**Cover Page**

**Topical White Paper submitted to the Biological and Physical Sciences in Space**

Decadal Survey 2023-2032

**FUNDAMENTAL MATERIALS RESEARCH**

**SOFT MATTER - THE NEXT DECADE AND**

**BEYOND IN SPACE MATERIALS RESEARCH**

Submitted by Simon A. Rogers

Department of Chemical and Biomolecular Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA. Email:sarogers@illinois.edu

Co-Authors (listed alphabetically)

James Gilchrist, Professor, Lehigh University

Safa Jamali, Professor, Northeastern University

Kelly Schultz, Professor, Lehigh University

Vivek Sharma, Professor, University of Illinois at Chicago

1. **Background**

Modern society relies on soft materials, which are important for foods, consumer products, biological materials, and energy and environmental applications. The interactions that hold soft materials together are often comparable in magnitude to thermal energy, making them especially susceptible to weak forces, including those due to gravity in terrestrial circumstances. The development of functional soft materials requires an understanding of their behavior close to, and far from equilibrium. Despite recent progress, many questions remain regarding how molecular-scale behavior dictates macroscopic properties in these systems. In many soft materials, forces and deformations can induce massive molecular or constituent reorganizations that manifest as transformations in the macroscopic material properties. Such behavior ultimately leads to the success or failure of a product, or rigorous protocols for the safe handling and efficient processing of soft materials. Additional complexities arise due to the transient conditions that are typically encountered in most environmental and biological situations, and well as industrial flow startup and cessation.

Soft matter science is rich and complex and couples novel experimentation with model and theory development. As in any physical science, the theories can only be tested by rigorous experiments that isolate effects and control for others. Approaches to studying soft materials are as varied as the materials themselves. Broad categories can be constructed, however, in terms of behaviors or material structure. Real-world materials often contain multiple ingredients or constituents whose complex interactions can lead to emergent behaviors, or simply make the system too complex to understand completely. Model systems that contain fewer ingredients, and therefore fewer interactions are therefore typically studied, with the development of their behaviors leading to an increase in our understanding of their more complex real-world counterparts.

We restrict our discussion here to behaviors and material classes where the ability to control microgravitational effects will allow for significant advances in our understanding of the weak forces that dictate their behavior. Specifically, we discuss opportunities in the study of buoyancy-driven flows and instabilities, colloidal gels and glasses, and foams.

1. **Buoyancy-driven instabilities**

Buoyancy-driven instabilities, commonly called natural convection, drive flow in a single-phase fluid due to variations in density. These instabilities are common in both natural and industrial terrestrial systems. Density variations are induced by temperature gradients that result in thermal expansion. Classic examples include large scale atmospheric motion that provides lift for aviators and soaring raptors near mountainous terrain and power-free convection associated with the cooling towers used for nuclear plants. At smaller scales, swirls found in heated liquids from the upwelling of lower density fluid are a result of complex convection patterns known as Rayleigh-Bénard convection [1]. These recirculation flows can enhance heat transfer in advantageous ways to cool a cup of coffee and yet cause destructive inhomogeneity during drying of automotive and other paints [2].

Inhibition of buoyancy-driven flows is difficult. One approach is to remove temperature gradients that cause density differences to stifle these flows. For example, rooms with sensitive instrumentation are sometimes outfitted with thermal panels on the walls to reduce temperature gradients that drive flow and resulting air currents that cause vibration [3]. However, several systems require the presence of temperature gradients as part of their design. For instance, fundamental studies of thermophoresis are plagued with inconsistency, in part caused by buoyancy-driven flows. Thermophoresis, the migration of small particles in thermal gradients [4], has been used widely for capturing aerosols for air quality monitoring [5] but are poorly understood in aqueous systems and complex fluids. Even though this process is poorly understood, thermophoresis has great potential for separation of nanoscale particles such as viruses for development of low-cost disease detection platforms [6]. However, most terrestrial experiments cannot separate thermophoretic particle motion from the convective motion of buoyancy-driven flows.

Only in microgravity can one completely stifle both convective motion and particle sedimentation. Through fundamental microgravity studies of thermophoresis, combined with measurements of particle Brownian motion, the surface forces that drive thermophoretic motion and local fluid properties can be characterized simultaneously. This approach enables high fidelity microgravity studies of thermophoresis in complex fluids with *temperature-dependent microstructure* [7] with the intent of designing new modes of rheology-dependent particle thermophoretic motion. Moreover, these studies, when paired with the ability to synthesize particles with varying size, shape, and surface heterogeneities, will give unprecedented information of thermophoretic transport. The results will provide the necessary knowledge to confirm existing or develop new theory of the role of surface charge and ionic strength on nanoparticle transport in temperature gradients that can drive innovations in disease detection, drug delivery, and environmental remediation techniques.

1. **Colloidal gels and glasses**

Over the past 15 years, and owing to a concerted effort at NASA, ISS and NSF, a series of experiments have been performed on the Fluids Integrated Rack (FIR) shaping much of our current understanding of colloidal gels and glasses [8]. Specifically, ACE and PACE experiments, enabling prolonged visualization of the particle dynamics, have helped us understand the pathways for arrest of structure, and formation of space-spanning networks in low and intermediate volume fractions of attractive colloids [9 – 13]. We have also learned a lot about nucleation and growth of colloidal glasses at larger concentrations. As informative, and foundational as these studies have been to current understanding of colloidal physics, virtually all of these experiments share two common limitations: 1- the systems studied are far from realistic and have been limited to ideal cases; and 2- the Liquid Microscopy Module (LMM) used in all of these studies is limited to quiescent condition imaging where equilibrium behaviors are observed.

Virtually all real-life particulate/colloidal systems of interest are highly heterogeneous in nature, having a range of particle sizes and interactions. An extremely important [and relevant to many terrestrial and extraterrestrial applications] example is soil, in which the size variation and physicochemical characteristics of particles make it impossible to predict/understand dynamics of the system from single component models [14]. On the other hand, to enable a technological leap from fundamental understanding of these systems, one would essentially need to understand the physics and dynamics of these particulate systems under flowing conditions. This is critical, as structure and properties of these systems are known to be coupled to flows which they are subjected to [15, 16]. With more extraterrestrial habitat explorations on the horizon, and an ever-increasing effort on additive manufacturing of particulate systems, the next decade of microgravity research should focus on “more realistic particulate matter” and “under flowing conditions”.

As gravitational forces will completely change the dynamic of particles with different sizes on the ground, the departure from model single component systems to more realistic models inherently makes microgravity a key component in colloidal science research for the next decade. Of particular interest is to understand the pathways in which one can design a highly heterogeneous system with desirable mechanics such as yield stress, elastic and viscous moduli. These are essential properties, for informed design of advanced manufacturing capabilities both on the ground and for extraterrestrial applications.

1. **Foams and films**

The stability, lifetime, and rheology of foams influence their properties and applications in water purification, mineral extraction, oil recovery, firefighting, and many foods, beverages, cosmetics, and nature. The pleasure of drinking fizzy fluids and the leisure offered by dishwashers is made possible by short-lived foams. In contrast, the shape and size distribution of bubbles underlies the texture and mouthfeel of food products like bread, popcorn, cakes, beers, and lattes. The drainage, stability and lifetime of liquid foams depend on the interplay of hydrodynamic and thermodynamic forces and fluxes that drive restructuring and drainage within the intricate three-dimensional architecture of foams [17 – 20]. Thus, it is desirable to understand and control the mass flux of gases between bubbles, of liquid within thin liquid films or foam films that enclose gas pockets, and from films into Plateau borders (PBs), the thicker channels formed by intersecting films [17 – 21]. The curvature gradient between liquid foam film and the PB causes a capillary / Laplace pressure gradient contributes the impelling forces for individual film drainage, whereas the impairing forces are primarily contributed by bulk viscous stresses, though sometimes, interfacial and bulk viscoelasticity of the foaming liquid also play a role [17 – 27]. As film thickness approaches the molecular length-scales, or when interfacial regions begin to overlap, the drainage can be further enhanced or reduced by an additional contribution from surface forces [23, 28, 29] that provide an excess pressure called disjoining pressure, which acts normal to the surface. Several reviews [19, 30, 31], textbooks [17, 18, 32, 33] present a survey of the current state-of-the-art understanding in foams that are carried out on earth, in the presence of nominal gravity conditions. It is well-known that gravitational effects contribute to the motion of thinner regions within single films, govern the shape of individual bubbles and the speed of their rise, affect the rate of coalescence and coarsening, and influence the microstructure and structural transitions in the foams.

It is well-established that characterizing and quantifying the influence of gravitational effects is necessary for unraveling the physicochemical mechanisms governing the lifetime, stability, rheology, and applications of liquid foams. The gist of microgravity studies carried out so far is as follows [34 – 40]. Experiments show that the foamability and foam lifetimes are substantially enhanced in microgravity. In addition to increased stability of the foams considered relatively stable on earth, even the foams deemed unstable on Earth become stable in microgravity. Several factors contribute to enhanced stability: suppression of gravitational drainage, both within foam films that separate individual bubbles and at the larger length scale spanning the entire foam head. An increase in capillary length allows bubbles to maintain the quasi-spherical shape for much larger sizes, and both coalescence and coarsening slow down as the individual films drain slower and thus, the flow through channels and nodes is also reduced. The stability of bubbly water is enhanced. Fascinatingly, the antifoam agents are rendered nearly ineffective due to the large film thickness and the absence of buoyancy.

The questions that remain unexplored are as follows:

(a) The influence of gravity on rheological response, with the possibility of visualizing and analyzing the deformation and rearrangement of bubbles, and changes in the size, shape, and number density of bubbles without complicating gravity-induced flows. Emphasis can be on foams with higher liquid fractions that are more susceptible to the impact of bubble coalescence, shape changes, and shape/size distribution.

(b) Though the influence of gravity on surfactant-based foams has received significant attention, protein-based foams, that are present in foods and beverages remain unexplored. Proteins provide more rigid and heterogeneous interfaces, have slower adsorption kinetics, present richer interfacial rheology effects, and hence discerning foamability and foam stability are more difficult.

(c) Coarsening in wet foams, and its influence on foam properties and applications can benefit the most from experiments that are not influenced by gravity-driven flows and instabilities.

1. **Recommendations and outlook**

The ability to probe soft material responses in the absence of gravitational effects, or in microgravity, will allow researchers to carefully exclude long-range body forces probe and expand our understanding of how weaker short-range interactions and surface forces affect the properties exhibited by soft materials. It is recommended that an increased focus be placed on more complex systems, where more and more varied interactions exist between constituents, and the systems studied more closely resemble those in use in industry or biology.

Additionally, an increased focus on out-of-equilibrium behaviors is recommended. Significant insight can be, and has been gained from studying soft matter at, or close to equilibrium. However, much remains to be learned from how soft matter behaves far from equilibrium, under conditions where many biological and industrial processes reside. An increased focus on “more realistic particulate matter” and “under flowing conditions” is therefore recommended for the next decade of soft matter research.

**References**

[1] Rayleigh, Lord. On the convective currents in a horizontal layer of fluid when the higher temperature is on the under side. Philos. Mag. 32, 529–546 (1916). https://doi.org/10.1080/14786441608635602

[2] Feng, L. & Mears, L. Energy Consumption Modeling and Analyses in Automotive Manufacturing Plant. J. Manuf. Sci. Eng. 138, (2016). https://doi.org/10.1115/1.4034302

[3] Cacho-Nerin, F., Parker, J. E. & Quinn, P. D. A passive hutch-cooling system for achieving high thermal-stability operation at the Nanoprobe beamline, Diamond Light Source. J. Synchrotron Radiat. 27, 912–922 (2020). https://doi.org/10.1107/S1600577520004932

[4] Ludwig, C. Diffusion zwischen ungleich erwärmten Orten gleich zusammengesetzter Lösungen. Sitz. Math. Naturwiss. Cl. Kais. Akad. Wiss 20, 539 (1856).

[5] Derjaguin, B. V. & Bakanov, S. P. Thermophoresis of Aerosol Particles. Nature 196, 669–670 (1962). https://doi.org/10.1038/196669a0

[6] Zhao, C., Cao, Z., Fraser, J., Oztekin, A. & Cheng, X. Optimization of nanoparticle focusing by coupling thermophoresis and engineered vortex in a microfluidic channel. J. Appl. Phys. 121, 24902 (2017). https://doi.org/10.1063/1.4973272

[7] Winter, H. H. & Mours, M. Rheology of polymers near liquid-solid transitions. Adv. Polym. Sci. 134, 165–234 (1997). https://doi.org/10.1007/3-540-68449-2\_3

[8] Meyer, W., R. Sicker, A. Abbott-Hearn, D. Chao, and F. Chiaramonte, NASA Physical Sciences Using the Light Microscopy Module (LMM) on the International Space Station (ISS) The Advanced Colloids Experiment (ACE) and MacroMolecular Biophysics (MMB).

[9] Leunissen, M.E., A. van Blaaderen, A.D. Hollingsworth, M.T. Sullivan, and P.M. Chaikin, Electrostatics at the oil–water interface, stability, and order in emulsions and colloids. Proceedings of the National Academy of Sciences, 2007. 104(8): p. 2585-2590. https://doi.org/10.1073/pnas.0610589104

[10] Lu, P.J., H. Oki, C.A. Frey, G.E. Chamitoff, L. Chiao, E.M. Fincke, C.M. Foale, S.H. Magnus, W.S. McArthur, D.M. Tani, P.A. Whitson, J.N. Williams, W.V. Meyer, R.J. Sicker, B.J. Au, M. Christiansen, A.B. Schofield, and D.A. Weitz, Orders-of-magnitude performance increases in GPU-accelerated correlation of images from the International Space Station. Journal of Real-Time Image Processing, 2010. 5(3): p. 179-193. https://doi.org/10.1007/s11554-009-0133-1

[11] Lu, P.J., E. Zaccarelli, F. Ciulla, A.B. Schofield, F. Sciortino, and D.A. Weitz, Gelation of particles with short-range attraction. Nature, 2008. 453(7194): p. 499-503. https://doi.org/10.1038/nature06931

[12] Bailey, A.E., W.C.K. Poon, R.J. Christianson, A.B. Schofield, U. Gasser, V. Prasad, S. Manley, P.N. Segre, L. Cipelletti, W.V. Meyer, M.P. Doherty, S. Sankaran, A.L. Jankovsky, W.L. Shiley, J.P. Bowen, J.C. Eggers, C. Kurta, T. Lorik, P.N. Pusey, and D.A. Weitz, Spinodal Decomposition in a Model Colloid-Polymer Mixture in Microgravity. Physical Review Letters, 2007. 99(20): p. 205701. https://doi.org/10.1103/PhysRevLett.99.205701

[13] Lu, P.J., J.C. Conrad, H.M. Wyss, A.B. Schofield, and D.A. Weitz, Fluids of clusters in attractive colloids. Physical Review Letters, 2006. 96(2): p. 028306. https://doi.org/10.1103/PhysRevLett.96.028306

[14] Tiessen, H. and J.J.S.S.S.o.A.J. Stewart, Particle‐size fractions and their use in studies of soil organic matter: II. Cultivation effects on organic matter composition in size fractions. 1983. 47(3): p. 509-514. https://doi.org/10.2136/sssaj1983.03615995004700030023x

[15] Crawford, B., D. Faulkner, and E.J.J.o.G.R.S.E. Rutter, Strength, porosity, and permeability development during hydrostatic and shear loading of synthetic quartz‐clay fault gouge. J. Geophys. Res., 2008, 113, B03207 https://doi.org/10.1029/2006JB004634

[16] Bailey, L., H.N. Lekkerkerker, and G.C.J.S.M. Maitland, Smectite clay–inorganic nanoparticle mixed suspensions: phase behaviour and rheology. 2015. 11(2): p. 222-236. https://doi.org/10.1039/C4SM01717J

[17] I. Cantat, S. Cohen-Addad, F. Elias, F. Graner, R. Höhler and O. Pitois, Foams: Structure and Dynamics, Oxford University Press, 2013. DOI:10.1093/acprof:oso/9780199662890.001.0001

[18] D. L. Weaire and S. Hutzler, The Physics of Foams, Oxford University Press, 1999. ISBN-13: 978-0198510970

[19] S. Cohen-Addad, R. Hohler and O. Pitois, Ann. Rev. Fluid. Mech., 2013, 45, 241-267. https://doi.org/10.1146/annurev-fluid-011212-140634

[20] P. M. Kruglyakov, S. I. Karakashev, A. V. Nguyen and N. G. Vilkova, Curr. Opin. Colloid Interface Sci., 2008, 13, 163-170. https://doi.org/10.1016/j.cocis.2007.11.003

[21] S. I. Karakashev, Exp. Fluids, 2017, 58, 1-40. https://doi.org/10.1007/s00348-017-2332-z

[22] E. Chatzigiannakis, N. Jaensson and J. Vermant, Curr. Opin. Colloid Interface Sci., 2021, 101441. https://doi.org/10.1016/j.cocis.2021.101441

[23] V. Bergeron, J. Phys.: Condens. Matter, 1999, 11, R215-R238. https://doi.org/10.1088/0953-8984/11/19/201

[24] H. A. Stone, S. A. Koehler, S. Hilgenfeldt and M. Durand, Journal of Physics - Condensed Matter, 2003, 15, S283-S290. https://doi.org/10.1088/0953-8984/15/1/338

[25] E. Chatzigiannakis and J. Vermant, Soft Matter, 2021, 17, 4790-4803. https://doi.org/10.1039/D1SM00244A

[26] E. Hermans, M. S. Bhamla, P. Kao, G. G. Fuller and J. Vermant, Soft Matter, 2015, 11, 8048-8057. https://doi.org/10.1039/C5SM01603G

[27] K. J. Mysels, S. Frankel and K. Shinoda, Soap films: Studies of their Thinning and a Bibliography, Pergamon Press, 1959. https://doi.org/10.1016/0095-8522(60)90062-3

[28] B. V. Derjaguin, N. V. Churaev and V. M. Muller, Surface Forces, Springer, New York, 1987. https://doi.org/10.1007/978-1-4757-6639-4

[29] C. Stubenrauch and R. von Klitzing, J. Phys.: Condens. Matter, 2003, 15, R1197. https://doi.org/10.1088/0953-8984/15/27/201

[30] N. D. Denkov, S. Tcholakova, K. Golemanov, K. Ananthpadmanabhan and A. Lips, Soft Matter, 2009, 5, 3389-3408. https://doi.org/10.1039/B903586A

[31] A. Saint-Jalmes, Soft Matter, 2006, 2, 836-849. https://doi.org/10.1039/B606780H

[32] J. F. Sadoc and N. Rivier, Foams and Emulsions, Springer, 1999. https://doi.org/10.1007/978-94-015-9157-7

[33] D. Fennell Evans and H. Wennerström, The Colloidal Domain: Where Physics, Chemistry, Biology, and Technology Meet, Wiley-VCH: New York, 2nd edn., 1999. ISBN: 978-0-471-24247-5

[34] P. Vega-Martínez, J. Rodríguez-Rodríguez and D. van Der Meer, Soft matter, 2020, 16, 4728-4738. https://doi.org/10.1039/D0SM00015A

[35] N. Vandewalle, H. Caps, G. Delon, A. Saint-Jalmes, E. Rio, L. Saulnier, M. Adler, A. L. Biance, O. Pitois, S. C. Addad, R. Hohler, D. Weaire, S. Hutzler and D. Langevin, International Symposium on Physical Sciences in Space, 2011, 327. https://doi.org/10.1051/epn/2014303

[36] D. Langevin and M. Vignes-Adler, European Physical Journal E, 2014, 37. DOI: 10.1140/epje/i2014-14016-3

[37] S. J. Cox and G. Verbist, Microgravity-Science and Technology, 2003, 14, 45-52. https://doi.org/10.1007/BF02870946

[38] M. Andersson, J. Banhart, H. Caps, D. Durian, F. Garcia-Moreno, S. Hutzler, B. Kronberg, D. Langevin, O. Pitois and M. Saadatfar, Journal of the Japan Society of Microgravity Application, 2008, 25, 241. https://doi.org/10.15011/jasma.25.3.241

[39] J. Banhart, F. Baumgartner, S. J. Cox, B. Kronberg, D. Langevin, S. Odenbach, D. Weaire and T. Wubben, in First International Symposium on Microgravity Research & Applications in Physical Sciences and Biotechnology, Vols I and Ii, Proceedings, ed. B. Schurmann, European Space Agency, Paris, 2001, vol. 454, pp. 589-596.

[40] H. Caps, H. Decauwer, M.-L. Chevalier, G. Soyez, M. Ausloos and N. Vandewalle, The European Physical Journal B-Condensed Matter and Complex Systems, 2003, 33, 115-119. https://doi.org/10.1140/epjb/e2003-00148-9.