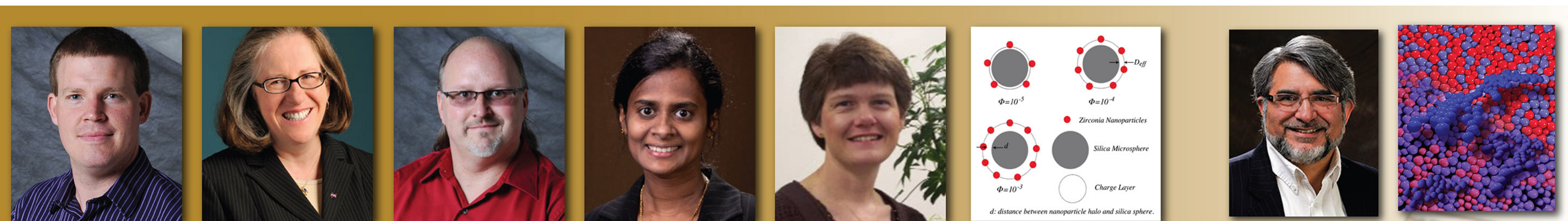
National Aeronautics and Space Administration

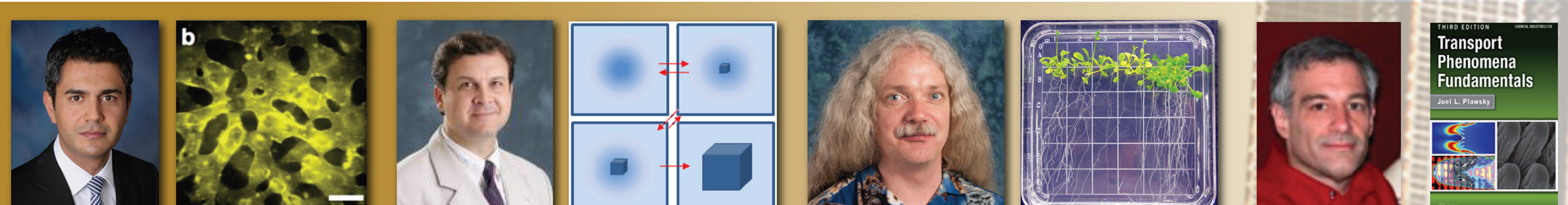
NASA Light Microscopy Module (LMM) on the International Space Station (ISS) Supporting Human Exploration of Colloids, Protein Crystals, and Plant Biology

Matthew Lynch, Procter & Gamble Principal Scientist — ACE–T6 3D confocal image — David Weitz, Harvard University — Peter Lu, Harvard University — ACE–M2R composite image slice from 3D confocal map — Edward Snell, Hauptman-Woodward Medical Research Institute, Inc. — Testing growth rate dispersion in macromolecular crystals

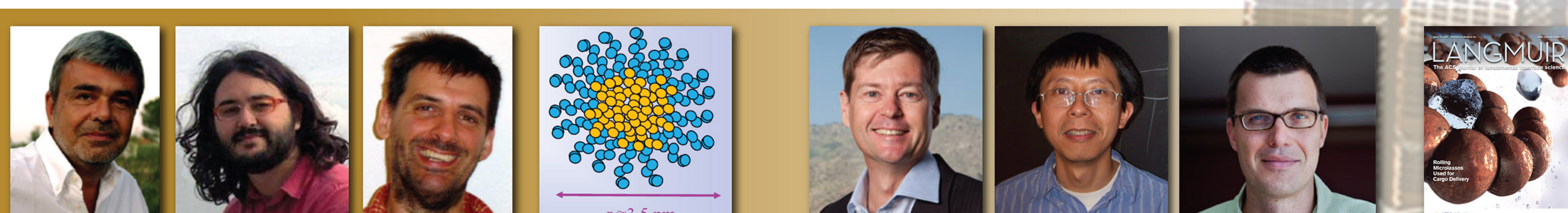


Stuart J. Williams, University of Louisville, Science Principal Investigator — Suzanne Smith, University of Kentucky, Managing Principal Investigator — Gerold Willing, University of Louisville, Co-Investigator — Hemali Rathnayake, Western Kentucky University, Co-Investigator — Janet Lumpp, University of Kentucky, Co-Investigator — Looking for nanoparticle haloing — Arjun Yodh, University of Pennsylvania — Rearrangements in colloidal glasses

Ned Seeman, New York University — Andy Hollingsworth, New York University — Paul Chaikin, New York University — Stefano Sacanna, New York University — Dave Pine, New York University — Mena Youssef, New York University — Self assembly of colloidal super cubes

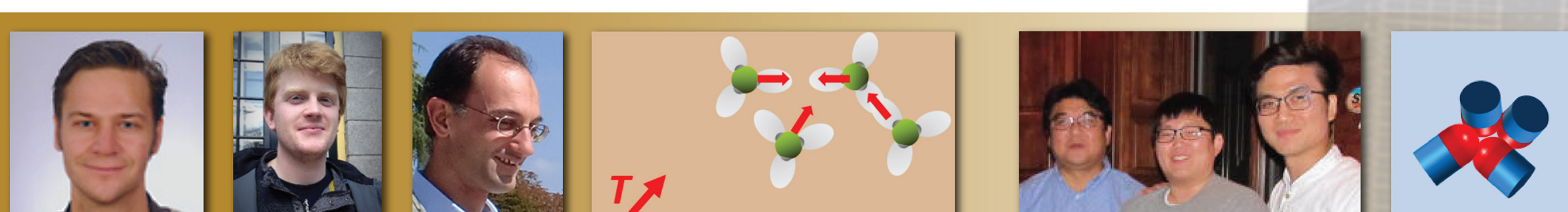


Ali Mohraz, University of California, Irvine — Confocal microscopy image of a bijel — Peter Vekilov, University of Houston — Dense cluster formation and subsequent nucleation — Simon Gilroy, University of Wisconsin — Studying plant growth on the International Space Station — Joel Plawsky, Rensselaer Polytechnic Institute — CVB on cover of textbook by Prof. Plawsky



Roberto Piazza, University of Milan—Italy — Stefano Buzzaccaro, University of Milan—Italy — Luca Cipelletti, University of Montpellier—France — Processes in ordered and disordered structures — David Marr, Colorado School of Mines — Ning Wu, Colorado School of Mines — Michael Solomon, University of Michigan — "Magnetic Microlassos for Reversible Cargo Capture, Transport, and Release"

Boris Khusid, New Jersey Institute of Technology — Monodisperse glasses on Earth crystallize in microgravity — Anna-Lisa Paul and Robert Ferl, University of Florida — Two different fluorescently tagged proteins inside a root reacting to growing in space — Larry DeLucas, University of Alabama at Birmingham — Measuring the effect of macromolecular transport on microgravity protein crystallization



Peter Schall, University of Amsterdam—The Netherlands — Piet Swinkels, University of Amsterdam—The Netherlands — Marco Potenza, University of Milan—Italy — Critical Casimir effect — Chang-Soo Lee, Jongmin Kim, Seong-Geun Jeong, Chungnam National University—South Korea — Self-assembly with Janus building blocks

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Recent and Ongoing Experiments Operating on ISS (Since the 2017 ASGSR Meeting)

ACE–T1 (Chang-Soo Lee, et al., Chungnam National University—South Korea)
Experiments in microgravity remove sedimentation, convection, and particle jamming enabling scientists to study new 3D structures formed from Janus particles. The shape anisotropy of colloidal building blocks will enable shape-selective interactions with directionality specificity designed for building significant complex structures. This work provides understanding and insights important for producing novel functional materials with applications in self-assembly, photonics, diagnostics, and the deep delivery of drugs and cosmetics. Analysis of data from this microgravity experiment has helped the science team to find a relationship between particle shape and composition with the particle's rotational diffusion coefficient—important for self-assembly.

LMMBio–1 and 4 (Larry DeLucas, Aerospace Corporation)
Protein Crystal Growth—The effect of macromolecular transport on microgravity protein crystallization. This experiment tests the hypothesis that the improved quality of microgravity-grown protein crystals is the result of two macromolecular characteristics that exist in a buoyancy-free, diffusion-dominated solution: (1) Slower crystal growth rates, due to slower protein transport to the growing crystal surface and (2) predilection of growing crystals to incorporate protein monomers versus higher protein aggregates are due to differences in transport rates. There are over 100,000 proteins in the human body and an estimated 10 billion throughout the global environment. To fully understand how they work and how they interact with each other, it is necessary to determine their 3D structure. High quality crystals were formed and the growth rate data captured for the current experiment that ended Oct. 22, 2018. This data complements the LMMBIO–1 data collected last year. The analysis of the transport data from the tagged dimers is ongoing. Data collection will continue upon the return of SpaceX–16 when the diffraction patterns of the samples will be observed using X-ray crystallography.

LMMBio–3 and 6 (Edward Snell, Hauptman-Woodward Medical Research Institute, Inc.)
Protein Crystal Growth—Finding where quality can be improved with microgravity growth. Examining the relationship between growth rate dispersion (identical crystals growing at different rates) and mosaicity (perturbations to crystal domain misalignment). Testing the hypothesis that crystals benefiting most from microgravity will be those that show the most growth rate dispersion on the ground. Structural biology of protein-protein complexes and integral membrane proteins are currently a high NIH priority due to their importance for systems biology, disease mechanisms, and structure-guided drug development. Understanding the structure of proteins reveals biological mechanism, the process of disease, and accelerates the development of new and improved pharmaceutical products. The aim is to improve the success and efficiency of this research area in space and as a result have broad impact for health research on the ground. ISS operations for LMMBio–6 are scheduled to begin Nov. 11, 2018.

APEX04 (Anna-Lisa Paul and Robert J. Ferl, University of Florida)
The APEX04 (EpEx–Epigenetic Expression) experiment seeks to use an unbiased genome-wide approach to define the changes in DNA methylation that occur in Arabidopsis during spaceflight, in order to better understand the spectrum of responses that allow adaptation to the spaceflight environment. The LMM component of the experiment examined green fluorescent protein (GFP) reporter gene products associated with the regulation of the epigenome in Arabidopsis.

ACE–T6 (Matthew Lynch, The Procter & Gamble Company)
Little is known about the coarsening of real-world colloidal gels. Most academic research has been done in idealized, monodispersed systems, where the various components in the dispersion are of a single size. However, recent work (Lynch and Weitz) demonstrated that polydispersity, or multiple sizes of particles in the polymer, makes a huge difference in the time scale of coarsening of weak gels, in many cases in excess of several orders of magnitude in time. Commercial systems are necessarily polydispersed systems, this being complicated and not well understood. There are at present no basic measurements/theories that allow us to understand the role of polydispersity in these processes. As a consequence, the ability to design effective products is hugely complicated. This experiment intends to change that. Several patents and a new product line are recent results of this work.

Petri Plants 2 [CARA–2–Characterizing Arabidopsis Root Attractions] (Anna-Lisa Paul and Robert J. Ferl, University of Florida)
The LMM component of the CARA–2 experiment will launch in late November, and will use the LMM to examine GFP gene reporter products associated with auxin and cytokinin signaling in Arabidopsis.

APEX–5 (Simon Gilroy, University of Wisconsin)
Determining how plants sense and respond to their environment and how these signals regulate plant development. The research emphasis is to try and understand these processes at the cellular level.

ACE–T7 (Paul Chaikin, et al., New York University)
This experiment involves the design and assembly of complex 3D structures from small particles suspended within a fluid medium. These so-called "self-assembled colloidal structures," are vital to the design of advanced optical materials. In the microgravity environment, where 3D structures are formed, insight will be provided into the relation between particle shape, crystal symmetry, and structure: a fundamental issue in condensed-matter science. ACE–T7 demonstrates the synthesis and 3D assembly of uniform fluorescent hollow silica microcubes in microgravity using depletion interactions. On Earth, assembly is 2D as a result of rapid sedimentation due to gravity. Thus, experiments were necessarily conducted in microgravity aboard the ISS are necessary to probe the nucleation and growth of crystals in 3D space. Operations are ongoing.

ACE–M2R (David Weitz and Peter Lu, Harvard University)
The ACE–M2R samples have been equilibrating on the ISS for several years. Recently, ACE–M2R collected a large and spectacular set of 3D confocal microscopy data on a colloid-polymer sample that has been kinetically-arrested in microgravity. These observations represent a "final state" of evolution. Strikingly, the sample has developed network-like structures with angular corners and sharp edges, which were resolved with micron-scale resolution in full 3D. Their microgravity equilibrium state may provide definitive statements on the long-term stability (aging) of these systems, which is important from the standpoint of fundamental science (modelling ideal systems), and should have practical applications in the development of better stabilizers for a number of household products favored by industry.

ACE–T2 (Peter Schall, et al., University of Amsterdam—ESA/ESTEC)
Designed to study self-assembly using temperature controlled critical Casimir forces below a critical temperature, the ACE–T2 experiment did not form these 3D structures the first time it was run; yet, when this run was taken above the critical temperature of its water-lutidine mixture, particles formed structures at select temperatures on liquid drops that changed interfacial tension with temperature. This enabled the science team to build in a controlled manner on work recently published in Nature by Chaikin, et al., that looks at the formation of icosahedral (and other) structures on soccer balls and viruses. Forming 3D superstructures using the Critical Casimir force is now a possible pursuit with an ACE–T2–3 reserve payload sample module.

ACE–T9 (David Marr and Ning Wu, Tao Yang, Colorado School of Mines; Michael Solomon, University of Michigan)
Microgravity enables the 3D imaging, folding, and assembly of complex colloidal molecules within a fluid medium. The colloidal molecules include long rigid and semiflexible colloidal chains, colloidal dimers with an isotropic surface properties, lock and key colloids, and metallodielectric Janus spheres. The fluid medium is an aqueous solution with different salt concentrations. These so-called "colloidal molecules; are vital to the design of advanced functional materials. Such structures will generally lead to arrays with reduced symmetry and enhanced directionality. They can interact with a broad range of electromagnetic radiation in unique ways and can exhibit collective photonic, plasmoinc, mechanical, electronic, or magnetic properties that are not manifested at the level of single particles. Recent experiments formed particle chains on the capillary surfaces, that may be able to form 3D structures given a higher concentration of particles. ACE–T9–2 is set to extend this work and understanding.

Preparations Are Underway To Operate the Following Experiments on ISS

LMMBio–5 (Peter Vekilov, University of Houston)
Solution convection and the nucleation precursors in protein crystallization. Explore the effects of solution shear flow on the nucleation of protein crystals, which may be enhanced or suppressed at different rates, including its complete absence, only possible in microgravity.

ACE–T10 (Roberto Piazza and Stefano Buzzaccaro, U. Milan—ESA/ESTEC)
ACE–T10 aims to investigate the growth kinetics, microscopic dynamics, and restructuring processes in ordered and disordered structures such as colloidal crystals, glasses and gels. The planned investigation is meant to address several questions, such as crystal nucleation in colloidal fluids, the origin of ageing in glasses and gels, the heterogeneous nature of the microscopic dynamics in these structures, and the role played in generating them by "depletion" forces induced by macromolecular additives. To this aim, microgravity studies are basically mandatory, because gravitational stresses strongly perturb the structure and growth kinetics of colloidal solids.

ACE–T12 (Stuart Williams, et al., U. Louisville—EPSCoR)
ACE–T12 will identify the structure of Nanoparticle Haloing (NPH) NPH aggregations as a function of nanoparticle concentration. This involves the design and assembly of complex 3D structures resulting from the interaction of different sized particles suspended within a fluid medium. These so-called "self-assembled colloidal structures" are vital to the design of advanced materials. In the microgravity environment, insight will be provided into the relationship between particle interactions and their shape, surface charge, and concentration. Their resulting structure and stability is a fundamental issue in condensed matter science. The use of the LMM on ISS will enable insight into finer control of the self-assembly (as well as directed-assembly) of such colloidal-based structures.

ACE–T4, Arjun Yodh (U. Penn.)
The ACE–T4 experiment consists of a series of samples containing dense suspensions of temperature-sensitive microscopic spheres, which are used to study the transition from an ordered crystalline packing to a disordered glassy packing. Observation on the space-microscope enables us to understand this effect. Regulating the temperature enables control of particle size, sample packing fraction, and allows for variance of particle size uniformity between samples; controlling temperature will enable the control of disorder in the samples. The goal is to understand how disorder affects the melting and freezing of materials.

ACE–T11 (Boris Khusid, NJIT; Paul Chaikin and Andrew Hollingsworth, NYU)
The Advanced Colloids Experiment–Temperature 11 (ACE–T11) experiment involves the design and assembly of complex 3D structures from small particles suspended within a fluid medium, and control of particle density phase behavior. These so-called "self-assembled colloidal structures" are vital to the design of advanced optical materials. Control of particle density and phase behavior—glassy or crystalline is important for making dense slurries and pastes used in 3D printing and additive manufacturing. In the microgravity environment, insight will be provided into the relation between particle shape, crystal symmetry, density, rheology, and polydispersity, which are fundamental issues in condensed matter science, ceramics, and additive manufacturing.

ACE–T5 (Ali Mohraz, U. California—Irvine)
Bicontinuous interfacially jammed emulsion gels (bijels) are a new class of soft materials that provide a platform for the synthesis of co-continuous composite materials for energy (large surface area electrodes) and health care applications. To expand the current their capabilities into a robust synthesis platform, a better understanding of bijel processability is needed. However, these materials are inherently comprised of multiple phases with disparate densities and complex interfacial interactions, leading to complicated physics during their processing, especially in the presence of gravity where ground-based experiments have already shown deviations from the expected morphological behavior in these systems.

CVB–3 (Joel Plawsky, RPI)
The original CVB experiment identified heretofore unseen phenomena in heat pipes including Marangoni induced flooding, reverse Marangoni jets, junction vortices, explosive nucleation, Leidenfrost condensation and apparent condensation at the heater wall. This work should provide similar surprises by pushing the alkane mixture toward a 50:50 mix and entering a regime were non-ideal interfacial behavior was observed in 1 g.

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