THE NASA MICROGRAVITY FUNDAMENTAL PHYSICS PROGRAM

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ABSTRACT

Gravity obscures some of the most subtle phenomena that are key to solving outstanding questions in physics today. To address these questions, the micro-gravity research division of NASA has recently formed a fundamental physics discipline. Currently, the research focus areas in this discipline are Low Temperature and Condensed Matter Physics (LT/CMP), Laser Cooling and Atomic Physics (LCAP) and Gravitational and Relativistic Physics (GRP). NASA objectives in these areas are to support ground-based research with flight potential, to develop research-enabling technologies and to conduct flight investigations. There are currently 54 on-going research investigations being funded, 8 of which are potential flight experiments. A review of the current directions of research in this discipline will be presented. NASA's plans for development of flight hardware to support research on the International Space Station over the next decades will also be discussed including the planned development of a cryogenic facility for providing an environment below 2 Kelvin for up to 6 months to future investigators.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) conducts a program of basic and applied research using the reduced-gravity environment to improve the understanding of fundamental physical, chemical, and biological processes. Current research disciplines in the NASA program are Biotechnology, Combustion Science, Fluid Physics, Fundamental Physics, and Material Science. Initially, the focus of the Fundamental Physics program was in the Low Temperature and Condensed Matter Physics (LT/CMP) area, but recently it has expanded to also include research in the Laser Cooling and Atomic Physics (LCAP) field and in Gravitational and Relativistic Physics (GRP). An extensive research program currently supports theoretical and ground-based experimental investigations. These activities form the intellectual underpinning of the research to be conducted in space.

The highly successful Lambda Point Experiment (LPE) (John Lipa, Stanford University) flew on a Shuttle mission in October 1992. LPE demonstrated that the lambda transition in helium remains sharp down to the one-nanokelvin level and verified, the Nobel prize-winning renormalization group theory of critical phenomena (Lipa *et al.*, 1996). Importantly, the LPE also demonstrated the feasibility of performing very complex high-resolution experiments in the space environment. The ZENO flight experiment (Robert Gammon, University of Maryland) that flew in March 1994 and in February 1996, studied fluctuations near the liquid-gas critical point of Xenon using laser light scattering. The Critical Viscosity Experiment (CVX) (Robert Berg, National Institute of Science and Technology) performed high precision measurements of the flow properties of Xenon gas near the critical point in August 1997. The Confined Helium Experiment (CHeX) (John Lipa, Stanford University) used high-resolution techniques similar to the LPE to investigate how the thermodynamic properties of helium are affected when the helium thickness is made very small. This so called 'finite size effect' influence the properties of all materials when they are made sufficiently small. For example, it has been predicted that within another decade, computer chips will reach the point where 'finite size effects' will have to be taken into account to optimize designs. The CHeX results have pioneered our understanding of this effect.

RESEARCH GOALS

The ultimate goal of Physics is to establish a unified description and understanding of fundamental laws governing the complex phenomena in our world at microscopic, macroscopic and cosmic scales of length and time. The broadest goal of the Fundamental Physics Discipline is to make major contributions to this understanding by utilizing the microgravity environment. We have adopted the following mission statement for our research program:

- "To Unlock Mysteries of the Universe by Exploring the Frontiers of Physics using Laboratories in Space"

Within this mission statement we have identified two over-arching program goals which combine to capture the full breadth of current and future research as follows:

- "To Discover and Explore Fundamental Physical Laws Governing Matter, Space, and Time"
- "To Discover and Understand Organizing Principles of Nature from which Structure and Complexity Emerge"

The first goal is more fundamental in nature and has the long-range potential of revolutionizing our view of the Universe in which we live. Research within this goal aims to answer questions such as: What is the range of validity of Einstein's general theory of relativity? Are there other fundamental forces of nature and how can we develop a unified theory for all forces? What is the nature of the Quantum world? What is the relationship between fundamental laws and the evolution of the physical world? Most of the research in the GRP discipline falls into this category while about half of the research in the LCAP discipline falls into this category. The Satellite Test of the Equivalence Principle (STEP) project (Francis Everitt and Paul Worden, Stanford University) is an excellent example of research in this category.

The second goal is more concerned with how the complexity we see all around us has emerged from basic principles of nature. Research within this goal aims to answer questions such as: How can we learn the underlying organizing principles from studies of matter under ideal and unique conditions? How do laws in the quantum world manifest at normal length and time scales? What is the role of symmetry in establishing structure in nature? How does the rich diversity we see around us arise from basic physical laws? Most of the research in the LT/CMP discipline falls into this category while about half of the research in the LCAP discipline falls into this category. Good examples of research in this category are the LPE and CHeX flight experiments mentioned above.

RESEARCH OBJECTIVES AND NEED FOR MICROGRAVITY

The objectives of the Microgravity Fundamental Physics program are to provide the researcher with the opportunities to contribute significantly to the goals spelled out above. The experiments in our discipline can be categorized by how they benefit from the microgravity environment. One set requires samples that are more homogeneous than can be attained on Earth. Foremost among these are critical-point experiments, for which the variation of the hydrostatic pressure throughout a sample of finite height limits the closeness of approach to the critical point. Another class of experiments involves the study of extremely delicate, high-porosity samples, say near the percolation limit, which would collapse under their own weight. Related to this is also the case of colloidal suspensions, which can not be maintained when the particles are large because of gravitational settling. A third category consists of investigations in which the object of study experiences gravitational acceleration and thus does not remain in the sample volume, as is the case for trapped atoms at extremely low temperatures and for freely suspended drops.

Another category of experiments, such as STEP for instance, would be impossible in the mechanically "noisy" environment that prevails on Earth and can be eliminated in space. The objectives of our research program are to provide for these diverse microgravity needs.

ANTICIPATED BENEFITS OF FUNDAMENTAL PHYSICS RESEARCH

The main scientific benefit from fundamental physics research stems from the fact that the field addresses far-reaching issues that transcend the boundaries of a particular field of science. It is typical that, at one extreme, the fundamental laws of our Universe, such as the law of gravitation, are the central issues. Clearly these laws are relevant to various extents in many branches of science. At another extreme, those unifying principles are studied which arise from the interaction of (infinitely) many degrees of freedom on vastly different length scales. Examples of this type of study can be found, for instance, in the research on critical phenomena mentioned above, which addresses fundamental problems of nonlinear physics that pertain equally to fluid, solid-state, chemical, or biological systems. In the long run it is expected that our program will make major contributions to a unified description and understanding of fundamental laws governing the complex phenomena in our world. Mankind will benefit from this deeper understanding by developing a more enlightened view of our Universe.

Ever since humans first developed scientific curiosity about the world in which we live it has been true that the fundamental physics of today provides the foundation of tomorrow's technology. The resulting technological advances have led to enhanced living standards for the average member of our society and to innovations needed by the space program. Examples of contributions of fundamental physics include, the research on gases at low temperatures, begun by low temperature physicists in the latter half of the Nineteenth Century. This research led to techniques for gas liquefaction, which today are applied to such diverse problems as freeze-drying of food products, rocket propulsion, operation of superconducting magnets, cryo-surgery, and magneto-encephalography. Particularly in recent decades we have seen many far-reaching examples of fundamental physics impacting dramatically and positively on our society. Well known are the effects of semiconductor physics on communications and computing technology, the relation between fundamental NMR studies in the laboratory and MRI imaging in our hospitals, and the impact of fundamental studies of laser physics on a whole host of technical problems. Other developments are less widely appreciated. For example, the development of the World Wide Web, which is in the process of changing our entire way of distributing and using information and knowledge, was initiated by researchers in physics who had a need to communicate massive amounts of information effectively over long distances between various laboratories. The NASA fundamental physics program is at the forefront in the development of such diverse technologies as ultra-sensitive sensors (many based on superconducting technology) and of highly accurate clocks. These technologies will likely find applications in the future human exploration space program as well as in enhancing the lives of people on Earth. Clocks not only provide the standard by which we tell time, but are crucial to the way we communicate and navigate on Earth, in the air, and in space

RESEARCH DIRECTIONS AND FUTURE PLANS

To meet the need of the LT/CMP community, NASA and JPL are planning to develop a Low Temperature Microgravity Physics Facility (LTMPF) for the International Space Station. A science, Industry and JPL partnership of joint participation through all phases of definition, development and test will implement the facility. The Industry partner, Ball Aerospace and Technology Corporation (BATC) was selected through a competitive technical selection process. A conceptual design for the facility that satisfies the need of the scientific community has been developed (Israelsson *et al.,* 1996). The design provides 6 months of cryogenic lifetime operating as an attached payload to the Japanese Experiment Module's Exposed Facility. The facility carries about two hundred and sixty liters of helium and accommodates two instrument inserts. Each instrument must fit within a volume defined by a cylinder with a diameter of 20 cm and a length of 50 cm. Other assumed constraints for each instrument is a mass limitation of 50 kg, a wire and plumbing count similar to the LPE and CHeX instruments, and a power dissipation at helium temperatures of 10 mW. The first two instruments are targeted for launch in this facility in November 2003. Candidate experiments for the first flight are Critical Dynamics in Microgravity (DYNAMX) (Robert Duncan, University of New Mexico), MIcrogravity Scaling Theory Experiment (MISTE) (Martin Barmatz, Jet Propulsion Laboratory), and Superfluid Universality Experiment (SUE) (John Lipa, Stanford University). DYNAMX will study the rich, largely unexplored, properties of superfluid helium driven away from equilibrium by introduction of a heat current[10]. MISTE[15] will perform very precise measurements of thermodynamic properties near the liquid/vapor critical point of ^{3}He to check scaling theories for critical phenomena. SUE[16] will measure the superfluid density exponent along the lambda line of helium in microgravity to check the universality prediction of the theory of critical phenomena. It is planned that the facility will fly at least every 24 months with new instruments installed. Candidate experiments for the second flight include Boundary Effects near the Superfluid Transition (BEST) (Guenter Ahlers, University of California Santa Barbara and Fengchuan Liu, Jet Propulsion Laboratory) and Experiments Along Co-Existence Near Tricriticality (EXACT) (Melora Larson, Jet propulsion Laboratory).

Recently NASA selected two flight experiment candidates in the LCAP area. The selections are Cesium Clock Experiment (CeCE) (Donald Sullivan, National Institute of Science and Technology) and Rubidium Clock Experiment (RuCE) (Kurt Gibble, Yale University). Both of these experiments aim to take advantage of the microgravity environment to develop more precise frequency standards than possible before and to use these highly accurate clocks to test fundamental physics principles. The development of these experiments is in the early definition phase and a decision has not yet been reached on how to best implement these flights. It is likely that NASA will develop experiment unique flight hardware for each of these experiments and fly them either attached to the outside of the International Space Station, or in a rack mount configuration inside the Space Station.

NASA has also made recent experiment selections for potential flight in the GRP area. The Superconducting Microwave Oscillator (SUMO) (John Lipa, Stanford Univeristy) will take advantage of the gravity free environment to develop a clock with superior stability at short time scales. This clock can be used both as a flywheel oscillator for the laser cooled atomic clocks described above and also to test fundamental physics principles. The Satellite Test of the Equivalence Principle (STEP) is a joint mission between NASA and the European Space Agency to test the equivalence of gravitational and inertial mass to about one part in 10^18. This will be accomplished by allowing two concentric, cylindrical test masses to 'fall' around the Earth in a drag-free satellite. The test masses are cooled to < 2K and are supported by frictionless, superconducting, linear bearings. Ultra-sensitive SQUID position detectors measure relative motion between the test masses. The satellite will be placed in a 400 km, sun-synchronous, polar, Earth orbit sometime after 2001. The nominal mission lifetime is three to four months.

ACKNOWLEDGEMENTS

The Jet Propulsion Laboratory, California Institute of Technology under contract with NASA carried out part of this work. Discussions with the Fundamental Physics Discipline Working group chaired by Guenter Ahlers are acknowledged.

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