randomly over the sphere of radius about r_d (see figure 1) and the pair interactions between grains are described by the potential shown in figure 1. Grain motions are damped by friction (to model viscosity of plasma neutral component) and stochastically accelerated by Langevin force (to model plasma fluctuations). The simulations reveal formation of a stable self-confined spherical structure in time. Local order analysis shows that some grains (about a few percents of their total number) have hcp lattice type, while the majority of grains are in a liquid state.

Effects of plasma fluxes lead to gravitation-like instabilities with an effective gravitational constant $G_{eff} \approx Z_d^2 e^2 |\psi_{min}| m_d^2$. For a dust size $a \approx 3 \mu$m, a mass density of the dust material of 2 g cm^{-2}, $Z_d \approx 10^3$ and $|\psi_{min}| \approx 10^{-4}$, the effective gravitational constant G_{eff} is approximately 6×10^4 cgs which is 10^{12} times larger than the usual gravitational constant $G = 6.7 \times 10^{-8}$ cqs. The effective Jeans length of this instability has the size of order r_d. The effective gravity affects only dust grains and therefore plasmas can be influenced by this attraction only through their interactions with the grains. The new effective instability of a dusty plasma leads to structurization of dust clouds similar to the effects caused by the usual gravitational instability.

Dust structures self-organized in the plasma environment have sharp boundaries such that they are isolated from each other by regions without grains (dust voids). This effect, observed in the laboratory as well as in micro-gravity experiments onboard the ISS [14], is well explained theoretically [15, 16]. The structures and crystals should self-generate additional confining forces due to the plasma fluxes directed into the structures, i.e. these structures serve as sinks of plasmas and the ram pressure of the plasma fluxes acts on the structures to make them self-organized, self-confined and dissipative. This self-contraction should be added to the the grain pairing; their joint effect leads to formation of dust helical structures.
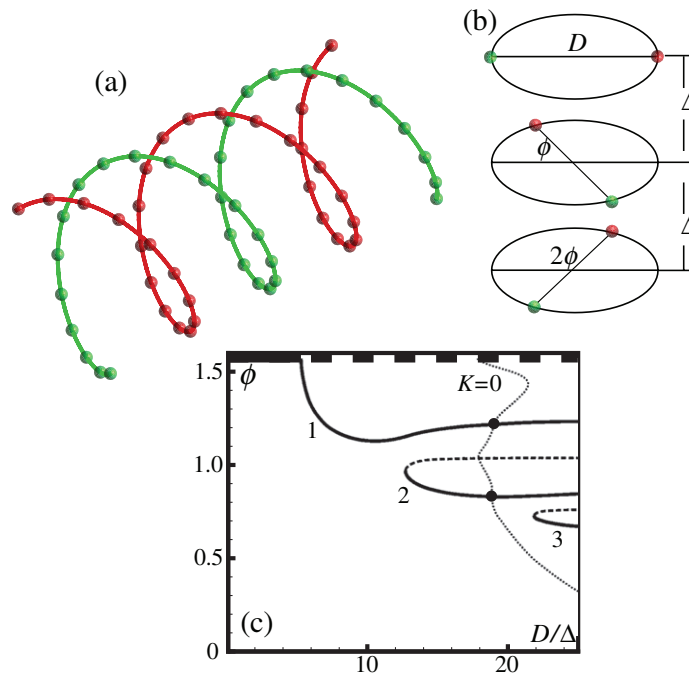
Figure 3. (a) and (b) Sketch of helical double winding grain structures similar to DNA. (c) Bifurcations in $(\phi, D/\Delta)$—plane of structures confined by external potential $Kr^2/2$; ϕ is the rotational angle in each plane of the helical structure; D is the diameter of the helical structure and Δ is the spatial separation of the planes of the helical structure; the line $K = 0$ corresponds to self-organized stable structures without external confinement $K = 0$ but with the presence of dust attraction [17].

3. Helical dust structures

Helical dust structures (an example is given in figure 3(a)), can be considered as equally separated flat structures with constant rotation angle between the planes (figure 3(b)). Their properties are of special interest for the problems discussed here. Figure 3(a) illustrates double helical dust structures similar to DNA. Molecular dynamics simulations of interacting grains with an additional gas friction show that any cylindrically symmetric grain distribution converts in time into a stable self-confined helical structure [17]. These specific stable dust structures form due to the grain pairing attraction as well as due to the external plasma flux created by the whole structures (and the anticipated ram pressure). In experiments in gas discharges with a longitudinal external electric field forming striations [18, 19], modulated cylindrical grain crystals were observed. As predicted by numerical simulations [17], these cylindrical crystals convert into helical structures with fewer grains per unit length. According to numerical experiments, highly symmetric spherical dust structures can be formed only when the spherical symmetry is externally supported (e.g. when all initial conditions are spherically symmetric). In the other cases, even a small asymmetry leads to formation of cylindrically symmetric and/or helical structures. In nature, some asymmetry always exists and therefore formation of helical structures is quite probable. First observations of dust self-confined moving helical structures
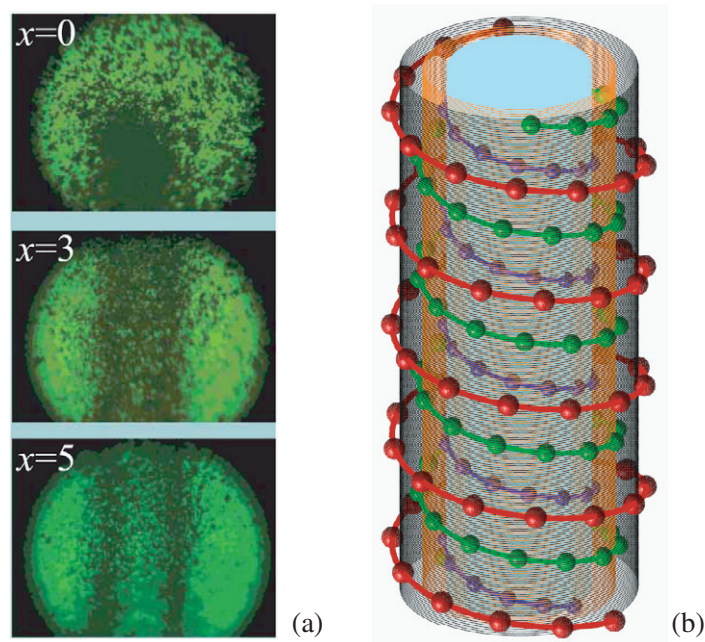
Figure 4. (a) Traces of helical structures on the walls of the chamber observed in dc cryogenic plasmas at $T_i = 2.7$ K. The traces of conical helical structure are shown black on the green background of discharge at several distances from the top of it; $x = 0$ mm—the 'head' of the structure, $x = 3$ mm—the middle of the structure and 5 mm—the end of the structure. The whole structure looks like a 'worm', hollow inside (having a dust void inside) and moving on cylindrical surfaces around the axis of discharge. (b) Sketch of the central part of the helical structure of the 'worm' deduced from the traces left of the structure on the wall of the discharge chamber, the grains are located at the surfaces of a few cylinders inside each other [20].

were done in dc cryogenic gas discharges [20]. The particle traces, moving in a self-organized way, are shown in figure 4. Similar ion helical structures were also observed in laser cooling traps [21].

Important features of dust helical structures observed in simulations [17] and indicated by analytical investigation of stability of helical structures and mode oscillations is the existence of numerous bifurcations in the dependence of the helical winding angle upon the diameter of the structure. An example of this helical structure behavior is demonstrated schematically in figure 3(c). Bifurcations in helical structures appear naturally and correspond to the critical conditions when any slight change in the helical structure diameter D results in a sudden change of the helical winding. We note that various helical structures with different bifurcations can be obtained in experiments using current cylindrical discharge plasma crystals by continuously decreasing the number of grains injected into the system. Numerical investigations show a universal character of these bifurcations. The helical structures have the unique property of bifurcations which can serve as memory marks. With increasing of diameter of the structure suddenly the rotational angle of the structure is changed. This is illustrated by figure 3(c) which shows that an increase of diameter of the structure at certain radius there appears possibility
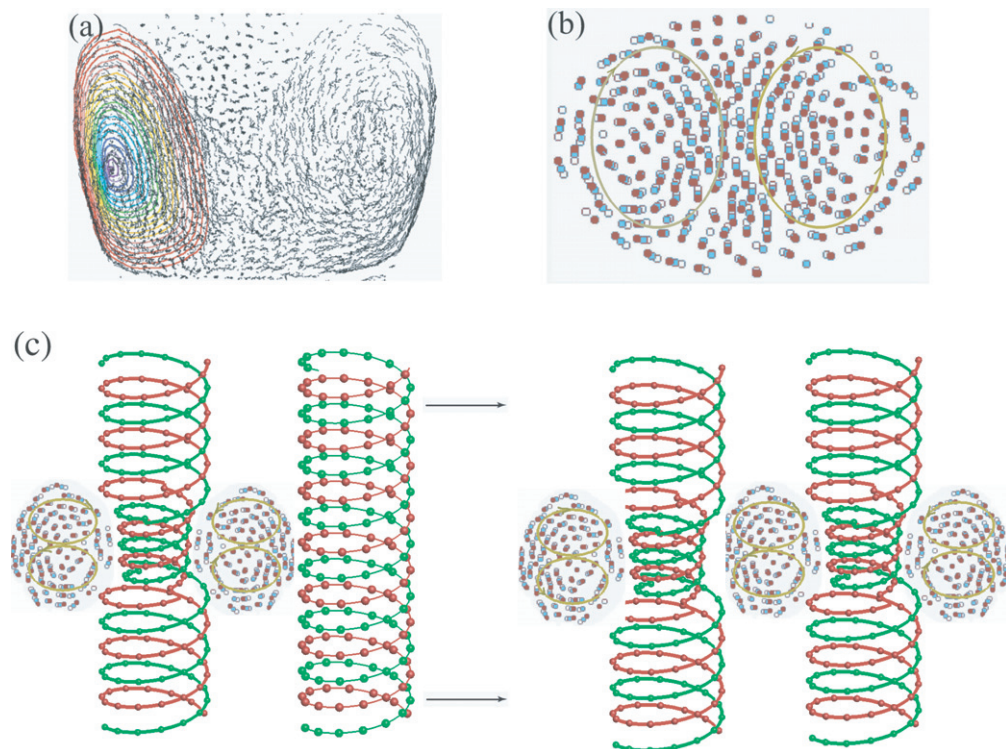
Figure 5. (a) The observed grain convection surrounding the cylindrical grain crystal. Different colors correspond to different grain velocities [18], The velocities vary from about $0.4\,\text{cm}\,\text{s}^{-1}$ (blue) up to $1.5\,\text{cm}\,\text{s}^{-1}$ (red). (b) The dust convection obtained in numerical simulations [19]. (c) Sketch of the model for helical structure duplication (reproduction). See details in the text.

of presence of two equilibrium vales of the rotational angle (the upper thick dashed line and the lower solid line) instead of one possible equilibrium value for the rotational angle before bifurcation (the upper thick line). After the bifurcation the solid thick dashed line represents an unstable branch and the solid lower line represents a stable branch. Thus the rotational angle at some critical radius is changing abruptly.

These bifurcations can serve as possible memory marks for the structures. The helical crystals can then store this information.

4. Replication of helical dust structures

Dust convection and dust vortex formation outside the structure is another natural phenomenon observed in laboratory experiments and in experiments onboard the ISS [14]–[16]. The physics of dust vortex formation is related to the grain charge inhomogeneity and its dependence on surrounding plasma parameters. The gradients of grain charges are supported self-consistently by the structure, and they are the reason for the non-potential character of the electrostatic force $-eZ_d\mathbf{E}$ acting on the grains and causing the vortex formation. Dust convection was observed in experiments on cylindrical dust crystals formed in modulated gas discharges [18] (figure 5(a)) and was obtained in numerical modeling [19] (figure 5(b)).

It is important that the helical crystals modulated in their radius are always surrounded by self-created dust convection cells. The helical dust structures, after they are formed, resemble features similar to those of DNA. In particular, they can transfer information from one helical structure to another via the dust convective cells surrounding any bifurcation of the helical structure. A rough sketch of a possible model of the helical grain structure reproduction is shown in figure 5(c).

Let us discuss some details about possible sequences of events during the reproduction. The abrupt change of the rotational angle will create an inhomogeneity in random halo dust grains surrounding the helical structure with grain charge gradient not collinear to the electric field and will create a force forming pair of toroidal vortices around the structure. For a negatively charged structure the upper toroidal vortex has a clockwise rotation while the lower has an anti-clockwise rotation. If another (second) helical structure has no bifurcation and moves close to that with bifurcation the vortices start to be created in this structure. Finally these vortices create the bifurcation in the second structure and transfer the information from the first structure to the other one.

The evolution of dust structures in the presence of plasma fluxes is related to the characteristic frequency of dust motions. In first instance, this can be estimated by the dust plasma frequency $\omega_{pd} \sim (Z_d^2 e^2/m_d r_d^3)^{1/2}$, where m_d is the mass of a dust particle. We note that characteristics of the potential well (located at r_d) and therefore the physics of plasma fluxes enter this expression via r_d and Z_d. This consideration destroys one of the current myths in astrophysics, namely, that the grain interaction is vanishing for distances larger than the linear Debye screening radius. This is obvious since inside the dust Jeans length (where the interactions are still effective) many grains are present for most dust clouds in space. For most situations, the plasma dust frequency of a few (or even a fraction of) Hz leads to times extremely short compared to typical astrophysical times. If grain structures exist in space, they have collective modes of oscillations which in principle can be detected as modulations of the infrared emission of different cosmic sources. The effective Jeans size of dust clumping is in the range that can be detected by the Spitzer telescope in observation of (the closest to the Earth) formations of dust clouds around stars and star outbursts preceding the formation of new planetary systems. The program to measure low frequency regular modulations from dust clouds with the effective structure sizes caused by the dust attraction instability can be included in, e.g. the Spitzer telescope project.

Our analysis shows that if helical dust structures are formed in space, they can have bifurcations as memory marks and duplicate each other, and they would reveal a faster evolution rate by competing for 'food' (surrounding plasma fluxes). These structures can have all necessary features to form 'inorganic life'. This should be taken into account for formulation of a new SETI-like program based not only on astrophysical observations but also on planned new laboratory experiments, including those on the ISS. In the case of the success of such a program one should be faced with the possibility of resolving the low rate of evolution of organic life by investigating the possibility that the inorganic life 'invents' the organic life.

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Appendix

A.1. Methods used for description of plasma crystal

Special methods have been developed to treat the plasma over-screening for present experiments with large grain charges which cause the screening to be nonlinear at short distances between the grains [9, 10]. The full nonlinear treatment of the screening polarization charges and plasma fluxes is rather complicated [12]. The progress was achieved on the basis of physical arguments showing that close to the grains the influence of fluxes on polarization is small. Neglecting the effect of fluxes the nonlinear screening was solved in [13] by using the approach of [22]. Far from the grain the coupling of fluxes and polarization charges became important but the polarization charge became small and one can use the linear approach to find the coupling. The *matching method at the distances where the nonlinearity starts to be weak* have been applied successfully [13] to describe the nonlinear over-screening.

A.2. Numerical simulation methods

The cooperative behavior of charged grains embedded in a plasma is due to electrostatic coupling between the charged particles, which are believed to interact via a potential which has both a repulsive and an attractive short-range component. 3D molecular dynamics simulations including electrostatic collisions between grains, neutral drag and stochastic Langevin force were performed to simulate the evolution of a dusty cloud. Free boundary conditions were used. To analyze the local order of grains, we used the bond order parameter method [23].

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