Decadal Survey on Biological and Physical Sciences Research in Space 2023-2032

Topical White Paper

Title: What follows is **Chapter 3**,
Suspensions, foams, emulsions, colloids, and granular materials—self-healing, tuning gravity, and life support for exploration
from the Report from the APS Division of Soft Condensed Matter Physics
DSOFT, NASA sponsored Workshop on:
Grand Challenges in Soft Matter Science: Prospects for Microgravity Research,
NASA/CP-20205010493, March 2021,
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Executive Summary

The worldwide community of soft matter has grown rapidly in size, impact, and scope since the last NASA report in 2003 as evidenced by the organization of the new Division of Soft Matter (DSOFT) at the American Physical Society, and the arrival of a dedicated international journal "Soft Matter" published by the Royal Society of Chemistry. At the suggestion of NASA's Physical Science Research Program in the Space Life and Physical Science Research and Application Division[1] for an update of the 2003 report on the NASA Soft and Complex Condensed Matter Workshop, Paul Chaikin, Noel Clark, and Sidney Nagel, organized a focus session and workshop for the 2020 American Physical Society (APS) March meeting under the auspices of the DSOFT. Due to the COVID–19 pandemic, the March meeting was canceled and the workshop "Grand Challenges in Soft Matter and Opportunities for Microgravity Research" was reincarnated as a remote Zoom (Zoom Video Communications, Inc.) meeting convened Thursday, March 26, 2020, from 11:30 a.m. to 1:30 p.m. EST. After a brief introduction, the ~100 participants (mostly from the United States with several joining from the European Union) separated into eight breakout sessions on

1. Self-organization only possible far from equilibrium—machines making machines
2. Instrumentation—from neuromorphic computing to large-scale self-assembly
3. **Suspensions, foams, emulsions, colloids, and granular materials—self-healing, tuning gravity, and life support for exploration**
4. Packings, simulation, and big data—artificial intelligence emulation of soft matter
5. Mechanical metamaterials and topological soft matter: allostery and auxetics—distributed energetics and mutation upon deployment
6. Soft matter, bioscience, and biotechnology—evolution and the marginal stability of life
7. Active patterning and structure formation—self-limiting assembly, actuation, and integration
8. Fluids: liquid crystals—self-assembly of the superlarge and superweak active clothing

The participants then reassembled for a presentation of conclusions and general discussion. Three overarching themes emerged from this workshop and are presented with additional details:

- Machines made out of machines
- Scalable self-sustaining ecosystems
- Active materials and metamaterials

[1] Space Life and Physical Science Research and Application Division has moved to the Science Mission Directorate and is now the Biological and Physical Sciences Division.

2.3 Suspensions, Foams, Emulsions, Colloids, and Granular Materials

2.3.1 An Explosion of New Building Blocks

Particles, droplets, and bubbles with and without surrounding fluids fill the world we experience every day and their study has engaged humanity from antiquity. So has their utilization. The first processed colloids were inks and paints with particles stabilized with surfactants such as the gum Arabic used in Egypt. Presently, they are industrially important from concretes, ceramics, and food to biotechnologies and medicine. In soft matter, they also serve as model systems for understanding the organization of matter from the atomic to the cosmological scale. The fact that they are observable in real space and real time has led to fundamental insights into transitions such as crystal-liquid melting and the formation of glasses (Pusey and van Megen, 1986). The basic question to be answered is how the elementary building blocks and their interactions and processing lead to bulk macroscopic properties. These are real-world problems involving hydrodynamic interactions, gravity, friction, charging, and hysteretic effects in both self-assembly and manufacturing.

Throughout the 20th century, the general field of colloidal science dealt with spherical particles and a few elementary forces, electromagnetism, Van der Waals attraction, excluded volume, and depletion interactions leading, for example, to crystals with simple symmetries. The 21st century has already seen a revolution in the types of particles available and a host of new interactions. There are now a plethora of shapes: ellipsoids, cubes, Janus and patchy particles, and even shape shifting particles (Hong, Jiang, and Granick, 2006; Youssef et al., 2016).

All of these can now be functionalized to have specific interactions that are programmable for complex self-assembly. Lock and key particles only fit together as their name implies; DNA and, more recently, protein-coated particles and droplets bind only to their complementary forming flexible or rigid chains; designed finite clusters and crystals as complex as diamond (see Figure 3) and clathrates can be assembled (Lin et al., 2017; He et al., 2020). Further we can now program sequential self-assembly of arbitrarily designed structures controlling even the handedness of their chirality (Zion et al., 2017). Other sections of this report elucidate how these particles and constructs can be activated. Advances in simulations and machine learning have enabled the use of these experimental tools in assembly of new materials and constructs. They have also helped elucidate the role of entropy in structure determination (van Anders et al., 2014).

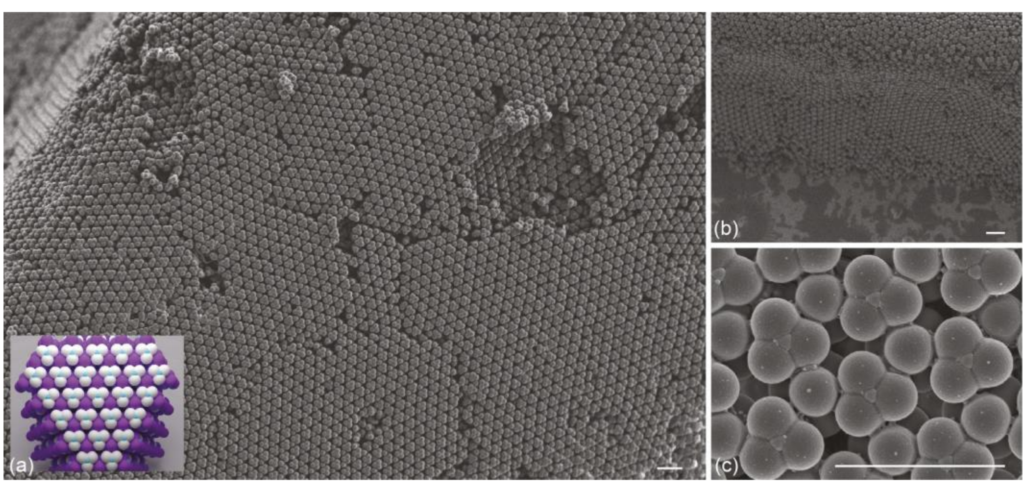

Figure 3.—Flexible probe being inserted into photoelastic granular material, performed in three different gravitational conditions (via parabolic flights), illustrating qualitative changes in behavior under reduced gravity. Bright particles are those experiencing higher local forces. *(a)* Microgravity. (b) Lunar gravity. (c) Martian gravity. Adapted from Featherstone et al., 2020.

The past several decades have seen the cross-fertilization of these different subfields and materials in soft matter. Granular materials are dominated by gravity and friction, which have found utility in novel mechanical and robotic artificial hand grippers (Brown et al., 2010). Recently, it has been realized that frictional effects are also important in colloidal suspensions as well as being involved, for example, in shear thickening (Lin et al., 2015). Granularlike colloidal behavior is also involved in the arrest of phase separation in the formation of bicontinuous gels (Cates et al., 2004), a labyrinthine form of a Pickering emulsion. Colloids anchor nematogens in liquid crystals (LCs) and direct topological defects and even the formation of knots. Colloids can also be suspended in plasmas, where inertia is important, leading to new nonequilibrium phenomena akin to hydrodynamic turbulence (Gogia, Yu, and Burton, 2020).

2.3.2 Prospects

While we have made great advances in understanding and controlling the self-assembly of particulate systems, the basic problem of going from microscopics to bulk properties is yet unsolved both for atomic and molecular and for colloidal systems. However, the processing of these systems in both equilibrium and nonequilibrium has, and will, lead to useful materials. For example, we have learned how to make equilibrium photonic crystals (He et al., 2020) and are on the track of isotropic hyperuniform photonic bandgap materials by nonequilibrium shear (Florescu, Torquato, and Steinhardt, 2009). Machine learning should point the way toward such a theory and statistical mechanics of building blocks with fixed or stimulus-responsive properties. A target might be a slurry with a variety of properties that can be tuned on demand. Recently, we have self-healing materials (Cordier et al., 2008). In situ resource utilization is especially important for space exploration and will inform terrestrial sustainability. Recycling, purification, and concentration systems rely on liquid interfaces, bubbles, and foam emulsions and dispersions. Advances are needed since present recycling efficiencies are on the order of 20 to 30 percent.

2.3.3 Microgravity

There have been more than two decades of development by NASA and ESA on instrumentation for colloidal research in microgravity, especially advanced microscopy. As noted in other sections, the problems are in the number of samples that can be run and in the crew time. We, therefore, need miniaturization and automation. Rheological measurements are of particular interest for this class of materials some of which are accessible by microrheology (Mason, Gang, and Weitz, 1996).

Gravity is highly relevant for the dynamics of granular materials (Guyon, Delenne, and Radjai, 2020), where it is the dominant interaction in many terrestrial experiments, particularly as regards industrial handling and processing. In foams, gravity-driven drainage is an important problem (Weaire and Hutzler, 2001) and in suspensions, pastes, and slurries, particle sedimentation influences, and often obscures, the interesting science and affects the processing protocols (Guazzelli and Morris, 2012). Therefore, microgravity is a particularly useful knob for testing the relative importance of various mechanisms: the ability to provide different degrees of gravity is a unique tool for fundamental research (see Figure 4 for example). Tunable processes such as self-assembly and manufacturing will be different in microgravity, potentially leading to new applications.

Space exploration provides some additional challenges and opportunities for particulate research (NASA, 2020). In low-humidity environments, charging effects from both unblocked radiation and tribocharging of vibrating grains can lead to hazardous circumstances for the missions themselves. An improved understanding of granular material under such conditions will provide important fundamental knowledge needed to explore fully planetary and other extraterrestrial bodies, particularly those with powdery surface regolith, and in particulate rings. Grains suspended in a plasma (dusty plasmas (Shukla and Mamun, 2015)) have been studied for more than a decade in microgravity conditions, so there is

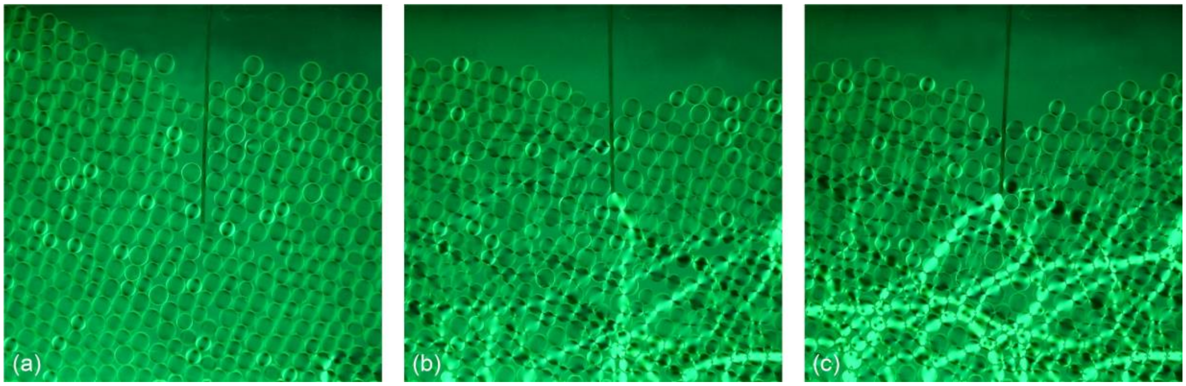

Figure 4.—Patchy, triangular, deoxyribonucleic acid (DNA) functionalized particles and crystallization of cubic diamond colloidal crystals. (a) Scanning electron microscope (SEM) images of 111 plane of colloidal diamond crystals. Crystals are about 40 μm across, with grain boundaries and point defects. Inset, computer-generated image showing 111 plane of colloidal diamond crystal for $d_{CC}/(2a) = 0.74$, consistent with SEM image. (b) Side view of crystal edge. Thickness of crystal is about 10 to 20 particles. (c) Magnified SEM image of 111 plane showing interlocking of particles, as designed. For particles shown in (a) and (b), $d_{CC}/(2a) = 0.73$ and $b/a = 1.20$; in (c) $d_{CC}/(2a) = 0.75$ and $b/a = 1.19$. In (a) to (c), scale bars are 5 μm. Adapted from He et al., 2020.

importance of conserving resources in spaceflight and extraterrestrial habitation, including those obtained by in situ resource production. Recycling efforts would certainly need to exceed what is presently the norm on Earth, and the mining or reprocessing of materials would often entail handling many types of particular materials of this class. The techniques developed for space exploration will feed back to improve sustainability and life on Earth.

References

Extensive references are provided for NASA/CP-20205010493, pp. 26-29, at https://ntrs.nasa.gov/api/citations/20205010493/downloads/CP-20205010493%20Final.pdf.