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Light Scattering for Complex Fluids Research on ISS: Investigator Dreams and Anticipated Hardware Development

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LIGHT SCATTERING FOR COMPLEX FLUIDS RESEARCH ON ISS: INVESTIGATOR DREAMS AND ANTICIPATED HARDWARE DEVELOPMENT

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ABSTRACT

The objective of this paper is to give an overview of a suite of microgravity complex fluids experiments utilizing laser light scattering as the primary diagnostic tool which NASA's Lewis Research Center is preparing to conduct on-board the International Space Station during the first decade of the next millennium, while acknowledging the heritage in microgravity light scattering that provides some of the basis for these experiments.

Since 1991 the definition, conceptualization, and development of flight-worthy light scattering instrumentation at the Lewis Research Center has been in full swing. To date, partial science returns for two complex fluids investigators from space flights of light scattering instrumentation have already been achieved. As the 1990s progressed, proposals for at least three other complex fluids investigators that were selected by NASA, based upon their scientific value and merit. These three additional investigators, along with the original two for whom a remaining portion of their science is still to be flown, make up a queue of investigators requiring complex state-of-the-art imaging and light scattering extended-microgravity instrumentation.

This paper will broadly describe the experiment objectives of these five complex-fluid Principal Investigators who are currently funded under NASA's microgravity fluid physics flight program, provide top level development schedules and timing for the flight projects supporting these experiments, and present details of the current flight concepts and planned flight instrumentation development.

*Member, AIAA.

INTRODUCTION

Beginning with two proposals in 1991 from academia in response to NASA Research Announcement NRA-91-OSSA-17, the definition, conceptualization, and development of flight-worthy light scattering instrumentation at the Lewis Research Center (LeRC) has been under way. The development originated from an Advanced Technology Development (ATD) for a Laser Light Scattering Instrument.[1,2]

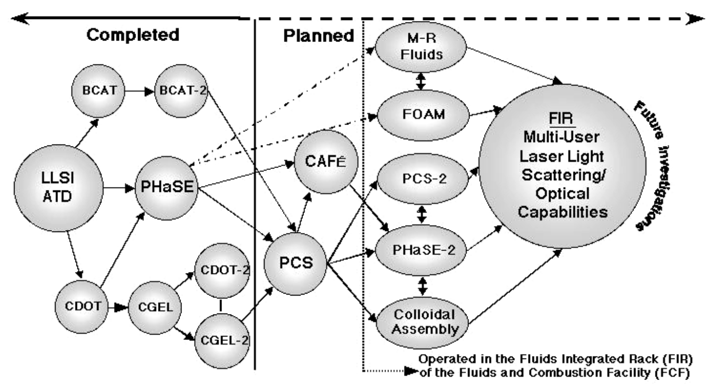

Figure 1: Evolution of Laser Light Scattering Instrumentation

Figure 1 depicts the evolution of light scattering flight instrumentation and its application to multiple flight experiments. The first science returns from this type of instrumentation, realized in the 1990's, include data gathered via the Colloidal Disorder Order Transition (CDOT) and CDOT-2 glovebox investigations, and the Physics of Hard Spheres Experiment (PHaSE) Spacelab experiment for Prof. Paul M. Chaikin (Princeton University) as well as the Binary Colloid Alloy Test (BCAT), BCAT-2, Colloidal GELation (CGEL), and CGEL-2 glovebox investigations for Prof. David A. Weitz (University of Pennsylvania). For both investigators, the area of study has involved utilization of colloidal suspensions comprised of hard polymethylmethacrylate (PMMA) spheres whose sole interaction potential is governed by repulsive particle forces. The purpose of these experiments was to investigate the physics of nucleation, growth, and structure determination of colloidal (both single-diameter particle and binary) systems, with a primary goal of understanding the physics of the liquid-to-solid phase transition. In both cases, due to demands on overall experiment complexity and the requirement to gain early science on existent carriers, the light scattering investigations that have flown to date have addressed only a subset of the total proposed science.

On board the International Space Station (ISS), LeRC intends to conduct the balance of Professor Chaikin's and Professor Weitz' science. Paul Chaikin's specific focus is to observe the effect that certain key hard sphere parametric conditions have on the solid-liquid equilibrium phase diagram, and how colloidal systems respond to a variety of applied fields which may force them into non-equilibrium configurations or help them order differently prior to growth. David Weitz' area of study is to promote/ understand the growth of novel colloidal structures to support a newly conceived discipline of "colloidal engineering".

In recent years three more investigators, Arjun G. Yodh (University of Pennsylvania), Douglas J. Durian (University of California at Los Angeles), and Jing Liu (California State University, Long Beach) have been selected for the fluid physics flight definition program. For Prof. Yodh, the area of study is colloidal assembly in entropically driven low-volume-fraction binary colloids. His science is similar to Prof. Chaikin's and Prof. Weitz', but all of his colloidal systems are governed by attractive particle interactions, not repulsive ones. Prof. Durian's area of study is aqueous foam rheology and stability in terms of underlying bubble-scale structure and dynamics. Foams, being a collection of polydisperse gas bubbles packed in a smaller amount of water containing surfactants, have much in common with emulsions and colloidal systems and can be studied by similar diagnostic approaches, including light scattering. Prof. Liu's area of study is to experimentally investigate the non-equilibrium pattern formations and phase transitions in magnetorheological (MR) fluids. MR fluids are colloidal suspensions in which an external magnetic field induces a dipole moment in each colloidal particle. Each of these three investigators also requires microgravity light scattering instrumentation.

Thus, there are at least five complex fluids Principal Investigators (PIs) presently supported by LeRC who plan to conduct future light scattering experiments on ISS. Microgravity research platform options which are available to them include the Physics of Colloids in Space Apparatus (PCSA) being developed for use in the Expedite the PRocessing of Experiments to Space Station (ExPRESS) Rack,[3] the Microgravity Science Glovebox (MSG),[4] and the Fluids and Combustion Facility's[5] Fluids Integrated Rack (FCF-FIR). All three platforms appear able to accommodate one or more of these five complex-fluids PIs. Extended periods of microgravity are needed for these investigations because these complex fluids, by nature, have large density differences between constituents (particle/ fluid for colloidal suspension, gas/ liquid for foam, etc.). Eliminating the driver for sedimentation and drainage for an extended period of time unmasks the fundamental processes to be studied (e.g., colloidal crystal growth, gel phase separation, or foam coarsening) over the timescales (days, weeks) at which these processes occur.

A basic description of light scattering involves an incident beam of electromagnetic radiation impinging on a scattering medium (e.g., complex fluid), with most of the radiation continuing in its original direction but with a small portion being scattered in other directions.[6] This scattered light, gathered by cameras or photodetectors, reveals information about the scattering medium itself, such as particle (or bubble) size, particle polydispersity, particle spacing, diffusion coefficients, as well as properties of the bulk aggregate. A light scattering instrument then consists essentially of one or more sources of electromagnetic radiation and one or more cameras or photodetectors.

Complex fluids include colloidal suspensions, gels, magnetorheological fluids, foams, and granular systems. Studies of colloidal suspensions, commonly referred to simply as colloids,[7] promise a more complete understanding of phase transitions, as well as offering to provide the basis for the design and synthesis of a new and better materials. Such materials might be those ordered on the length scale of light in all three dimensions, with fascinating new properties to potentially make them suitable for optical switches or filters, or as photonic band gap structures. Foams, having a solid-like elastic character but still being able to flow under shear, are of great scientific interest to us and an increase in our understanding of the physical origin of their unusual rheology should help improve the way foams are used in our everyday lives. In magnetorheological fluids, controlling rheology induced by a magnetic field has many potential applications, from shock absorbers and clutch controls to robotic joint controls.

This paper will sequentially describe the experiment objectives of each of the five complex-fluid PIs while giving as much background as deemed important to help grasp the basic science concepts, provide a broad overview of the timing and schedule for these experiments, and present details of the current flight concepts and planned flight instrumentation development.

EXPERIMENT OBJECTIVES OF THE FIVE PRINCIPAL INVESTIGATORS

Experiment Objectives of Paul M. Chaikin

Professor Paul M. Chaikin and Professor William B. Russel (both of Princeton University) proposed the *Dynamics of Hard Sphere Colloidal Dispersions* in response to NRA 91-OSSA-17. The essence of their proposal is to gain a complete understanding of the hard sphere system, its dynamics and transitions.

Hard sphere systems,[8,9] in particular colloidal suspensions of monodisperse spheres that cannot penetrate each other and do not otherwise interact, share a fundamental characteristic with atomic systems - both undergo a transition from a disordered liquid state to an ordered solid state under the proper conditions, such as when water molecules become ordered to form ice. Atomic interactions are very complex, with much more still to be learned. One powerful approach to the study of phase transitions is to investigate systems of simpler, larger particles that behave in a manner similar to the atomic system. These investigators from Princeton use colloidal suspensions of microscopic PMMA spheres that are capable of being probed using visible light.

To date, Chaikin and Russel have already participated in three flights to achieve early, broad results as well as to conduct light scattering studies at a macroscopic level. The CDOT glovebox investigation flew in October 1995, PHaSE flew in July 1997, and CDOT-2 flew in October 1998. Each of these experiments yielded significant results, beginning with CDOT.[10,11,12] Under CDOT large dendritic crystallites grew in samples which, on Earth, produce a sediment of much smaller crystallites. In addition, a sample which was glassy on Earth actually crystallized in microgravity, a completely unexpected result. For PHaSE,[13] significantly high fidelity measurements of the kinetics of nucleation and growth as well as the elastic modulus of the solid phase were made. These high fidelity measurements were successfully performed on samples having volume fractions (i.e., the fraction of the total sample volume actually filled by the spheres) of $ø = 0.528$, 0.552, 0.575, all either within the coexistence or crystalline regions of the hard sphere phase diagram.[14] Because of gas bubbles in four of eight sample cells and flare, which obscured the Low Angle scattering measurements, only a portion of the PHaSE science was accomplished.[15]

For Chaikin and Russel's experiment opportunities upcoming on ISS, the objectives of the experiments are to carry out further investigation of critical fundamental questions in colloid science including nucleation, growth, structure, dynamics, and rheology of colloidal crystals, to observe the effect that certain key hard sphere parametric conditions have on the equilibrium phase diagram, and to investigate how colloidal systems respond to a variety of applied fields which may force them into non-equilibrium configurations or help them order. In order to achieve the remaining science of Chaikin and Russel's proposal, two different instrument systems are required. First, a large volume sample with associated imaging and light scattering instrumentation is required to enable macroscopic (bulk) investigations for nucleation and growth, dynamics, and structure. Second, a thin cell sample with associated light microscope, laser and light scattering instrumentation, and laser tweezers is needed to perform microscopic investigations for particle level characterization and manipulation. To conduct the large volume sample investigation, an instrument similar to what was flown for PHaSE is currently in development in the

Physics of Colloids in Space Apparatus (PCSA) to be flown in ExPRESS Rack. For the thin cell samples, a new microscope-based system – the Light Microscopy Module, to be flown on the Fluids and Combustion Facility Fluids Integrated Rack (FCF-FIR) - is intended to provide for particle level characterization.

In utilizing a flight within the Physics of Colloids in Space Apparatus, Chaikin and Russel will continue the investigations they initiated with PHaSE on MSL-1, further exploring the phase diagram with the use of samples of different volume fractions. The name of this experiment is the Colloid Augmentation Flight Experiment (CAFÉ).

Using the microscope-based system, Chaikin and Russel subsequently plan to utilize video microscopy[16] (and limited light scattering) to observe nucleation, growth, dynamics, and structure of colloidal crystals, and will investigate how colloidal systems respond to a variety of applied fields which may force them into non-equilibrium configurations or help them order. Specifically, they intend to: a) determine the volume fractions at which a fluid changes to a crystal, b) find the crystal structure of the equilibrium solid phase, c) contrast nucleation and growth in gravity and microgravity, especially in the region of the ground-based glass transition (which they have found does not occur in microgravity), d) quantitatively test the dendritic growth model, e) explore the role of polydispersity on the phase diagram and the structure of the different phases, and f) explore the susceptibilities to external fields and the microrheology of the different phases. The current title of this experiment is PHaSE-2 in the Light Microscopy Module (LMM).

Experiment Objectives of David A. Weitz

Professor David A. Weitz (University of Pennsylvania) and Professor Peter N. Pusey (University of Edinburgh) proposed *Colloidal Physics in Microgravity* in response to NRA 91-OSSA-17. The essence of their proposal is to study the formation of novel materials from three kinds of colloidal suspensions, and to explore their physical properties. The three kinds of colloidal suspensions are: binary colloidal alloys, colloid polymer gels, and fractal aggregates.

The binary colloidal alloys are made up of sub-micron PMMA spheres suspended in a liquid. The spheres are the same acrylic type particle used to date in the Chaikin and Russel investigations, but in the case of binary alloys, two different sized spheres are dispersed in the liquid. Under certain conditions, it has been found that binary dispersions at size ratio r=0.58 form both the AB_2 and the AB_{13} superlattice structures. AB_2 consists of a simple hexagonal arrangement of large A particles, with the smaller B particles filling all the interstices between the A layers, while in AB_{13}, icosahedral clusters of 13 small B particles are body centered in a simple cubic lattice of A particles. Weitz and Pusey believe that someday these binary colloidal systems may become useful in communications technologies as optical filters or displays. Colloidal polymers are similar to binary colloidal alloys but with spherical acrylic particles of one size and a chainlike polymer particle added to the colloidal suspension. Polymers are often added to colloids to control their properties and adjust their behavior. In paint, polymers control the way the paint spreads across a surface. Weitz and Pusey are studying these colloidal structures with the hope of learning how they form, how stable they are, and how strong they are. Fractal aggregates are structures formed from colloidal particles where the basic structural shape of any one part is similar to the structural shape of the whole object. A Christmas tree, a snowflake, or a fern are good examples of fractal structures. For the investigations with fractal aggregates, three types of colloidal particles are significant to study: polystyrene, silica, and gold. Each is to be suspended in water and combined in-situ during the mission with a salt solution to form the fractal aggregate sample. Like the colloidal systems of Chaikin and Russel, these systems are also capable of being probed using visible light.

To date, Weitz and Pusey have already participated in four space flights intended to achieve early, broad results as well as to determine whether the optimum mixtures identified in ground based research were also optimum in microgravity. BCAT and BCAT-2 revealed that the optimum size ratio (r=0.58) is the same in microgravity as it is on Earth, while the optimum volume fraction for crystal growth in microgravity ($ø$=0.54) is higher than the optimum value on Earth.[17] CGEL, reusing the apparatus flown by CDOT to enable rudimentary Static and Dynamic Light Scattering to be performed on all three kinds of colloidal suspensions, was not able to carryout any of its light scattering measurements due to the Progress Vehicle collision with Mir in 1997.

Nevertheless, photography of the CGEL samples performed during the course of the mission did reveal important findings about the stability of colloidal crystals in microgravity as well as the effect of polydispersity on crystallization.[18] CGEL-2, having occurred in October 1998, has not yet made public its results and conclusions.

For Weitz and Pusey's experiment opportunities upcoming on ISS, the objectives of the experiments are to develop the basic principles for synthesizing several different sorts of materials, to determine the fundamental properties of these materials, to fully develop the evolving field of "colloid engineering", and to create materials with novel properties using colloidal particles as the precursors. Their objectives are planned to be addressed in two steps. First, the determination of the fundamental structures, dynamics, and properties of the three kinds of colloid suspensions will be conducted using the PHaSE-heritage light scattering instrument, the Physics of Colloids in Space Apparatus. The name of this experiment is the Physics of Colloids in Space (PCS). Second, the creation and evaluation of materials with novel properties by using the first step findings and by using new materials requires the particle level characterization capabilities intended for the microscope-based Light Microscopy Module. The current title of this experiment is PCS-2 in the Light Microscopy Module (LMM).

Experiment Objectives of Arjun G. Yodh

Professor Arjun G. Yodh and Professor Alan T. Johnson (University of Pennsylvania) proposed *Colloidal Assembly in Entropically Driven, Low-Volume-Fraction Binary Particle Suspensions* in response to NRA 96-HEDS-01-100. The essence of the proposal is to create photonic band-gap colloidal surface crystalline materials from high and low density particles in low volume fraction binary particle suspensions using entropy driven crystallization.

Investigating the mechanisms of colloidal assembly in a low volume fraction system should assist in developing methodologies to produce photonic band gap surface crystals. These systems of low volume fraction of large particles in solution with higher volume fraction small particles have entropically driven crystallization.[19] The large particles near a wall exclude less volume than they do when far from the wall. Hence, more volume is available to the small particles and thus, larger entropy is possible for the small particles. Such crystals are weakly bound and fragile. In ground-based tests, the particle interactions and crystallization are influenced by sedimentation, restricting investigations to neutral buoyant systems or to short times which prevent creation of novel photonic band gap crystals. This experiment plans to employ techniques of video microscopy to observe local crystal structure, size, and quality of crystals as a function of time. A spectrophotometric microscopic technique is intended to be used to measure photonic band gap properties. The idea is to determine the directional and frequency dependence of light transmission through these crystals. Particle manipulation methods to bias or direct the growth of the colloidal structures and properties may also be explored at the microscopic level. These methods could possibly include the use of surface templates, lithographic grids, in-situ fluid/particle substitution or laser tweezers.

The microscope-based Light Microscopy Module, with some augmentations to the sample cell and the addition of hardware to support the spectrophotometry measurements, is anticipated to serve Yodh and Johnson's requirements also.

Experiment Objectives of Douglas J. Durian

Professor Douglas J. Durian (University of California at Los Angeles) proposed *The Melting of Aqueous Foams* in response to NRA-94-OLMSA-05. The essence of the proposal is to understand the unusual elastic character of aqueous foams in terms of their underlying microscopic structure and dynamics by using rheological and light scattering measurements.

Microscopic information about bubble packing and dynamic rearrangement are planned to be determined through multiple light scattering: Diffusive Transmission Spectroscopy (DTS) and Diffusing Wave Spectroscopy (DWS). Foams are made up of mostly gas and a few percent volume fraction of liquid, however their behavior has a solid-like elastic character and can flow under shear. Professor Durian's proposed research seeks to provide insight into the microscopic structure and dynamics of foam under shear stress. Fundamental guidance for the development of materials with more desirable rheology and stability characteristics may be gained through his proposed research.

Foams have many different uses in everyday life, from fire fighting, isolating toxic materials, and oil recovery to detergents, foods, mousse, shaving cream and toothpaste. Within these applications undesirable conditions can occur and there is a need to be able to control the mechanical properties and stability. In order to control the foam properties, the microscopic structure and dynamics must be understood. The physical mechanisms that affect foam stability are not understood, in part because the structure, bubble distribution and dynamics are not accessible by traditional methods of study such as surface observation, freeze fracture, electrical conductivity, or external pressure.[20]

Professor Durian's space flight experiment, FOAM, plans to exploit the use of multiple light scattering and rheology to extract information concerning the foam structure and dynamics of aqueous foams. From the microscopic measurements of bubble structure and dynamics, Professor Durian expects that foam will become less elastic and relax faster as a function of increasing liquid content and strain rate. The study of aqueous foams is difficult on earth because, over time, gravitational drainage of liquid from in between gas bubbles cannot be prevented. DTS should enable a measurement of the average bubble size, thus leading to an understanding of the structure, while DWS should enable a quantitative measurement of foam dynamics.

Experiment Objectives of Jing Liu

Professor Jing Liu (California State University, Long Beach) proposed Magnetorheological Fluids: *Rheology and Nonequalibrium Pattern Formation* in response to NRA-94-OLMSA-05. The essence of the proposal is to investigate experimentally the nonequilibrium pattern formations and phase transitions in Magnetorheological (MR) fluids and to determine the effect of the structures on fluid rheology.

A magnetorheological fluid consists of a suspension of colloidal particles, each of which contains many tiny, randomly oriented magnetic grains. When these particles are subjected to a magnetic field, a dipole moment is induced in the particles. The dipole-dipole interaction between particles results in chain formation and thus produces a phase change from liquid to solid. The structure formations are dependent on the strength of the magnetic field, the ramping rate of the field, the volume fraction of the suspension and the allowable length of the chains. The resultant structure then determines the viscosity.[21] An MR fluid with a variable yield strength that can be switched on and off repeatedly can be utilized in technology applications such as shock absorption, clutching, damping, and joint control.

The object of the experiment is to study the structures induced by variable ramping of the applied magnetic field, variable volume fraction systems, and by variable cell geometries leading to confined and unconfined growth of the structures. Additionally, the phase transition, the dynamics and kinetics, the interaction mechanisms of the colloids, and the rheological properties will be studied. To achieve this science, the development of hardware that incorporates the simultaneous operation of controllable magnetic fields, a variable cell size, a strain-controlled rheometer, Static Light Scattering, and video microscopy is required.

TOP LEVEL DEVELOPMENT SCHEDULES AND TIMING FOR THE FLIGHT PROJECTS

Currently there are conceived seven flight development projects to address the required science for these five complex fluids investigators. These projects are the Physics of Colloids in Space (PCS) experiment, the Colloidal Augmentation Flight Experiment (CAFÉ), the PHaSE-2 experiment, the PCS-2 experiment, the Foam Optics And Mechanics (FOAM) experiment, the Field Induced Rheological Structure Transitions (FIRST) experiment, and the Colloidal Assembly experiment. For a given flight project, the solid single- or double-headed arrows in Figure 1 imply a strong heritage/ synergy in either science content or instrument techniques, while the dotted arrows imply at least a mild flight hardware heritage. The PCS and CAFÉ experiments are planned to be sequentially conducted in hardware manifested for deployment and operations on ISS in the ExPRESS Rack, with this first set of hardware launched in April of 2000.

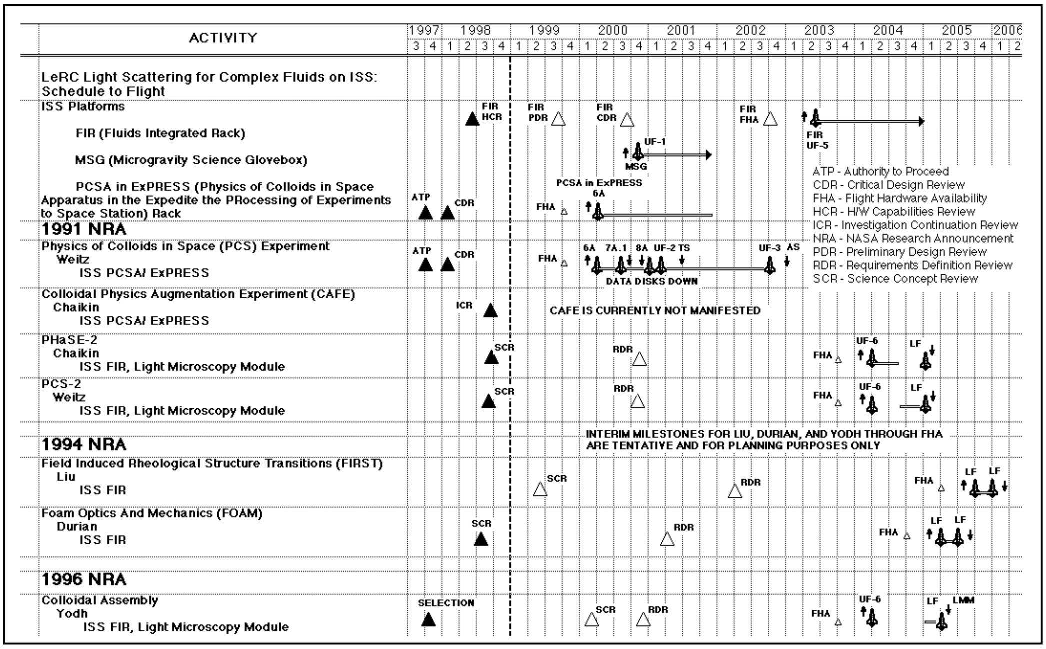

Figure 2: LeRC Light Scattering for Complex Fluids Research on ISS: Top Level Development Schedules and Timing

The PHaSE-2, PCS-2, and Colloidal Assembly experiments are currently conceived to be conducted in the Light Microscopy Module in the Fluids Integrated Rack, with the first of these experiments to be launched as early as April of 2004. The FOAM and FIRST experiments are planned as separate experiments in the Fluids Integrated Rack (FIR) launched in 2005. The top level development schedules and timing for the seven projects to the degree that they have been planned appears in Figure 2. The top level deployment and timing for the three microgravity platforms – the PCS Apparatus in the ExPRESS Rack, the Microgravity Science Glovebox, and the FCF's Fluids Integrated Rack – are included in the figure as a reference.

PLANNED FLIGHT INSTRUMENTATION DEVELOPMENT

The hardware for each of these projects is described as follows.

PCS

The experiment hardware for the Physics of Colloids in Space (PCS) has been based significantly on the flight instrument developed for Chaikin / Russel for PHASE, with hardware improvements/ enhancements made to resolve technical difficulties which plagued PHaSE and to accommodate the science and diagnostic requirements of Weitz and Pusey.[22] These experiment hardware systems provide visual imaging and light scattering diagnostics to examine colloid samples. The colloid sample of 3 milliliters is contained in an optical cell that is designed to permit Dynamic and Static Light Scattering, and Bragg and Low Angle scattering via two orthogonal paths. The sample cell shown (Figure 3) has a cylindrical cavity for the sample material.

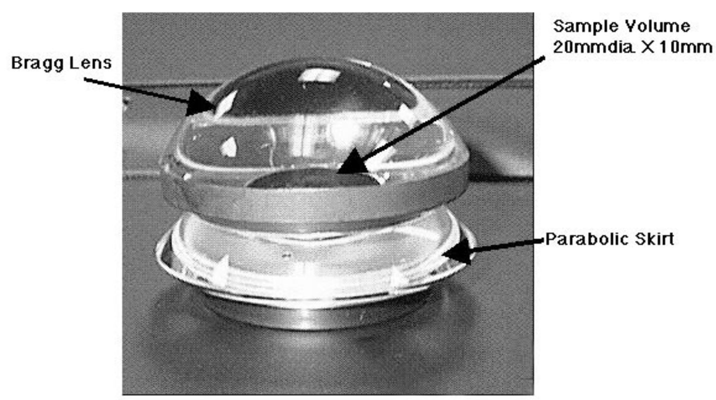

Figure 3: PCS Sample Cell

The Bragg and Low Angle scattering is obtained by launching the laser along the cylindrical volume's axis. The spherical lens part of the cell focuses the transmitted and scattered light onto a hemispherical screen for diagnostic measurement via a digital camera. The lens and screen capture the scattered light over the range of 10^o to 60^o.

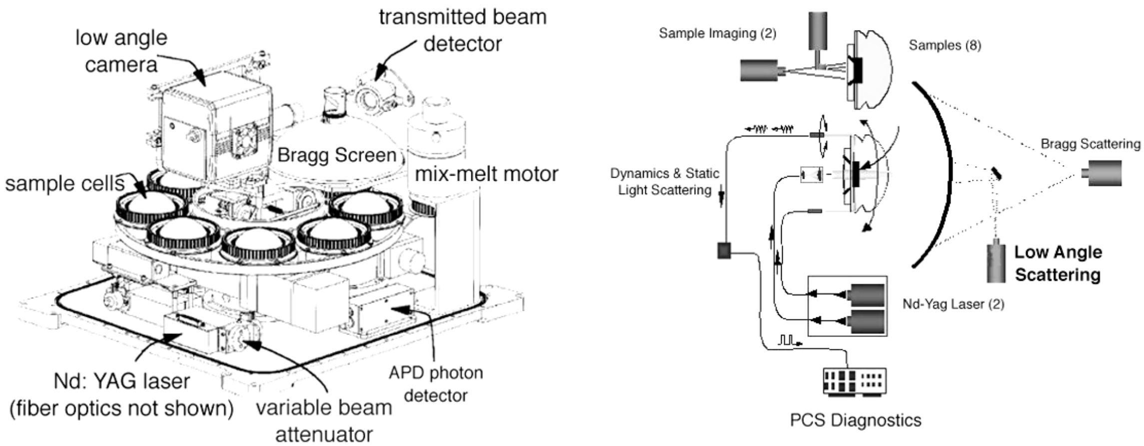

Figure 4: PCS Test Section and Optical Measurements Block Diagram

The scattered light at low angles is captured via another digital camera and via another set of optics mounted on the spherical Bragg screen. The Low Angle optics consist of a dump spot (0.5 mm wide drill bit) to block the transmitted beam and reflect a portion of it to a detector for measurement, a lens and a mirror. The optics permit observation of the scattered light from 0.4° to 7.0° (field of view based on being centered off the scattering axis). The Bragg and Low Angle diagnostics provide static information on the structure formation. The Low Angle also provides dynamic information from analyzing the intensity from each speckle. Another laser light is launched into the outer bottom skirt of the sample cell. The light strikes the parabolic surface of the cell and is orthogonally reflected through the cylindrical sample volume along its radius. Similarly, the transmitted and scattered light is reflected off the parabolic surface and out the bottom of the sample cell. Two optical fibers positioned a fixed 180° apart capture the scattered light and carry it to Avalanche Photo Diodes for photon counting. The transmitted light is directed to a photodetector for power measurement. The two pick-up fibers are mounted to a rotary stage that permit measurement of the scattered light over 11° to 169° (191° to 349°).

The experiment hardware provides for eight sample cells that are mounted in a carousel. The carousel and associated rotary stage provide for rotating each sample into the diagnostic stations (two imaging and the scattering station). At the scattering station, the sample cell interfaces with a belt system that provides for sample rotation to support Dynamic Light Scattering measurements and to perform rheology. The fractal samples require mixing of the colloid particle solution and a salt solution. To achieve this, one sample cell design has two diaphragm cavities off the main cylindrical sample volume, which interface with two rods off a cam and motor.

All the aforementioned diagnostics and systems are housed in a sealed enclosure referred to as the Test Section (Figure 4). This unit is accompanied by another box that houses all the power distribution, control circuitry, data acquisition and data storage components, the Avionics Section. The Avionics Section is comprised of two drawers. The upper drawer houses the power control module, current sensors, circuit breakers and three removable hard drives. Two of the hard drives are for data storage capable of recording 18 Gigabytes of digital data. The third drive houses the system control software. All three can be removed and replaced on-orbit. The lower drawer contains the data acquisition boards in a PCI/ISA BUS. The acquisition system provides three framegrabbers to interface with the four cameras in the Test Section. It also includes Flexible Instrument correlators to handle the signal data from the APDs. The Test Section and Avionics Section are accommodated in an EXPRESS Rack and utilize the Rack power, water and air cooling, and telemetry. The experiment operations are performed from the ground from the LeRC Telescience Support Center and from a Remote Operations Site at the University of Pennsylvania. The Remote Site permits the science team to conduct the experiment over the several months on ISS at their worksite.

PCS is scheduled for launch to ISS in April 2000, with operations occurring until March 2001.

CAFÉ

CAFÉ will be implemented by reusing the Test Section hardware comprised by the PCS Apparatus to support Chaikin and Russel's investigations of the phase diagram, mainly the behavior of hard spheres near and beyond glass transition, and the effects of polydispersity. Plans are in place to improve the Low Angle diagnostics by providing for observation down to 0.1°. This may be accomplished by incorporating a separate positional control of the Bragg and Low Angle dump spot. The Test Section will be returned from ISS, refurbished, and transported back to ISS to remate with the Avionics Section.

CAFÉ is not currently manifested for flight at this time.

Light Microscopy Module

The science needs for the three experiments requiring a thin cell sample with enhanced imaging, light scattering, and particle manipulation techniques, PHaSE-2, PCS-2, and Colloidal Assembly, are intended to be met via an instrument built upon a light microscope. Such an instrument, the Light Microscopy Module, is being conceived and is currently in technical definition. While high magnification flight microscopy is new to LeRC, employment of the most of the required digital imaging and light scattering techniques are not. The LMM is being designed around an upright style commercial microscope, because upright microscopes currently have a greater degree of motorization than inverted microscopes. A schematic of the essence of the Light Microscopy Module, i.e., the upright microscope with its attachments and features, appears in Figure 5.

The microscope, shown in silhouette in the figure, would be a commercial unit capable of performing standard microscopy techniques. The use of Koehler illumination, using high numerical aperture condenser and objectives, should enable high magnification, high resolution images to be taken of colloidal systems held within 100 micron deep microscope slides. Oil immersion optics are highly desired to enable the high numerical apertures that reduce flare and help gather as much light as possible for contrasting, as well as to enable light scattering and other additional optical techniques.

Due to sample size and ability to change out sample stages, it appears that several hundred nominally 1cm x 2 mm x 100 micron thick samples would be accommodated.

Laser tweezers and confocal microscopy are engineering capabilities high in priority for the PIs. Confocal microscopy promises to reduce scattered light during imaging, while laser tweezers should enable manipulation of colloidal particles to tailor desirable colloidal crystal patterns or initial conditions. Both subsystems can be visualized as actual add-on packages external to the microscope. The laser tweezers would essentially be designed around an infrared laser (like an undoubled Nd:YAG) and a two axis gimballing system to direct the laser light. The confocal system might include its own camera to collect the digital images acquired via this technique.

In transillumination [box 1, Figure 5], a white light source, as well as a source of 532 nm (frequency-doubled Nd:YAG) laser light, and a source of collimated variable frequency monochromatic light, are required. The Kohler white light is essential to support brightfield, darkfield, phase contrast, and DIC transillumination microscopy techniques, while the 532 nm laser light and the collimated variable frequency monochromatic light are essential to support light scattering and spectrophotometry, respectively, via the microscope. The Kohler light might be provided either by a Tungsten Halogen bulb or a diode light source. The laser light and collimated variable frequency monochromatic light beams are required to be translated in an image-conjugate plane upstream of the microscope's condenser optics to allow for high incident angles.

The flight microscope features up to a 0.9 Numerical Aperture (NA) condenser with 8 positions to support the transillumination techniques [box 2, Figure 5].

In epi-illumination [box 3, Figure 5], a diode light source for narrow band and (possibly) wide field light is required to support fluorescence microscopy. Use of a 'Rhodamin' fluorescence staining dye might enable a source of frequency-doubled Nd:YAG laser light to be used in epi-illumination. For flight, the use of a mercury vapor arc lamp is a less feasible alternative due to safety concerns with this light source.

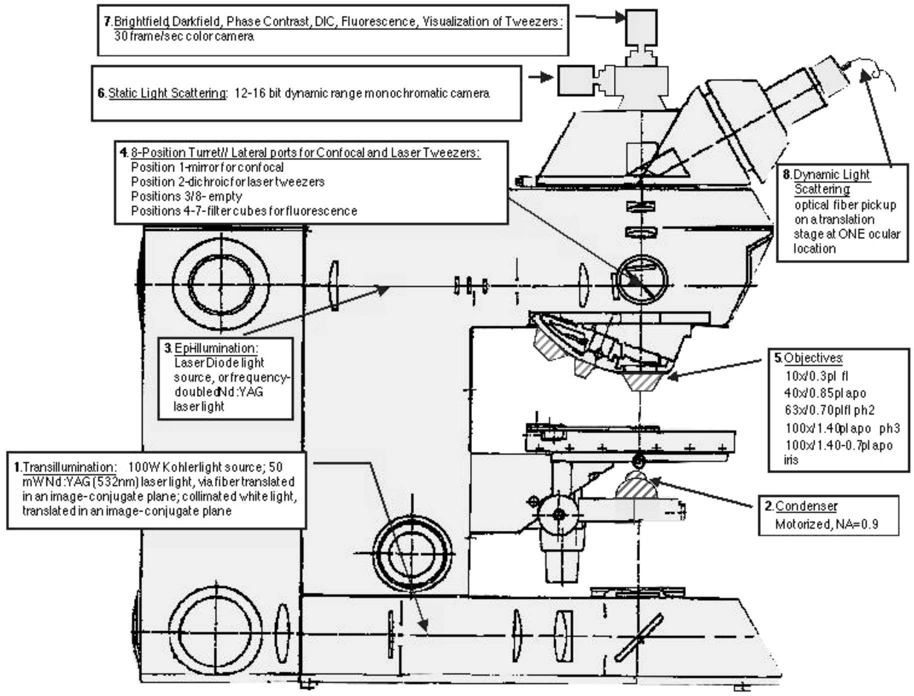

Fig. 5. Upright Microscope Concept for Light Microscopy Module

The flight microscope features an 8-position 'filter' turret downstream of the specimen plane to support the microscopy, imaging, and particle manipulation techniques that are introduced in epi-illumination [box 4, Figure 5]. One position on the filter turret would contain a 100% reflecting mirror to allow for a 'spinning disk' confocal unit to operate from a lateral port. The second position on the turret would contain a dichroic to allow reflection of 1064 nm infrared light for laser tweezers via a lateral port. Most of the remaining turret positions would be available to accommodate filter systems for fluorescence microscopy.

The flight microscope concept currently features a suite of 5 objectives [box 5, Figure 5] for low magnification (10x), medium magnification (40x and 63x), and high magnification (100x) to support imaging, light scattering, and tweezing techniques. The 100x objectives are oil immersion objectives.

Up to three output ports would be directly utilized for cameras or photodiode output devices [boxes 6, 7, and 8, Figure 5]. The first output device needed is a color camera, having at least a 30 frame per second (fps) rate, to allow for video microscopy (or highly-magnified-motion-picture) of the colloidal samples while utilizing the standard contrasting techniques (e.g., darkfield, phase contrast). The second output device is a high resolution (at least 12 bits working) monochromatic camera positioned in the objective back focal plane to enable Static Light Scattering and spectrophotometry. The third output device is a fiber optic collector positioned in the objective back focal plane on a x-y translation stage, probably at one of the standard ocular (eyepiece) locations. The photons gathered by this collector would travel, via a fiber optic cable, to an Avalanche Photo Diode or PhotoMultiplier Tube device where they would be counted. The counts would then be processed by a correlator.

The Light Microscopy Module, with PHaSE-2 and PCS-2 samples is intended to be launched to ISS in April 2004, with operations occurring until January 2005. Colloidal Assembly samples may be launched simultaneously with the LMM, or in January 2005 for changeout for the PHaSE-2 and PCS-2 samples, with operations occurring until April 2005.

FOAM

The test chamber for the FOAM experiment which contains the foam samples is required to accommodate video microscopy, diffusing light spectroscopy, and rheological measurements.

Some of these techniques require hardware that already has a flight heritage with LeRC. DWS measurements are required at several different foam thicknesses, with DWS in backscattering performed at the thickest section of foam. A cone-and-plate geometry best suits this methodology. Figure 6 depicts a concept for the experimental apparatus.

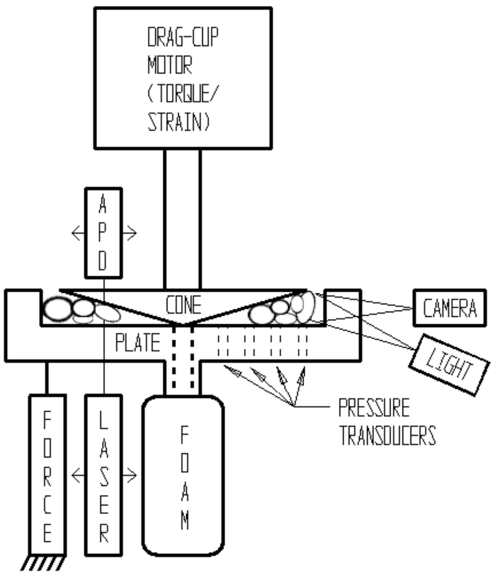

Figure 6: FOAM Experimental Apparatus

The sample cell will be filled with foam of a known composition and allowed to coarsen over a specified period of time. This process will be monitored by video microscopy as well as the two diffusing light spectroscopies. A series of rheology measurements at various strain rates will be applied to the foam sample over a 24-hour period, and synchronized with DWS measurements. After the strain rate sweep, the foam is allowed to coarsen until the average bubble size increases, and the series of measurements is repeated.

The FOAM experiment is intended for operation on ISS utilizing the FIR in April of 2005. The FIR will provide the PI with a laboratory style optics bench on which the flight experiment can be configured, and a laser that can be used for laser light scattering measurements. The laser is expected to be sufficient for the FOAM experiment. For obtaining the measurements from the diffusing light spectroscopies, a laser beam will be directed onto the foam sample at a specified radial distance. The optical configuration is illustrated in Figure 7.

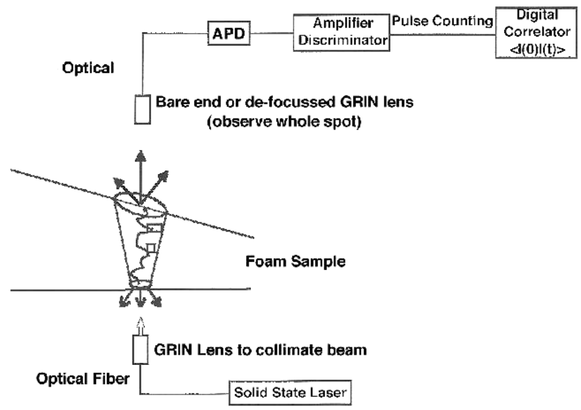

Figure 7: Diffusing Wave Spectroscopy Optical Configuration

The proposed program of DTS plus DWS, video microscopy, and rheology versus liquid content, strain rate, and foam age will provide a fundamental understanding of the interrelationships between bubble structure and dynamics, and the macroscopic stability and mechanical properties of aqueous foams. The program has been successfully demonstrated for dry foams in ground-based studies.

FIRST

The proposed science, requiring video microscopy, light scattering, and rheological measurements, has diagnostic techniques similar to the FOAM experiment. The experiment utilizes different investigative techniques depending on which cell geometry is being studied: the confined or the unconfined cell. Two different sets of hardware may be developed based on the differing cell geometries. The following hardware descriptions are preliminary concepts and will likely evolve as the science becomes more defined.

In the case of the unconfined geometry, both Diffusing Wave Spectroscopy and Dynamic Light Scattering are proposed for use in determining the structures that result from varied field strength and ramp rates. The samples will be placed in the center of a helmholz magnetic coil for study. A fiber ring of 17 fixed fibers (around a 180-degree arc) will surround the samples to pick up scattered light. The scattered light will then be recorded by Avalanche Photo Diodes, the counts correlated, and the data provided for analysis. The Microgravity Science Glovebox is a candidate platform for this experiment.

The concept for the investigation of the confined geometry is more complex (Figure 8). This hardware must also be able to vary the strength and ramp rate of the magnetic field as in the unconfined case. However, the instrument is also required to incorporate a method to vary the height of the sample (parallel to the field), to allow for varied volume-fraction samples, and to acquire Static Light Scattering images, microscopic images of the structure, and rheological properties of the samples. It is desirable that all of these systems operate simultaneously.

At the heart of the design is a controlled-strain parallel-plate rheometer. Each cell is required to provide a variable gap so that the sample volume fraction can be studied at several different confined geometries. Although the rheometer is the baseline concept for obtaining rheology measurements, optical birefringence is also being investigated as a substitute for the rheometer.

Static Light Scattering images are required during structure formation and at equilibrium. The hardware concept for the collection of Static Light Scattering images is based on the design used in the PHaSE experiment hardware. A laser in the red wavelength (to reduce absorption) will be launched into the sample parallel to the magnetic field and the Static Light Scattering patterns will be imaged in both the Theta and the Phi directions.

Two additional cameras with high magnification are needed for video microscopy both parallel and perpendicular to the field. Images are required at several depths into the sample. It is desirable that the samples would subsequently be solidified through some polymerization technique to retain their structure after removal of the magnetic field.

Surrounding the samples in either the unconfined or confined geometries is a magnetic coil in a helmholz configuration. The coil will have controllable ramp rates and patterns.

The ‘confined geometry’ FIRST experiment is intended for operation on ISS utilizing the FIR in October of 2005. The FIR will provide all controlling software, image processing, data storage, and command and control capabilities for remote operation from the ground.

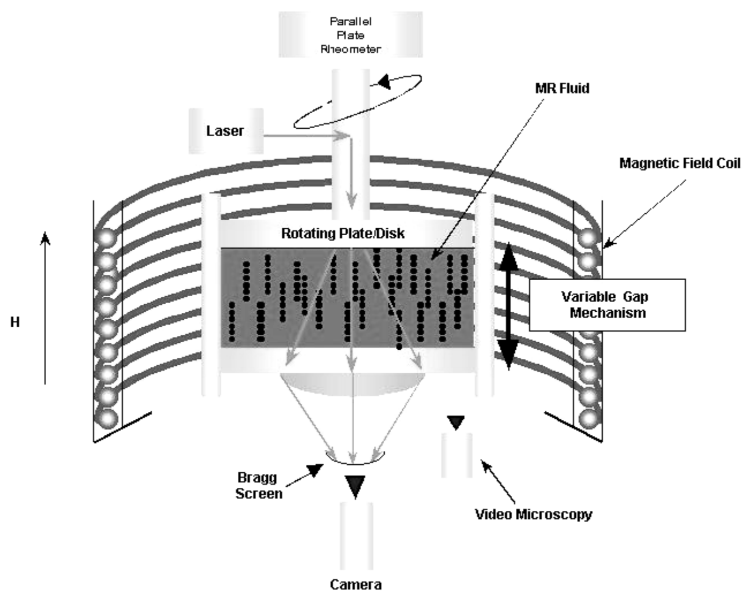

Figure 8: Field Induced Rheological Structure Transition FIR Concept

SUMMARY

In summary, this paper has broadly described the experiment objectives of five complex-fluid Principal Investigators who are currently funded under NASA's microgravity fluid physics flight program, has provided top level development schedules and timing for each of the seven proposed flight projects supporting these experiments, and has presented details of their current flight concept and planned hardware development. Five of the proposed flight experiments, PCS, CAFÉ, PHaSE-2, PCS-2, and Colloidal Assembly appear able to be accommodated in two hardware modules - the PCS Apparatus in the ExPRESS Rack, and the Light Microscopy Module in the Fluids and Combustion Facility's Fluids Integrated Rack (FCF-FIR). The two other experiments, FOAM and FIRST, have synergy in a number of related diagnostic techniques, such as controlled-strain rheometry, diffusing light spectroscopies, and video microscopy, and are also planned to be flown in the FIR. All of these complex fluids experiments require light scattering techniques that build upon the technical and flight heritage in light scattering instrumentation that has been established at LeRC.

NASA's Lewis Research Center is preparing to conduct a host of very exciting complex fluids light scattering experiments utilizing available microgravity research platform options on-board the International Space Station during the first decade of the next millennium.

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13. ABSTRACT ***(Maximum 200 words)***

The objective of this paper is to give an overview of a suite of microgravity complex fluids experiments utilizing laser light scattering as the primary diagnostic tool which NASA's Lewis Research Center is preparing to conduct on-board the International Space Station during the first decade of the next millennium, while acknowledging the heritage in microgravity light scattering that provides some of the basis for these experiments. Since 1991 the definition, conceptualization, and development of flight-worthy light scattering instrumentation at the Lewis Research Center has been in full swing. To date, partial science returns for two complex fluids investigators from space flights of light scattering instrumentation have already been achieved. As the 1990s progressed, proposals for at least three other complex fluids investigators that were selected by NASA, based upon their scientific value and merit. These three additional investigators, along with the original two for whom a remaining portion of their science is still to be flown, make up a queue of investigators requiring complex state-of-the-art imaging and light scattering extended-microgravity flight instrumentation. This paper will broadly describe the experiment objectives of these five complex-fluid Principal Investigators who are currently funded under NASA's microgravity fluid physics flight program, provide top level development schedules and timing for the flight projects supporting these experiments, and present details of the current flight concepts and planned flight instrumentation development.

14. SUBJECT TERMS

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