



The Light Microscopy Module A Facility Overview - History and Science

ASGSR
November 6, 2021



BPS

BIOLOGICAL AND
PHYSICAL SCIENCES

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LMM ACE NASA Project Manager for NASA GRC

Light Microscopy Module (LMM)

Launch on Shuttle 17A – August 2009

Forty experiments over 11 years

LMM Operational hours:
8/2009-10/2021 = **18,100 hours**



BPS

BIOLOGICAL AND
PHYSICAL SCIENCES

Light Microscopy Module Retrospective

The Light Microscopy Module (LMM) is a modified commercial, highly flexible, state-of-the-art light imaging microscope facility that provides researchers with powerful diagnostic hardware and software onboard the International Space Station (ISS). The LMM enables novel research of microscopic phenomena in microgravity, with the capability of remotely acquiring and downloading digital images and videos across many levels of magnification. The way that matter is organized and moves on the microscopic level profoundly affects the macroscopic world and an understanding of such processes helps scientists and engineers build more efficient materials and machines for both Earth and space environments.



1. Monochrome camera

2. Microscope

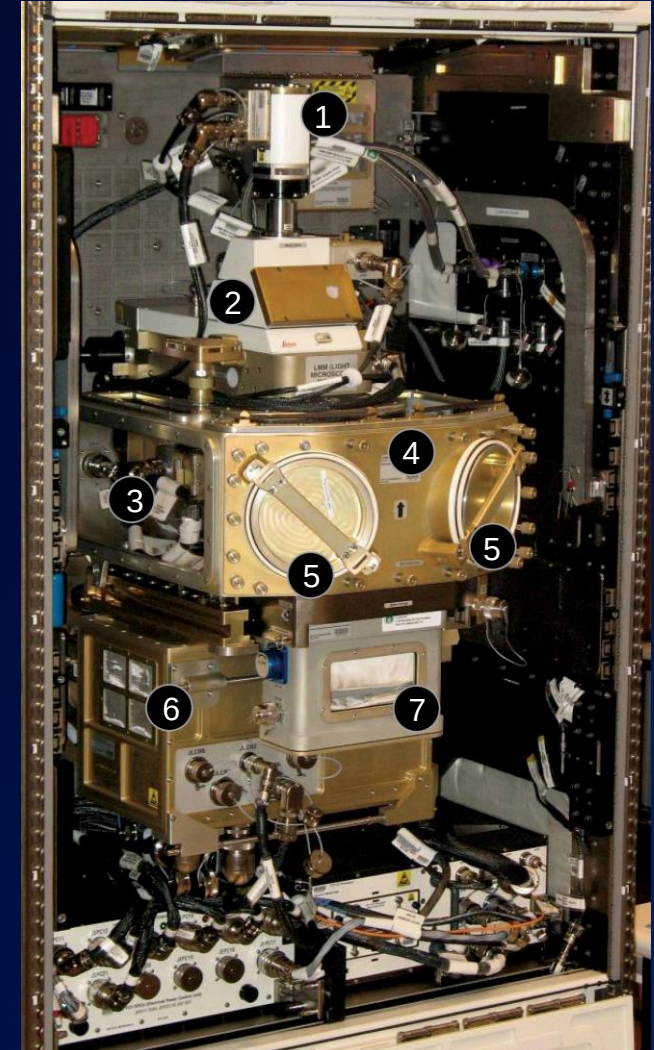
3. Auxiliary fluids container, side view

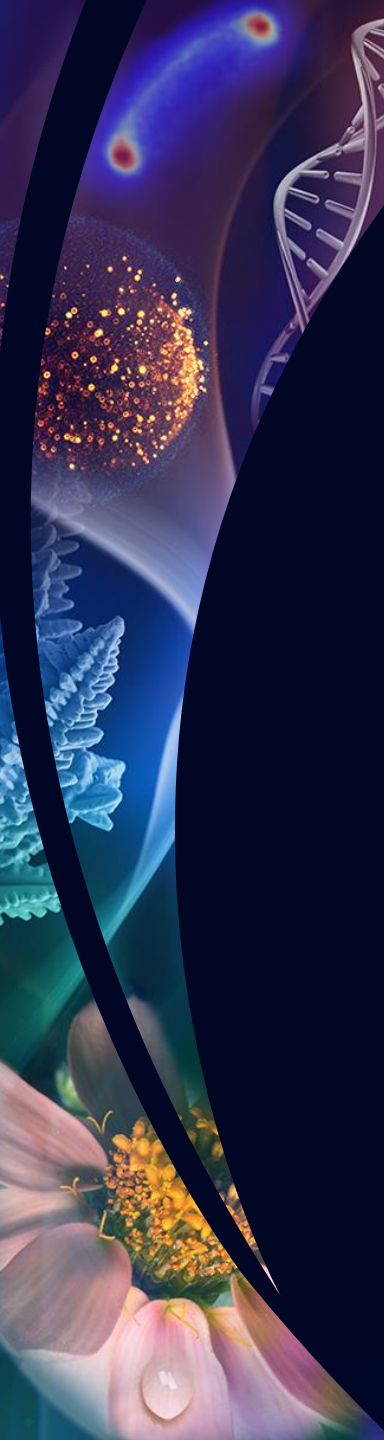
4. Auxiliary fluids container, front view

5. Glove ports

6. LMM control box

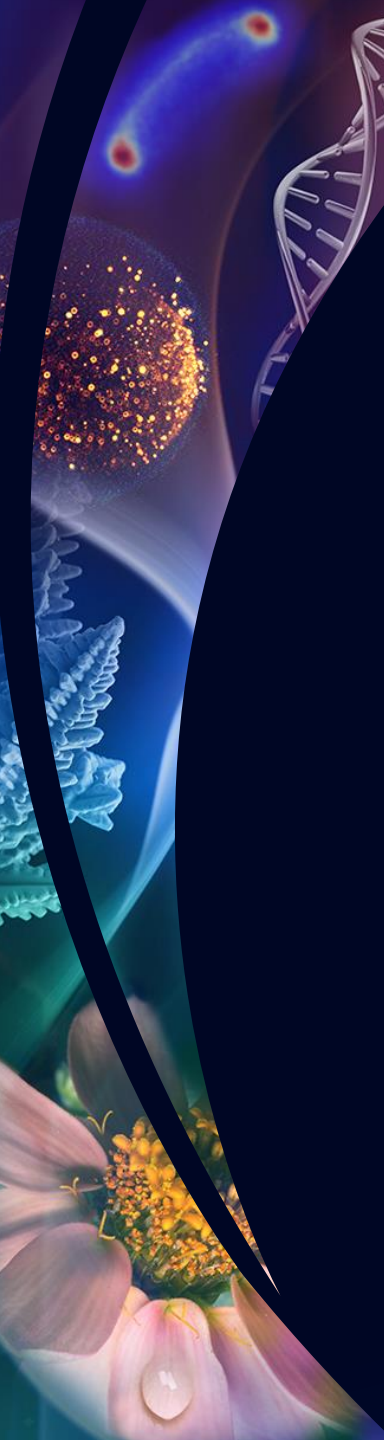
7. Equipment transfer module





Forty Experiments Over 11 Years

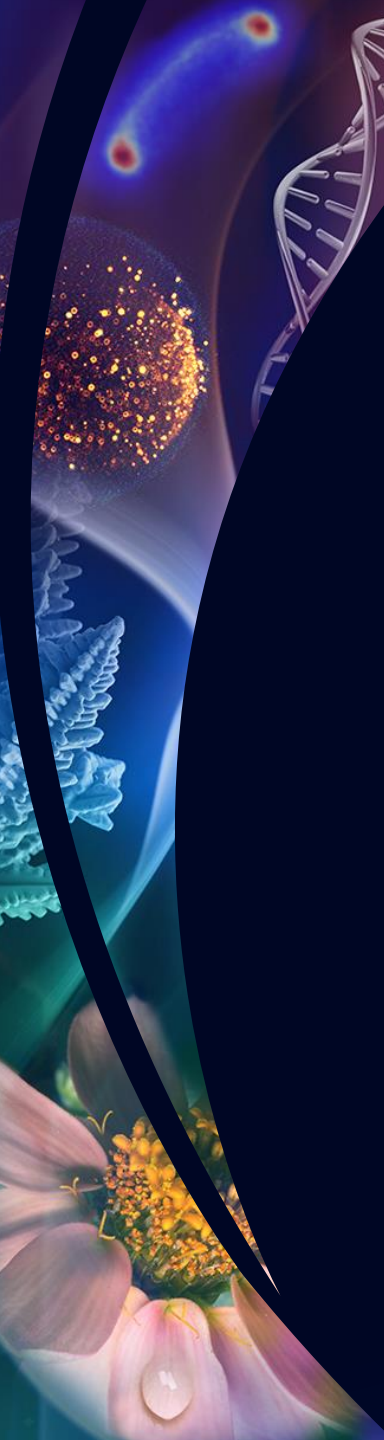
- Thermo-Physics – Constrained Vapor Bubble (CVB) 2010 to 2012
- Biology Demonstrations 2012 to 2013
- Light Microscopy Module (LMM) BioPhysics – Protein Crystals 2014 to 2016
- Plant Biology 2014 to 2015
- CASIS Diffusion – Medical Device Demo 2015
- Advanced Colloids Experiment – Bulk Heating (ACE-H) 2014
- Advanced Colloids Experiment – Manual/Passive (ACE-M) 2013 to 2021
- Advanced Colloids Experiment – Temperature Control (ACE-T) Experiment 2015 to 2021
- Advanced Colloids Experiment With 3D Confocal and Temperature Control (ACE-T) Experiments 2016 to 2021



Thermo-Physics—Constrained Vapor Bubble (CVB)—1 and –2

2010 to 2012

- CVB-1 [20mm, 30mm, 40mm and control sample]
Wayner / Plawsky—Rensselaer Polytechnic Institute (RPI)
- CVB-2 [30mm] Plawsky / Wayner—RPI
- CVB represents a passive, wickless heat pipe ideally suited to obtain engineering and fundamental data on phase change heat transfer driven by interfacial phenomena.
- CVB is a basic scientific study in interfacial phenomena, microgravity fluid physics and thermodynamics, a basic study in thermal transport and an engineering study of a passive heat exchanger.
- This optical study of vapor bubbles constrained in transparent glass cells at variable temperature increases the basic understanding of heat and mass transfer at phase-change interfaces. The information obtained from the study optimizes the design and operation of passive heat transfer devices for Earth and microgravity environments and is critically important for the successful completion of long-term lunar and Mars missions.



Biology Demonstrations

2012 to 2013

Jacob Cohen (NASA Ames Research Center)

- LMM-Bio-1, -2, and -3 (*C. Elgans*)

Light Microscopy Module (LMM)

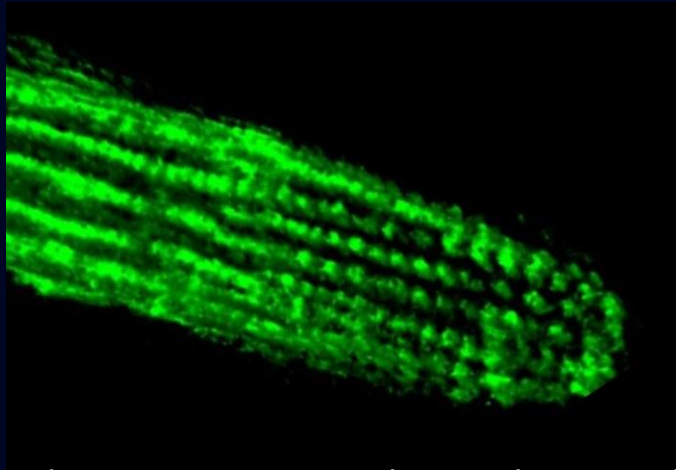
BioPhysics-Protein Crystals 2014 to 2016

- LMM BIO-1 and -4 (Delucas, Betzel – U. Hamburg)
- LMM BIO-2 and -5 (Vekilov– U. Houston)
- LMM BIO-3 and -6 (Snell–Hauptman-Woodward Medical Research Institute)

Plant Biology

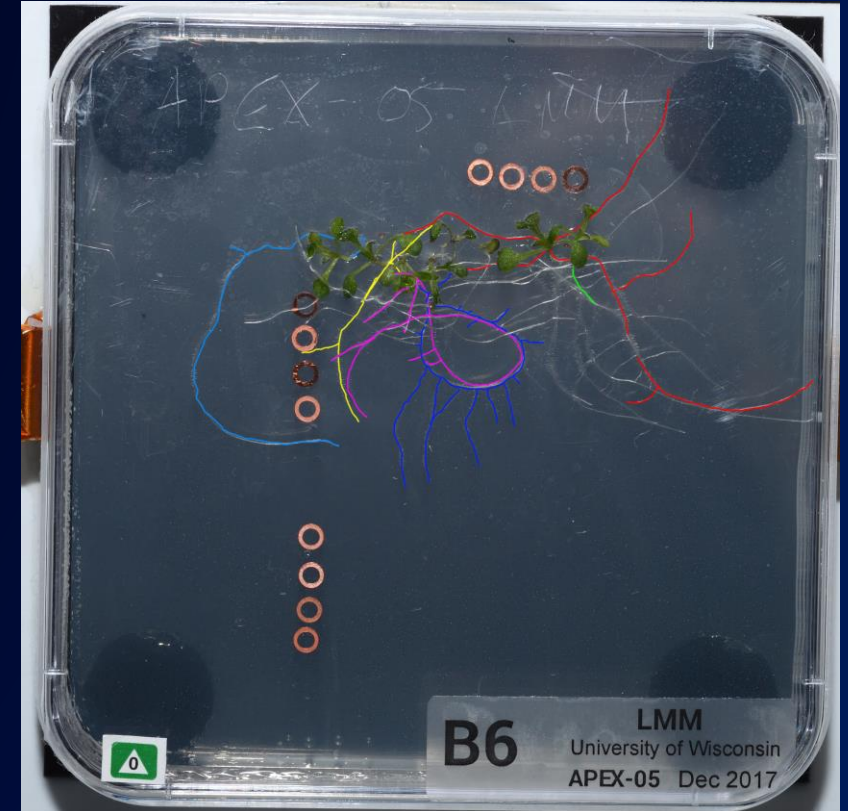
2014 to 2015

- CARA (Paul/Ferl – U. Florida)
- APEX-4 (Ferl/Paul – U. Florida)

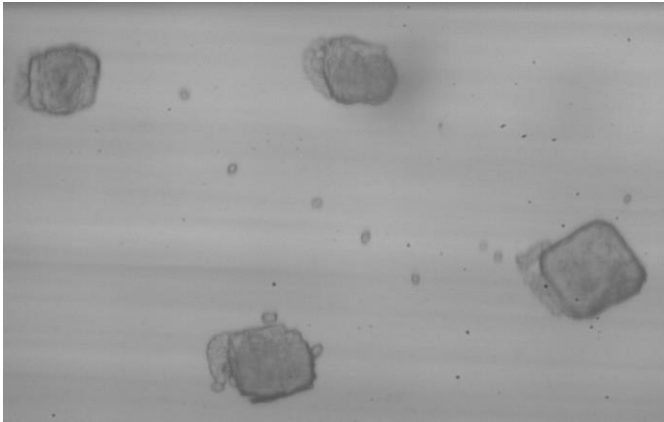


Fluorescent image taken with LMM of *Arabidopsis thaliana* root expressing pSCR::SCR-GFP

- APEX-5 (Advanced Plant Experiment-5): Test of Arabidopsis Space Transcriptome series (TOAST III) – (Gilroy – UW-Madison)



APEX-5 Image. 10 cm Petri dish plate with Arabidopsis plants mapping plant growth at point of insertion into LMM.



LMMBIO 4-2 October, 9 – 23, 2018
Larry DeLucas (Lysozyme at 10X)



LMMBIO 6-1 Operations November 13 to
December 9 with Eddie Snell



APEX-5 Operations December 15 – 17, 2018
with Simon Gilroy



LMMBIOIO-2/5 January 24 – February 16, 2019

CASIS Diffusion—Medical Device Demonstration 2015

- LMM-Microchannel Diffusion Experiment (MDE) (Grattoni – Houston Methodist Hospital)

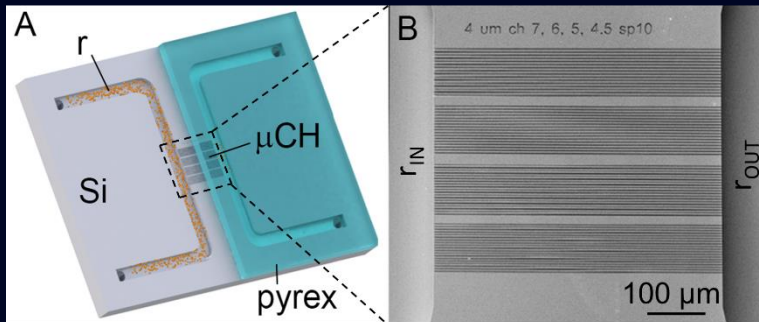


Figure 1. A) 3D rendering of the μF chip structure showing the silicon (Si) substrate, the pyrex layer, the particle reservoirs (r), and the parallel set of microchannels (μCH). B) Scanning electron microscopy micrograph of the microchannel sets with inlet and outlet reservoirs (r_{IN} , r_{OUT} respectively).

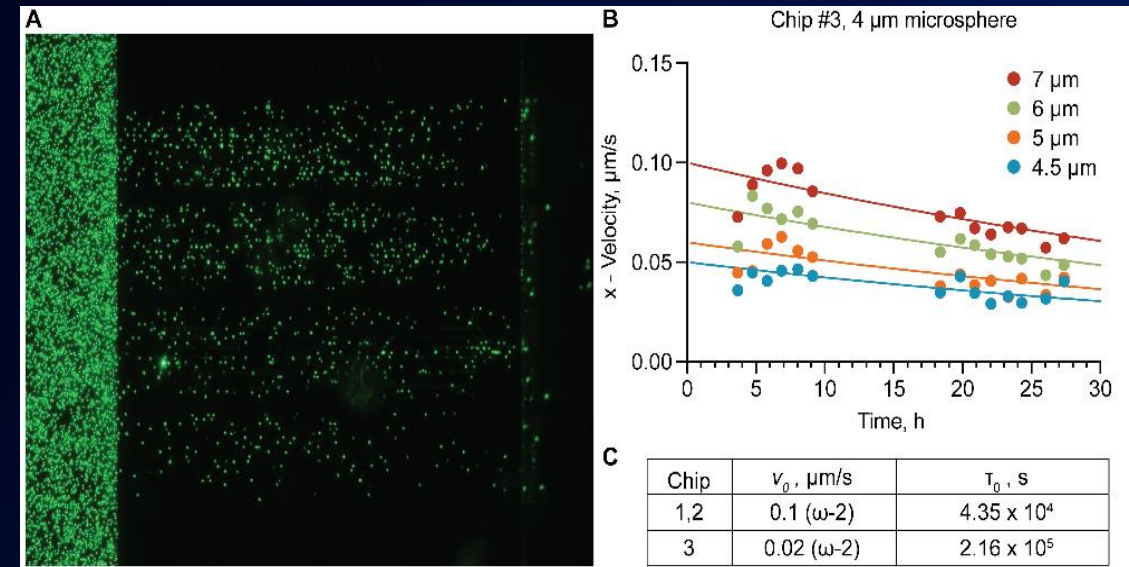


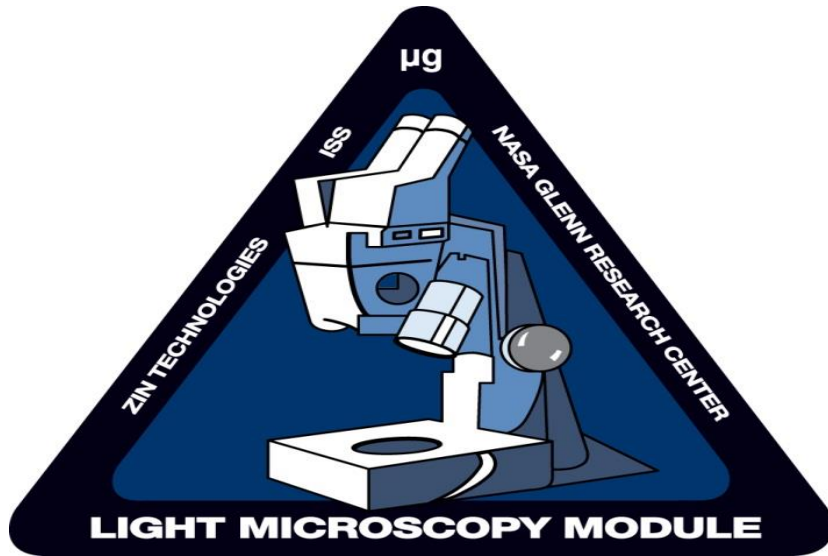
Figure 2. A) Fluorescence microscopy image captured via the LMM microscope with 4 μm MPs. B) Average velocity values and fitting obtained for 4 μm MPs at pH 9 and high MP concentration. C) Values of the initial velocity v_0 and time scale τ_0 obtained through fitting of experimental data with an exponential decay function.

Microparticle imaging was successfully executed for 4 μm MPs. These provided a strong fluorescence signal, clearly distinct from noise (Figure 2A). However, due to the radiation damage to the LMM camera, we were not able to confidently distinguish the signal obtained from 1 μm MPs with respect to the noise. In light of this, data analysis was exclusively performed for 4 μm MPs.

Fundamental Science → Understanding
and
Colloidal Engineering → Applications



Light Microscopy Module (LMM) and the Advanced Colloids Experiment (ACE)



ISS021E033216

Fluid Integrated Rack (FIR) and Light Microscopy Module launched August 2009.

Assembly and checkout complete January 2011.

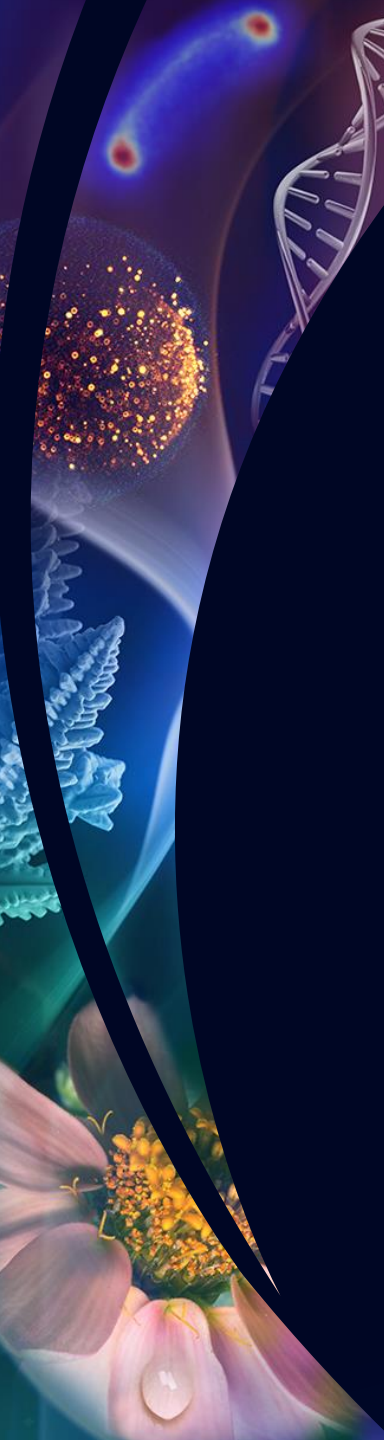
Then used for CVB experiment. 2013 - 2015: Bio and ACE-Manual (ACE-M).

2016 - 2021: Confocal.

Enabling Soft-Matter Microgravity Research Fundamental Science and Colloidal Engineering at the Particle Level



Advanced Colloids Experiment
(ACE)



Advanced Colloids Experiment-Bulk Heating (ACE-H) 2014

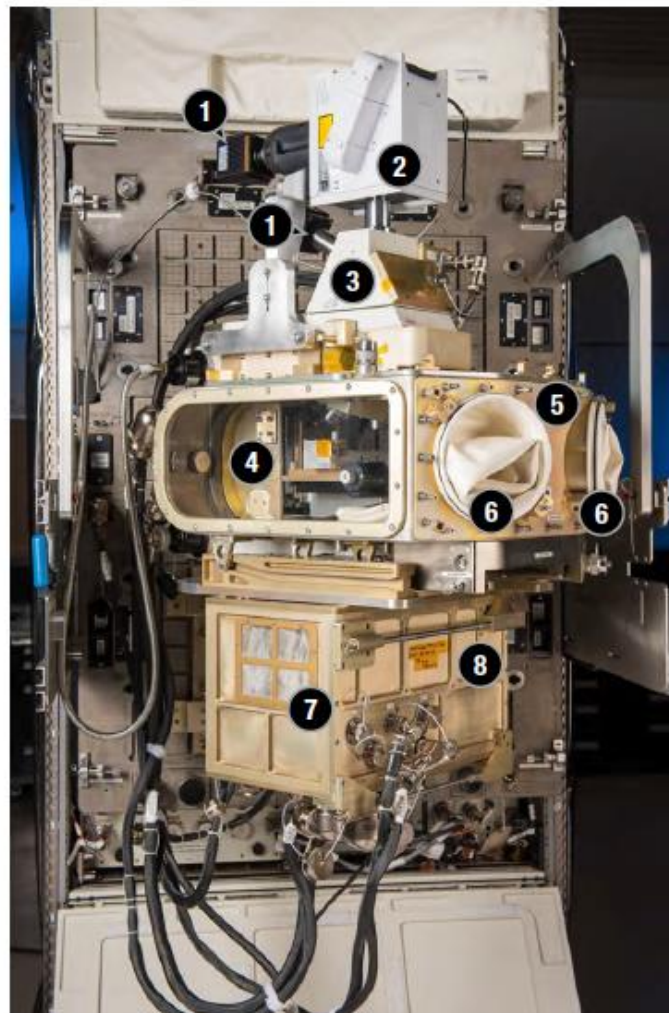
- ACE-H1 (Yodh – PENN)
- ACE-H3 (Williams/Willing – UL)

Advanced Colloids Experiment—Manual/Passive (ACE-M) 2013 to 2021

- ACE-M1 (Matthew Lynch, The Procter & Gamble Company)
- ACE-M2 and ACE-M2R (Weitz/Lu – Harvard)

Light Microscopy Module (LMM)

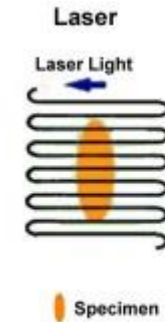
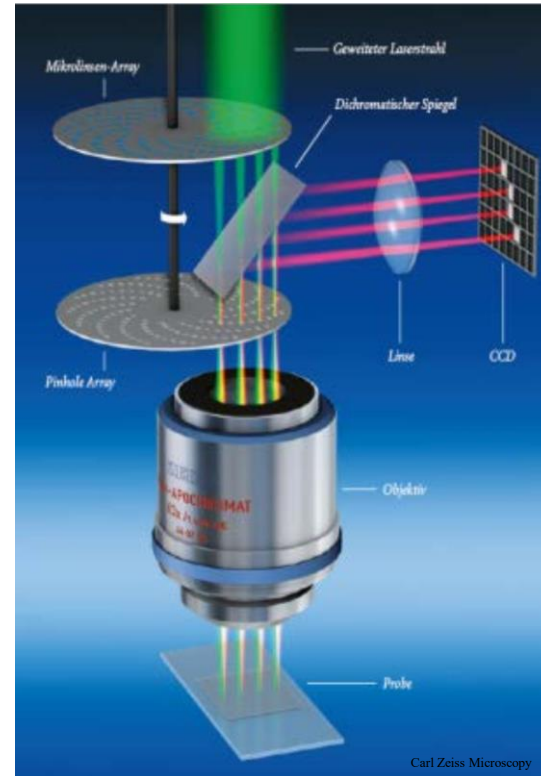
- 1** IMPERX GEV-B2020 cameras
—Available 2016
- 2** Yokogawa CSU-X1
confocal scanner
—Available 2016
- 3** Microscope
- 4** Auxiliary fluids container—
side view
- 5** Auxiliary fluids container—
front view
- 6** Glove ports
- 7** LMM control box
- 8** Equipment transfer module
location



Confocal (3D) Microscopy on the
International Space Station (ISS)

Advanced Colloids Experiment – ACE

Confocal Microscopy Concept



The difference between traditional and confocal microscopy

Focus 50 μm below cover slip

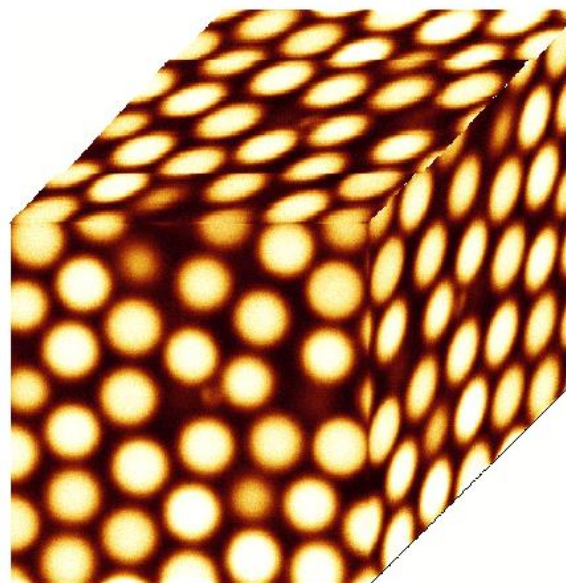
Traditional microscopy
doesn't see through
objects well; out-of-
focus light obscures
in-focus light



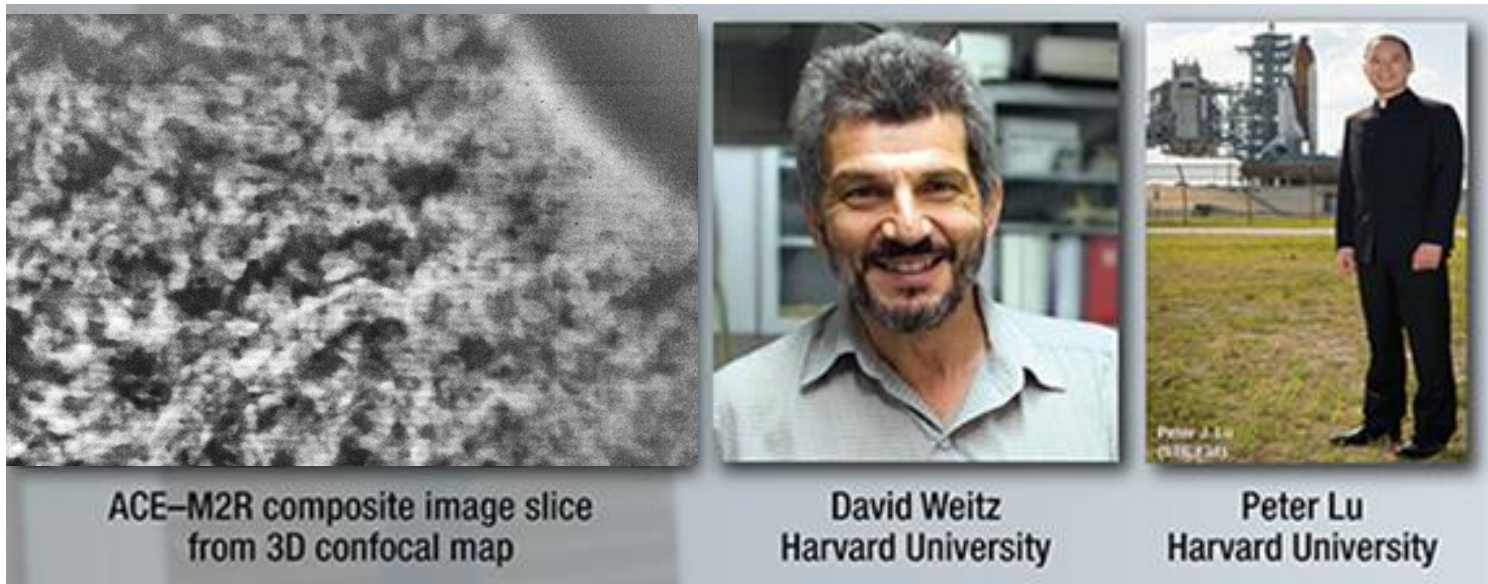
*Focus 200 μm below
(near bottom of well)*



Confocal microscopy
rejects out-of-focus
light, to look
through semi-
transparent objects



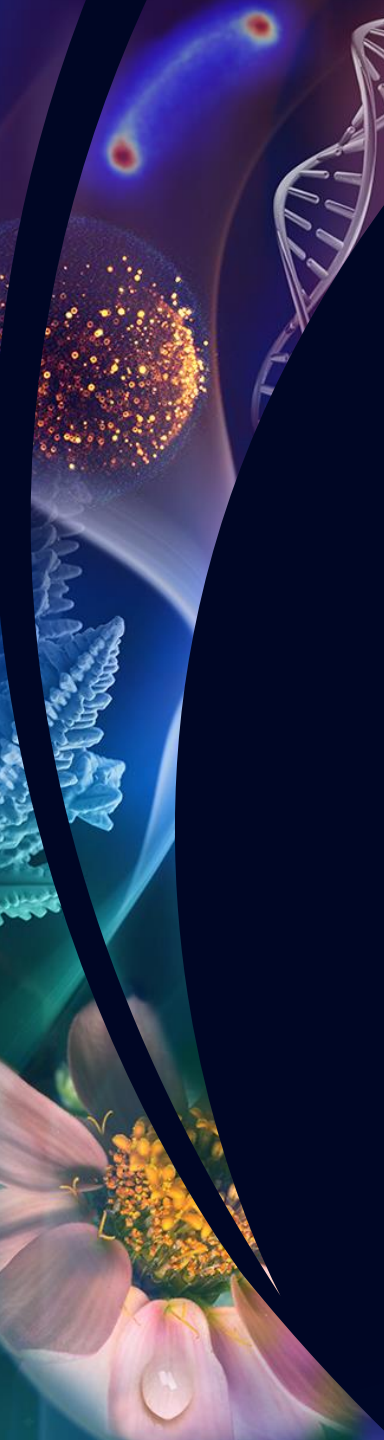
**3D image is built out of
2D XY sections while
stepping through Z axis.**



ACE-M2R (David Weitz and Peter Lu, Harvard University) [From final report]

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.

Our ACE-M-2/R observations represent a “final state” of evolution, as the sample has undergone kinetic arrest and sat in stowage for several years and is no longer evolving. Previous determinations of when a sample stops evolving, i.e., kinetic arrest, have been made on timescales of days to weeks; our ISS-based experiment thereby extends that time horizon by several orders of magnitude. Strikingly, the sample has developed network-like structures with angular corners and sharp edges, as shown in the figure below, which we resolve with micron-scale resolution in full 3D; these structures are quite different from those seen in the mixtures with similar composition that we observed with photography in the BCAT series of experiments (BCAT-3, BCAT-4, BCAT-5, and BCAT-6). In those cases, the samples separated into two phases, and the interfaces between the two remained smooth, and the structures formed evolved constantly until there was one cm-scale spherical droplet of one phase surrounded by the other.



ACE–T Experiments

With 3D Confocal and Temperature Control 2016 to 2021

- **ACE–T6 Colloidal Stabilizers**

Matthew Lynch, Ph.D. The Procter & Gamble Company

- **ACE–T7 Cubes**

Paul M. Chaikin, Ph.D., New York University
Stefano Sacanna, Ph.D., New York University
Andrew D. Hollingsworth, Ph.D., New York University
David Pine, Ph.D., New York University
Ned Seeman, Ph.D., New York University

- **ACE–T10–1 and –2**

Roberto Piazza, Ph.D., University of Milan/ESA
Stefano Buzzaccaro, Ph.D., University of Milan/ESA

- **ACE–T2 Critical Casimir Forces**

Peter Schall, Ph.D., University of Amsterdam/ESA

- **ACE–T4**

Arjun Yodh, Ph.D., University of Pennsylvania

- **ACE–T5–1, –2, and –3 Bijels**

Ali Mohraz, Ph.D., University of California, Irvine

- **ACE–T12–1 and –2 Nanoparticle Haloing**

Stuart J. Willaims, Ph.D., University of Louisville
Paul M. Chaikin, Ph.D., New York University

- **ACE–TR–1 and –2 Ellipsoids**

Boris Khusid, Ph.D., The New Jersey Institute of Technology
Lou Kondic, Ph.D., The New Jersey Institute of Technology
Paul M. Chaikin, Ph.D., New York University
Andrew D. Hollingsworth, Ph.D., New York University

- **ACE–T11 and ACE–T11R Hard Spheres**

Boris Khusid, Ph.D., The New Jersey Institute of Technology
Paul M. Chaikin, Ph.D., New York University
Andrew D. Hollingsworth, Ph.D., New York University
Alton Reich, Streamline Automation LLC

- **ACE–T9–3 Magnetic Chains**

David Marr, Ph.D., Colorado School of Mines
Ning Wu, Ph.D., Colorado School of Mines

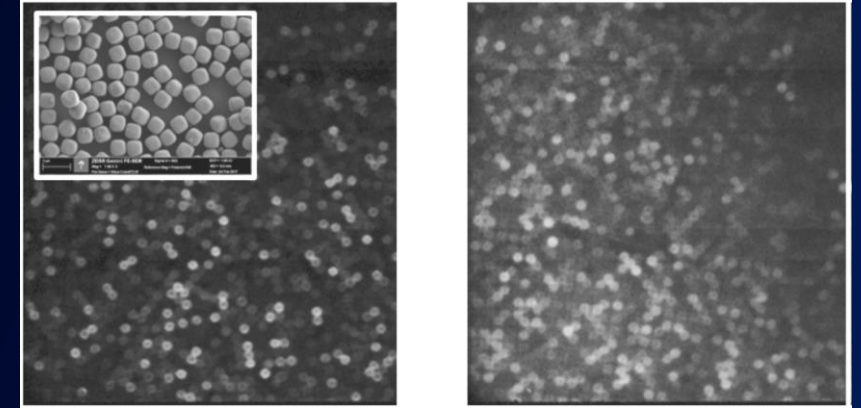
- **ACE–T1 to 3 Janus Particles**

Chang-Soo Lee, Ph.D., Chungnam National University

ACE-T7 Cubes

Paul M. Chaikin, Ph.D., Stefano Sacanna, Ph.D., Andrew D. Hollingsworth, Ph.D., David Pine, Ph.D., and Ned Seeman, Ph.D., 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. After performing confocal microscope z-stacks in a few regions in Capillary 3, we noticed that crystals have grown much larger, and crystals in the bulk volume seem to exist.



ACE-T7 Long Duration, November 5-8, 2018 Paul Chaikin (3D assembly of Super-cubes) see following page

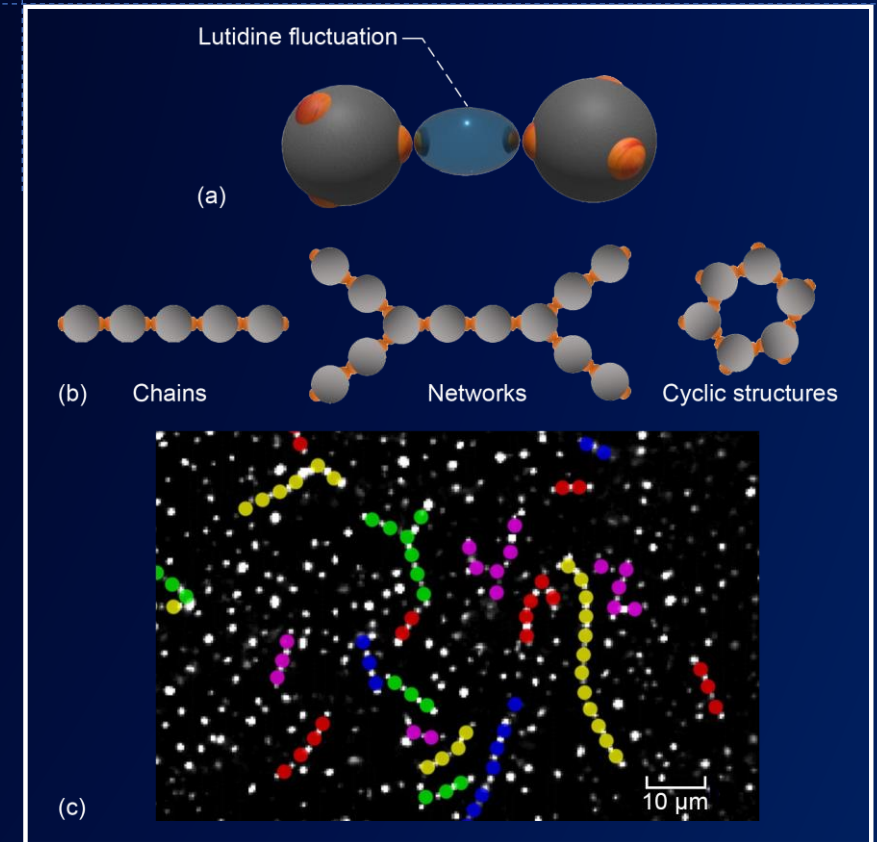


One ACE-T7 slice from a confocal stack that shows large 3D crystals forming – not seen on Earth. Data analysis underway.

ACE-T2 Critical Casimir Forces

Peter Schall, Ph.D., University of Amsterdam

- The Advanced Colloids Experiment-Temperature-2 experiment looks at the assembly of complex structures from micron-scale colloidal particles interacting via tunable attractive interactions.
- The samples contain suspensions of trifluoroethyl methacrylate (FEMA) colloidal particles (10 percent volume) of type A and B in binary solvents composed of water (H_2O , 68 percent mass) and lutidine (32 percent mass), that upon nearing the critical solvent temperature ($T_c \sim 32^\circ\text{C}$) give rise to critical Casimir interactions between the particles.
- Regulating the temperature enables control of the particle interactions, which for these mixtures of particles A and B are different, leading to the growth of complex structures, and provide a better understanding of how complex interactions lead to complex structures, and to understand the dynamics of growth of these structures.



- a. Colloids binding via their patches.
b. Possible structures of pure di-patch (left), mixtures of di- and four-patch (center) and four-patch particles (right).
c. LMM with superimposed colored dots illustrating the assembled particles clusters.

ACE-T6

Matthew Lynch

**Corporate Research, Procter & Gamble,
Cincinnati, OH, USA**

**Department of Chemical Engineering,
University of Delaware, Newark, DE, USA**

Paolo Palacio-Mancheno

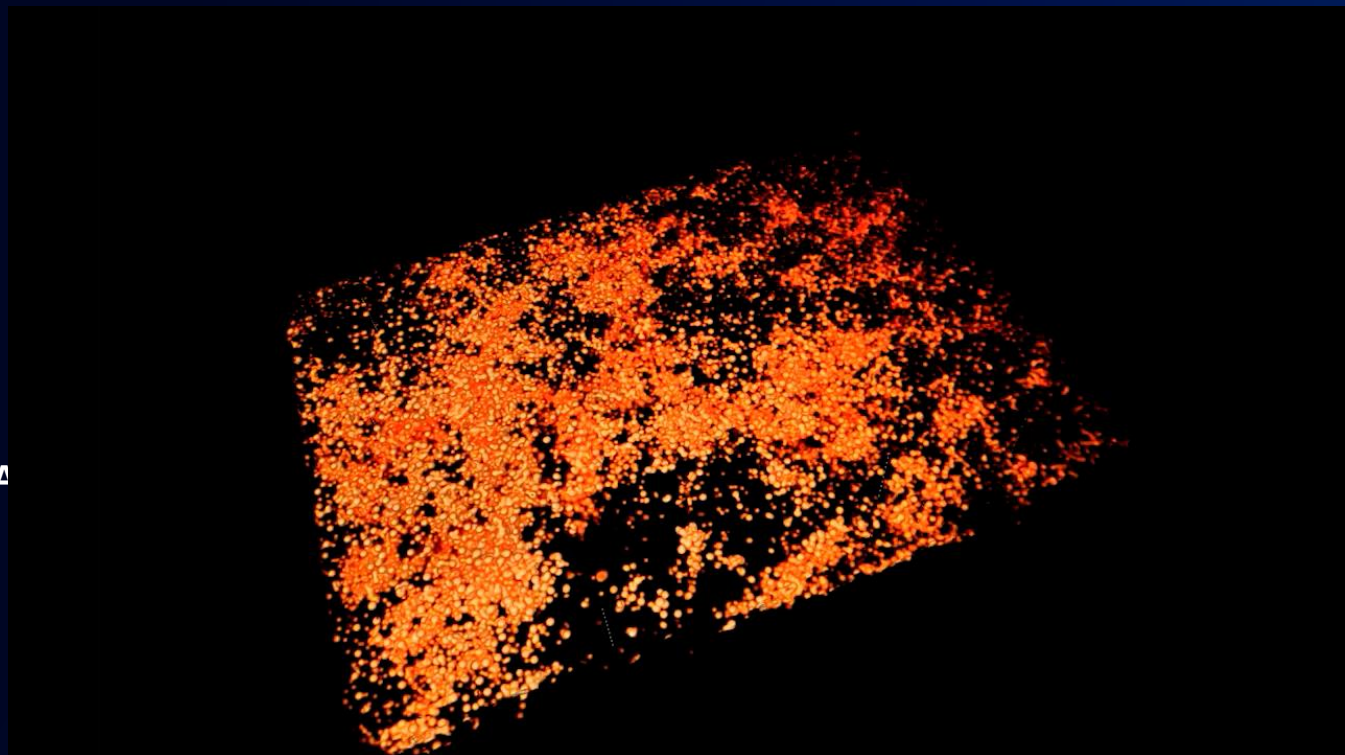
**Corporate Research, Procter & Gamble,
Cincinnati, OH, USA**

Mark Pestak

**KBR, Space Engineering Division
Cleveland, OH, USA**

Prof. Tom Kodger

**Physical Chemistry and Soft Matter,
Wageningen University and Research,
Wageningen, NL**



3D Confocal image acquired with the
Light Microscopy Module on ISS



“This fundamental work has been of great value, both in
developing of commercial product and inspiring a series of
granted patents
US 10,076,583, US 10,080,814 and US 10,143,764”



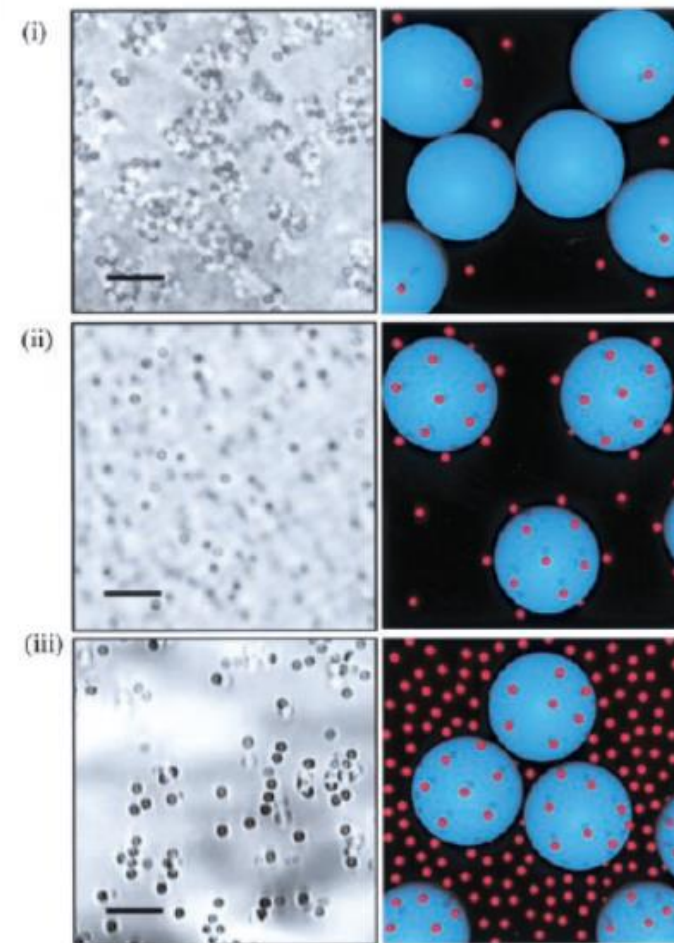
Great work by Victor Glover on March 19, 2021, Allowed FIR to continue in a new contingency mode of operations



ACE-T12-2 Experiment Operations Team at the GRC GIPOC. L to R: Amber Krauss, Louis Chestney, Deena Dombrosky, and Helen Brown ZIN Technologies.

Studying Nano-particle Haloing ACE-T12-2

This experiment investigates the role of smaller charged nanoparticles (of different concentrations in the three capillaries) in enhancing the stability of larger particles (of the same concentration in the three capillaries) and/or enhancing the crystallinity of aggregates. This interaction is also known as nanoparticle haloing (NPH). We have mixed and imaged three capillaries. The present observations have been at ambient temperature and are being used to develop the analysis processes to automatically identify colloidal aggregates through a computer program specifically designed for these experiments. The results can then be used to not only determine the size of and spacing between aggregates, but to also determine their movement over both short and long-time scales (see figure below). Advances in the understanding of Nano-particle haloing could have a significant role in improving the efficiency of solar arrays. This work has the potential to increase the collection efficiency of solar collectors for adding charge carriers, moving the present 13-15% collection efficiency closer to the theoretical value of 30-40%. Additional observations are being made to record any changes in the physics guiding NPH after a sample temperature change from ambient to 50 °C has been introduced. The Science Team, Professors Stuart Williams and Gerold Willing and Master's candidate Adam Cecil are from the University of Louisville (Kentucky) and are sponsored by NASA Established Program to Stimulate Competitive Research (EPSCoR).



The three ACE-T12-2 samples have different concentrations that behave very differently

PROFESSOR STUART WILLIAMS
CO-INVESTIGATOR, ACET-12-2 EXPERIMENT
UNIVERSITY OF LOUISVILLE

NASA Glenn Research Center



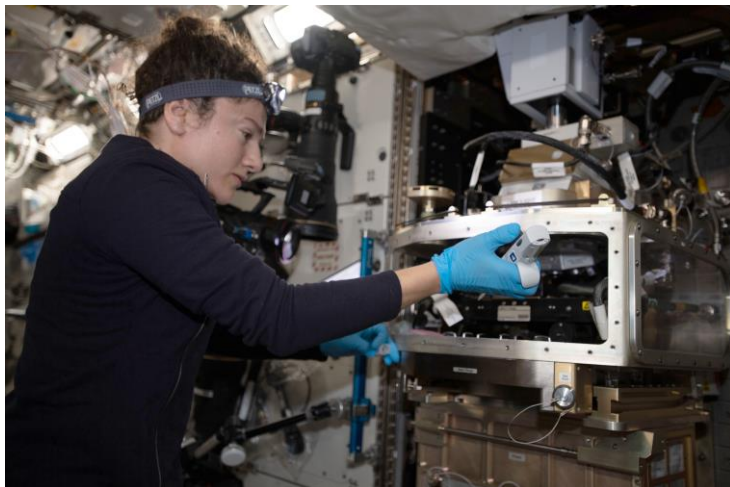


PROFESSOR GEROLD WILLING
CO-INVESTIGATOR, ACET-12-2 EXPERIMENT
UNIVERSITY OF LOUISVILLE

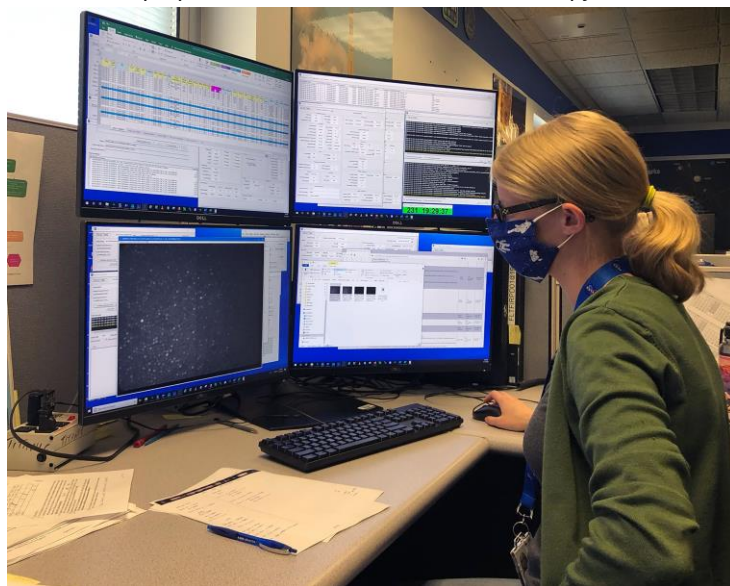


ACET-12-2





Jessica Meir prepares ACE-T4 for 100x oil microscopy with LMM.



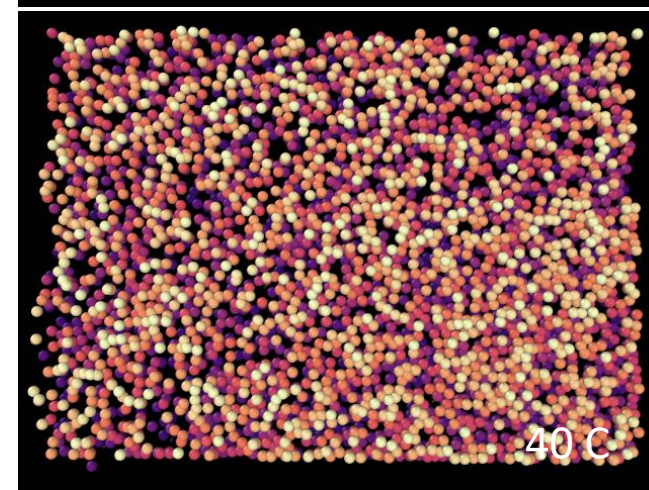
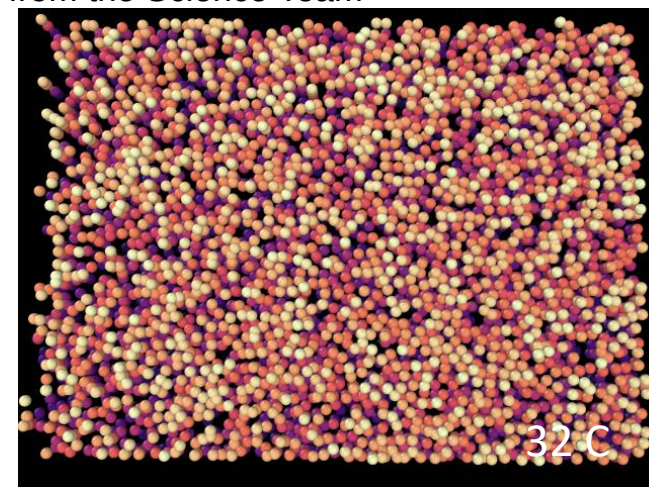
Emily Johnson, ZIN-Tech, GRC/GIPOC operations for ACE-T4-2.

Advanced Colloids Experiment with Temperature Control - 4 (ACE-T4-2)

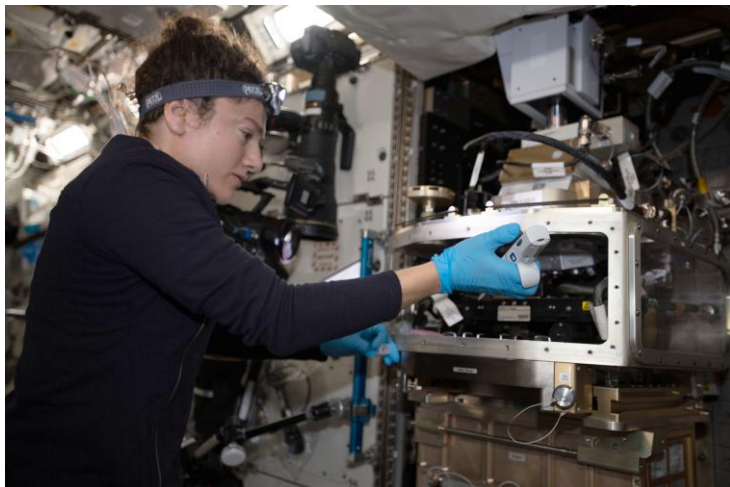
Preliminary Results and Observations from the Science Team

The second module for the Advanced Colloids Experiment with Temperature Control - 4 (ACE-T4-2) completed the first of three samples on August 5, 2020. This is the fourth of six samples. The remaining two samples will be operated over the next 3 to 4 weeks at the Glenn ISS Payload Operations Center (GIPOC). The test matrix has samples of different concentrations and dopants that react at different temperatures. As the temperature increases, the particles get smaller creating a stress throughout the gel structure and ultimately cracks the gel. Certain additives (dopants) can influence gel microstructure and hold potential to affect failure mechanisms. The samples are observed in real time using the GRC-managed Light Microscopy Module (LMM) and three-dimensional (3-D) confocal scanning camera. The understanding of the performance (and ultimate failure) of gel structures affects everyday consumer products and new technologies such as 3-D printing. In space, stresses on these gel structures can be observed on a timescale thousands of times longer than on Earth.

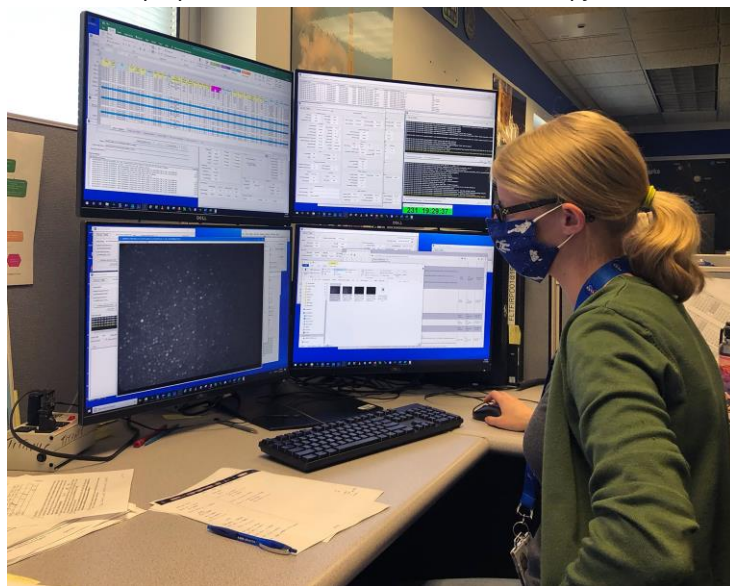
The color spectrum represents the image contrast and tells us about the focal plane and depth of the particles. The changes in the contrast between temperatures 32 °C and 40 °C indicate a structural change in the sample as we change temperature.



Arjun Yodh, Xiaoguang Ma, Chandan Mishra, Analisa Hill University of Pennsylvania (PENN)



Jessica Meir prepares ACE-T4 for 100x oil microscopy with LMM.



Emily Johnson, ZIN-Tech, GRC/GIPOC operations for ACE-T4-2.

Advanced Colloids Experiment with Temperature Control - 4 (ACE-T4-2)

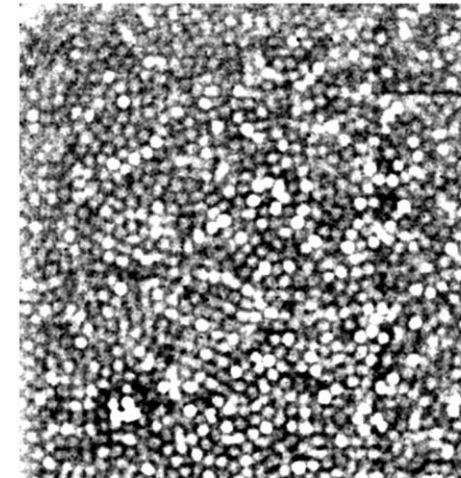
Preliminary Results and Observations from the Science Team

Summary of ACE-T4-2 Activity August 19, 2020.

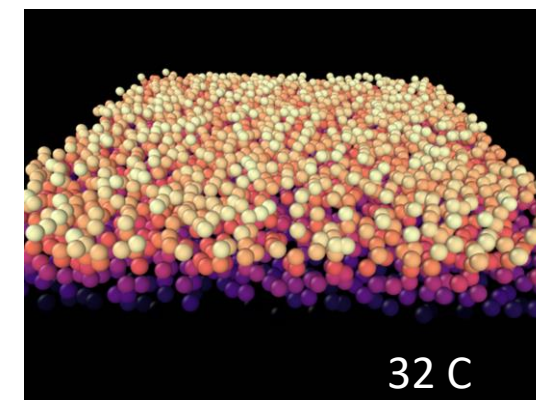
Tonight we will finish the second week of measurements on Sample Module 2 for ACE-T4-2. Our primary accomplishment this week was to complete a set of dynamics experiments on Capillary 1 of Sample Module 2. We also obtained low (2.5x objective) and high (100x oil objective) magnification images of Capillary 2 and Capillary 3, which will be useful for designing experiments for week three.

Per Capillary 1, the work this week built on week one work, which obtained 3D **static** images of the steady-state average microstructure of the colloidal gel in Capillary 1 as a function of internal stress (which is controlled by sample temperature). The **dynamics** experiments of week 2 investigated several issues associated with the temporal and spatial fluctuations of these “average” microstructures. The first set of studies in the second week generated “movies” of the vibrational motions of the individual particles in the gels at a fixed temperature (fixed packing and internal stress). The correlations of the particle motions in these movies enable us to determine the so-called phonon modes of the gel. The softest modes, *i.e.*, modes with lowest energies, are often indicative of the optimal reconfiguration route when the sample changes state. The second set of dynamics experiments directly measured the microstructure reconfigurations following a step-change in internal stress (a sample temperature jump). Again, this is another way to learn about how gels respond to mechanical stress. A third set of experiments explored dynamics and microstructure in samples with gradients of internal strain/stress, *i.e.*, brought about by spatial temperature gradients along the capillary. These data will require extensive image analysis, but our preliminary observations clearly show that the more porous gels that we see at higher temperature exhibit collective dynamical fluctuations involving large groups (branches) of bonded particles. In the **Figure** right, we show two images of the gel in Capillary 1 at 32 degrees: a typical unprocessed black-and-white image, which is what the camera sees, along with a preliminary 3D rendering of the gel.

In total, this research will teach us about the structure and dynamics of gels. Gels are important materials that not only find applications in everyday products such as toothpaste and pharmaceutical gel capsules, but also in high-tech processing schemes such as those that arise in 3D-printers. Our work will provide information about the microstructure of gels, and about how gels evolve and break in response to internal stresses that are different from stresses due to gravity that arise on earth. These insights, enabled by microgravity, could be useful for the design of tougher and more durable gels.



Both images from capillary 1, taken at 32C



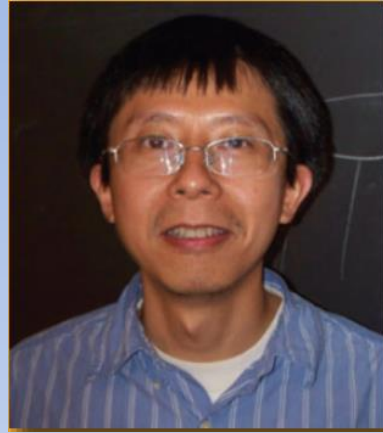
Arjun Yodh, Xiaoguang Ma, Chandan Mishra, Analisa Hill University of Pennsylvania (PENN)



ACE-T9 Science Team



David Marr (PI)
CSM



Ning Wu (Co-I)
CSM

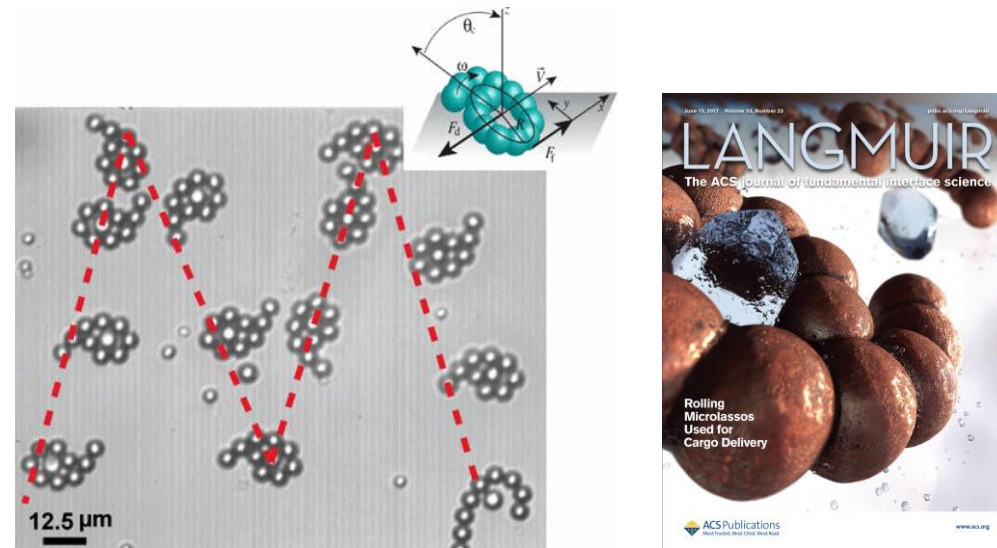


Tao Yang
CSM



Ramona Mhanna
CSM

NASA Supported Colloidal Engineering Research on the Front-Cover of *Langmuir*:

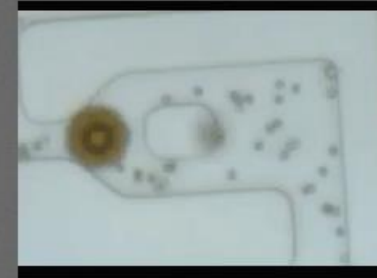
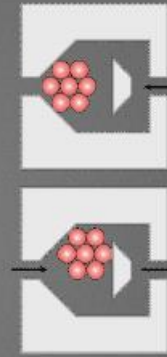
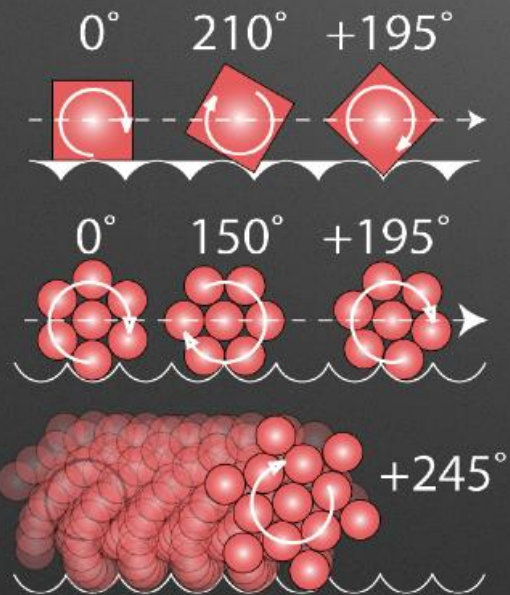


The use of microbots created from micron-size particles to create lassos that can be used to transport micron-sized cargo and release it is highlighted in the June 13 (2017) issue of *Langmuir* (and on its front-cover) [1]. This approach successfully loaded cargo ranging from 1.8 to 13.2 μm using a 16-mer (colloid particle) lasso whose largest diameter is $\sim 13.6 \mu\text{m}$ under a weak field of 3.3 mT. The authors show that these magnetic lassos can roll at substantial velocities, with precise spatial control by manipulating both field strength and phase lag. Moreover, the lasso can curl around and capture cargo tightly and transport it based on a wheel-type mechanism. At the targeted destination, cargo is easily released upon field removal and the lasso can be readily reused. Since the entire process is physically controlled with no chemistry for attachment or disengagement involved, this system can potentially be used for transporting diverse types of cargo under different solution conditions. The upcoming Advanced Colloids Experiment (ACE) - ACE-T9 flight experiment will use magnetic fields and the future ACE-E3 flight experiment plans to use electric fields in microgravity (in the absence of sedimentation) to pursue the creation of 3D controllable microstructures. This work by David Marr, Ning Wu (Colorado School of Mines), *et al.*, acknowledges partial support through NASA Grant NNX13AQ54G.

POCs: William Meyer, USRA, 216-433-5011; Ronald Sicker, MSI, 216-433-6498.

1. "Magnetic Microlassos for Reversible Cargo Capture, Transport, and Release," [Tao Yang](#), [Tonguc O. Tasci](#), [Keith B. Neeves](#), [Ning Wu*](#), and [David W. M. Marr*](#), Department of Chemical and Biological Engineering, Colorado School of Mines, Golden, Colorado 80401, United States, *Langmuir*, Article ASAP, DOI: 10.1021/acs.langmuir.7b00357

Applied Magnetic Fields

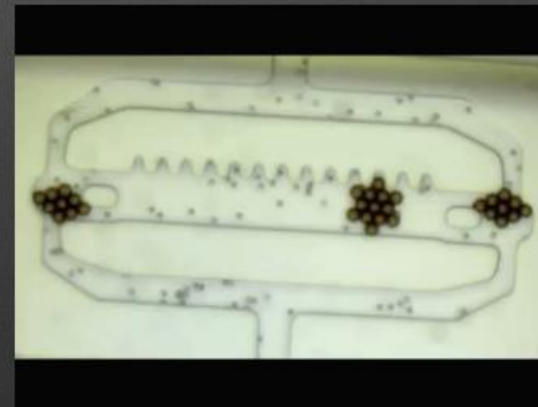


Valves

Mixers



Pumps



Using Colloids to Mimic Protein Folding: ACE T9-3

Science Team:

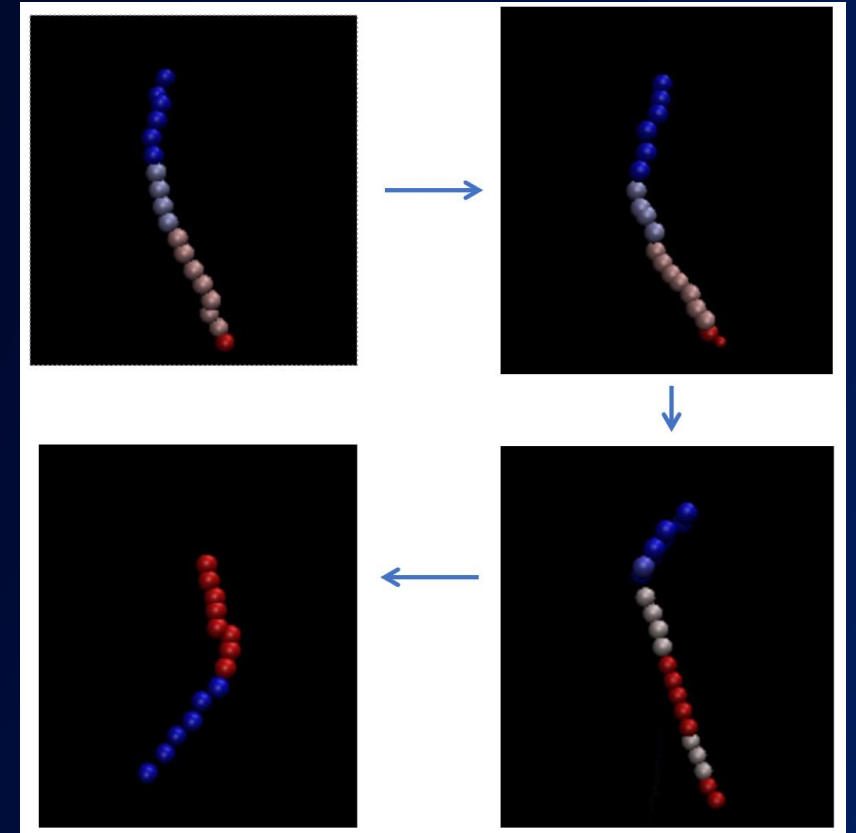
- Professors David Marr and Ning Wu and Dr. Ramona Mhanna at the Colorado School of Mines

LMM Facility:

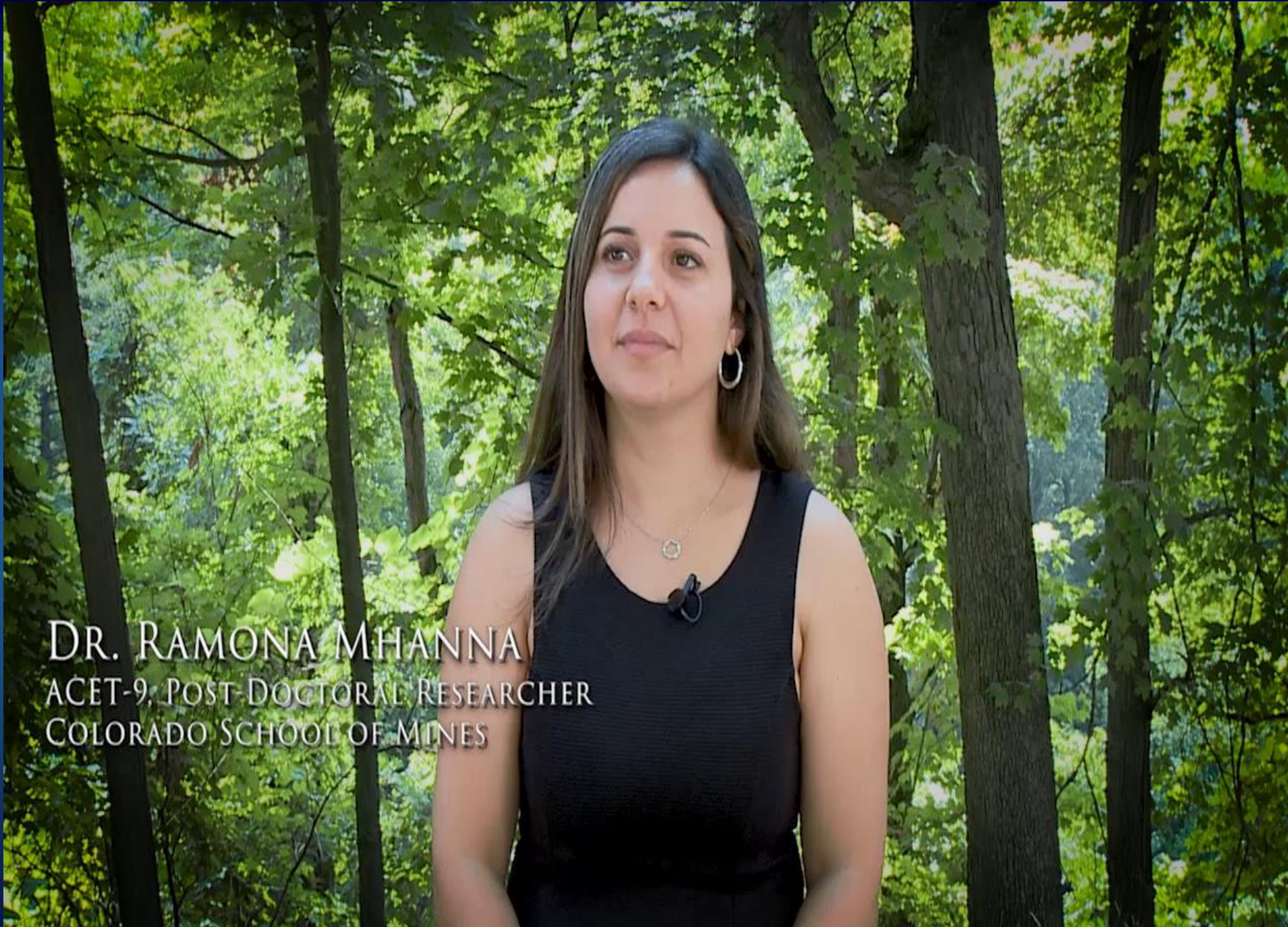
- Micron sized beads in Dimethyl Sulfoxide (DMSO)
- Mimics protein functional groups
- 3D hierarchical folding (quaternary structure) of proteins

Observations:

- The beads elucidate 3D folding dynamics of protein
- Brownian motion and relaxational dynamics of beads were studied, using the magnetic field



The temporal evolution (from left to right) of the 3D structure of a flexible chain. The different colors correspond to different depth levels of the particles. The lower or larger number of particles is due to the chain coming in or out of the field of view of the measurement.

A portrait of Dr. Ramona Mhanna, a woman with long dark hair, wearing a black sleeveless top and a necklace. She is standing in a forest with many green trees. The background is slightly out of focus.

DR. RAMONA MHANNA
ACET-9, POST-DOCTORAL RESEARCHER
COLORADO SCHOOL OF MINES

Hydrophobicity Affects Colloidal Motion: ACE T1-3

Science Team:

- Professor Chang-Soo Lee, Dr. Seong-Geun Jeong and Reya Ganguly (Chungnam National University (CNU), South Korea)

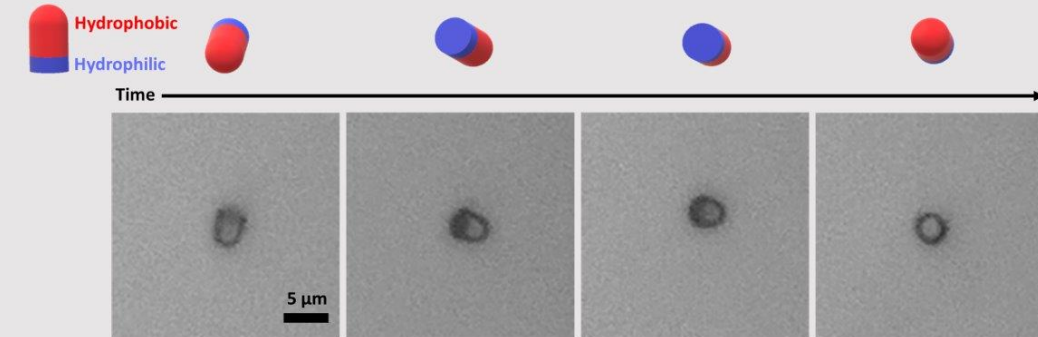
LMM Facility

- Bullet-shaped Janus particles
- Hydrophobic nose
- Hydrophilic cylinder
- Ratio of hydrophobic surface to hydrophilic: 0, 30 and 70%

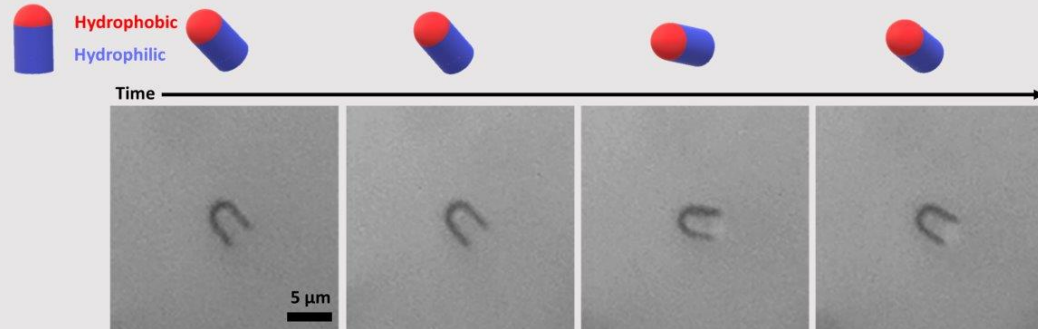
Observations:

- With the increase hydrophobic fraction in Janus particle:
 - Brownian rotational motion increased
 - Particle stayed at any place for longer duration.

A. 70% hydrophobic particle



B. 30% hydrophobic particle



The ACE-T1 experiment's time-lapse sequence of pictures shows the rotational dynamics of 3 x 5-micron Janus particles by setting the ratio of their hydrophobic and hydrophilic parts: 30:70 and 70:30 ratios shown above. This effects Brownian rotational motion.

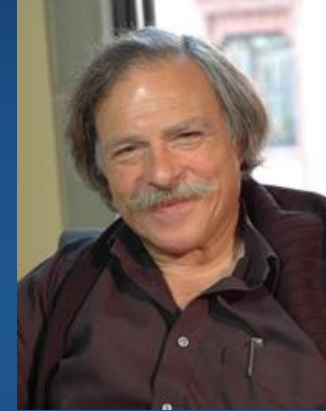
ACE-T11 [hard spheres] and ACE-TR [ellipsoids] science team



Boris Khusid
NJIT

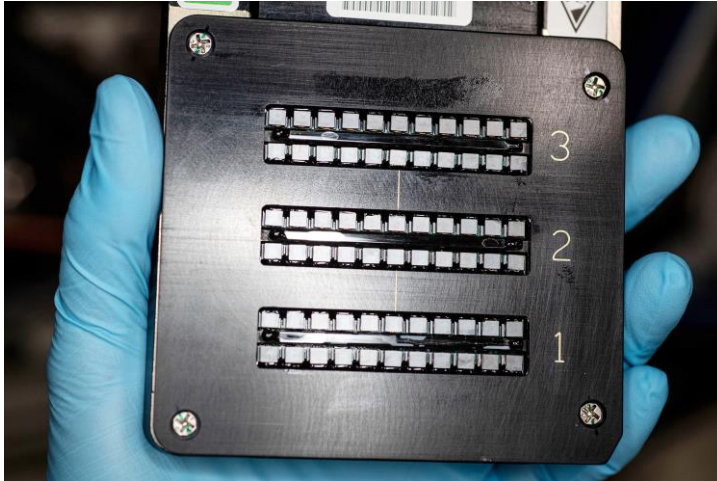


Andy Hollingsworth
NYU



Paul Chaikin
NYU

New Jersey Institute of Science and Technology (NJIT)
Center for Soft Matter Research – New York University (NYU)



NASA astronaut and Expedition 64 Flight Engineer Kate Rubins installed ACE-TR-2 sample module on January 14, 2021.

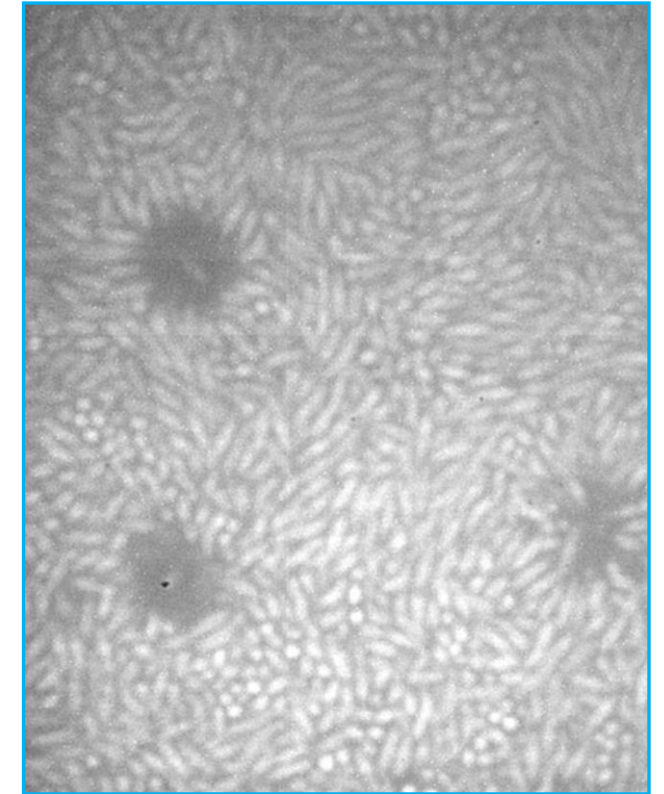


Sam Duton, ZIN-Tech, and Terri Miller, KBR/ZIN at the GRC/GIPOC for ACE-TR-2.

Preliminary science results from Advanced Colloids Experiment with Temperature Control – TR-2 (BPS facility and REMIS/NSF sponsor)

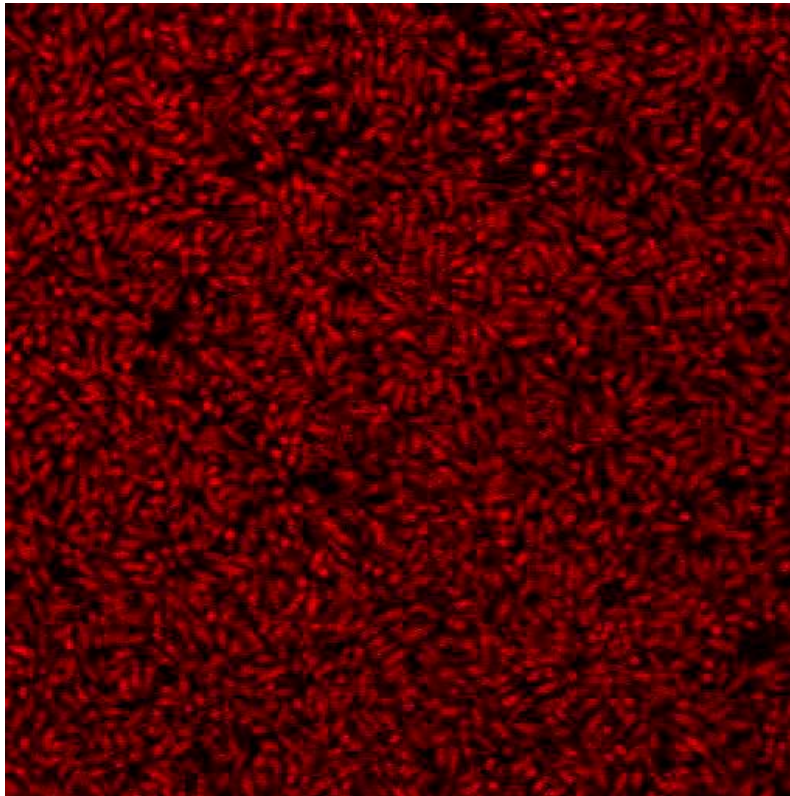
For the ACE-TR-2 (Ellipsoids) flight experiment [NJIT (Boris Khusid) and NYU (Paul Chaikin and Andrew Hollingsworth)] running on the International Space Station (ISS), a large bubble developed in sample module 2, capillary 3 (SM2, C3). This capillary is showing bubble motion due to expansion or generated flow (possibly Marangoni forces) which drives motion of the particles. In the absence of the bubble, we do not see particle movement with temperature change or gradient because there is no thermophoresis (no Soret effect).

This work provides understanding about concentrated colloidal suspensions of elliptical particles and models the behavior of liquid crystals and their defects (called Hedgehogs), which are well below the resolution of an optical microscope. These results may also be important because of potential uses in photonics.

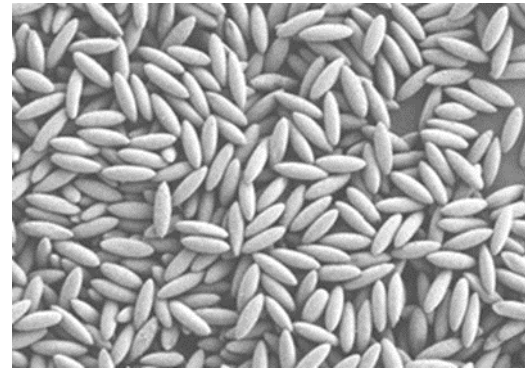


After cycling the temperature (that moved the bubble) Nematic ordering of elliptical colloidal particles and associated defects are now being seen in ACE-TR-2, capillary 3.

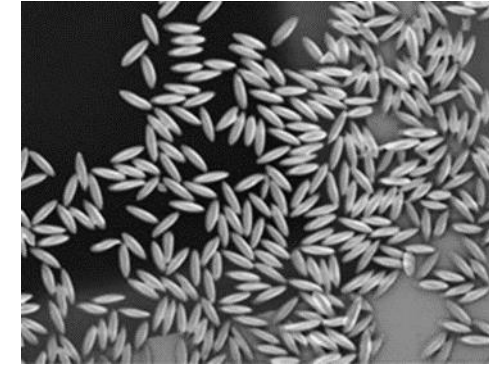
ELLIPSOIDAL COLLOIDS



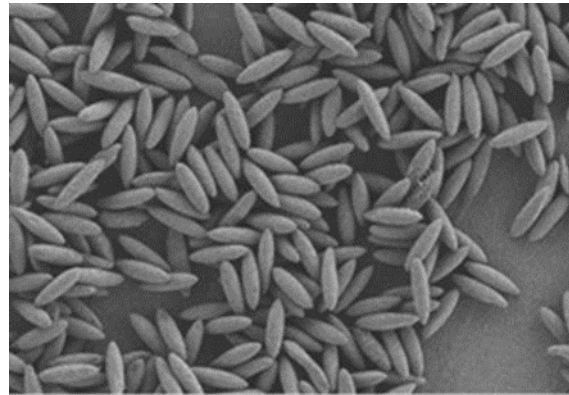
Leica SP5 confocal
 63 X glycerol, 543 nm HeNe



CSF-02-139A pulls 5 6b 7 8 9
 $\alpha \approx 3.0$



CSF-02-139B pull 1
 $\alpha \approx 3.7$



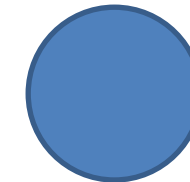
CSF-02-139C pull 10
 $\alpha \approx 3.8$



$\alpha = 3.8$



$\alpha = 3.0$



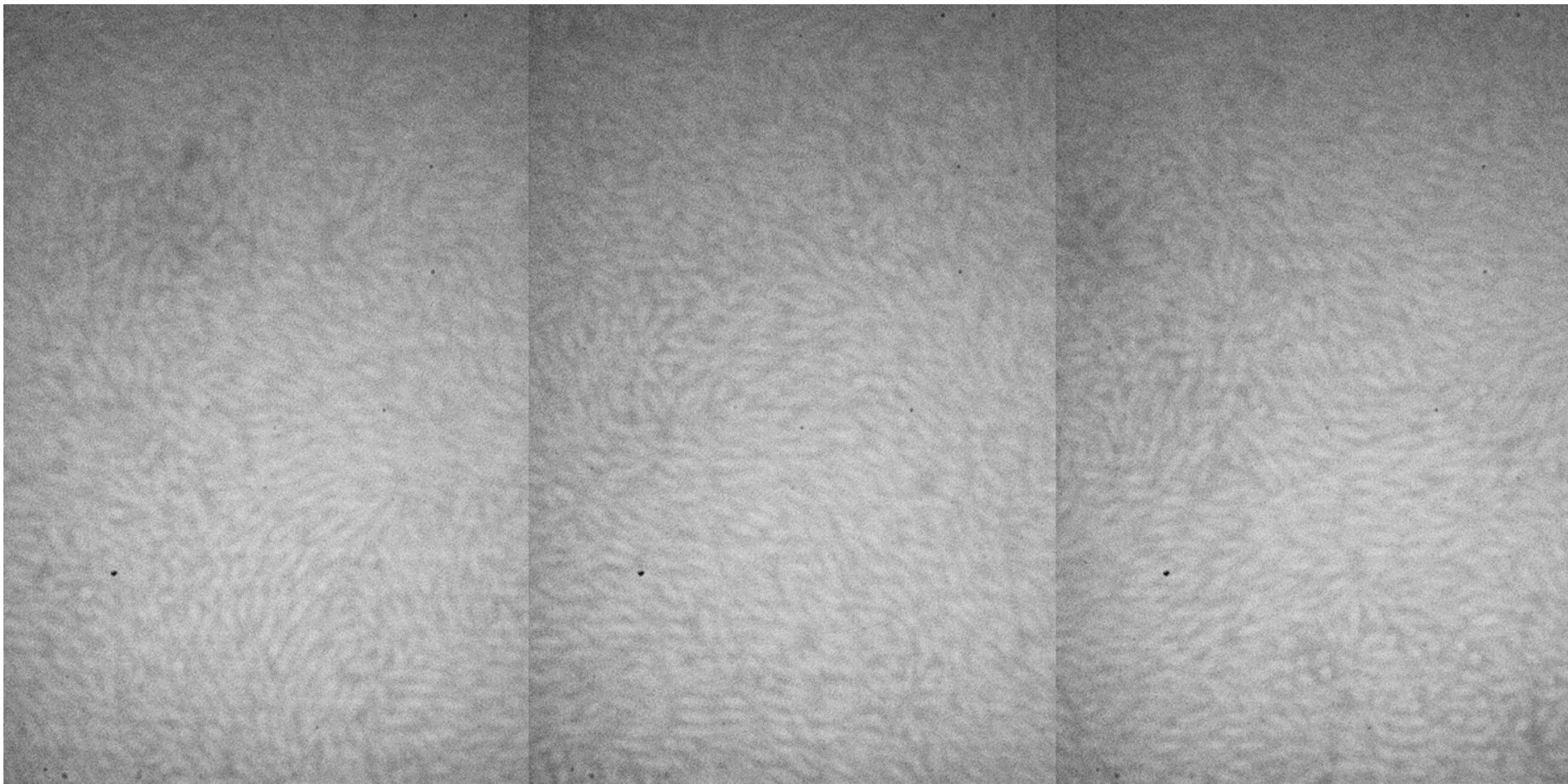
$\alpha = 1.0$



ACE-TR ELLIPSOIDS



Large nematic domains in scanning along the capillary axis on ISS



2020/10/05, 17:21:25.535, CnFcl, ACETR,
S3001, C3, X100, X-16674, **Z0+15**, P4,
E458961, 00945

2020/10/05, 17:21:29.535, CnFcl, ACETR,
S3001, C3, X100, X-16566, **Z0+15**, P5,
E458961, 00946

2020/10/05, 17:21:33.535, CnFcl, ACETR,
S3001, C3_X100, X-16457, **Z0+15**, P6,
E458961, 00947



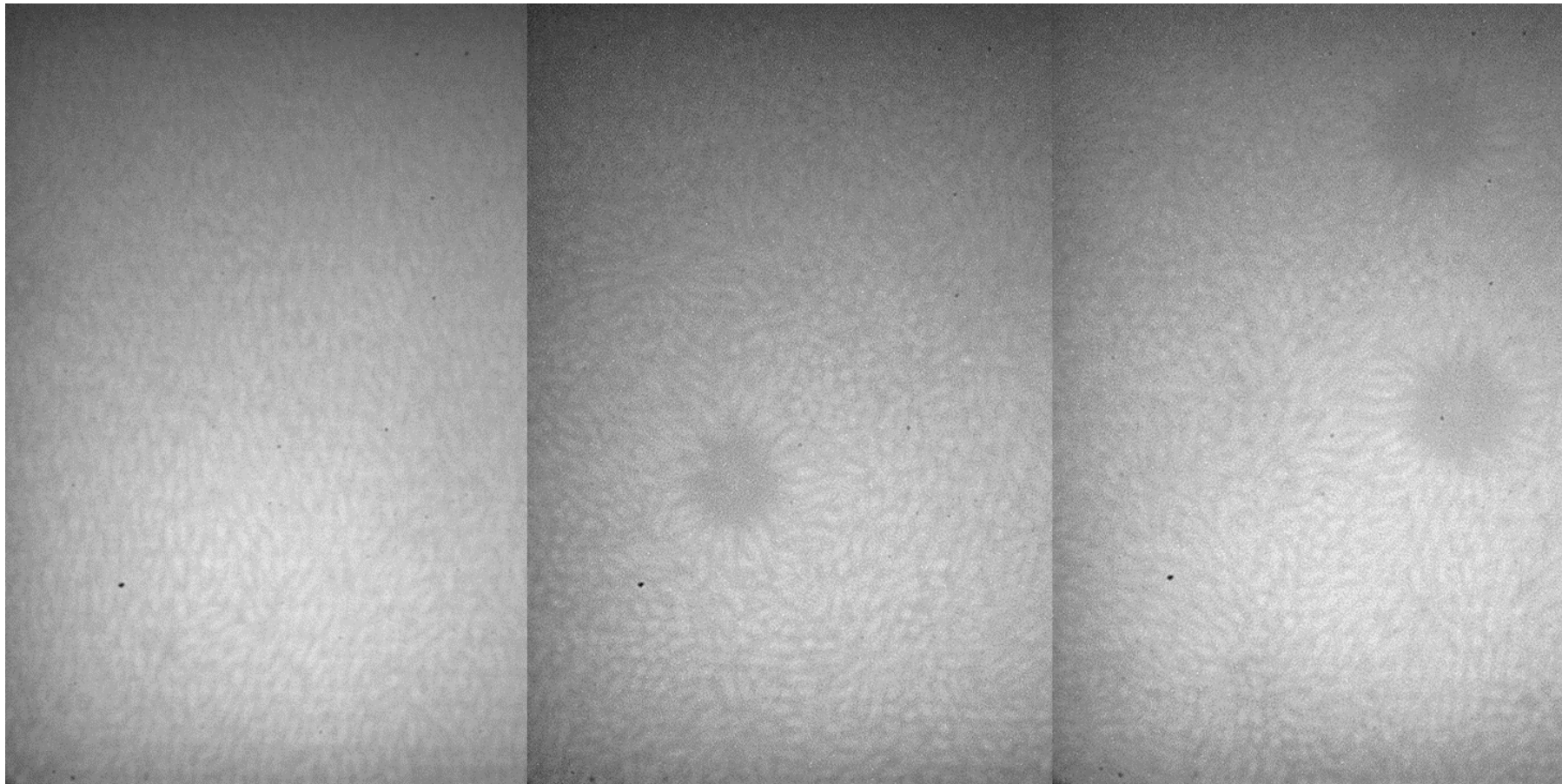


ACE-TR ELLIPSOIDS



Finding that microscopic colloidal ellipsoids mimic the molecular-sized structures, along with their defects, commonly called ‘hedgehogs’ in the liquid crystal community provides an important support for theoretical predictions.

Nematic domains and associated “hedgehog” defects on ISS



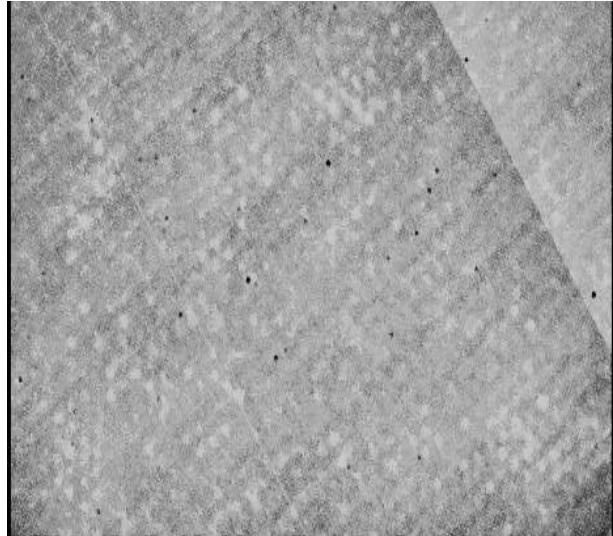
2020/09/24, 22:14:56.768, CnFcl, ACETR,
S3001, C3, X100, X-13964, P29, E443412,
00250

2020/09/24, 22:16:56.833, CnFcl, ACETR,
S3001, C3, X100, X-10712, P59, E443412,
00280

2020/09/24, 22:15:40.701, CnFcl, ACETR,
S3001, C3, X100, X-12771, P40, E443412,
00261

$$\phi_{\text{FCC}}=0.74$$

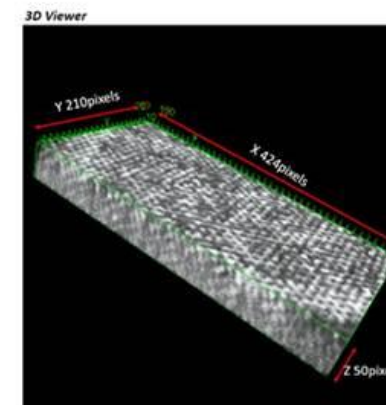




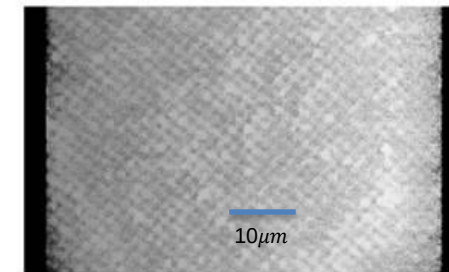
One of the first 3D models assembled from a single Confocal Stack. Analysis will continue for some time. Approximately 4 Terabytes of data with 700,000 images was collected. The particles are 1 micron. Each dot is a single particle with the fluorescent dye responding to the laser in FIR/LMM.

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A



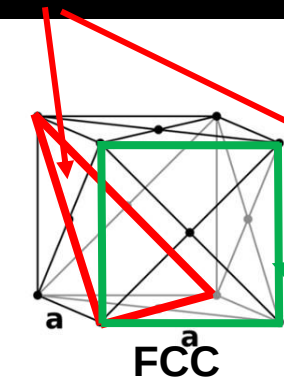
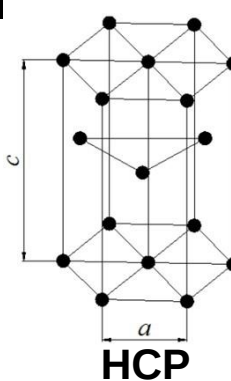
B

Most metals adopt hexagonal close packed (HCP) and face-centered cubic (FCC) structures

[https://en.wikipedia.org/wiki/Periodic_table_\(crystal_structure\)](https://en.wikipedia.org/wiki/Periodic_table_(crystal_structure))

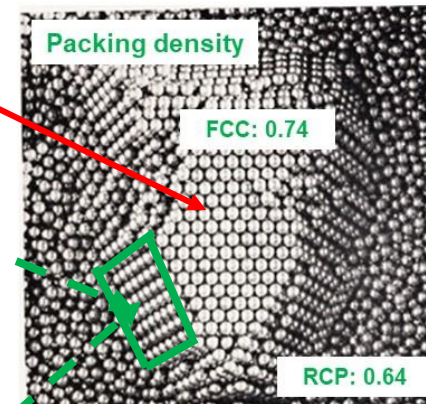
1 H HEX	2 He HCP	3 Li BCC	4 Be HCP	5 B RHO	6 C HEX	7 N HEX	8 O SC	9 F SC	10 Ne FCC	11 Na BCC	12 Mg HCP	13 Al FCC	14 Si DC	15 P ORTH	16 S ORTH	17 Cl ORTH	18 Ar FCC	19 K BCC	20 Ca FCC	21 Sc HCP	22 Ti BCC	23 V BCC	24 Cr BCC	25 Mn BCC	26 Fe FCC	27 Co FCC	28 Ni FCC	29 Cu FCC	30 Zn HCP	31 Ga ORTH	32 Ge RHO	33 As HEX	34 Se ORTH	35 Br FCC	36 Kr FCC	37 Rb BCC	38 Sr FCC	39 Y HCP	40 Zr BCC	41 Nb BCC	42 Mo BCC	43 Tc HCP	44 Ru FCC	45 Rh FCC	46 Pd FCC	47 Ag FCC	48 Cd HCP	49 In TETR	50 Sn TETR	51 Sb RHO	52 Te HEX	53 I ORTH	54 Xe FCC	55 Cs BCC	56 Ba FCC	57 La FCC	58 Ce FCC	59 Pr FCC	60 Nd FCC	61 Pm FCC	62 Sm FCC	63 Eu FCC	64 Gd FCC	65 Tb FCC	66 Dy FCC	67 Ho FCC	68 Er FCC	69 Tm FCC	70 Yb FCC	71 Lu FCC	72 Hf FCC	73 Ta FCC	74 W FCC	75 Re FCC	76 Os FCC	77 Ir FCC	78 Pt FCC	79 Au FCC	80 Hg FCC	81 Tl FCC	82 Pb FCC	83 Bi FCC	84 Po FCC	85 At FCC	86 Rn FCC	87 Fr FCC	88 Ra FCC	89 Ac FCC	90 Th FCC	91 Pa FCC	92 U FCC	93 Np FCC	94 Pu FCC	95 Am FCC	96 Cm FCC	97 Bk FCC	98 Cf FCC	99 Es FCC	100 Fm FCC	101 Md FCC	102 No FCC	103 Lr FCC	104 Rf FCC	105 Db FCC	106 Sg FCC	107 Bh FCC	108 Hs FCC	109 Mt FCC	110 Ds FCC	111 Rg FCC	112 Cn FCC	113 Nh FCC	114 Fl FCC	115 Mc FCC	116 Lv FCC	117 Ts FCC	118 Og FCC
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Hexagonal array



Packing Factor of HCP and FCC: 0.74
Random close packing (RCP): 0.64

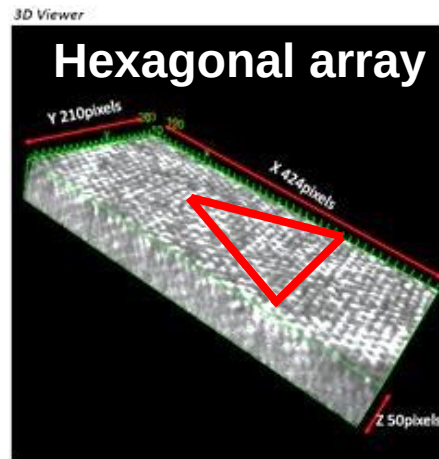
Bernal, Proc R Soc A 280, 299 (1964)



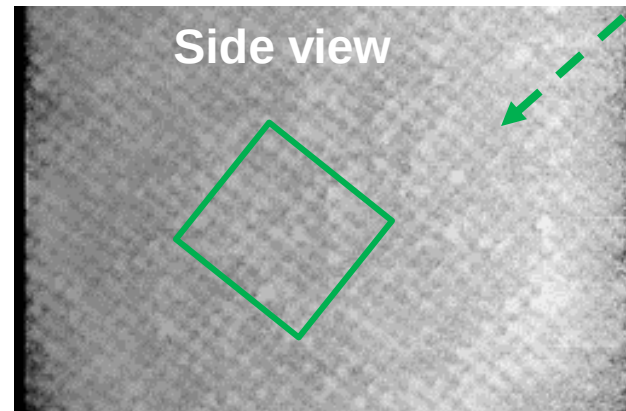
Ball bearings. FCC crystal surrounded by 'liquid' formed by shearing.

After ACE-T11 Experiment 2021

~100 Gb confocal images and videos
FCC crystal is of the size of the capillary
27 mm x 1.5 mm x 0.15 mm



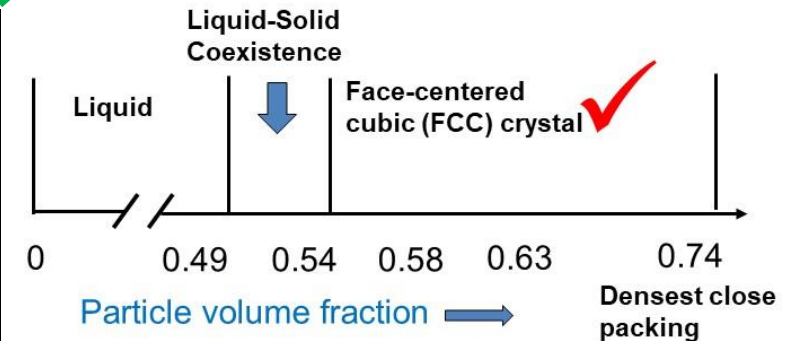
3D image stacks: ~ 40 x 20 x 5 microns.



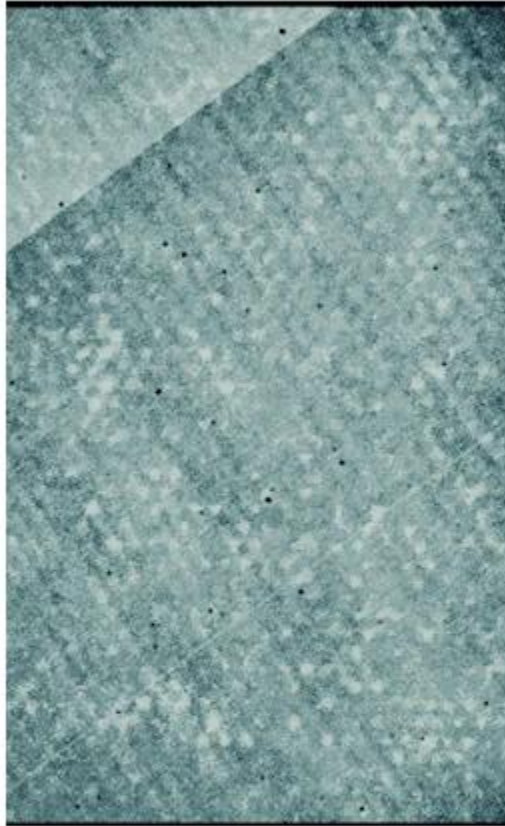
Square phase cross section of FCC crystal near (100) plane; identified ~ 520 spheres of 1.3 μm in diameter

Theory does work!!!

First confirmation of theory



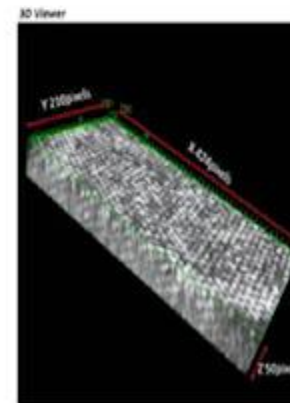
Monodisperse fluorescent polymethyl methacrylate (PMMA) particles $1.29 \pm 0.02 \mu\text{m}$



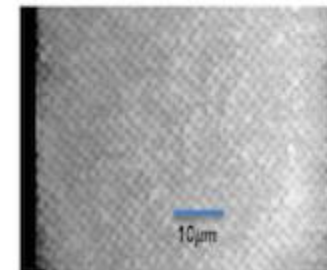
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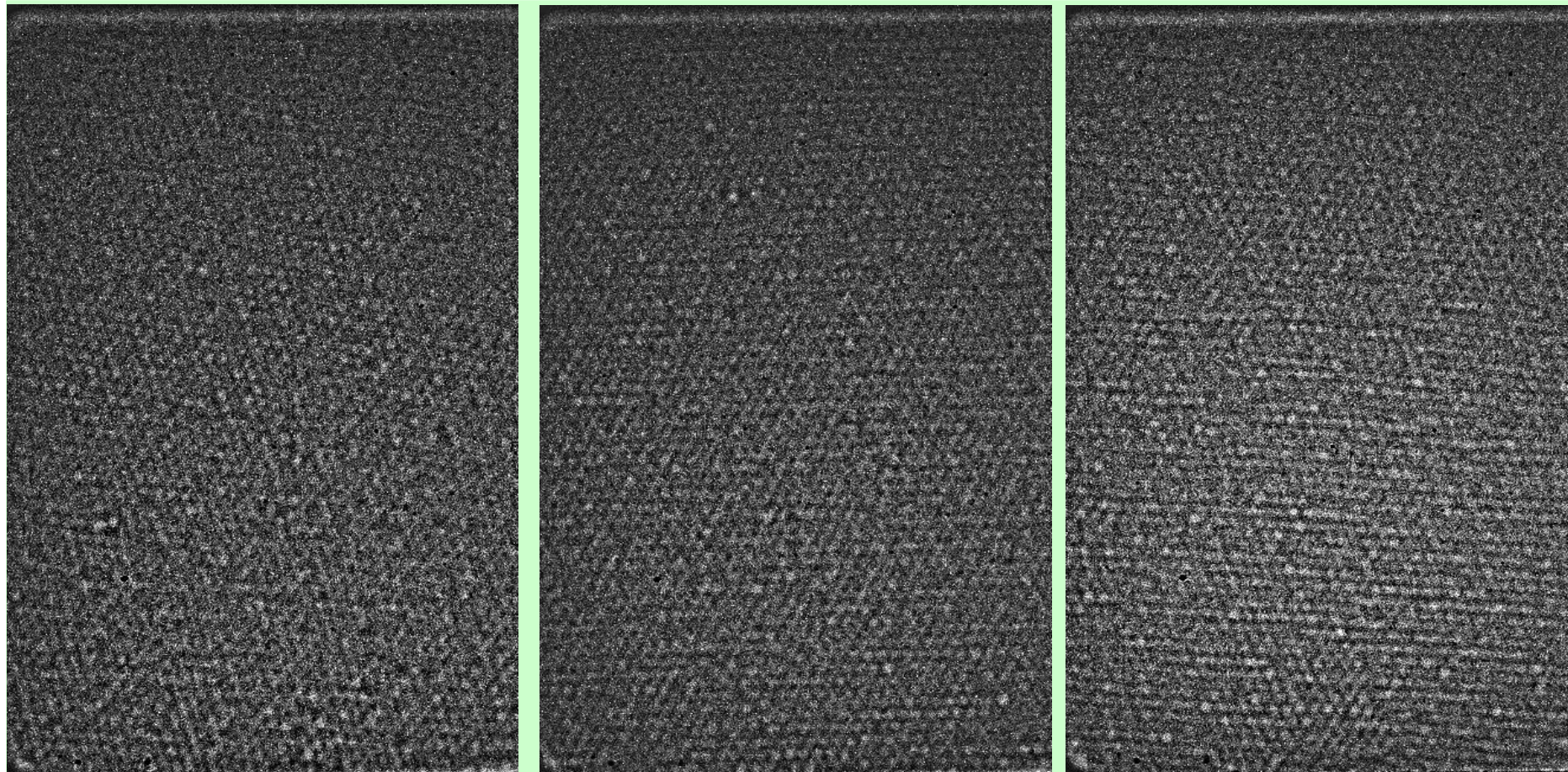
A



B

COLLOIDAL CRYSTALLIZATION ON ISS

Confocal microscopy: Magnification 100 X, oil immersion objective



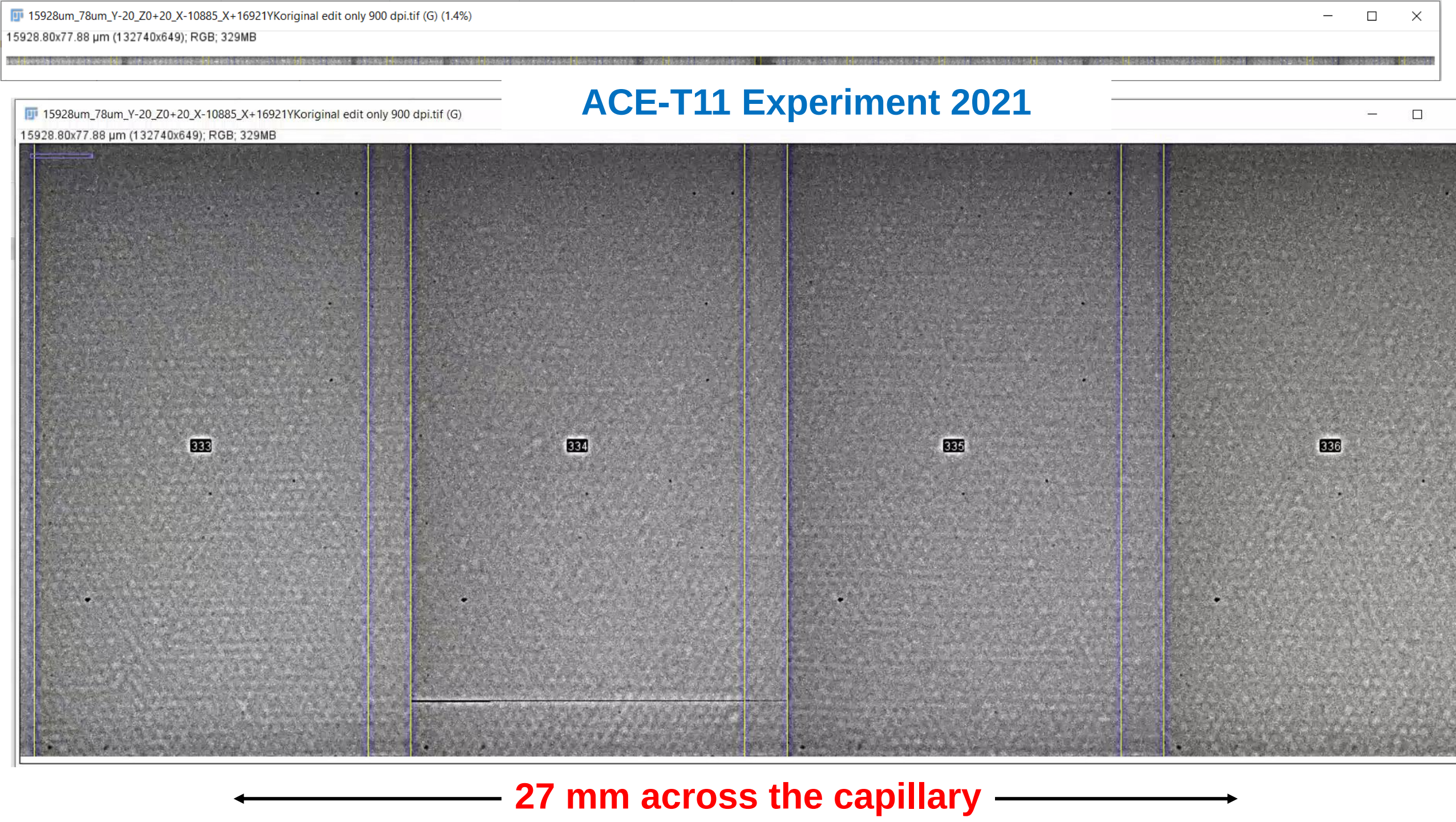
X= -10.885 mm

X= -2.836 mm

X= +16.921 mm

← 27 mm across the capillary →

Parallel crystalline lines in every portion of the images across the entire 2.7 cm of capillary.





Acknowledgements

- Thanks to Gayle DiBiasio for graphics design.
- Thanks to William Fetcher for video production.

National Aeronautics and
Space Administration



2020 GLENN RESEARCH CENTER VIRTUAL AGENCY HONOR AND CENTER AWARDS CEREMONY



SILVER ACHIEVEMENT MEDAL

PRESENTED TO

Michael A. Bohurjak

*For exceptional achievement developing and operating
a series of advanced colloids experiments on the International
Space Station to advance complex fluid technologies*

Acknowledgements:
The entire team for the Light
Microscopy Module received
NASA's 2020
Sliver Achievement Medal.



NASA Silver Achievement Medal

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