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OPPORTUNITIES FOR SOFT MATTER RESEARCH IN SPACE

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Introduction. Soft materials—materials that can be deformed and restructured by thermal or mechanical stresses at room temperature—are ubiquitous in our everyday lives. The milk we drink in the morning (a colloidal dispersion), the gel we put in our hair (a polymer mixture), and the plaque that we try to scrub off our teeth (a bacterial biofilm) are all familiar examples. Because they are so easily deformed, such materials—which include liquids and liquid mixtures, colloidal dispersions, polymer solutions and gels, foams, liquid crystals, granular materials, many biological materials, and even many active and living materials—typically have disordered microstructures and highly non-linear responses to external stimuli. Thus, they challenge conventional understanding based on the study of model materials with ordered microstructures and linear responses—motivating fascinating new scientific questions at the interface of biology, chemistry, materials science, mathematics, physics, and engineering. In addition, owing to continuing advances in materials synthesis, such materials can now be formulated to have highly predictable and tunable physicochemical properties. Thus, not only does the study of soft matter help us better understand the world around us, but it also holds great promise in developing solutions to societal challenges such as the need for water security, more sustainable and resilient materials, and improved ways to manage health. Developing such solutions will not only have value to humans on Earth, but will likely also benefit human exploration of space [1]. Here, we outline some current and emerging areas of the field of soft matter, and propose opportunities for future research in space. We note that due to page limitations, we are not presenting a comprehensive overview of this field, but rather, highlight some areas of research explored by our group in which activity in this field has been particularly rapid recently.

Microfluidics. Advances in the ability to process and study fluids at micro- and nano-scales provide new opportunities for improved handling of fluids and materials in space [2]. For example, microfluidic technologies provide a way to produce large quantities of emulsions, drops of one fluid within another, having precisely controlled sizes, compositions, and morphologies [3]. These drops can be used as small-scale microreactors for the isolation and handling of useful chemical compounds [4]; they can also be used as templates for the production of solid microcapsules that encapsulate and release materials in a programmable manner [5], which may be useful for targeted release of high-value compounds in space applications.

Microfluidics also provide new opportunities to tune the mixing of fluids and chemicals in space; while at such small scales, mixing is typically limited by diffusion, geometric or external perturbations (e.g., mechanical, electromagnetic) can be designed to overcome this limitation [6]. Another approach is to use additives to modify the fluid rheology, which can promote mixing by generating flow instabilities that can even create chaotic, turbulent-like flows [7], despite the typically negligible influence of inertial forces at such small scales. Advances in microscale flow visualization now enable researchers to directly visualize such flow-induced mixing (Figure 1).

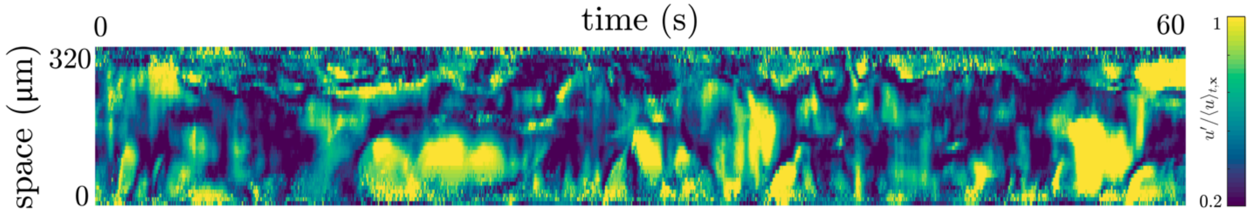

Figure 1. Space-time kymograph plot of chaotic fluid mixing generated by polymer elasticity within a single pore of a 3D porous medium. The color shows the magnitude of velocity fluctuations u' normalized by the temporally- and spatially-averaged velocity $\langle u \rangle_{t,x}$. Adapted from [8].

Microfluidic technologies also have a long history of being used in studies of immiscible fluid displacements, in which the competition between viscous and capillary forces can be tuned to control fluid flow. For example, microfluidics have provided insights into the physics underlying interfacial instabilities such as viscous fingering and capillary fingering [9], yielding guidelines for how to tame such instabilities for improved liquid delivery using e.g., designer porous media [10, 11] (Fig. 2).

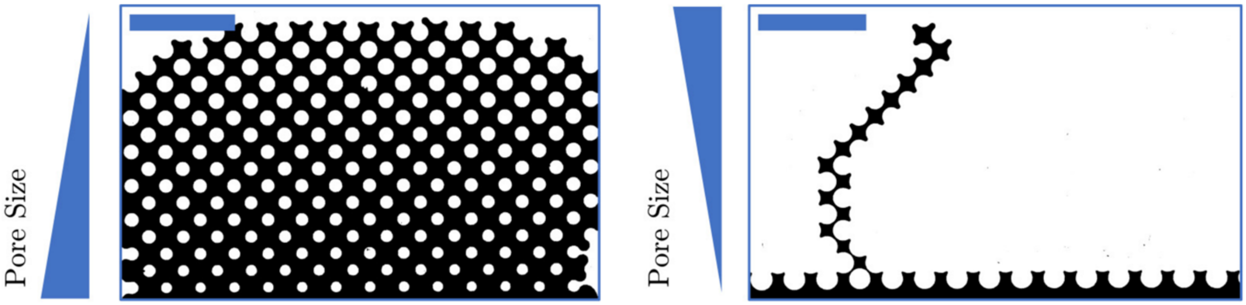

Figure 2. Images of a nonwetting fluid (black) displacing a wetting fluid (white) from a microfluidic porous medium with obstacles of differing sizes (circles) that generate a pore size gradient along the flow direction (bottom to top). When the pore size decreases along the flow direction, the immiscible fluid interface is stable and propagates as a uniform front (left). By contrast, when the pore size increases, the fluid interface is unstable and propagates via a single fingered channel (right). Scale bars are 5 mm. From [11].

Capillary-driven flows can also be used to pump fluids over large length scales and in programmable pathways—in many cases, autonomously and without external power sources. Indeed, this approach is often used by plants to generate massive hydraulic loads to pump fluid over large heights (up to ~100 m high!) using capillary suction generated by nanoscale pores in their leaves [12]. To prevent plants from drying out, these pores must be surrounded by a sufficiently humid micro-environment, which is often achieved using stomata, microscale pores that open and close in response to environmental stimuli—enabling plants to simultaneously self-regulate water, heat, and gas fluxes, and inspiring synthetic mimics using stimulus-responsive soft materials [13]. Such an approach can be used to design "breathable" fabrics that self-regulate moisture and heat transfer [14], of potential use by space explorers. It also has been explored in the context of paper microfluidics, in which microscale flows are generated using porous cellulose-based materials [15]—representing a potentially cheap, straightforward, highly-tunable, biodegradable, and biocompatible route to fluid handling and even low-cost diagnostics for health.

Colloids. Micro- and nano-scale colloidal particles are components of many industrial, pharmaceutical, and personal care formulations of potential use in space. Advances in materials chemistry now enable the synthesis of particles of controlled sizes, shapes, compositions, and ability to change their properties in response to chemical, temperature, and electromagnetic stimuli, as well as control over the interactions between particles [16]. In parallel, advances in theoretical and computational models of colloidal structure and dynamics have yielded deeper understanding of e.g., colloidal self-assembly into crystals, ordered phases of polyhedra, and disordered gels and glasses [17].

Building on these advancements, an emerging frontier of research is the design of colloidal particles capable of performing useful chemical reactions. For example, colloidal particles can be engineered using catalytic nanomaterials, such as bimetallic and zero valent iron nanoparticles, that are particularly promising for water remediation because of their ability to spread through complex terrain [18], high reactive surface area, and their ability to remediate common pollutants such as heavy metals and chlorinated solvents [19]. A related recent advance has been in the development of chemically-powered colloids that can self-propel [20], whose applications are described further below.

Active and living matter. Living systems are inherently multicomponent, disordered, rheologically complex, and are often out of equilibrium. A growing body of research has used ideas and tools from soft matter to shed light on the diverse mechanical and transport properties of living systems. Bacterial communities, for example, have been an attractive system to study in part due to the critical roles they play, both harmful and beneficial, in agriculture, biomedicine, ecological and environmental processes, and industrial operations—all of which will likely be of considerable importance in space exploration. Moreover, bacteria have diverse and tunable transport properties, shapes, sizes, and surface chemistries, growth behavior, and abilities to transform chemicals. Hence, studies have focused on elucidating the mechanisms by which bacteria:

(i) Form surface-attached communities and self-replicate in complex environments [21];
(ii) Self-propel and navigate complex environments, enabling them to colonize new terrain, perform mechanical work, and create turbulent-like fluid flows to mix or pump fluids over large length and time scales [22];
(iii) Sense and respond to environmental (e.g., mechanical and chemical) stimuli [23];
(iv) Regulate their population-scale morphologies and physicochemical properties [24, 25];
(v) Self-organize into dense clusters akin to thermodynamic phases [22] or in hierarchically-structured communities composed of different strains/species with differing requirements for survival [22, 26].

Such studies not only provide fundamental insights into biology, but also suggest new ways to predict and control the behavior of bacterial communities—and potentially other forms of active and living matter—in complex environments. This capability will be important for e.g., leveraging beneficial bacteria for water purification, agriculture in extreme settings, and maintaining the health of space explorers [27].

Similar research questions have also been addressed for other forms of active and living matter: prominent examples include collections of eukaryotic cells, other microscopic organisms such as algae and protists, archaea, and sperm, subcellular active matter such as enzymes and driven biopolymer assemblies, more macroscopic forms of active matter such as driven granular media, birds, fish, large mammals, and robots, and active synthetic colloids [22]. Such synthetic systems can recapitulate many of the characteristics of living systems, suggesting a way to design novel forms of soft matter that can behave like, and potentially even exceed the capabilities of, living systems and perform useful functions to humans.

Another emerging frontier of research is in designing “Engineered Living Materials” (ELMs)—soft materials (e.g., polymer matrices) containing living cells that continue to form, assemble, or alter the material itself, such as through secretion of extracellular polymers [28, 29]. Drawing on advances in synthetic biology, such living materials have promise to be made of diverse biological compounds, recycle and sustainably process their constituent components, self-heal and self-generate, and respond to diverse external stimuli by e.g., changing shape. Emerging soft matter engineering approaches also enable ELMs to be 3D-printed in complex architectures (Fig. 3), thereby expanding the possible design space of soft and living matter.

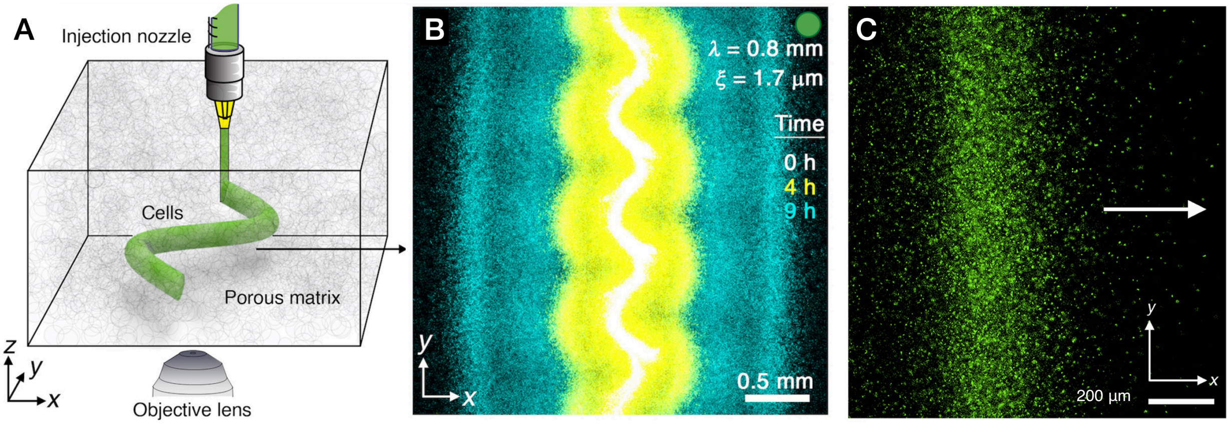

Figure 3. (A) Schematic of 3D printing of bacteria in a porous, granular hydrogel matrix. (B) Superimposed experimental micrographs (different colors show different times) of bacteria spreading collectively from a 3D-printed population with an undulatory initial structure; the spreading cells smooth out these morphological perturbations. λ and ξ refer to the undulation wavelength and matrix mean pore size, respectively. (C) Magnified view of a front of bacteria collectively migrating by chemotaxis. (A-B) are from [30] and (C) is from [31].

Hydrogels. A challenge associated with space exploration is developing ways to manage water (for drinking, irrigation of plants, etc.) Hydrogels—cross-linked networks of hydrophilic polymers that can absorb over a thousand times dry weight in water while still retaining integrity—provide a way to address this challenge. For example, hydrogels have promise in agriculture to act as reservoirs of water, absorbed from rain or during irrigation, that can hydrate plant roots even under dry conditions [32]. Motivated by this promise, studies of water absorption by hydrogels in model granular media akin to soil (Fig. 4A) are now providing quantitative guidelines—utilizing theories of polymer physics, granular physics, and soft mechanics—for the use and formulation of hydrogels that are optimized for water absorption in a given soil and at a given depth [33]. A related application of hydrogels is in cement-based building materials, where hydrogel amendment has potential to help create structures that are more durable [34]. These applications of hydrogels will likely be of particular use in space applications towards the design of ecosystems that can sustainably manage water fluxes and withstand extreme conditions. Furthermore, advances in materials chemistry have yielded diverse other classes of hydrogels with highly tunable sorption characteristics, biocompatibility, and ease of manufacture in complex geometries—making them appealing for applications in the design of shape-morphing and self-healing materials [35] (Fig. 4B) and soft robots [36], as well as low-energy and sustainable forms of water purification [37].

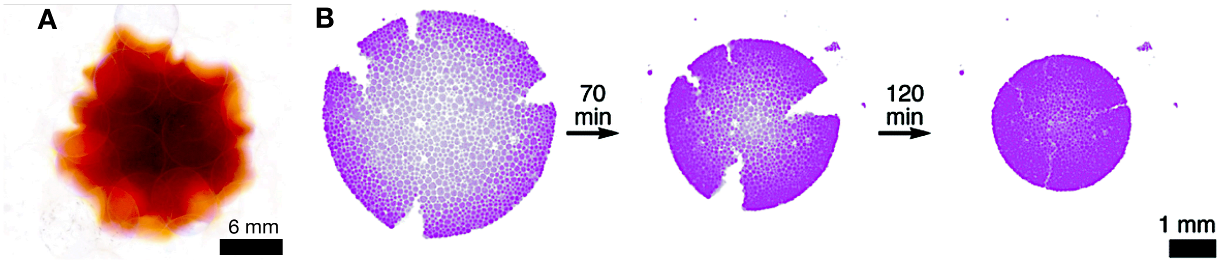

Figure 4. (A) Image of spatially non-uniform water absorption by a hydrogel (brown) swollen within a granular packing (faint circles); adapted from [33]. (B) "Self-closing" of a cracked hydrogel packing; from [35].

Outlook. NASA's Physical Sciences Research Program at the International Space Station (ISS) has a long history of experiments that have provided crucial new insights in the field of soft matter, such as in the study of colloidal self-assembly (ACE, BCAAT, PCS), colloidal rheology (InSPACE), liquid crystals (OASIS), and complex fluids rheology (SHERE). Building on this storied history, the recent advances in the field of soft matter described above provide new opportunities for research that will uniquely advance scientific knowledge, meet space exploration mission needs, and provide terrestrial benefits. These opportunities are detailed above and summarized below. In all these cases, because the properties of the soft material systems being utilized rely sensitively on e.g., relatively weak surface, interfacial, and entropic interactions, and often are composed of fluids, gels, particulates, and biological materials that are not density-matched, gravitational forces impart new effects and complexities in their operation—particularly over large heights and time scales. Thus, it will be particularly interesting to explore how these systems behave in microgravity, in which gravitational effects are suppressed, enabling a cleaner analysis of the underlying behavior.

1. Explore the use of *microfluidic technologies* for the production of micro- and nano-capsules for encapsulation and stimulus-response of key compounds. A key area for future research will be to broaden the range of drop/capsule sizes, compositions, and morphologies that can be produced, as well as improving the scalability and throughput of microfluidic approaches.
2. Tune microfluidic geometries and fluid rheologies to develop systems for self-regulated water and heat transport, without any external energy sources, in a programmable manner, that can also be tuned by external stimuli such as environmental light/heat.
3. Develop new forms of *colloidal matter* whose phase behavior and macroscopic properties (e.g., mechanical, electromagnetic, shape) can be programmed, and that can recapitulate and potentially exceed the ability of living systems to transform chemicals, sense and respond to stimuli, and perform mechanical work.
4. Explore how the unique behaviors of *active and living systems*, such as their ability to self-propel, self-replicate, and self-organize, are influenced by gravitational stresses (as recent experiments [38] have begun to explore under 1*g* conditions on Earth)—which could both provide deeper insights into active matter, as well as provide guidelines for the management of e.g., biofilms in spacecraft and their implications for the health of space explorers.
5. Develop new forms of *engineered living materials,* and related composite materials comprising active components, that can potentially yield new forms of soft robots or smart fabrics.
6. Investigate the use of *hydrogels* and hydrogel-based materials in helping to design sustainable ecosystems, fabrics, and robots that more effectively manage water.

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