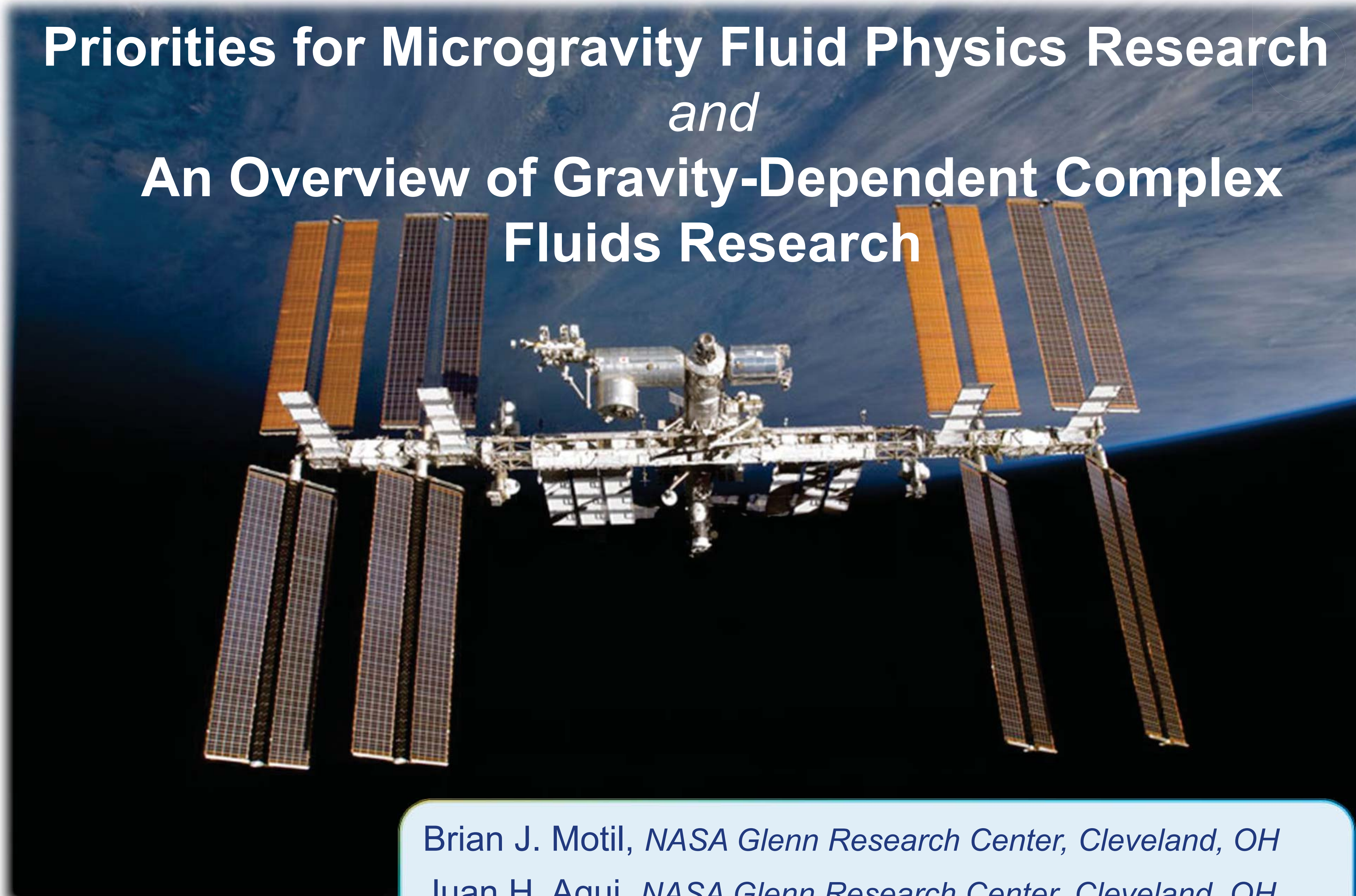
Priorities for Microgravity Fluid Physics Research *and* An Overview of Gravity-Dependent Complex Fluids Research



Brian J. Motil, *NASA Glenn Research Center, Cleveland, OH*

Juan H. Agui, *NASA Glenn Research Center, Cleveland, OH*

Francis P. Chiaramonte, *NASA HQ, Washington, DC*

Why Study Fluids in Space?

"When the influence of gravity on fluid behavior is diminished or removed, other forces, otherwise of small significance, can assume paramount roles."

- NRC Report to NASA, 2003

To enable space exploration.
- Two-phase flow systems for heat transfer and life support.
- Long term propellant storage.
- Excavation, material handling and *in-situ* resource utilization.

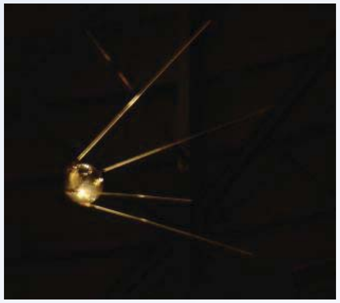
To advance science.
- Model "atomic" systems at an observable scale (colloids).
- Study self assembly and crystallization – advance knowledge of phase transitions.
- Study fluid systems near critical points.

To enable technologies on earth.
- Reveal effective rheological properties of non-Newtonian fluids and suspensions.
- Stabilization of foams.
- Understand the aging of gels and late collapse (P&G) – increasing product shelf life.
- Can gain critical insights into strongly non-linear systems (multiphase & interfacial problems) where gravity constitutes a significant perturbation or instability or complicates the interpretation of experimental results.

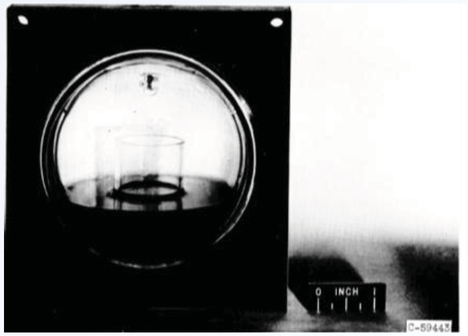
Macroscopic consequences of gravity on fluids include:
- *Stratification of different densities.*
- *Hydrostatic pressure gradient.*
- *Sedimentation (when particles are freely suspended).*
- *Buoyancy-driven convection.*
- *Drainage of liquid films.*

Fluids in Space

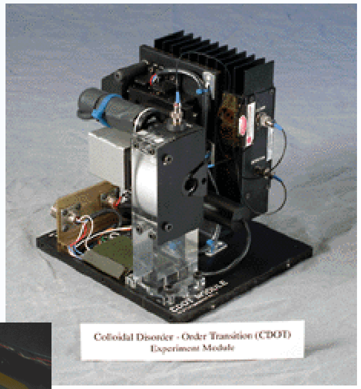
1957: The same year that Sputnik-1 orbited the planet – Robert Siegel (GRC) conceived a drop tower experiment to study a force often masked by gravity yet critical to almost every life form.



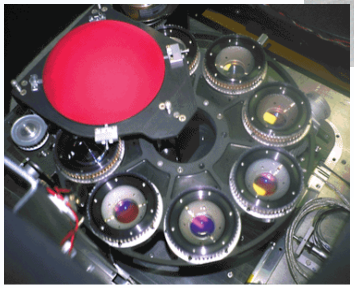
1962: The first "fluids" experiment was conducted in space on the Mercury-Atlas 07 by Scott Carpenter to study the liquid-vapor interface in a baffled tank in weightlessness. (NASA TN D-1577, 1963).



1995: The Colloidal Disorder-Order Transition (CDOT) shuttle flight experiment tested fundamental theories that model atomic interactions in USML-2 on Columbia.



2001: Physics of Colloids in Space (PCS) flew as the first US Rack Level experiment on the ISS.



TODAY….

Fluid Physics and Complex Fluids Today

Fluid Physics
- Two-phase flow
- Phase separation
- Boiling, condensation
- Capillary and interfacial phenomena

Complex Fluids
- Colloids
- Liquid crystals
- Foams
- Granular flows

Fluid Physics on ISS

Fluid Physics

- Two-phase flow
- Phase separation
- Boiling, condensation
- Capillary and interfacial phenomena

Two-phase flow (without heat transfer)

- Packed Bed Reactor Experiment (PBRE)
- Dynamics of Liquid Film/Complex Wall Interaction (DOLFIN II)

Phase separation

- Two-Phase Flow Separator Experiment (TPFSE)

Boiling, Condensation

- Constrained Vapor Bubble-2 (CVB-2)
- Boiling eXperiment Facility (BXF)
- Multiphase Flow and Heat Transfer Experiment (MFHT)
- Flow Boiling and Condensation Experiment (FBCE)
- Two-Phase Electro-hydrodynamics (EHD) Conduction-Driven Heat Transport Device
- Zero Boil-Off Tank Experiment (ZBOT), -2

Capillary and interfacial phenomena

- Capillary Channel Flow (CCF)
- Capillary Flow Experiments-2 (CFE-2)

Two-Phase Flow (without heat transfer)

PI: Dr. Brian Motil, NASA GRC
Co-Is: Prof. Vemuri Balakotaiah, U. of Houston & Julie L Mitchell, NASA, JSC

Packed Bed Reactor Experiment (PBRE) - 2014

- Will investigate the role and effects of gravity on gas-liquid flow through porous media which is a critical component in life-support; thermal control devices; and fuel cells.
- Will validate and improve design and operational guidelines for gas-liquid reactors in partial and microgravity conditions.
- Preliminary models predict significantly improved reaction rates in 0-g.
- Models developed from early 0-g aircraft tests led to the successful operation of **IntraVenous fluid GENeration (IVGEN)** in 2010 providing the ability to generate IV fluid from *in situ* resources on the ISS.
- Provides test fixture to test future two-phase flow components.

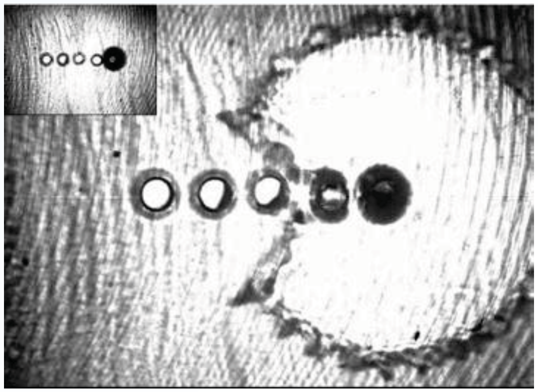
Volatile Reactor Assembly (VRA) on STS 89

IVGEN Deionizing resin bed

Dynamics of Liquid Film/ Complex Wall Interaction (DOLFIN II)

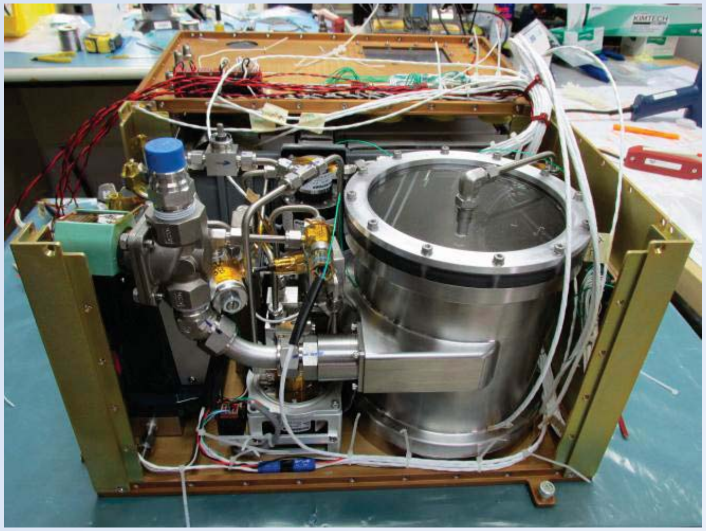
- ESA led experiment to develop continuum models to describe interactions between spreading fluids and chemically and/or morphologically complex surfaces using 0-g environment.
- Developing the ability to manipulate surface flows in microgravity is a key to thermal management solutions in space exploration.
- US PI (Yarin) will perform experiments on spray cooling over specially patterned surfaces.

US Co-I: Prof. Alexander Yarin, University of Chicago
ESA PI: Prof. Cameron Tropea, Institute of Fluid Mechanics and Aerodynamics (SLA) Technische Universität Darmstadt

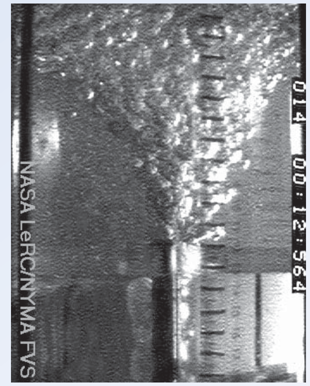


Drop impact onto a porous target

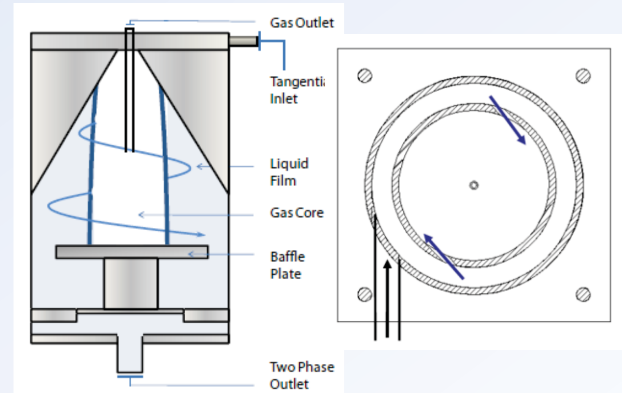
Gas-Liquid Separation Devices



Pumped Separator for PBRE



Reduced Gravity Bubble Vortex



Cyclonic Concepts

PI: Dr. Georges Chahine and Xiongjun Wu, DynaFlow, Inc.
PI: Prof. Yasuhiro Kamotani, Case Western Reserve University
Co-I: Prof. Jaikrishnan Kadambi, Case Western Reserve University

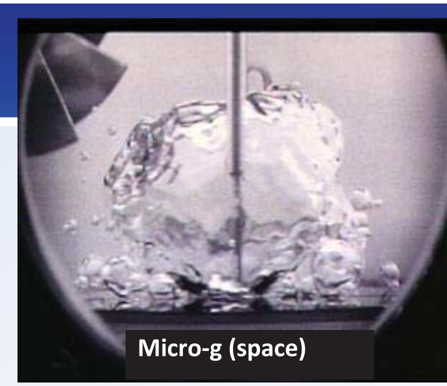
Two-Phase Flow Separator Experiment (TPFSE) – 2019 (*or sooner !!*)

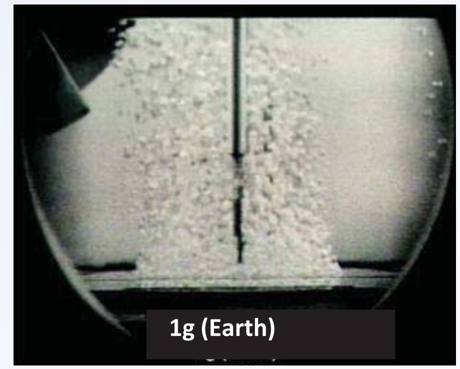
- Two PI Teams will share common test hardware to study different aspects.
- Will address the design and performance of passive two-phase flow separator technologies.
- Determine range of flow rates for acceptable performance.
- Quantify the effect of fluid properties and separator geometry.
- Determine separator response and stability envelope to startup, shutdown and liquid slugging conditions.
- Passive separation is critical to high reliability and low power gas-liquid systems for used in thermal control and life support.

Boiling and Condensation

1-g Flow Boiling (heating from the bottom)

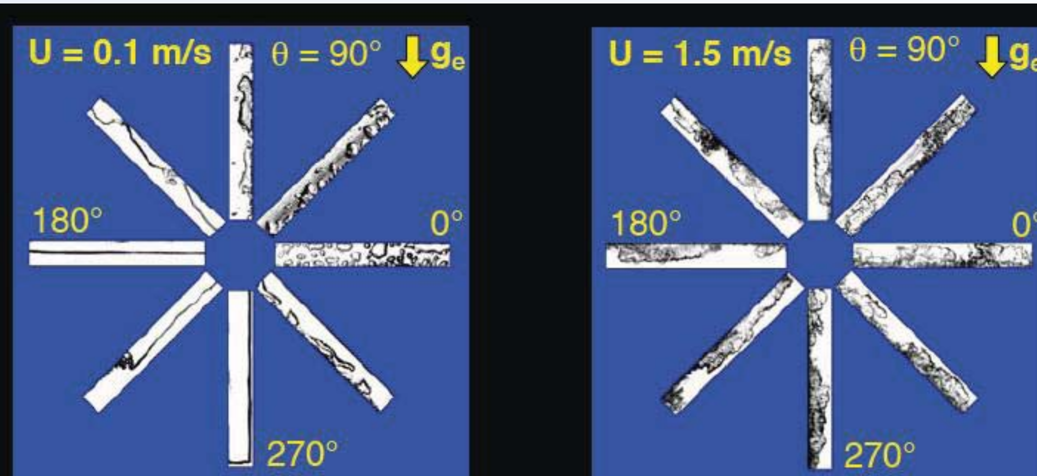
0-g Flow Boiling





Pool Boiling

- Heat transfer problems in 0-g must consider the combined effects of the lack of buoyancy driven convection (within a single phase) as well as the lack of buoyancy forces between phases.
- Examples include heat pipes (CVB); Pool Boiling (BXF); Flow Boiling and Condensation (FBCE).
- Devices in the next generation of space systems are projected to dissipate heat fluxes that far exceed the capabilities of today's cutting-edge thermal management schemes.
- Critical Heat Flux (CHF) is the most important thermal design parameter for boiling systems involving both heat-flux-controlled devices and intense heat removal.
- Exceeding CHF can lead to permanent damage, including physical burnout, of the heat-dissipating device.



(a) (b)

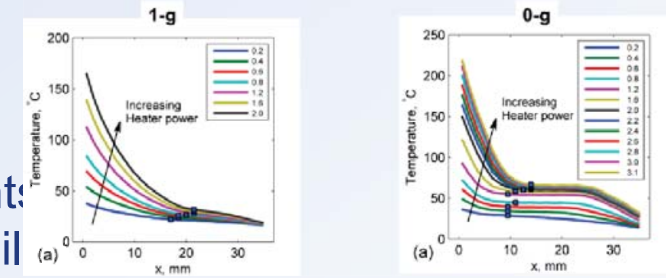
FIG. 6 Vapor behavior just prior to CHF for different orientation at (a) U = 0.1 m/s and (b) U = 1.5 m/s (Zhang, Mudawar and Hasan, 2002).

Boiling and Two-Phase Flow Laboratory *Purdue University*

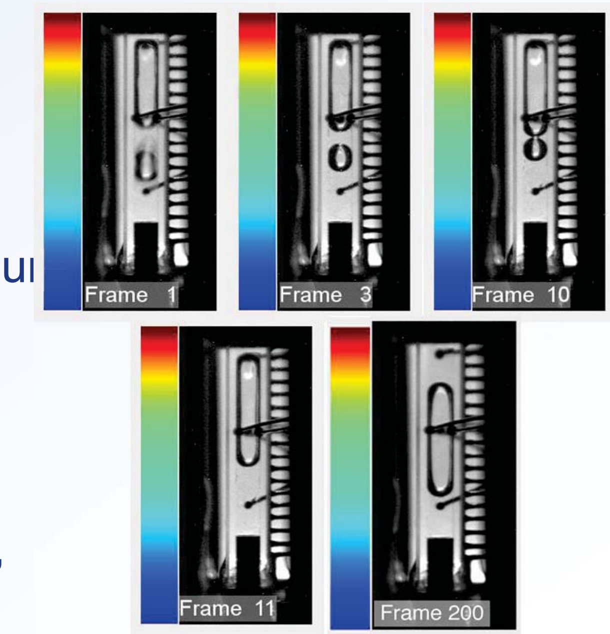
Boiling (Evaporation) and Condensation

Constrained Vapor Bubble (CVB) Experiment – **2009 & 2013**

- Prototype for a wickless heat pipe in microgravity – based on corner flows.
- Used pure Pentane as operating fluid for first set of experiment
- Provided fundamental transport data including the overall stabil flow characteristics, average heat transfer coefficient in the evaporator, and heat conductance as a function of heat flow rate and vapor volume.
- Interferometry technique obtained direct measurements of fluid curvature and thickness.
- Bank of thermocouples measured the temperature gradients.
- Visualized film stability and shape of dry out regions with a microscope in detail never obtained before in microgravity.
- CVB-2 (2013) will extend data to a *binary mixture* rather than a pu fluid (Pentane – Isohexane).
- <u>Results from CVB-1</u>:
  - There is more internal fluid flow in microgravity.
  - Dryout could not be observed in microgravity.
  - Heat pipes run “hotter” and at higher pressure in microgravity, while the surface intended to be cooled, runs cooler.
  - Unexpected phenomena were observed and enhanced in microgravity including meniscus oscillations and single bubble nucleation phenomena.



Comparison of heating power (1-g vs 0-g).



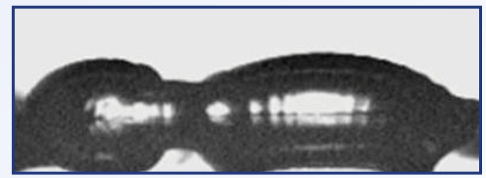
Unexpected Explosive Nucleation in 0-g.

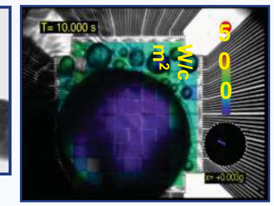
PI: Prof. Joel L. Plawsky, Rensselaer Polytechnic Institute
Co-I: Prof. Peter C. Wayner, Jr., Rensselaer Polytechnic Institute

Boiling and Condensation

Boiling eXperiment Facility (BXF) – 2011

- BXF included two separate pool boiling investigations:
  - **Microheater Array Boiling Experiment (MABE)**
  - **Nucleate Pool Boiling Experiment (NPBX)**.
- Advanced understanding of local boiling heat transfer mechanisms & critical heat flux in microgravity for nucleate and transition pool boiling.
- Detailed measurements of bubble growth, detachment and subsequent motion of single and merged (larger) bubbles.
- Enhanced the development of two-phase thermal management systems, which provide isothermal control with reduced radiator area and mass.
- MABE (Kim) recently published results in J. of Heat Transfer on two regimes for predicting pool boiling behavior: buoyancy and surface tension dominated boiling regimes.





(Top) Paulo Nespoli installing BXF in MSG. (Above left) Coalescence of vapor bubbles on NPBX wafer. (Above right) MABE subcooled nucleate boiling in μg colorized to illustrate actual heat flux.

PI: Prof. Vijay K. Dhir, University of California, LA
PI: Prof. Jungho Kim, University of Maryland

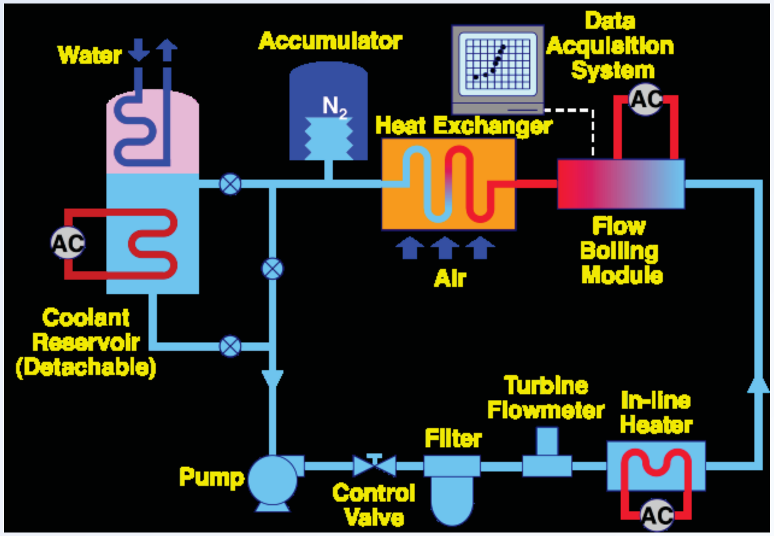
Multiphase Flow and Heat Transfer Experiment (MFHT) - 2020

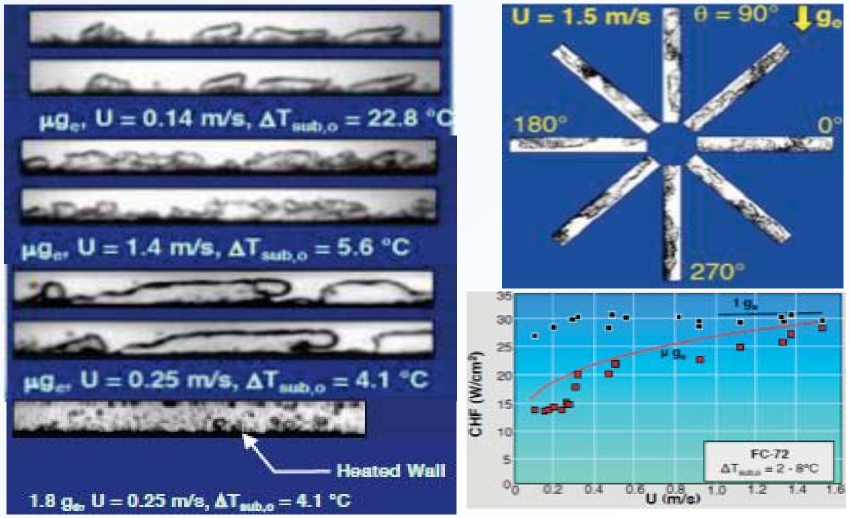
- Will develop models that incorporate two-phase flow regimes and fluid conditions to predict local heat transfer coefficients from subcooled nucleate boiling through critical heat flux (CHF) and dryout.
- Will obtain local measurements of the wall heat transfer coefficient with high temporal and spatial resolution using an infrared video (IR) camera.

Flow Boiling and Condensation Experiment (FBCE) – 2017

- Will develop mechanistic models for microgravity flow boiling Critical Heat Flux (CHF) and dimensionless criteria to predict minimum flow velocity required to ensure gravity-independent CHF.
- Will develop mechanistic model for microgravity annular condensation and dimensionless criteria to predict minimum flow velocity required to ensure gravity-independent annular condensation; also develop correlations for other condensation regimes in microgravity.
- PI recently concluded successful 0-g aircraft testing.
- Approach will be to develop an integrated flow boiling/condensation experiment to facility follow-on researcher.

PI: Prof. Issam Mudawar, Purdue University
Co-I: Dr. Mojib Hasan, NASA GRC



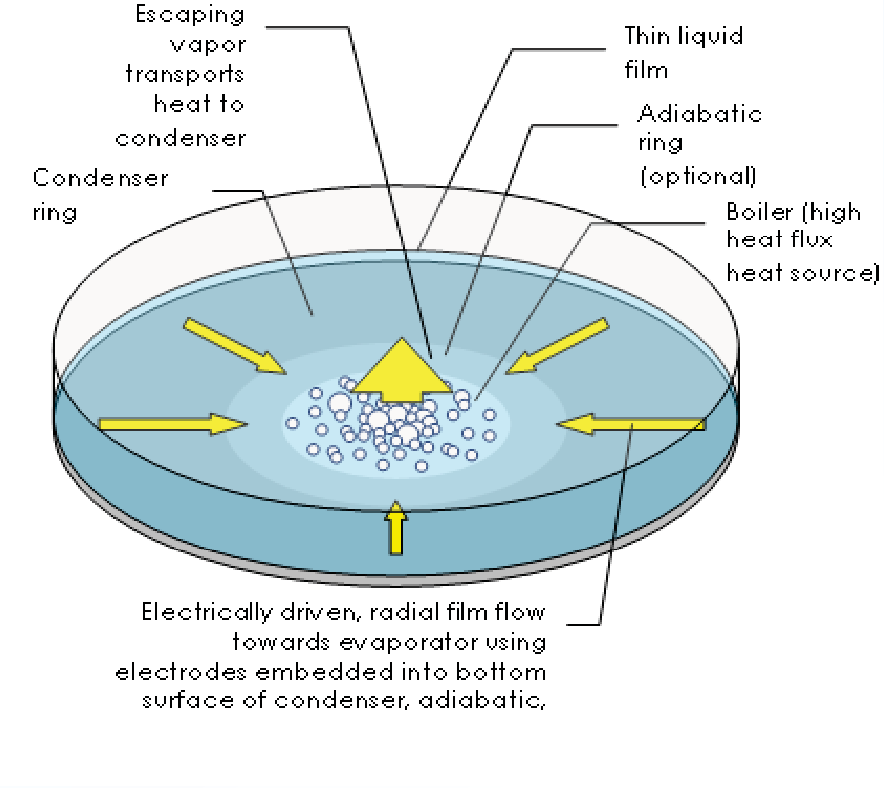


Critical Heat Flux (CHF) data and model predictions for microgravity and Earth gravity for flow boiling.

Boiling and Condensation

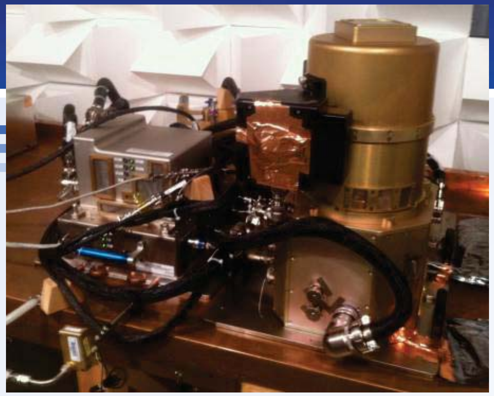
Two-Phase Electro-hydrodynamics (EHD) Conduction-Driven Heat Transport Device – 2020

- Will develop fundamental understanding and physical models to characterize the effects of gravity on the interaction of electric and flow fields in the presence of phase change.
- Will characterize electrowetting effect on boiling and CHF in the absence of gravity.
- Electro-wetting of the boiling section will repel the bubbles away from the heated surface in microgravity environment.
- Micro-scale devices have extremely high heat fluxes due to the small heat transfer surface area.
- Provides a robust, non-mechanical, lightweight, low-noise and low-vibration device.
- Recently concluded successful 0-g aircraft testing demonstrating EHD pump works well in 0-g.



PI: Prof. Jamal Seyed-Yagoobi, Worcester Polytechnic Institute
Co-I: Jeffrey Didion, NASA GSFC

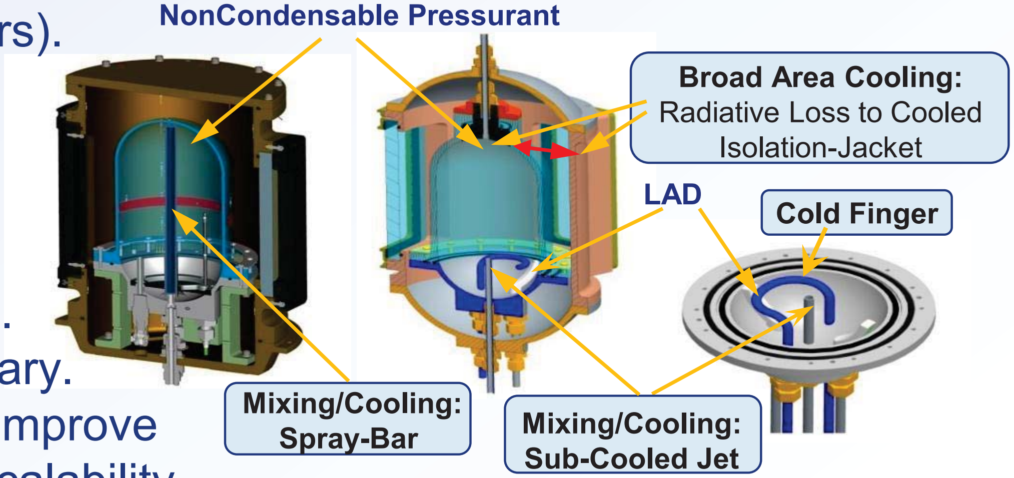
Boiling and Condensation



ZBOT EU

Zero Boil-Off Tank Experiment (ZBOT) - 2014

- Will study storage tank pressurization & pressure reduction through fluid mixing in microgravity (ZBOT-1).
- Add the effects of non-condensable gasses (ZBOT-2). The presence of noncondensables produces barriers to the transport of the vapor to and from the interface creating gradients of the gaseous concentrations along the interface. This changes the pressurization rates.
- Possible ZBOT-3 to characterize tank thermal destratification and pressure reduction through active cooling schemes for: (i) sub-cooled jet mixing (ii) spray-bar mixing; and (iii) broad area cooling with intermittent mixing.
- Leveraging this work with OCT Cryogen Propellant Storage and Transfer (CPST) project (~$400M technology demo in 6-7 years).
- ZBOT provides an instrumented test section with controllable BCs; velocimetry; and flow visualization, but with non-cryogen. CPST provides a scaled up demo using a real cryogen fluid with limited instrumentation. These two flight experiments are complimentary. Data from these experiments will be used to improve & validate numerical models enabling good scalability for future systems.

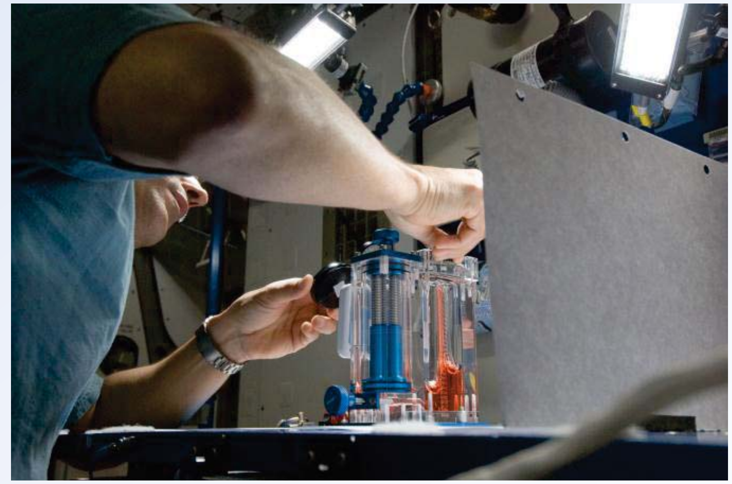


PI: Dr. Mohammad Kassemi, NCSER
Co-I: Dr. David Chato, NASA, GRC

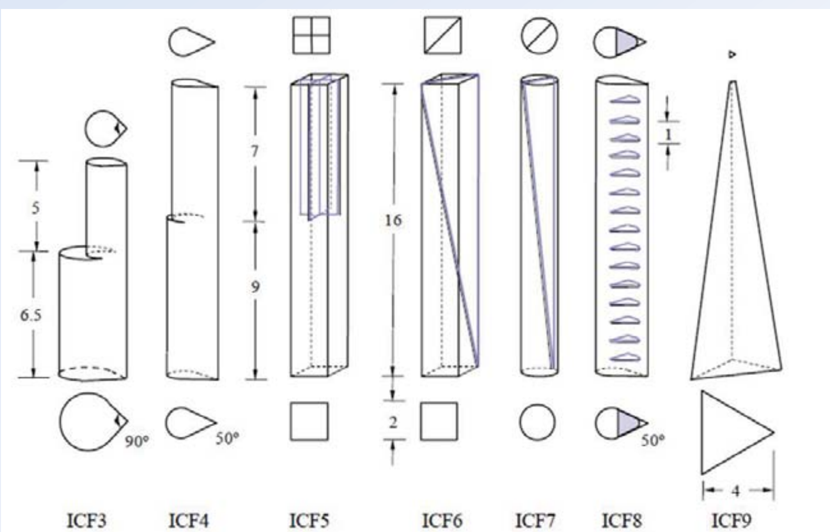
Capillary and Interfacial Phenomena

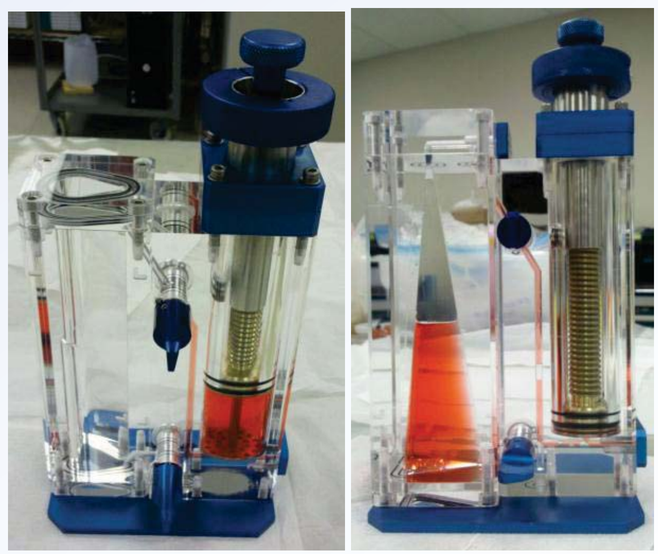
The **Capillary Flow Experiment (CFE 1&2) -2004 through 2013**

- Series of handheld test vessels with various test geometries to investigate the behavior of capillary flow phenomena in geometries found in capillary vanes, screens, and wicking structures.
- The results have applications in propellant storage & transfer, thermal control systems, and advanced life support systems for spacecraft.
- Critical wetting vane angles have been determined to within 0.5 degrees for Vane Gap 1 and 2 experiments.
- CFE-2 is investigating flow of fluids in interior corners and vane gap geometries: ICF4 & 9 on ISS, ICF3, 5-8 to follow.
- Recently published findings in J. Fluid Mechanics (2011).

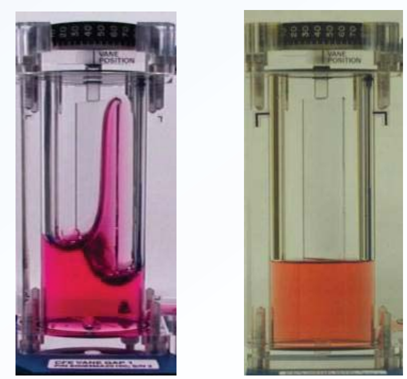


Astronaut Joe Acaba adjusting the vane angle during a recent CFE-2 Vane Gap 2 (VG2) experiment run on ISS (August 10, 2012)





Interior Corner Flow Modules (ICF4 and ICF9).



0-g *1-g*

45° vane angle

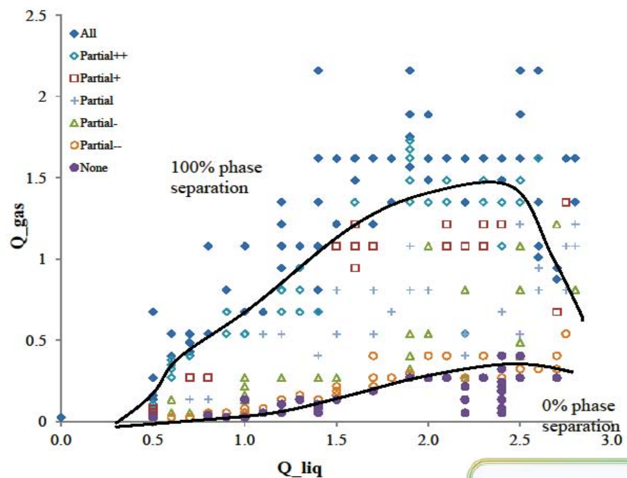
PI: Prof. Mark Weislogel, Portland State University… **“the microgravity scientist”**

Capillary and Interfacial Phenomena

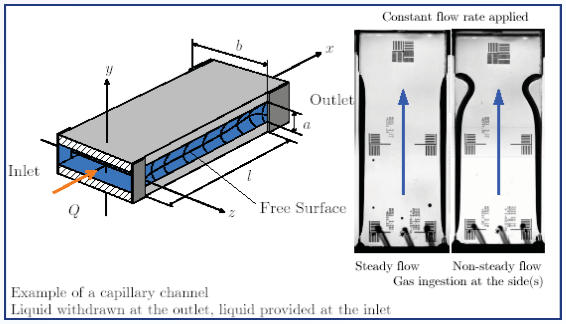
The **Capillary Channel Flow (CCF) Experiment – 2010 - 2013**

- Led by the German Space Agency (DLR) with a US/NASA Co-Investigator (M Weislogel, Portland State U.).
- Study of open channel capillary flow.
  - The cross section of the flow path is partly confined by free surfaces.
- Experiment has led to high fidelity models that accurately predict maximum flow rates for an open capillary channel.
- Research is critical to on-orbit fuel transfers and in space propulsion systems that utilize capillary vanes.
  - Current design of spacecraft fuel tanks rely on additional reservoirs (higher mass) to prevent the ingestion of gas into the engines during firing.
- CCF-3 scheduled to operate in early 2013.

Astronaut Scott Kelly installing CCF in MSG in Dec 2010.



Gas-Liquid Phase Separation Flow Regime Map

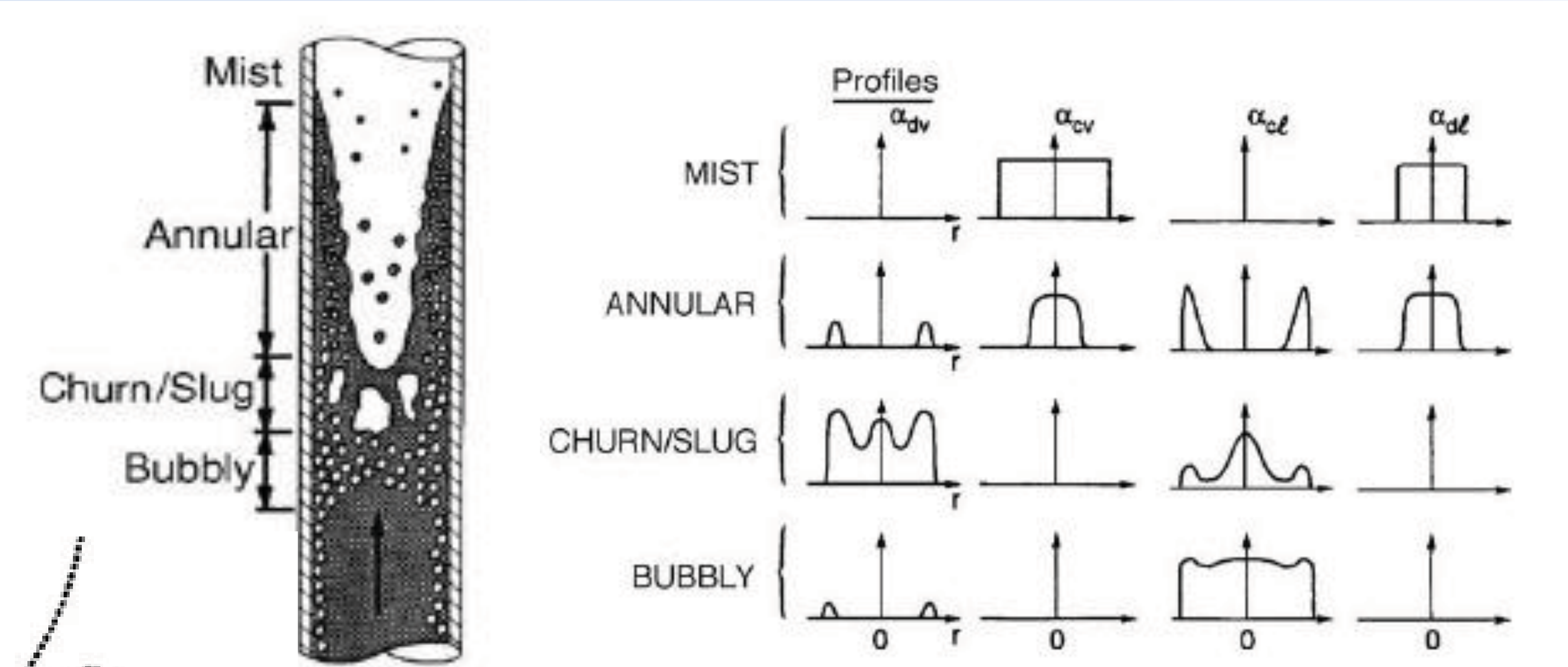


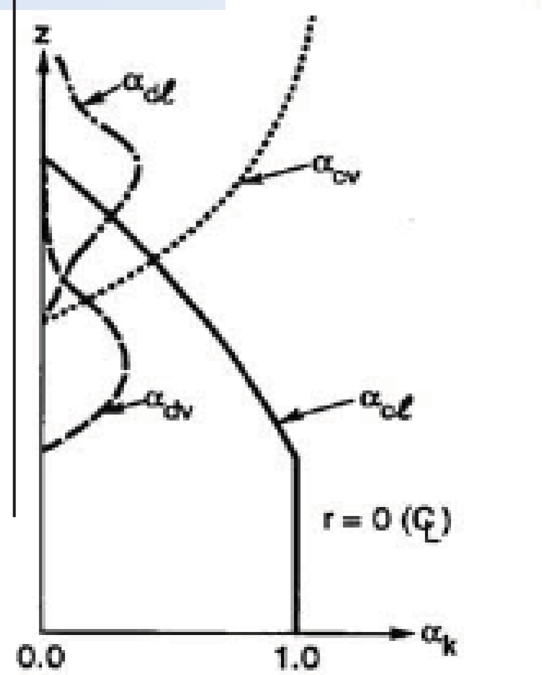
Capillary Channel Flow Test Unit (flat plate and groove geometries)

PI: Prof. Michael Dreyer, ZARM
US Co-I: Prof. Mark Weislogel, Portland State University

State of the Art in Two-Phase Flow

- Reasonably good (useful) models in two-phase flow have been developed for terrestrial applications such as nuclear reactors.
- Regardless of the particular situation, multiphase flows are generally complicated and to a large extend models are empirically based.
- However models developed for specific industries still provide a good starting point to motivate further research into model development for two-phase flows for low gravity applications.
- Still use simple models which include lumped parameter and one-dimensional models such as homogeneous equilibrium models, phase-slip models and drift-flux models.
- Computational Multiphase Fluid Dynamic (CMFD) models are also available such as the two-fluid, four-field model developed by Lahey and Drew [2001, 2005].
- CMFD models predict the velocity and pressure fields in each phase and the volumetric fractions of the continuous liquid and vapor fields and the dispersed liquid and vapor fields.
- CMFD models rely heavily on empiricism and experimental data is a vital source of input for such models.





Typical results of a 2-fluid, 4-field CMFD model [Lahey, 2005]

State of the Art in Two-Phase Flow

- Direct Numerical Simulation (DNS) can be used to provide input to CMFD type models, reducing (but not eliminating) the dependence of experiments, Lahey [2009].
  - DNS can be used to develop closure laws for two-fluid CMFD models.
  - Interfacial force densities in Momentum Eqn. (2), can be determined from the DNS results by partitioning the interfacial force density into "drag" and "non-drag" components (e.g., virtual mass, lift, and dispersion).

$$\mathbf{M}_{ij}^{(D)} = 0.125 \rho_{ij} C_D \left(v_{dv} - v_{cl} \right)$$

$$\mathbf{M}_{ij}^{ND} = \phi_{ij} \rho_{ij} \left[\frac{D_v \mathbf{v}_{jv}}{Dt} - \frac{D_l \mathbf{v}_{jl}}{Dt} \right] + \phi_{ij} \rho_{ij} C_L \left| \mathbf{v}_{dv} - \mathbf{v}_{cl} \right| \left(\mathbf{v}_{dv} - \mathbf{v}_{cl} \right) A_{Iij}'''$$

- DNS can be used to supplement the results of carefully chosen space experiments so that multi-phase flow models can be developed and applied to space systems to reduce the number and cost of experiments.
- **Has not been applied to 0-g two-phase flow yet.**

State of the Art in Two-Phase Flow

- The nature of low-gravity applications and limited access to the low-gravity environment creates unique difficulties in the creation of reliable predictive (CMFD) models.
- Integrating modeling and experiment provides a potentially productive approach, especially if DNS is included as a supplement to experiments.
- Unique opportunity exists for limited experiments on ISS in this decade to resolve microgravity two-phase flow challenges. These are critical to many areas of spaceflight (power, propulsion, life support, thermal control, etc.).
- There is also a strong need to simply build a quality database of operating parameters for the most common components particularly those that can either operate in a more efficient manner in 0-g or those that solve common anomalies faced in 0-g fluids systems that frequently bring an entire system off-line until it can be fixed or replaced.

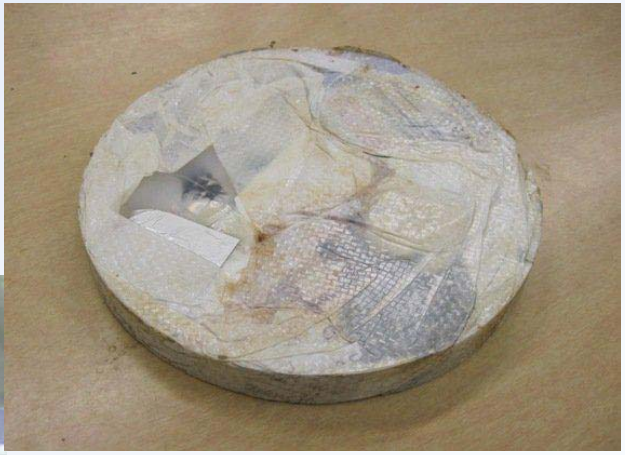
Horizontal pipe on Earth.

Aboard the Space Shuttle.

The radically different flow morphologies require different theoretical models in order to be able to predict these flows.

For example…

The Heat Melt Compactor Gen-3 will fly on ISS



Complex Fluids on ISS

Complex Fluids

- Colloids
- Liquid crystals
- Foams
- Granular flows

<u>Colloids and Rheology:</u>

- Physics of Colloids in Space (PCS)
- Binary Colloidal Alloy Test (BCAT) -3, -4, -5, -6
- Advanced Colloids Experiment (ACE) -1A, -1B, -2, -3
- Investigating Structures of Paramagnetic Aggregates from Colloidal Emulsions – 2/3 (InSPACE-2/3)
- Shear History Extensional Rheology Experiment I, II (SHERE I, II)

<u>Liquid Crystals:</u>

- Observation and Analysis of Smectic Islands in Space (OASIS)

<u>Foams:</u>

- Foam Optics And Mechanics (FOAM)
- Particle STAbilised Emulsions and Foams (PASTA)

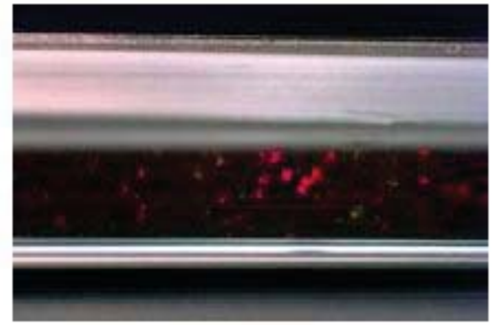
<u>Granular Flows:</u>

- Compaction and Sound in Granular Matter (COMPGRAN)

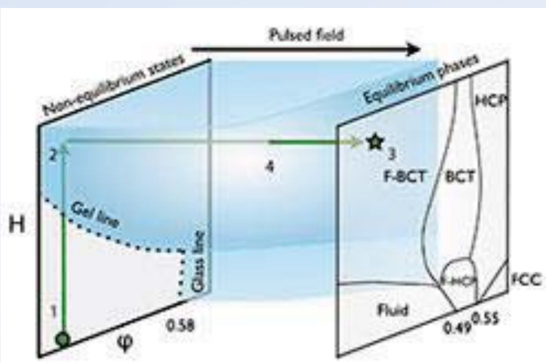
Colloids & Rheology

In microgravity, you can…

- Gain insight into many diverse fields (phase transitions, nucleation and growth of crystals, glass formation, etc.
- Understand processes such as phase separation rates to develop underlying theory for predicting product shelf life (P&G).
- See and control how structures form – colloidal engineering.
- Study self replication, develop nano-pumps.
- Create lock-and-key reactions – building blocks for colloidal self-assembly.
- Eliminate sedimentation to study true effects of other forces.

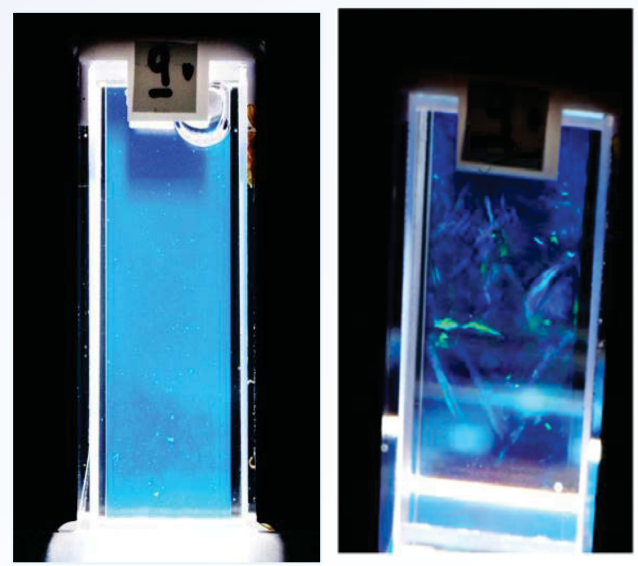


Colloidal dendrites



Directing nano-building blocks to self-assemble (InSPACE-2)

Particle aggregation of fluid (InSPACE-3 - 11/16/12)



1-g 0-g
Colloidal glass (BCAT)

Soft Condensed Materials (Colloids)

"NASA realized the important role of microgravity research when the field of complex fluids was in its infancy. Within the complex fluids community, NASA's fostering of this developing area is well acknowledged. For almost two decades, important discoveries in the field were reported at the annual NASA complex fluids meeting…"

"For example, between 1998 and 2000, the research sponsored by the program produced several hundred papers that were published in internationally recognized journals. Of these papers, more than 120 were published in the Journal of Fluid Mechanics and Physics of Fluids, two prominent journals for fluid dynamics; 44 in Physical Review Letters, a leading physics journal; 8 in Nature; and 7 in Science, the last 2 of which are among the most prestigious scientific journals in the world. This new field has developed into an important research area of physics and materials science and is now found in the science departments of every major university in the world. Complex fluids and soft matter are a key component of the microgravity research of space agencies internationally."

Committee for the Decadal Survey on Biological and Physical Sciences in Space; National Research Council, 2011

Soft Condensed Materials (Colloids) – PI Teams

Project Scientist: Dr. William Meyer, NCSER

PCS:
PI: David A. Weitz, Harvard University
Co-I: Prof. Peter N. Pusey, University of Edinburgh
PI: Prof. Paul Chaikin, Princeton University

BCAT-3/4:
PI: Prof. David Weitz and Co-I: Dr. Peter Lu, Harvard
PI: Prof. Paul Chaikin, NYU
Co-I: Dr. Andrew Hollingsworth, NYU
PIs: Prof. Barbara Frisken / Dr. Arthur Bailey, Simon Fraser University / Canadian Space Agency (CSA)

BCAT-5:
PI: Dr. Matthew Lynch and Tom Kodger, Proctor and Gamble (P&G)
PI: Prof. David Weitz and Co-I: Dr. Peter Lu, Harvard University
PI: Prof. Barbara Frisken and Co-I: Dr. Arthur Bailey, Simon Fraser University / Canadian Space Agency (CSA)
PI: Prof. Paul Chaikin and Co-I: Dr. Andrew Hollingsworth, NYU
PI: Prof. Arjun Yodh and Peter Yunker, U. Penn.

BCAT-6:
Dr. Matthew Lynch and Tom Kodger, Procter & Gamble (P&G)
Prof. David Weitz and Dr. Peter Lu, Harvard University
Prof. Paul Chaikin and Dr. Andrew Hollingsworth, NYU
Prof. Arjun Yodh and Peter Yunker, UPenn

ACE:
PIs: Paul Chaikin (NYU, US), David Weitz (Harvard, US), Arjun Yodh (U. Penn, US); Matthew Lynch (P&G); Stefano Buzzaccaro, Roberto Piazza (U. Milano, I); Luca Cipelletti (U. Montpellier, F); Peter Schall, Sandra Veen, Gerard Wegdam / Marco Potenza (U. Amsterdam, NL / U. Milano, I); Chang-Soo Lee (CNU, S. Korea)

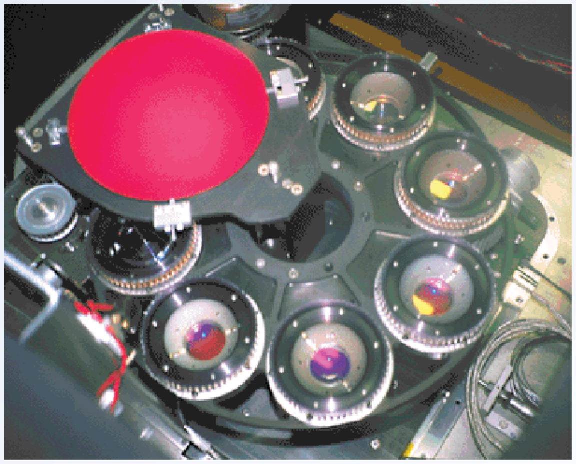
Soft Condensed Materials (Colloids)

The **Physics of Colloids in Space (PCS) - 2001**

- The experiment enabled scientists to monitor colloidal suspensions using:
  - –Dynamic and Static Light Scattering.
  - –Bragg and Low Angle Scattering.
  - –Imaging over longer time periods.
- Designed to study the phase behavior, growth dynamics, morphology, and mechanical properties of different types of colloidal suspensions.
- Many basic questions about phase diagrams, thermodynamic stability, and phase transformation kinetics were answered.
- Detailed information about the structure and properties of fractal aggregates was obtained over a much wider range of measurement with more relevant conditions than possible on earth.

The **Binary Colloidal Alloy Tests (BCAT-3/4/5/6) - 2003 to 2012**

- Each is a set of notebook sized investigations – 10 samples each.
- BCAT-3/4 significantly advanced understanding in critical point behavior of fluids, binary alloys, and surface crystallization.
- BCAT-5 studied phase separation kinetics, phase separation competing with crystallization, how seed particle size and concentration effect crystal growth in microgravity, and seeing temperature controlled melting and crystallization.



PCS Samples

Astronaut Bill McArthur photographing BCAT samples

BCAT-5 Slow Growth Sample Module

Soft Condensed Materials (Colloids)

The **Binary Colloidal Alloy Tests (continued)**

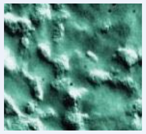
- BCAT-6 continues with studies on aging of gels and late collapse, wall seed initiated crystals in the absence of gravitational jamming, non-biological self-assembly with DNA, and 3D crystallization of disks, growth and melting.

The **Advanced Colloids Experiments (ACE)- 2012 - 2020**

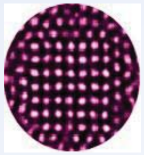
- Just launched this year to continue advancing our understanding in extending product shelf life, colloidal engineering, self-assembly, non-biological self-replication, etc.
- Microscope features a range of magnifications up to 100x magnification (oil coupled objectives).
- In 2016 a confocal head and camera will be added to enable 3-D imaging.
- ACE will consist of 5 test themes with features including the following modules: Standard, Heating, Temperature Gradient, Electric Field, and ultimately confocal microscopy for all modules.

In Summary:

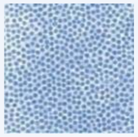
- The Microgravity Soft-Condensed Matter Research Program has already led to many scientific breakthroughs and discoveries.
- The ISS provides the unique opportunity to study the long duration dynamics of colloidal systems free from the effects of gravity – which causes sedimentation, jamming, convection, etc.
- New Complex Fluids NRA to be released very soon.



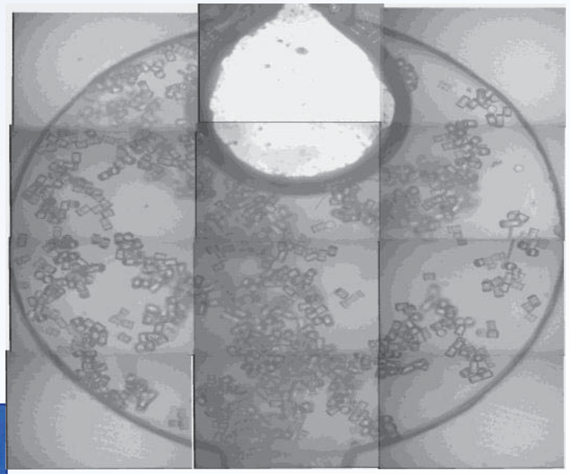
Weitz: Colloidal engineering



Chaikin: Order and patterns



Yodh: Melting and crystallization



ACE-1 Janus particles which form unique 3-d structures on ISS in 0-g from Prof. Chang-Soo Lee, CNU (South Korea)

BCAT-6 Slow Growth Sample Module

Rheology & Morphology of Complex Fluids

PI: Prof Eric Furst, U. of Delaware
Prof. A. Gast, MIT/Lehigh U. (InSPACE-1)

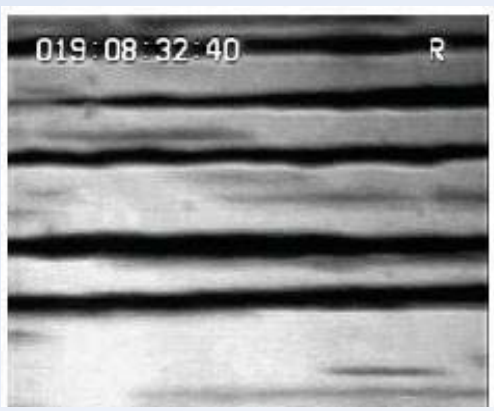
Investigating the Structures of Paramagnetic Aggregates from Colloidal Emulsions-3 (InSPACE-2/3) – 2002 to 2012

- Launched in 2002 with the goal of determining the true 3-D low-energy (equilibrium) structure of an Magneto-rheological (MR) fluid while under DC and pulsed magnetic fields.
- Applications for limb and dextrous motion in robotic components, human-robotic interfaces for EVA suits, improved active damping systems for bridges and buildings (earthquake damage).
- -2 observed a regime of buckling instability in the 3-D structures.
- -3 is currently installed in the MSG on the ISS and will investigate the effect of non-spherical super-paramagnetic particles on the kinetics and formation of these aggregate structures that affect the visco-elastic properties of MR fluids. Operations are currently underway.
- Published findings in Proceedings of the National Academy of Sciences (2012)

The **Shear History Extensional Rheology Experiment (SHERE II) - 2007 to 2011**

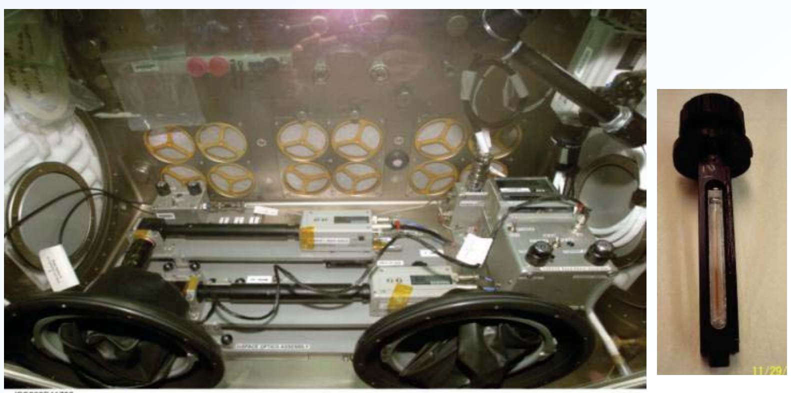
PI: Prof. Gareth McKinley, MIT

- The SHERE hardware was designed to study the effects of pre-shearing by rotation on a polymer fluid while it is being stretched (elongated). In many industrial polymer processing operations the material experiences a complex flow History with both shear and extensional characteristics.
- SHERE II extended the studies by adding a rigid inert filler to change the fluid properties.



InSPACE-2 MR fluid microstructure chain in a 2 Hz pulsed magnetic field

Astronaut Mike Fincke in front of SHERE hardware in MSG

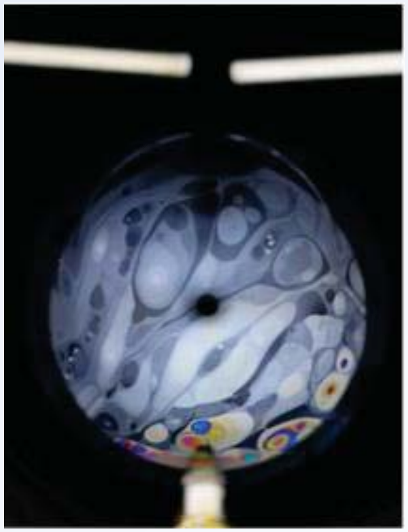


InSPACE in MSG with Vial Assembly containing MR fluid on right

Liquid Crystals

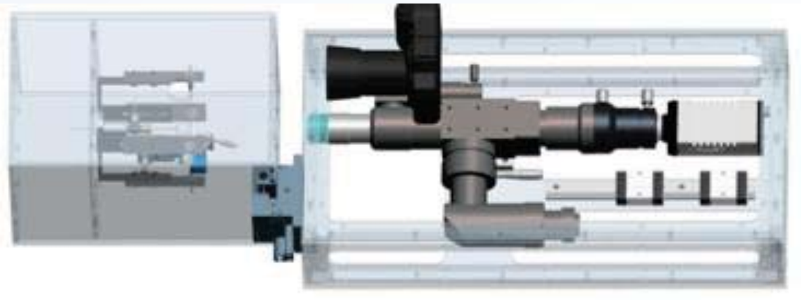
Observation and Analysis of Smectic Islands in Space (OASIS) - 2014

- Will use 0-g to study the interfacial and hydrodynamic behavior of freely suspended liquid crystals.
- Specifically it will study basic 2D hydrodynamics/fluid physics, probe droplet/island diffusion, hydrodynamic interactions, and droplet/island coalescence.
- Has application for ferroelectric liquid crystal micro-displays and very high speed electro-optic devices.
- OASIS will consist of 4 modules that will support; freely suspended bubble film formation; pico liter droplet injection; external E field perturbation; and dynamic bubble oscillations.
- Recently completed 0-g aircraft tests (ESA) - testing a bubble inflation system in microgravity as well Pressure Quenching and Pulsation; Thermocapillary; Inkjet Droplet Device; Air Jets; and E-Field.



2012 Parabolic Flight showing liquid crystal bubble and islands

PI: Prof. Noel Clark, University of Colorado, Boulder



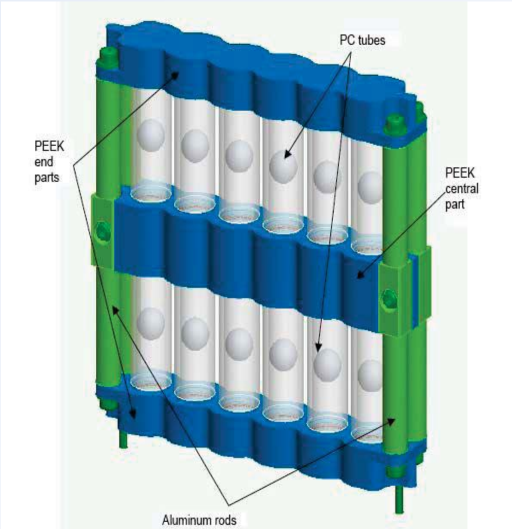
Micro Observation and Illumination Assembly

Foams

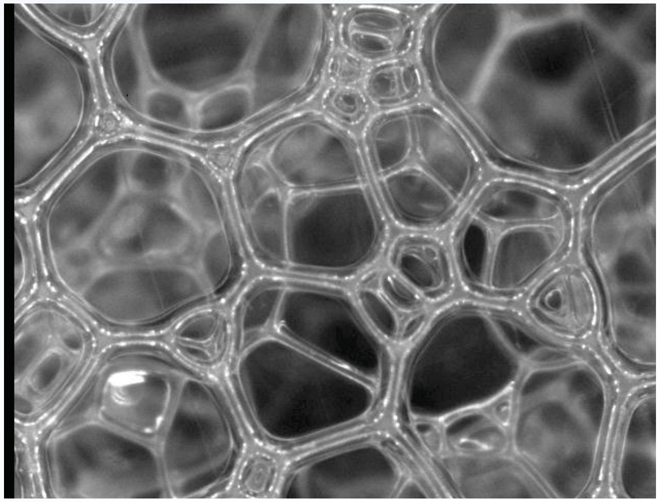
ESA funded: **Foam Optics And Mechanics (FOAM) – 2013 (for US PI)**

- ESA will develop all hardware and use the Fluids Science Lab (FSL).
- Studies to develop materials (foams) with more a desirable rheology and better stability.
- Microgravity eliminates draining.
- On board rheometry and light scattering techniques will provide the rheology and coarsening in terms of microscopic structure and dynamics.
- US PI will study issues related to the FOAM C (Foam Coarsening) experiment and assisting the development of a spectroscopic system for the FOAM optical hardware system.

PI: Prof. Douglas Durian, Univ. of Pennsylvania



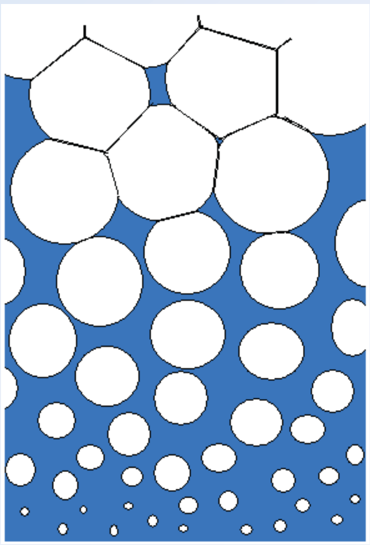
FOAM Stability Test cells



Foams

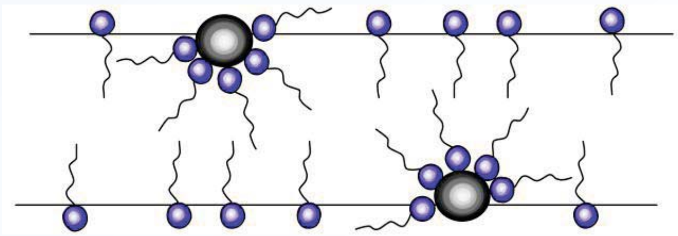
ESA funded: **PArticle STAbilised Emulsions and Foams (PASTA) – 2013 (for US PI)**

- Will study foams and emulsions forming and stabilizing.
- Collaborative research effort of all PIs from 14 institutions from 10 countries, multiple flight experiments of "PASTA" using existing hardware.
- US PI will participate in LIFT (Liquid Film Tensiometer) under development by Italian Space Agency for to study the single bubble interface laden with particles or polymers.
- Microgravity conditions facilitate mechanistic determination of foam destabilization by elimination of draining. Additionally sedimentation is also attenuated, which allows decoupling of the adsorption of monomeric and aggregated particles.
- Goal is to tune the stabilizing or destabilizing action of a particle/surfactant system, depending on the demands of a respective application.



Inhomogeneity in a foam or emulsion due to drainage in normal gravity

PI: Prof. James Ferri, Lafayette College,
ESA PI, Team Coordinator: Dr. Reinhard Miller, Max Planck Institute of Colloids and Interfaces & 14 P.Is (Germany, France, Italy, U.K., Switzerland, Russian Federation, Canada, Spain, Greece)



Liquid film stabilized by a particle-surfactant mixture. Film is stable only if the respective adsorption layers exist.

Granular Flows

ESA funded: **Compaction and Sound in Granular Matter (COMPGRAN) – 2013**

- Will quantify the random packing characteristics near the jamming transition of granular materials.
- Will measure the transmission of sound during the various packing configurations.
- Will observe the 3D stress field in compacted granular systems.
- Need to collect empirical data on non-gravitational forces in granular flows.
- Develop and test hardware and analysis tools for experiments using sound measurements and 3D stress-birefringence visualization. This more broadly enables advanced instrumentation for many granular physics experiments.
- US PI recently completed initial levitation experiments for 2D photoelastic studies.

PI: Prof. Robert P. Behringer, Duke University
ESA PIs: Matthias Sperl (DE), Eric Clement (FR), Stefan Luding (NL), Matthias Schroeter (DE)

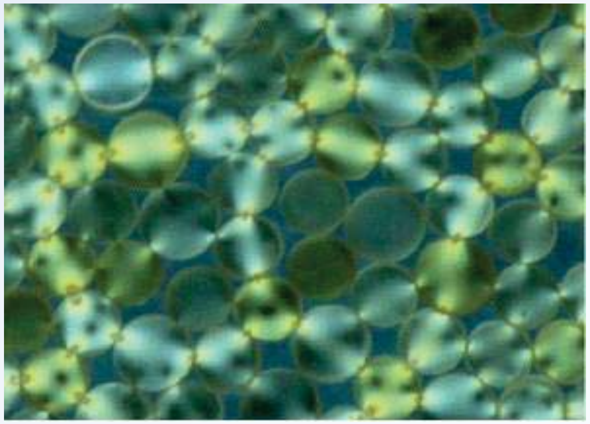


Image of birefringent particles under stress

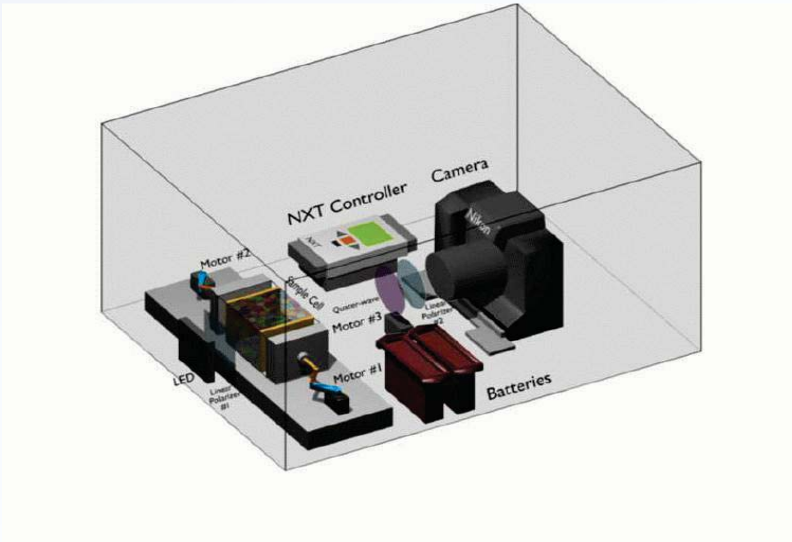


Figure 7: *Setup for 3D stress-birefringence that was flown on-board DLR PFC-13.*

Possible Future work in Colloids

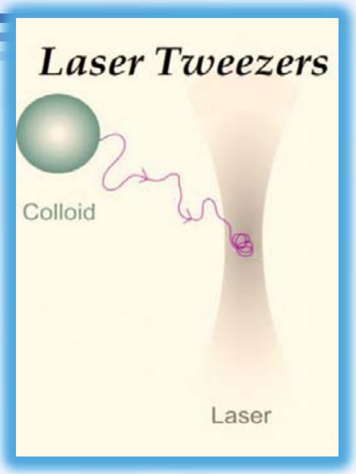
Add capabilities to the existing ACE hardware.

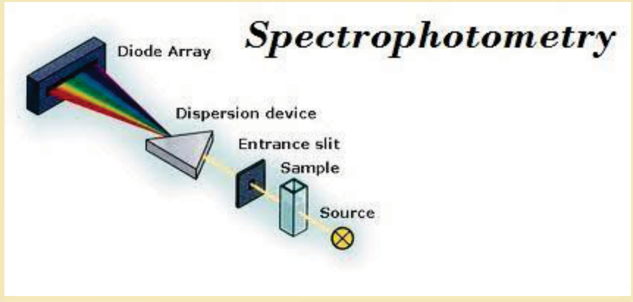
- Add COTS holographic laser tweezers to the ACE microscope. This is a significant enhancement.
  1. This enables individual particle control and characterization. Introduce individual defects and see and understand how nature heals.
  2. Laser tweezers also allow cluster manipulation for growing ordered structures from patterned layers whose spacing can now be controlled. This is for seeing how to best coax a structure or pattern to realize a needed technology, *e.g.*, photonic crystals.

- Add Piezo-microscope stage stabilization or very fine stage position marking and recording. Dynamic feedback or position recording will "cancel" vibration effects to ensure that each 2-D image is in the same X-Y position as those above it and below it.

- Add spectrometry capabilities for quantifying new colloidal crystals and their growth rates. The more quantitative the data the better the science. And the decision for the next experiment can be made in "real-time".

- Plan to add (already approved) new cameras and support electronics for frames rate of up to 60 second (fps) when observing 3-D confocal images, instead of the present 7 fps. Allows more experiments and the ability to complete the same experiment (when taking 3-D stacks of data).





Possible Future work in Granular Flows

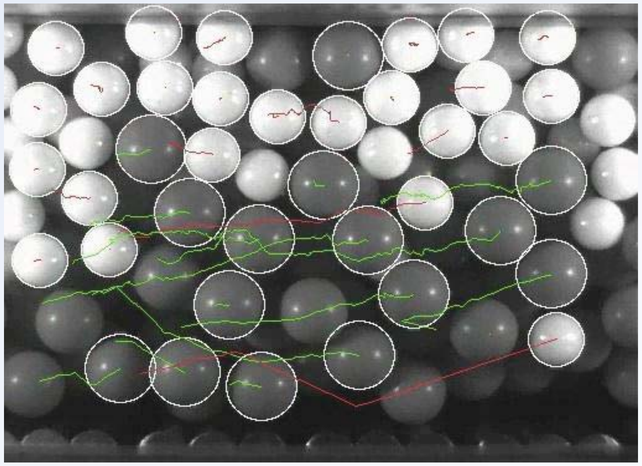
Initiate a Granular Materials test capability on ISS.

- Granular mechanics and flows arise in a wide range of Industries ($1 trillion/year) Pharmaceutical, Food, Chemical, Detergents, Agricultural, Metallurgy, Plastics, Cement, Mining, etc.
- Excavation and operations on Planetary surfaces will fail without some predictive capability (almost none exists today).
- Experiments in 0-g constitute archival data against which to test theories and improve models of inter-particle contacts and fluid particle interactions by isolating and understanding the non-gravitational forces and eliminating density-gradients.
  - Need to study both static (jammed) and dynamic (flowing) states.
- Also critical to water/ice extraction, dust mitigation, etc.
- Excellent area for Industry/Government collaboration.

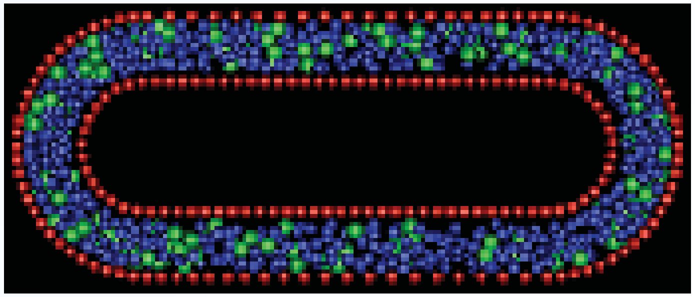
Potential Applications:

- Earthquake engineering
- Soil mechanics and foundation engineering
- Planetary vehicle engineering
- Powder technology
- Terrestrial and Planetary geology
- Mars exploration
- Erosion processes

Jamming in 1-g



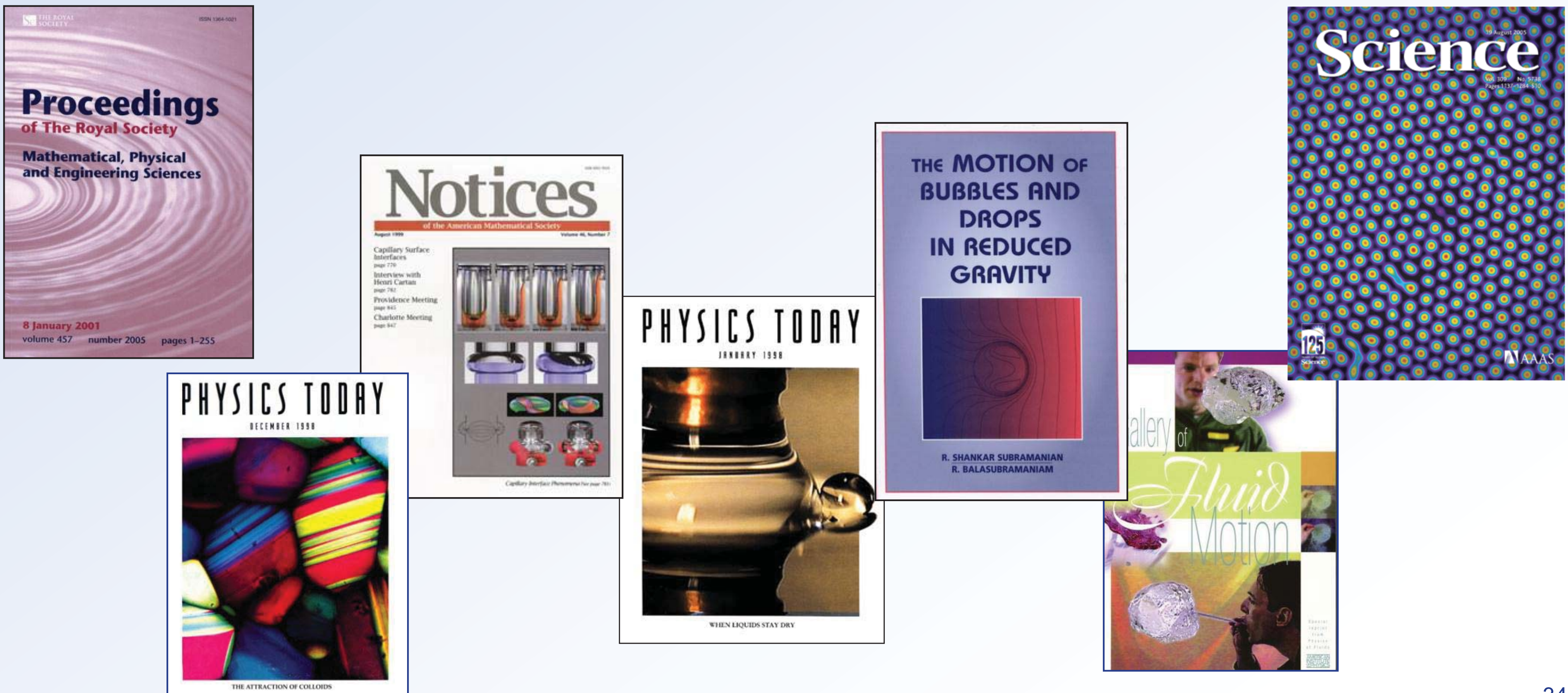
Collisional Segregation in 0-g



Study of granular particles size segregation driven by mechanisms other than gravity in a binary mixture (green/blue) of spheres

Conclusion

- There are many areas in microgravity fluids that have provided new and important insights for over 60 years… and much more to come!
- NASA and our International Partners have made large investments in the ISS and experimental hardware, but time is short and budgets are limited…
- Develop "guided" research groups in areas such as:
  - Multiphase Flows; Flow Boiling; Colloids; Granular Flows; Dynamics and Instabilities, Interfacial Phenomena, etc.



Backup charts

- 2-Fluid, 4-Field CFMD models have the form:

$$\frac{\partial \phi_{ij}\rho_j}{\partial t} + \nabla \cdot \left(\phi_{ij}\rho_j \mathbf{v}_{ij} \right) = \Gamma_{ij} + \dot{m}_{ij}''' \ , \qquad (1)$$

$$\frac{\partial\left(\phi_{ij}\rho_j \mathbf{v}_{ij} \right)}{\partial t} + \nabla \cdot \left(\phi_{ij}\rho_j \mathbf{v}_{ij}\mathbf{v}_{ij} \right) + \nabla\left(\phi_{ij} p_j \right) - \nabla \cdot \left(\phi_{ij}\left[\mathbf{T}_{ij} + \mathbf{T}_{ij}^{T} \right]\right) \qquad (2)$$

$$- \phi_{ij}\rho_k \mathbf{g} - \mathbf{M}_{ij} - \mathbf{M}_{ij}^{W} = \Gamma_{ij}\mathbf{v}_k + \dot{m}_{ij}''' \mathbf{v}_{\tilde{ij}} \ ,$$

$$\frac{\partial\left(\phi_{ij}\rho_j h_{ij} \right)}{\partial t} + \nabla \cdot \left(\phi_{ij}\rho_j \mathbf{v}_{ij} h_{ij} \right) + \nabla\cdot\left(\phi_{ij}\rho_j \mathbf{v}_{ij} h_{ij} \right) - \nabla \cdot \left(\phi_{ij}\left[\mathbf{q}_{ij}'' + \mathbf{q}_{ij}''^{T} \right]\right) \qquad (3)$$

$$-D_{ij} - \phi_{ij} q_{ij}''' - \frac{Dp_{ij}}{Dt} - q_{Iij}'' A_I''' = \Gamma_{ij} u_{Iij} + \dot{m}_{ij}''' u_{\tilde{ij}}$$