Active Particle and Active Matter Research in Space

Biological and Physical Sciences in Space
White Paper

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I. INTRODUCTION

Active particles and active matter have recently emerged as a topic of enormous potential bridging the fields of physics and biology. Active particles are characterized by their ability to take energy from their environment and drive themselves far from equilibrium [1,2]. Examples of active matter are natural objects like bacteria, flocks of birds, school of fish etc., but also artificial, man-made objects like Janus spheres and rods, chiral particles or artificial self-propelled microswimmers [2]. Here, we propose to study active particles and active matter, especially in complex (dusty) plasmas under the microgravity conditions of Space.

In physical research, active matter particles often Janus particles are employed (see Fig. 1) that consist of two halves of different (surface) material. Upon interaction with an environment, e.g. illumination by a laser or chemical/physical reactions to a surrounding liquid, these two halves react differently. Hence, their asymmetry induces a directionality in the particle. From that, novel dynamical properties emerge that are widely different from standard particles in terms of structure, phases, hydrodynamics, kinetics, and non-equilibrium statistical properties.

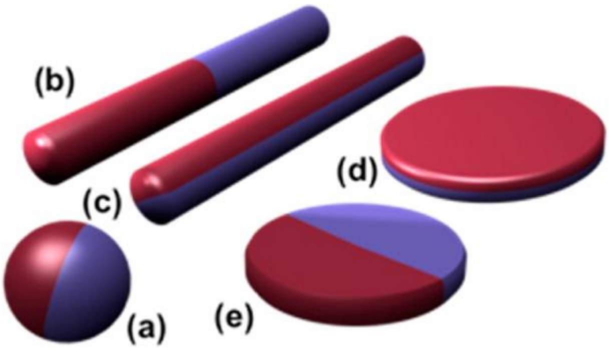

Figure 1: Different types of Janus particles: (a) Janus spheres, (b),(c) Janus rods, (d), (e) Janus disks. From [3].

Active particles perform a non-thermal motion which often is directed, tumbling or rotating. From that kind of active motion, a plethora of novel behavior emerges, like swarming, aligning, clustering, self-crowding ("jamming"), active microrheology, active turbulence, active baths and many more. Active particle and active matter have, e.g., been studied in physical systems such as colloidal suspensions where particles with special surface properties or shapes move in a liquid, see [2] for an overview. Such experiments are often restricted to two-dimensional motions.

Now, complex (dusty) plasmas in Space offer a unique environment to study active matter. Complex plasmas consist of micrometer-sized particles immersed in a gaseous plasma where the particles attain high negative charges and form strongly coupled systems [4]. Under microgravity conditions of a Space platform, extended three-dimensional dust systems can be generated where the particle dynamics is only weakly damped by the ambient plasma. In contrast to colloidal suspensions with short-range, dipolar hydrodynamic interactions [5], in complex plasmas long-range interactions among the particles prevail that can be tuned from monopolar to (non-reciprocal) dipolar. Also, in complex plasmas the three-dimensional motion of the constituent particles can be determined on the kinetic individual-particle level using high-speed cameras and advanced image analysis techniques. Hence, the full phase space of the system is accessible.

Hence, active matter in complex plasmas in Space allow us to open up and explore an entirely novel terrain and a whole new parameter space can be scrutinized. These studies will require efforts in dedicated experiments, especially under microgravity, numerical simulations and analytical descriptions.

A suitable platform to study these active particle systems with appropriate diagnostics can be found in the COMPACT facility planned for the International Space Station [6]. COMPACT offers unprecedented experimental capabilities by featuring homogeneous and tunable plasma conditions for the trapping and manipulation of extended dust clouds as well as novel stereoscopic video diagnostic techniques.

II. POSSIBLE RESEARCH AREAS

Studies in three-dimensional complex systems with active particles address a multitude of relevant questions of (strongly-coupled) many-particle systems on the kinetic level of individual particles. Active particles in such experiments might be Janus particles and metal-coated particles which under radiation, e.g. from a laser-beam, perform non-thermal motions. First experiments [7] using active Janus particles in a monolayer dusty plasma reveal rich dynamical properties, see e.g. Fig. 2. These Janus particles consist of two different hemispheres that differently react to laser illumination and thus drive the particle motion. In another experiment, metal-coated particles are found to show increased dynamics upon illumination [8].

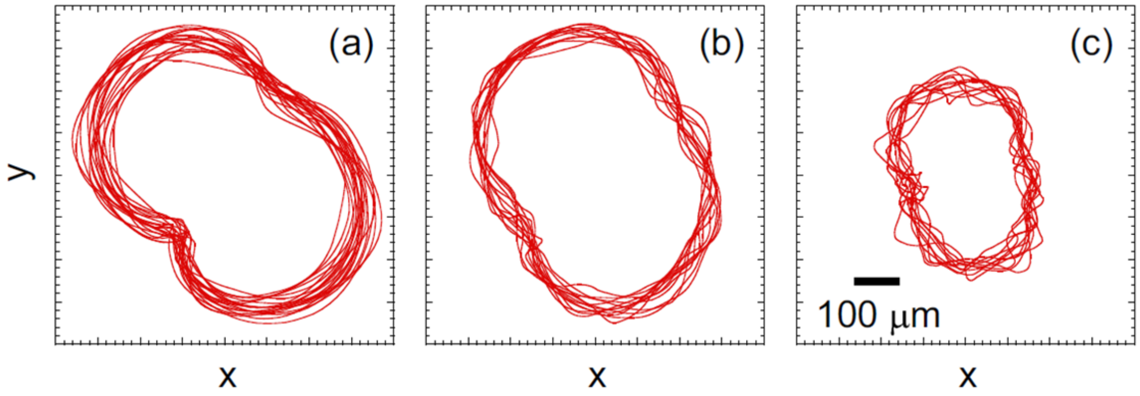

Figure 2: Trajectories of a single Janus particle in the experiment. From Ref. 7.

- *Structure and phase diagram in dust clouds of active particles*: The local and global structure of the dust cloud in a system with active particles is of high interest. Mixtures of varying shares of active and standard particles can be used to change the energy input into the system. By changing the relative size of the active and standard particles regimes of different coupling strengths can be explored. Questions of interest will be whether crystalline patches of standard particles can survive in the presence of active particles [9] or how many active particles are required to drive the entire system into an unordered state. Also, it is of interest how do active and standard particles mix and whether the active particles (randomly) disperse in the cloud of standard particles or whether they tend to form clusters. Moreover, it can be studied how the energy of the active particles will be dissipated in the standard cloud and on which length scales and at which rates.

- *Statistical properties of active particles:* Active particles take energy from the surroundings and turn that into a non-thermal motion. Single active particles can be characterized by their persistence length (or time) which is the mean length (or time) that the particle travels in a certain direction. A second parameter is the mean velocity of the active particle. This mean velocity can also be interpreted as a mean force against friction of the particle with the neutral gas environment. Third, the time scale for re-orientation (rotation) of a particle needs to be pinpointed. From that, also an effective temperature can be associated to an active particle. In experiments with active Brownian particles in rarefied gas media, including weakly ionized plasmas, both overdamped and underdamped motions are found possible [10]. The transition from overdamped to underdamped regime is easily accomplished by changing the buffer gas pressure. The COMPACT experiments with self-propelled particles have great potential for studying active Brownian motion since they enable to control the damping rate of the medium over a wide range.

- *Emergence of cooperative/collective behavior:* Emergence of cooperative or collective behavior is one of most fascinating questions in systems with active particles. Examples of such a behavior are swarming, clustering or self-crowding (“jamming”). Swarming results from the collective interaction of (neighboring) active particles. There, the active particles align along a “mean” relative motion and a swarm behavior of the particles emerges, see Fig. 3. According to cooperative models the system of active particles exhibits a (multi-step) phase transition from undirected motion to swarms moving in the same direction when the density of active particles is increased. It is very intriguing to study such type of behavior in active dusty plasmas where the interaction is quite long range and three-dimensional.

  Clustering and self-crowding occurs when the active particles are blocked in their motion by other oppositely moving particles. Then, small aggregates of mutually blocking particles can build clusters in a medium of otherwise unblocked active particles. Clustering and crowding require relatively high particle density since in three dimensions there are many possible paths on which the particles can evade each other. In this sense, the transition from a non-blocking, fluid-like behavior to a clustering and crowding state can be viewed as a form of a fluid-to-glass transition [11].

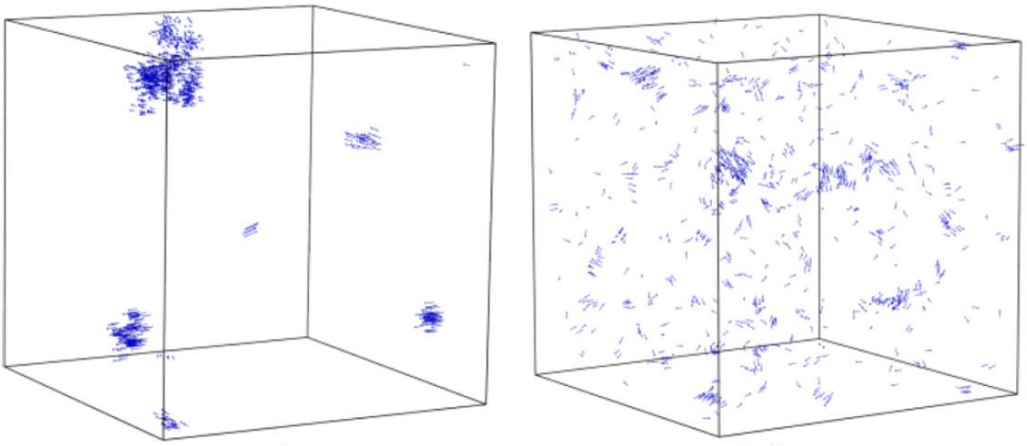

Figure 3: Snapshots of 1000 so-called active Vicsek particles at low speed and density at low noise level (left) and high noise level (right). From Ref. 12.

- *Rheology, turbulence and sound waves in dust systems with active particles:* From a more general viewpoint, how can a fluid picture of flow, turbulence and sound waves be held up in a dust system with active particles. It is to be studied whether and how the fluid model has to be extended to account for this situation or whether the entire situation can be described only in terms of a kinetic treatment. The response of a dust system with active particles to an external shear stress is of very intriguing. The active particle component of a mixture with standard particles will most certainly induce a viscoelastic, non-Newtonian behavior. This non-Newtonian behavior then is of enormous influence on the formation of vortices and turbulence in these systems. Since the active particle have an inherent drive cooperative behavior of the active particles with externally driven vortices might emerge. Vortices can be driven externally e.g. by plasma gradients. Then, the structure of the flow field in these active vortices is of interest as well as its dependence on coupling strength and (active) particle density. Alternatively, the active particles can drive small-scale or large-scale vortices due to their active behavior. In a similar manner, on the one hand the active particles will drive sound waves in a dust system and on the other hand existing sound waves will be influenced by the presence of active particles.

The progress in the field of active particles and active matter is closely connected to the further development of particles, their surface properties, the surface patterning and the particle shapes for realizing active particles with a wide variety of dynamics upon interaction with different driving sources. Furthermore, advanced novel diagnostic techniques for spatially and temporally resolved diagnostics of particle trajectories are required. The image analysis calls for cutting-edge data (image) handling and machine learning approaches for image analysis. The COMPACT facility planned for the International Space Station [6] combines these requirements and will allow to address the discussed research areas. Hence, COMPACT offers a unique platform to study these active particle systems.

III. Summary

In this white paper for the Biological and Physical Sciences in Space we propose to study active particles and active matter in complex plasmas under microgravity conditions. Complex plasmas allow the study of the virtually undamped dynamical properties in terms of the full three-dimensional particles' phase space. In complex plasmas the particle interactions can be tuned offering to investigate important and vastly unexplored fundamental questions of (active) many-particle systems. These include structure and phase diagrams of active matter as well as their statistical properties. Moreover, most relevant questions are related to the emergence of cooperative behavior and the hydrodynamic properties.

The COMPACT facility provides an ideal experimental base to address these questions.

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