New Microgravity Fundamental Physics Research Areas in the ISS Era

Ulf E. Israelsson[1] Mark C. Lee[2],

[1]*Jet Propulsion Laboratory, Pasadena, CA, 91109 USA*
[2]*NASA Headquarters, Code U, Washington, D.C., 20546 USA*

ABSTRACT

NASA's microgravity fundamental physics program has used the Space Shuttle to perform high resolutions experiments in space. As we come to the end of the Shuttle era, we will begin to perform research aboard the ISS. A large stable of ground based experiments have been selected from NASA Research Announcements in a variety of disciplines. These investigations will form the backbone from which to select future flight candidates. Research in Laser Cooling and Atomic Physics will enable us to operate highly precise clocks in space. Low temperature physics experiments will use a liquid helium facility with a six-month lifetime. This facility can also support experiments in gravitational physics. Researchers in biological physics will be offered an opportunity to develop future experiments that can benefit from space experimentation. An overview of the future research directions and the benefits to the community of performing research aboard the ISS will be presented.

INTRODUCTION

Science is driven by the inexplicable need of humans to understand the intricacies of the universe we observe around us. Physics establishes a foundation for many other branches of science and provides the intellectual underpinning for maintaining and further developing today's high technology society. In NASA's program, physicists seek to explore and understand the fundamental physical laws governing matter, space, and time. By examining the smallest and largest building blocks that make up the universe we will develop a better understanding of the basic ideas, or theories, that describes the world. NASA's interest in fundamental physics research is due to the fact that a space environment can provide access to different space-time coordinates and can free experimenters from the disturbing effects caused by gravity on the Earth. NASA researchers also seek to discover and understand the organizing principles of nature from which structure and complexity emerges. Even though the basic laws of nature are very simple in principle, the universe that has arisen under the direct influence of these laws is amazingly complex and diverse. By performing well thought out experiments away from the disturbances caused by Earth's gravity, we can learn better where the complexities observed around us have evolved from and how to employ nature's principles in service to humanity. Research today is becoming increasingly cross disciplinary. It is no coincidence that cross-disciplinary teams of researchers are increasingly addressing some of the most compelling and important questions facing society today. Physicists are key players for many aspects of these activities. As an example, biological physics provides a vital link between fundamental research, techniques, and methods and the more complex fields of structural biology, molecular structures, cellular biology, and fundamental biology.

The pursuit of the goals described above will benefit society over the long run in ways we can not yet foresee. For example, the study of physical laws and natural principles with the highest precision requires advances in instruments. These instrumentation advances in turn provide the foundation for tomorrow's breakthrough technologies thus contributing to the competitiveness of American industry and supporting an enhanced human presence in space. The pursuit of knowledge also educates tomorrow's scientists and technologists and fulfills the innate human desire to understand our place in the universe. Humankind's concept of the universe we live in is changing as the tools that NASA places in space, such as the Hubble Space Telescope, detect new astronomical objects and novel events. Our description of these phenomena depends strongly on the details of our understanding of fundamental forces such as gravity.

NASA is pursuing, or has plans to pursue, research in a variety of different disciplines. These research areas are described next.

GRAVITATIONAL AND RELATIVISTIC PHYSICS

Gravitational and relativistic physics is one of the most fundamental areas of physics. To date, physicists have determined that there are four kinds of forces that operate on matter: gravity, electromagnetism, and the "strong" and "weak" forces within atomic nuclei. Gravity is the weakest of these forces, yet paradoxically the most dominant as it acts over great distances. In fact, the entire history of the universe can be pictured as a struggle to counter the gravitational force with the predictable outcome that all matter will succumb to it. In this regard, the gravitational force is the most fundamental and influential of the known forces in nature. Due to gravity, every bit of matter in the universe is under the influence, even if infinitesimally so, of every other bit of matter. Relativity theories argue that gravitational forces apply equivalently to all bodies. Furthermore, Einstein's theory of general relativity places gravity at the heart of the structure of the universe, describing that even the orderly space-time structure of the Universe can be "warped" near a body of large mass, such as the Sun, or Earth. This warp would even affect clocks. These changes to the very fabric of space and time near a large body are dramatic in their importance but also very subtle and difficult to measure accurately. However, they are large enough that they must be taken into account even in routine astronomy observations and in measuring the position of satellites and planets. Advanced technologies must be used to detect and characterize these minute changes, so that the corrections due to relativistic phenomena can be accurately accounted for. NASA's microgravity fundamental physics programs currently are sponsoring the development of several experiments designed to improve accuracy in the measurements of these effects and to test the basic foundations for Einstein's theory.

The Satellite Test of the Equivalence Principle, STEP, is a Code U Code S collaboration recently submitted to the SMEX announcement of opportunity. STEP aims to test one of the basic postulates of Einstein's theory, namely the equivalence of gravitational and inertial mass, to an unprecedented accuracy of one part in 10^{18}. The results from this experiment can have a profound impact of our understanding of the detailed structure of the forces acting in the universe and may contribute to the goal of unifying all forces of nature into a common description. There have been some recent theoretical models that predict a violation of the equivalence principle at a level that is potentially reachable by STEP. The principal investigator for STEP is Prof. Francis Everritt from Stanford University.

The Superconducting Microwave Oscillator (SUMO) experiment will place a high-precision clock in Earth orbit to test Einstein's prediction that time varies depending on the strength of gravity. The clock rate will be measured at different positions around Earth and at different levels of the local gravitational field. NASA is also investigating the potential to use SUMO as a flywheel oscillator for more conventional clocks thereby allowing them unprecedented performance even at longer time scales. There is a strong interest in the scientific community, both in the US and in Europe, to fly multiple clocks of different design in Space at the same time to gain important scientific information. NASA is also developing clocks based on laser-cooling techniques that will be used for relativity tests and also for other purposes. They are described in the next section. The principal investigator for SUMO is Prof. John Lipa from Stanford University.

LASER COOLING AND ATOMIC PHYSICS

While studies in gravitational and relativistic physics examine the fundamental laws describing the universe on a large scale, it is equally important to look at the tiny building blocks of matter and how they display the same fundamental laws. Laser cooling and atomic physics examines this area. Atoms are the smallest systems in which we can study the basic laws of nature. New techniques allow the use of laser light to cool and probe individual atoms as a starting point for exploration. Careful study of individual atoms bridges the gap between the smallest realistic building blocks of matter and the complex behavior of large systems. Furthermore, conducting these experiments in space allows researchers to remove the influence of gravity and manipulate matter freely, without having to counteract "falling" of the specimens within the instruments. The ability to observe the behavior of atoms completely under the experimenter's control promises novel results and new insights previously hidden from view in Earth-bound laboratories.

We are developing space experiments to study clouds of atoms cooled by laser light to very near absolute zero, yet freely floating without the forces that would be needed to contain them on Earth. These conditions allow measurements of higher precision and longer observation times. Using these techniques we are also developing improved clocks, both for testing basic theories of nature and for technological applications in space.

The Primary Atomic Reference Clock in Space (PARCS) will further our understanding of the basis of time itself. A second is defined by the energy released by the vibration of cesium atoms. Atomic clocks on Earth measure this vibration with high precision but always under the influence of gravity. By operating an atomic clock in space, we can improve our definition of time and the accuracy of timekeeping. PARCS will use the improved time keeping to test predictions of Einstein's theory and will make available improved timekeeping to researchers on the ground. PARCS is planned for operation aboard the International Space Station for a 6 month period in the 2005 – 2005 timeframe. The principal investigators for PARCS are Drs. Don Sullivan and William Phillips from the National Institute for Standards and Technology.

The Rubidium Atomic Clock Experiment (RACE) will take advantage of the much reduced collision shift in Rubidium as compared to Cesium to develop e clock with an accuracy of one part in 10^{17}. This represents two orders of magnitude better performance than currently achievable on the ground and a factor of ten improvement from PARCS. RACE will be launched one to two years after PARCS, taking advantage of lessons learned from the PARCS development. The principal investigator for RACE is Prof. Kurt Gibble from Yale University.

CONDENSED MATTER PHYSICS

Like laser cooling and atomic physics, low temperature and condensed matter physics is the study of fundamental laws of nature at the atomic level. Condensed matter physicists examine the properties of solids and liquids, the states of matter in which atoms are packed closely together. Of particular interest to researchers in the NASA program is the behavior near a critical point, or conditions of pressure and temperature at which the properties of two different phases become similar. For example, a substance at the liquid-vapor critical point exhibits no distinction between the liquid phase and the vapor phase. Properties of the substance often display anomalies at a critical point. Many of these unusual phenomena can best be studied at low temperatures, where thermal noise (heat induced vibration) is much reduced. By understanding the complex critical behavior of low temperature materials, such as liquid helium, we will learn more about the critical properties of many other systems. Examples are metallic alloys, magnetic materials, groups of fundamental particles, and even larger-scale phenomena, such as the percolation of water or the movement of weather patterns, all of which exhibit critical point behavior. Critical behavior is a function of not only temperature but also of pressure. Therefore the pressure must be uniform throughout the sample under observation. Gravity causes a pressure difference in any fluid sample, so the critical phenomena can only be observed in a very small region on the Earth. If an experiment is conducted in space, the pressure can be uniform across the sample, and much more comprehensive measurements can be made. Furthermore, in free fall, a sample drop can be freely suspended without the interference of a container. This freedom from external constraints is not possible in an Earth-bound laboratory.

Two high-resolution experiments have been concluded in this field on the Space Shuttle. These are the Lambda Point Experiment (LPE) and the Confined Helium Experiment (CHeX). Both experiments measured the specific heat of helium samples near the transition to the superfluid phase with very high precision. The experiments verified that our understanding of cooperative phenomena agrees with reality. The LPE measurements were performed on a bulk golf-ball size sample providing information about bulk, macroscopic properties. LPE verified that a critical point remains sharp even down to within a billionth of a degree of the transition. The CHeX experiment was performed on slabs of helium about 57-micron thick, providing valuable information about finite size effects. Results from CHeX are indicating that our current understanding of how scaling between different sizes works may need some re-interpretation. The principal investigator for LPE and CHeX was Prof. John Lipa from Stanford University.

Ongoing investigations study the behavior in mixtures and in confined media and test the universality of critical phase transitions and the scaling laws at such points. In addition, the dynamic behavior is studied to detect predicted non-linear responses to driving forces, and the effects of finite size and of boundaries are studied near critical points. For example, studies are being performed of large-scale quantum systems to learn the hydrodynamics of such systems and of the melting and freezing of quantum crystals.

A low temperature microgravity physics facility is being developed to allow the continuation of this research program in the International Space Station era. This new facility will allow experimenters much longer duration in a microgravity environment thereby enabling studies of more subtle principles of nature. The facility will enable two experiments to operate simultaneously for a duration of up to 6 months. Once the helium is depleted, the facility will be brought back to Earth and a new set of instruments will be integrated and prepared for operation on-orbit. The first flight of this facility will occur in 2005. Experiments selected for the first flight are the Critical Dynamics in Microgravity Experiment (DYNAMX) and the Microgravity Scaling Theory Experiment (MISTE). DYNAMX will study non-equilibrium dynamics near the superfluid transition and will explore how the detailed properties of helium are affected by the application of a symmetry breaking heat current. The principal investigator for DYNAMX is Prof. Robert Duncan from University of New Mexico. MISTE will explore detailed predictions of scaling theory and how they apply to the liquid-vapor system. MISTE is using pure helium 3 as their sample. The principal investigator for MISTE is Dr. Martin Barmatz from the Jet Propulsion Laboratory.

The second flight of the facility is planned for 2007. Candidate experiments for this flight include the Boundary Effects near the Superfluid Transition (BEST) led by Prof. Guenter Ahlers from the University of California, Santa Barbara, and the SUMO experiment mentioned previously. BEST will study finite size systems under non-equilibrium conditions by applying a heat current to samples of helium near the superfluid transition confined in various geometries.

BIOLOGICAL PHYSICS

The physical sciences form the underpinning for the life sciences and although buried within the complexity of most biological systems, the study of the physical principles that govern these biological systems will have a profound fundamental impact on our understanding of biology. Many physicists have been drawn to the study of biology by the desire to understand the mechanisms of living organisms. They have found a niche in applying their scientific methods to problems that lies at the boundaries of physics, chemistry, and biology. Some (like Francis Crick) have contributed profoundly to our understanding of life. Others have found that their skill as instrumentalists can change medicine, as evidenced by such advances as tomography and magnetic resonance imaging. While still others have used their skills in mathematics to propose theories for neural networks, electron transfer and non-linear phenomena such as heart rhythms. Working in concert with life scientists and thereby forming interdisciplinary teams, physicists can not only probe complex biological problems but also help to guide and develop new devices based upon observing biological systems. Nature abounds with examples where one or more of the underlying mechanisms governing the function of a biological process may reveal new insights into physical processes. In a variety of biological systems, the transfer of energy from one form (*i.e.* mechanical) into another (chemical) takes place. The interface between biology and physics will be a rich instructional base for the development of novel approaches for sensors and other devices.

NASA has included biological physics in the latest research solicitation. From this solicitation, NASA will select a nucleus of ground researchers that defines the program and allows us to jointly work toward establishing a space research program in the future. NASA anticipates this field to evolve into studies in the biological sciences that is in one way or another profoundly connected to the principles of physics. In such research, the understanding of the underlying physics, which may be closely tied to the effects of earth's gravity, should be moved forward. Examples of these areas of research include high-resolution measurements of the thermophysical properties of DNA, RNA and more complex assemblies, studies of molecular microstructure self-assembly. Of particular importance is the study of single molecules directly making possible a much more detailed understanding of principles of folding, unfolding, and replication. Other research examples include studies of carbon nano-tubes and determining their use in novel applications.

ACKNOWLEDGMENTS

The Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration carried out part of this research. Stimulating discussions with Michael Devirian and Lute Maleki of JPL are acknowledged.