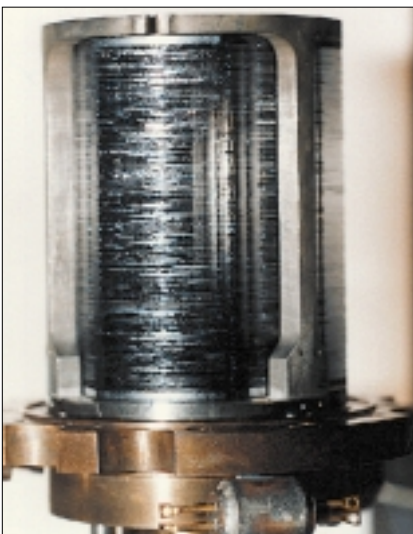


Getting down to the fundamentals

In attempting to understand its complex nature, scientists search for simple laws that not only describe the universe, but also predict behavior within it. However, discovering these laws is not enough, since simple rules do not necessarily produce simple outcomes. Fundamental physics laws give rise to complex phenomena, so it is vital to understand how these laws translate into the complexity we observe in nature.

The precision and accuracy of Earth-based measurements limit some research in fundamental physics. Conducting these experiments in space can reduce these limitations and improve results. To determine what fundamental physics research areas can best take advantage of a space environment, the Jet Propulsion Lab has developed a Fundamental Physics in

CHeX, which flew on Columbia in 1997, measured the effects of finite size on the heat capacity of helium in space. This heat capacity calorimeter contains the helium between nearly 400 thin silicon disks spaced 57 μm apart.



Space Road Map as part of its Fundamental Physics in Microgravity Research Program. The road map provides an ambitious program and identifies two primary challenges that drive lab research and prompt us to do experiments in space.

The first challenge is to explore and understand the fundamental physical laws governing matter, space, and time. By examining both the smallest and largest of our universe, we may better understand the basic laws that describe it. Several questions need to be answered:

- How broadly applicable is general relativity? Where might this theory break down?
- What is the nature of black holes? What can gravity waves tell us about the evolution of the universe?
- How can quantum theory be reconciled with gravitation?
- Do all bodies fall similarly, regardless of their make-up? Do all clocks keep the same time?
- Are there new forces that are yet to be discovered?

The second challenge is to discover and understand the organizing principles of nature from which structure and complexity emerge. By studying nature apart from Earth's gravity, one can understand how the universe developed. Again, questions arise:

- Can the simple elegance of fundamental theories be applied to complex systems?
- Is the Renormalization Group technique valid under all conditions?
- How do finite size and nonequilibrium conditions alter the properties of matter?
- How can quantum effects be used for practical devices? What are the limits of resolution of such devices?
- What is the role of symmetry (or-

der) in establishing self-organized or chaotic behavior?

- How does broken symmetry give rise to complex patterns?

To answer these questions, research is focused on three topics in modern physics: gravitational and relativistic physics, laser cooling and atomic physics, and low-temperature and condensed matter physics.

In the future, the fundamental physics discipline may explore other research areas in physics where a space environment is beneficial. Two such potential research growth areas are particle physics and biological physics.

Gravitational physics

Gravitational and relativistic physics is perhaps the most fundamental area of study. Physicists have determined that four kinds of forces operate on matter: gravity, electromagnetism, and the "strong" and "weak" forces within atoms. Gravity is the weakest yet most dominant of these, as it can act from great distances.

Every bit of matter in the universe is under the influence, even if infinitesimally, of every other bit of matter. Einstein's theory of general relativity places gravity at the heart of the structure of the universe, proposing that even its orderly space-time structure can be "warped" near a body of large mass, such as the Sun or the Earth. This warp would affect even clocks.

These changes are subtle and difficult to measure; however, 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 achieved.

Several missions and experiments designed to improve the accuracy of measuring these effects are planned or proposed. All use the large mass of the Sun, or the Earth, to measure the distortion to space-time they cause, and can only be done beyond the pull of

Earth's gravity. Two of these experiments are STEP and SUMO.

- The Satellite Test of the Equivalence Principle (STEP) will carry precision instruments to compare the gravitational and inertial mass of two test samples. Einstein's equivalence principle assumes that these two masses should be identical, but only the most accurate of measurements can validate this. STEP will improve on previous measurements a millionfold.

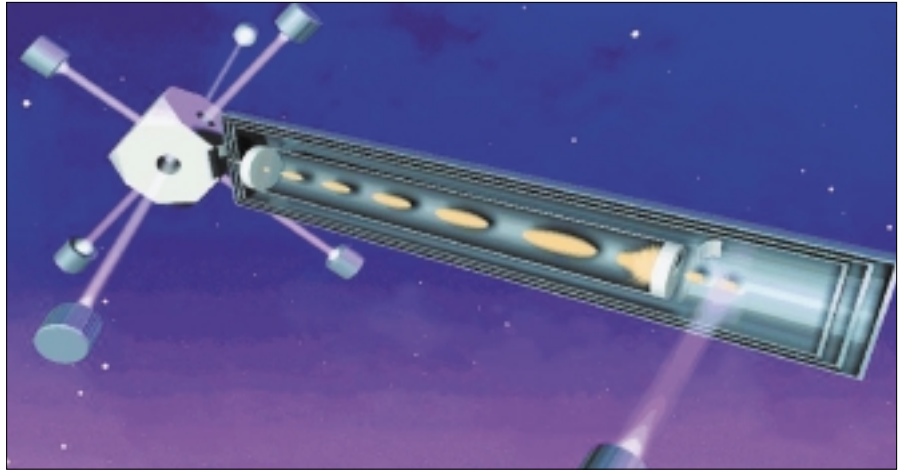
- The Superconducting Microwave Oscillator (SUMO) will place a high-precision clock in Earth orbit to test Einstein's predicted local positional invariance 100 times better than previous determinations. The frequency of the oscillator will be measured at different positions around Earth and at different levels of the local gravitational field.

Laser cooling and atomic physics

While gravitational and relativistic physics examines fundamental laws on a large scale, it is equally important to examine the tiny building blocks of matter and how they manifest the same laws. Atoms are the smallest systems through which we can study these principles. New techniques allow us to use laser light to cool and probe individual atoms. By carefully working with individual atoms, we can compare the smallest pieces of matter and the complex behavior of large systems.

Conducting these experiments in space allows us to remove the influence of gravity and manipulate matter freely, without having to counteract specimens "falling" within the instruments. By observing the behavior of atoms completely under the experimenter's control, we have the promise of novel results and new insights previously hidden from view in Earth-bound labs.

In space experiments, clouds of atoms cooled by laser light to very near absolute zero can be studied. These atoms can freely float without the forces that would be needed to



PARCS will use pulses of cooled cesium atoms aboard the ISS to develop the most accurate clock possible. NASA would make this timing signal available to researchers on the ground.

contain them on Earth. This allows measurements of higher precision and longer observation times. Cold atoms can also be used to build better clocks and frequency standards.

Several experiments are being developed in this area. For example, the Primary Atomic Reference Clock in Space (PARCS) will deepen the understanding of the basis of time. A second is defined according to the energy released by the vibration of cesium atoms. While atomic clocks on Earth do this with high precision, it is always under the influence of gravity. By operating an atomic clock in space, the definition of time and the accuracy of timekeeping can be improved. The clock will also be used to perform tests of Einstein's theory of general relativity to a much higher precision than ever previously achieved.

The Rubidium Atomic Clock Experiment will improve on the clock standard set by PARCS by exploiting the advantages of using rubidium instead of cesium. This experiment will also perform tests of Einstein's theory and will gather data on cold collisions free from Earth's gravity.

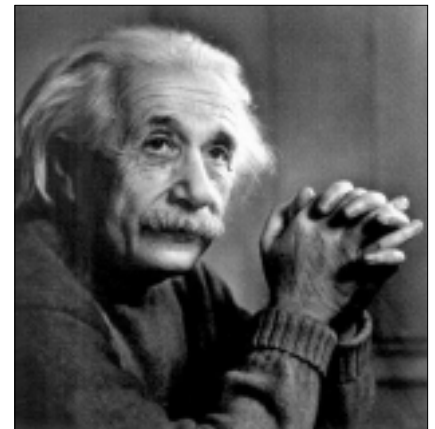
Low-temperature and condensed matter physics

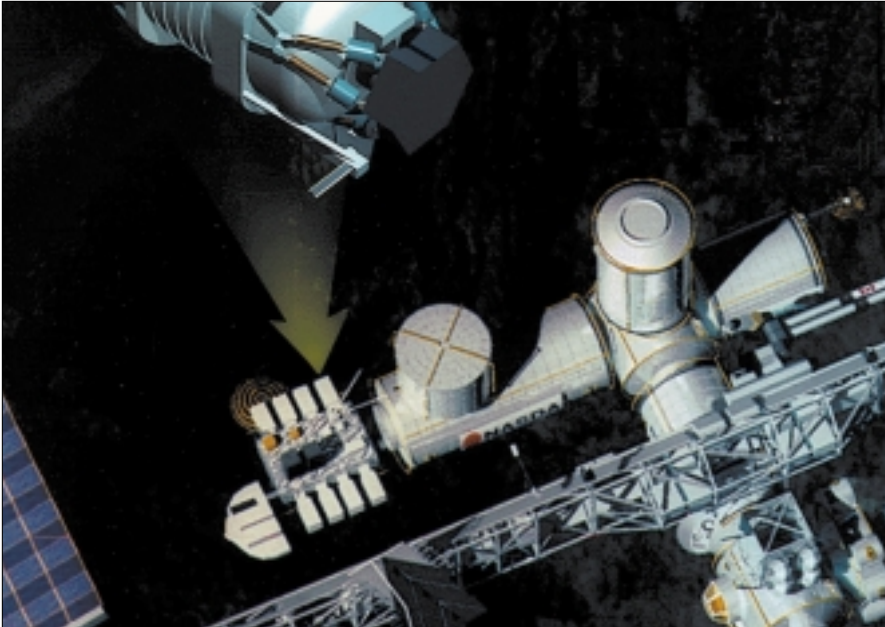
The condensed phase of simple gases provides a unique test bed for the predictions of fundamental theories. Par-

ticular combinations of pressure and temperature yield a "critical point" where there is no distinction between different phases of matter. For example, the difference between the liquid and vapor phases disappears at a liquid/vapor critical point.

This unusual behavior is inherent in the properties of ordinary gases and other substances. Many of these phenomena can best be studied at low temperatures, where thermal noise is significantly reduced. By understanding the complex critical behavior of low-temperature materials such as liquid helium, one can learn more about critical properties of metallic alloys, magnetic materials, groups of fundamental particles, and larger scale phe-

Albert Einstein





The Low Temperature Microgravity Physics Facility will provide researchers in fundamental physics an environment within a few degrees of absolute zero for experiments lasting many months.

nomena such as the percolation of water or the movement of weather patterns. The unique properties that exist near critical points can also be used to prepare samples in well-known conditions to test effects of a boundary on matter and to study nonequilibrium phenomena.

Since critical behavior is a function of temperature and pressure, the pressure must be uniform throughout the sample. Gravity causes a difference in pressure, so the critical phenomena can only be observed in a very small region. In space, the pressure can be uniform across the sample and more comprehensive measurements can be made. Furthermore, a drop of sample material can be freely suspended, without the interference of a container. This freedom from external constraints is not possible in an Earth-bound lab. Several experiments are being developed in this area:

- Critical Dynamics in Microgravity will study a sample of helium at the critical transition point between an ordinary liquid and a superfluid. A small heat current will be applied to allow studies of nonequilibrium phenomena.

- The Microgravity Scaling Theory Experiment will measure many properties of helium at the critical transition

from liquid to gas. The measurements will be used to determine scaling relations between the different properties.

- The Superfluid Universality Experiment will test the principle that some key properties of matter are invariant under a wide range of conditions. Helium near the critical point will be used for this study.

- Experiments Along Coexistence Near Tricriticality will perform a rigorous examination of helium mixtures at the critical point where normal liquid, superfluid, and instability can coexist.

- Boundary Effects on the Superfluid Transition will provide the first test of the theory that describes the effects of size and solid boundaries on thermal flow near a phase transition.

Research to date

All of the space research accomplishments in the microgravity physics discipline have been achieved aboard the Space Shuttle. Although this program has been productive, research has been limited by experimentation times of less than 10 days and a lack of flight opportunities. Researchers are looking forward to the longer experimentation times the International Space Station will provide.

- The Lambda Point Experiment, or

LPE, which flew as part of the first U.S. Microgravity Payload (USMP-1) mission in 1992, confirmed the validity of the Renormalization Group theory of critical phenomena with unprecedented accuracy by probing 100 times closer to the critical region than ever before. The RG theory constitutes one of the greatest achievements in the field of theoretical physics in the past 30 years.

The RG concept has opened up the possibility of solving a variety of problems that are among the most difficult ones in theoretical physics. Applications of the RG theory range from elementary particle physics (quark confinement, gauge theories), to statistical physics (critical phenomena, percolation, and pattern formation), and include condensed matter physics (inter-active Fermi systems, localization, and turbulence).

Therefore, a successful quantitative test of the predictions of RG theory by the LPE has far-reaching implications. They go well beyond the physics of liquid helium or even the field of critical phenomena and may be regarded as a major success of the interaction between experimental and theoretical physics in general.

The increased understanding and use of the RG treatment can be applied to disciplines such as percolation, pattern formation, and evolution of turbulence. This will help scientists develop better models for how water seeps through soil, how frost heaving occurs in arctic climates, and how turbulent weather systems evolve.

Other significant contributions by the LPE were an unambiguous demonstration that gravitational smearing can be removed in a microgravity environment and that very complex measurements can be performed in the space environment.

- The Critical Fluid Light Scattering Experiment (ZENO), which flew both on USMP-2 and USMP-3, measured the decay rates and the correlation length of the density fluctuations in a sample of xenon very near the liquid-gas critical point. ZENO employed laser light-scattering techniques as its main data-gathering mode. Results essentially agreed with theoretical expectations,

although resolution of the data was limited by an unanticipated local heating effect near the optical windows.

•The Critical Viscosity of Xenon Experiment used a novel overdamped oscillator aboard the Shuttle to measure the viscosity of xenon near the liquid-vapor critical point in the frequency range from 2 to 12 Hz. The measured viscosity divergence agrees with the RG calculation. Viscoelastic behavior was found to be an increasing contribution to the viscosity as the critical point is approached. A reflight of the experiment is planned to study other aspects of xenon's viscosity near the critical point.

•The Confined Helium Experiment (CHeX) flew as part of USMP-4 in November 1997. The experiment used high-resolution techniques similar to LPE to investigate how the thermodynamic properties of helium are af-

ected when its thickness is made very small. This "finite size effect" influences the properties of all materials when they are made sufficiently small. For example, it has been predicted that within another decade or so, computer chips will reach the point where finite size effects will have to be taken into account.

The data obtained from the CHeX flight will be invaluable for this, and the experiment operated very well. The primary limitations on the measurements were the time available at the operating temperature and disturbances in the microgravity environment. Results were found to be in much better agreement with theoretical predictions than with extrapolations based on ground data, confirming earlier suspicions that the ground-based data were not a reliable test of theory. However, some devia-

tions from the model were noted and are currently being analyzed.



The Fundamental Physics in Microgravity Research Program has been experiencing growth over the past few years. Flight experiments to date have been accomplished exclusively on the Shuttle, but plans are under way to allow experimenters long-duration access to space using the space station. The fundamental physics community is looking forward to taking advantage of this new opportunity. The Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA, carried out part of the research reported here.

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