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Self-Organized Non-Extensive Structures in Complex Plasmas

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The physics of complex plasma systems containing a micro-particle component (dust) is a new and quickly emerging area at the frontier of physics and theoretical physics, plasma physics, solid-state physics, space physics and astrophysics. Structures in complex plasma systems, especially such non-extensive structures as dust particle clusters, strings, vortices, and voids, attract particular attention since they can be easily obtained in experiments and allow theoretical treatment at the most fundamental level.

Structural properties of systems with limited number of particles interacting via long-range forces - the so-called non-extensive systems are a hot point of current scientific research, both for their highly non-trivial self-organization displayed and for the considerable conceptual and methodological difficulties they present. A central issue is how self-organization, formation, arrangement, phase transitions and related symmetries are realized in small systems. On the other hand, the small systems became currently the subject of intensive applied research related to the development and applications of nanomaterials, microdevices, microstructures and microsystems. Progress in these studies is impossible without understanding of the behavior of small systems. Evidently, new insights into the physics of such “small” systems as well as development of a proper description are needed.

In this paper, we present the complex dusty plasma as a recently emerged object where self-organized non-extensive systems can be studied. The obvious advantage of using complex plasma to model systems of interacting particles is the relative ease of the generation and manipulation of the plasma, as well as the experimentally suitable timescales for it to relax to an equilibrium state and to respond to changes in the external parameters. Moreover, unlike an actual atomic liquid or solid, the dust particles can be directly detected individually by optical means, because the particles are large.

The complex plasma systems are highly capable for self-organization and can dynamically adjust their microscopic and global parameters through self-consistent nonlinear responses to changes in the external control parameters and/or plasma conditions (e.g., gas/plasma composition, pressure, or input power/ionization) or in the internal dust subsystem (e.g., the dust charge and/or size variation). The dust structures are often observed in laboratory experiments; they range widely in size, shape, order, symmetry and can represent different forms of self-organization such as clouds and voids, 3D and 2D crystalline lattices, strings, clusters, complex agglomerates. There are also numerous structures formed in natural environments such as in the interstellar space, planetary atmospheres, ring structures, cometary tails, etc. For instance, planetary rings are the examples of the self-organized complex plasma structures in space environment

When considering the basic physics of complex plasmas, special attention should be paid to the open character of this system. The fundamental openness of the dust-plasma system is due to the plasma flows absorbed by the dust. However, merely accounting for the plasma particle capture processes is not sufficient, since without a balancing source for the plasma particles there cannot exist a self-consistent stationary state. Generally, the energy and plasma particles have to be supplied externally to maintain the system in the equilibrium state. It is therefore necessary to take into account the creation of the plasma particles, for example, by an ionization source. For most plasma it is then also necessary to include related plasma-particle loss and transport mechanisms. Since the ionization, transport, and recombination are all density dependent, all electrostatic processes in the system can be strongly affected. This opens the possibility that the presence of dust can affect the entire discharge system through modification of the ionization transport-recombination balance. The complex dusty plasma system tends to self-organize itself in order to “reinstate” the number of the plasma electrons lost from the plasma to the dust and reestablish the pristine charge/particle distribution

Complex plasma is a system where self-organization occurs in many ways. Complex plasma systems represent a unique mutual arrangement of two ensembles of charged species, namely an ionized gas (plasma) and a solid disperse phase (dust). Depending on the specific environment (for example, it can be space or laboratory plasmas) and prevailing conditions of the system, the two charged particle species can be arranged differently with respect to each other. For example, when fine dust particles nucleate in a laboratory discharge, a weakly interacting dust subsystem is fairly uniformly dispersed over the plasma bulk. However, under the action of variousA complex plasma with the micron-sized grains is quite stable, and self-organization processes can usually develop over longer time scales (such as those associated with relatively large and therefore heavy dust particles). In the micrometer size range, a large (a few thousand or ten thousand electron charges) electric charge accumulated by the dust particle favors the charge-induced self-organization of the plasma-dust system into strongly coupled dust particle structures – dust (or plasma crystals).

The dust-plasma crystal formation is one of the most striking examples of the dust self-organization when micrometer-sized particles form regular arrays exhibiting various lattice-like structures. In most of the laboratory experiments, the gravity pulls the relatively heavy particles down in the sheath until the gravitational force (as well as other forces acting in the same direction, e.g., the ion drag force) is balanced by the sheath electric field force. Because of the clear distinction between the horizontal (parallel to the electrode) and vertical directions (where the plasma is non-uniform and the ions are flowing towards the electrode), the system structures in a quasi-two-dimensional manner, with often clear two-dimensional (2D) features, e.g., the hexagonal-type lattice cells. However, smaller 2D structures (such as dust clusters) can reveal other symmetries. Under certain conditions the dust structures exhibit phase transitions in the gas-, liquid-, and crystalline-like states. The ordering forces are mostly electrostatic, however, the dipolar effects, the (anisotropic in some cases) plasma shielding, the focusing of the ion flows, etc., can play a significant role. Dust structures in plasma are perfect examples of complex systems because of many various constituents, with the extensive and intensive interactions between them, as well as numerous space and time scales involved. The main interest is related to the processes of formation, arrangement, symmetry and transitions appearing in open dissipative systems of interacting dust particles.