Fiscal Year:	FY 2022	**Task Last Updated:**	FY 06/13/2022
PI Name:	Khusid, Boris Ph.D.		
Project Title:	Advanced Colloids Experiment-Temperature and Gradient Control (ACET11)		
Division Name:	Physical Sciences		
Program/Discipline:			
Program/Discipline--Element/Subdiscipline:	COMPLEX FLUIDS/SOFT MATTER--Complex Fluids		
Joint Agency Name:		**TechPort:**	No
Human Research Program Elements:	None		
Human Research Program Risks:	None		
Space Biology Element:	None		
Space Biology Cross-Element Discipline:	None		
Space Biology Special Category:	None		
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Zip Code:	07102-1982	**Congressional District:**	10
Comments:			
Project Type:	FLIGHT	**Solicitation / Funding Source:**	2013 Complex Fluids & Macromolecular Biophysics NNH13ZTT001N
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No. of PhD Candidates:		**No. of Master' Degrees:**	
No. of Master's Candidates:		**No. of Bachelor's Degrees:**	
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Flight Program:	ISS		
Flight Assignment:	ISS--Space X-19 NOTE: End date changed to 8/31/2022 per NSSC information (Ed., 12/10/21)		
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Task Description:	NOTE 1/21/2020: Continuation of "Kinetics of Electric Field-Driven Phase Transitions in Polarized Colloids," grant NNX13AQ53G, with same Principal Investigator Dr. Boris Khusid. Motivation: The widespread use of colloidal processes for scalable manufacturing of structured materials emphasizes a critical need for improving fundamental understanding of the role of external fields in directing non-equilibrium phenomena in suspensions. The challenge is due to kinetic limitations because the particles can be trapped into metastable configurations for a long time due to the lower mobility of multi-particle structures compared to that of individual particles. Microgravity offers a unique opportunity to study these phenomena by removing masking gravity effects, such as particle sedimentation, convection, and jamming. The proposed research addresses both fundamental and technological questions in the science of colloids aimed at understanding the equilibrium and metastable crystalline, liquid, and glassy structures and the use of these materials in additive manufacturing. Objectives: Conduct tests in the International Space Station (ISS) Advanced Colloids Experiment (ACE) facility to elucidate the mechanisms of non-equilibrium phenomena underlying the assembly of colloidal particles assisted by temperature field gradients and suggest novel routes for processing functional materials. Methodology: A novel approach will be used to study mechanisms for formation of metastable and glassy phases in suspensions in the ISS and for comparison on Earth. A single sample will be exposed to a temperature gradient to cover the interesting range of particle densities. As the particle density is directly measured by microscopy, a priori knowledge of the gradient profile is not required. Experiments will involve setting up a temperature gradient to observe the resulting structures and then locally mix a region of known density to watch it glassify or crystallize. Quantitative data on the suspension rheology will come from microrheology measurements through tracking particle thermal motion. Deliverables: Understanding of non-equilibrium phenomena in colloids driven by temperature gradients and experimental database for the control and manipulation of colloidal structures in space and terrestrial applications.
Rationale for HRP Directed Research:	
Research Impact/Earth Benefits:	Research Overview • Why is the research needed? New functional materials are created using micron-sized particles suspended in fluid (called colloids) that self-organize into crystalline structures or amorphous glass phases by means of entropic forces or under the control of non-equilibrium drive as supplied, for example, by temperature gradients. The ACE-T11 experiments in the ISS utilizes confocal 100 X microscopy for time- and space-resolved 3D imaging of the arrangement of spherical colloidal particles, and examines the influence of temperature gradients on the particle motion and arrangement (referred to as thermophoresis). • What is accomplished? In ACE-T11, the phase behavior of micrometer-sized colloidal particles in long-duration microgravity is studied in the ISS on dense suspensions at volume fractions f~0.60-0.63. The particles are found to self-organize into face centered cubic (FCC) colloidal crystal of the capillary size (27 mm x 1.5 mm x 150 µm). It is the first confirmation of the theory for the phase behavior of hard spheres, the simplest model of matter with a crystallization transition. In contrast, colloidal crystals formed on Earth do not grow larger than several hundreds of micrometers due to gravitational settling. • What is the impact of the research? Ultimately, the ability to design functional structures – based on micrometer-scale building blocks – with a variety of well-controlled three-dimensional bonding symmetries, amorphous structures and different rheologies will allow the development of new devices for chemical energy production and storage, photonics and communication, and a new set of slurries and pastes useful for additive manufacturing. Such materials might include photonic crystals with programmed distributions of defects. Optical technology utilizing such materials may offer intriguing solutions to unavoidable heat generation and bandwidth limitations facing the computer industry. New insights were gained in the ISS experiments on the formation of crystalline phases as distinct from the amorphous glass, a question raised by previous microgravity studies, as yet unresolved, whether glass phases found on Earth would readily crystallize in microgravity. In particular, it was revealed that molecular dynamics simulations of equilibrium work when gravitational effects are unimportant. They therefore can be used for simulations of materials processing in microgravity. • Space Applications: Eventually, future space exploration may use self-assembly and self-replication to make materials and devices that can repair themselves. Self-assembly and evolutionarily-optimized functional units are key to long-duration space voyages. Even more immediate is the requirement of replacement parts and specialized repair facilities for space missions. 3D printing and additive manufacturing will be necessary for future space missions. The development of particle slurries and pastes with the appropriate rheological properties that work in both microgravity and conventional gravity will be needed. One objective of the experiments conducted in the ISS is to develop new materials that cannot be formed on Earth. • Earth Applications: This investigation involves several fundamental and practical aspects of soft matter science with potential applications on Earth. Self-assembly processes are crucial to making functional materials and devices from small particles. Improved design and assembly of structures fabricated in microgravity may have use in a variety of fields from medicine to optoelectronics on Earth. Ultimately, the ability to design and build functional structures based on colloids will allow new devices for chemical energy, communication, and photonics, including photonic materials to control and manipulate light. The rapidly growing fields of 3D printing and additive manufacturing rely on the assembly and sintering of particle aggregates and the preparation of high-density slurries and pastes of different colloidal materials and with different rheological and mechanical properties is a main goal of these studies.
Task Progress:	The study was conducted within the scope of the originally proposed research plan. The New Jersey Institute of Technology (NJIT) and New York University (NYU) researchers worked in closed collaboration with researchers from the NASA Glenn Research Center and engineering team from ZIN Technologies, OH to process and analyze confocal microscopy images of colloids collected in the International Space Station (ISS) experiments in 2020-2021. One exciting aspect of the microgravity experiments in the ISS is the realization that in microgravity we can build large colloidal photonic crystals with a three-dimensional ordered arrangement of particles that survive reentry to Earth. A three-dimensional photonic crystal is the optical analogy to an atomic lattice, in which the refractive index repeats periodically in three directions on the scale of the light wavelength. The particle sizes, shapes, and properties can be varied based on the wavelength of light we wish to control with colloidal photonic crystals. Due to the unique properties,

	photonic crystals operating at infrared wavelengths are expected to be crucial for applications in remote sensing, fiber-optic communication, chemical analysis, biomedical diagnostics, optical computing, security, and defense. Fabrication of large three-dimensional colloidal crystals on Earth remains a challenge as the particle assembly is strongly influenced by gravity effects, such as particle sedimentation, convection, and jamming.
Bibliography Type:	Description: (Last Updated: 09/17/2023)
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Patents	63/365667. Provisional patent issued June 2022. Jun-2022 Murphy M, Lei Q, Khusid B, Hollingsworth AD, Chaikin PM, Meyer WV. "Method and Apparatus for Fabrication of Large Three-Dimensional Single Colloidal Crystals for Bragg Diffraction of Infrared Light."