

SPACE-BASED RESEARCH IN FUNDAMENTAL PHYSICS AND QUANTUM TECHNOLOGIES

SLAVA G. TURYSHEV*, ULF E. ISRAELSSON, MICHAEL SHAO and NAN YU

*Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Drive, Pasadena, CA 91109-0899, USA
turyshev@jpl.nasa.gov

ALEXANDER KUSENKO and EDWARD L. WRIGHT

*Department of Physics and Astronomy, University of California,
Los Angeles, CA 90095-1547, USA*

C. W. FRANCIS EVERITT, MARK KASEVICH, JOHN A. LIPA
and JOHN C. MESTER

*Hansen Experimental Physics Laboratory,
Department of Physics, Stanford University,
Stanford, CA 94305-4085, USA*

ROBERT D. REASENBERG and RONALD L. WALSWORTH

*Harvard-Smithsonian Center for Astrophysics,
60 Garden Street, Cambridge, MA 02138, USA*

NEIL ASHBY

*Department of Physics, University of Colorado,
Boulder, CO 80309-0390, USA*

HARVEY GOULD

*Lawrence Berkeley National Laboratory,
One Cyclotron Road, Berkeley, CA 94720, USA*

HO JUNG PAIK

*Department of Physics, University of Maryland,
College Park, MD 20742-4111, USA*

Space offers unique experimental conditions and a wide range of opportunities to explore the foundations of modern physics with an accuracy far beyond that of ground-based experiments. Space-based experiments today can uniquely address important questions related to the fundamental laws of Nature. In particular, high-accuracy physics experiments in space can test relativistic gravity and probe the physics beyond the Standard

Model; they can perform direct detection of gravitational waves and are naturally suited for investigations in precision cosmology and astroparticle physics. In addition, atomic physics has recently shown substantial progress in the development of optical clocks and atom interferometers. If placed in space, these instruments could turn into powerful high-resolution quantum sensors greatly benefiting fundamental physics.

We discuss the current status of space-based research in fundamental physics, its discovery potential, and its importance for modern science. We offer a set of recommendations to be considered by the upcoming National Academy of Sciences' Decadal Survey in Astronomy and Astrophysics. In our opinion, the Decadal Survey should include space-based research in fundamental physics as one of its focus areas. We recommend establishing an Astronomy and Astrophysics Advisory Committee's interagency "Fundamental Physics Task Force" to assess the status of both ground- and space-based efforts in the field, to identify the most important objectives, and to suggest the best ways to organize the work of several federal agencies involved. We also recommend establishing a new NASA-led interagency program in fundamental physics that will consolidate new technologies, prepare key instruments for future space missions, and build a strong scientific and engineering community. Our goal is to expand NASA's science objectives in space by including "laboratory research in fundamental physics" as an element in the agency's ongoing space research efforts.

Keywords: Fundamental physics in space; general and special theories of relativity; Standard Model extensions; gravitational waves; cosmology; astroparticle physics; cold atoms; quantum sensors; science policy.

1. Introduction

Today, physics stands on the threshold of major discoveries. Growing observational evidence points to the need for new physics. Efforts to discover new fundamental symmetries, investigations of the limits of established symmetries, tests of the general theory of relativity, searches for gravitational waves, and attempts to understand the nature of dark matter were among the topics that had been the focus of the scientific research at the end of the last century. These efforts have further intensified with the discovery of dark energy made in the late 1990's, which triggered many new activities aimed at answering important questions related to the most fundamental laws of Nature.^{1,2}

The 2003 Report "Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century",^a issued by the National Academy of Science's Board on Physics and Astronomy, identified the most critical research areas that require support to meet the profound challenges facing physics and astronomy today. It became a blueprint for multiagency efforts at the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the US Department

^a"Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century," Board of Physics and Astronomy (The National Academies Press, 2003). In particular, the report identified the following eleven questions that are shaping the modern research in astronomy, astrophysics, and cosmology: (i) What is the dark matter? (ii) What is the nature of the dark energy? (iii) How did the Universe begin? (iv) Was Einstein right about gravity? (v) How have neutrinos shaped the Universe? (vi) What are nature's most energetic particles? (vii) Are protons unstable? (viii) What are the new states of matter? (ix) Are there more space-time dimensions? (x) How were elements from iron to uranium made? (xi) Is a new theory of matter and light needed?

of Energy (DOE), aiming at meeting the evident challenges in our understanding of matter, space, time, and the Universe. Although the report provided a list of strategic recommendations allowing NASA, NSF, and DOE to select various fundamental physics projects among their top priorities, more work is needed. In addition, some of the science opportunities, including those offered by space-based laboratory research in fundamental physics,^b were overlooked.

The nature of matter on the Earth and the laws governing it were discovered in laboratories on the Earth. To understand the nature of matter in the Universe and the laws governing it, we must move our laboratories outside the Earth. There are two approaches to physics research in space: one can detect and study signals from remote astrophysical objects (the “observatory” mode) or one can perform carefully designed experiments in space (the “laboratory” mode). The two methods are complementary and the latter, which is the focus of this paper, has the advantage of utilizing the well-understood and controlled environments of a space-based laboratory. Existing technologies allow one to take advantage of the unique environments found only in space, including variable gravity potentials, large distances, high velocity and low acceleration regimes, availability of pure geodetic trajectories, microgravity and thermally stable environments (see App. A for details). With recent advances in several applied physics disciplines, new instruments and technologies have become available. These include highly accurate atomic clocks, optical frequency combs, atom interferometers, drag-free technologies, low-thrust micropropulsion techniques, optical transponders, long-baseline optical interferometers, etc.³ Some of these instruments are already space-qualified, thereby enabling a number of high-precision investigations in laboratory fundamental physics in space. As a result, space-based experiments are capable of reaching very high accuracies in testing the foundations of modern physics. Furthermore, because experimental physics research complements the observational disciplines of astronomy and astrophysics, it is possible that independent confirmation by space-based fundamental physics experiments may be required to fully explain any future observations of, for example, “detection” of dark matter particles or identification of the source of dark energy.

As was demonstrated at the two recent international “Quantum to Cosmos” workshops,^c there is a growing community of researchers worldwide interested in performing carefully-thought-out laboratory physics experiments to address some of the modern challenges that physics faces today, by utilizing the benefits of a

^bReprioritization of space efforts initiated by NASA in 2004 led to the termination of a successful “Microgravity and Fundamental Physics” program managed by the former Office of Biological and Physics Research. As a result, no program for space-based laboratory research in fundamental physics currently exists.

^c“From Quantum to Cosmos: Fundamental Physics Research in Space,” Airlie Center, Warrenton, VI, USA, May 21–24, 2006; <http://physics.jpl.nasa.gov/quantum-to-cosmos>; “From Quantum to Cosmos — II: Space-Based Research in Fundamental Physics & Quantum Technologies,” Bremen, Germany, June 10–13, 2007; <http://www.zarm.uni-bremen.de/Q2C2>

space environment. The recent report of the Committee on Atomic, Molecular, and Optical Sciences (AMO2010)^d emphasized the significant discovery potential of future space-based experiments using new technologies and laboratory techniques, especially in their ability to probe the fundamental laws of Nature at the highest levels of accuracy. The 2006 Report from the Dark Energy Task Force also endorsed the important role of gravitational experiments as an effective means to discover new physics that might also be at play on cosmological scales and that might be responsible for the small observed acceleration of the cosmological expansion of the Universe.^e

The 2005 Position Paper by the European Physical Society (EPS)^f highlighted the strong discovery potential of space-based experiments in fundamental physics and argued for space flight opportunities specifically dedicated to this area of research. The EPS' recommendations further supported the efforts of the European Space Agency's (ESA) Fundamental Physics Advisory Group (FPAG)^g — an influential group of European scientists that advises ESA on scientific direction in fundamental physics research in space. As a result, ESA's Cosmic Vision 2015–25 process^h marks a breakthrough for fundamental physics: for the first time, a major space agency has given full emphasis in its forward planning to missions dedicated to exploring and advancing the limits of our understanding of many fundamental physics issues, including gravitation, unified theories, and quantum theory. NASA would benefit from a similar bold and visionary approach.

This paper is organized as follows. In Sec. 2 we discuss the status of space-based research in fundamental physics, present examples of experiments that could provide significant advances in the field in the near future, and emphasize scientific and societal benefits of this space science discipline. Each subsection discusses the significance of physics to be addressed, emphasizes the role of space for a particular kind of experiment, and presents a list of potential missions. In Sec. 3 we argue for coordinated multiagency support for space-based research in fundamental physics and present a set of policy recommendations which, if adopted, would re-energize the entire field of research in fundamental physics. In App. A we present the benefits

^d“Controlling the Quantum World,” Committee on Atomic, Molecular, and Optical Sciences (AMO2010), Board on Physics and Astronomy (The National Academies of Press, July 2006). An Electronic version of the report is available from the NAP website http://www.nap.edu/catalog.php?record_id=11705

^e“Report from the Dark Energy Task Force,” June 6, 2006, at [astro-ph/0609591]; an electronic version of the Report is available at http://www.nsf.gov/mps/ast/aaac/dark-energy-task_force/report/detf_final_report.pdf

^f“The Need for Space Flight Opportunities in Fundamental Physics,” a Position Paper of the European Physical Society (EPS), published on the occasion of the centenary of Albert Einstein's *annus mirabilis* (2005) and available from EPS' website: http://www.eps.org/papers_position/paper_index.html

^gWebpage of ESA's Fundamental Physics Advisory Group (FPAG): <http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=33212>

^hFor details on the ESA's Cosmic Vision 2015–25 process and the recent Call for Mission Proposals, visit <http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=40794>

of space-based deployment for precision physics experiments. In App. B we discuss the history of fundamental physics research at NASA and its current programmatic status.

2. Fundamental Physics in Space: Great Potential for Discovery

The fundamental physical laws of Nature are described by the Standard Model and Einstein's general theory of relativity. The Standard Model specifies the families of fermions (leptons and quarks) and their interactions by vector fields which transmit the strong, electromagnetic, and weak forces. General relativity is a tensor field theory of gravity with universal coupling to the particles and fields of the Standard Model.

Despite the beauty and simplicity of general relativity and the success of the Standard Model, our present understanding of the fundamental laws of physics has several shortcomings. Although recent progress in string theory^{4,5} is very encouraging, the search for a realistic theory of quantum gravity remains a challenge. This continued inability to merge gravity with quantum mechanics indicates that the pure tensor gravity of general relativity needs modification or augmentation. It is now believed that new physics is needed to resolve this issue. Recent work on scalar-tensor extensions of gravity and brane-world gravitational models, and also efforts to modify gravity on large scales, motivate new searches for experimental signatures of very small deviations from general relativity on various scales, including on the spacecraft-accessible distances in the solar system.

In addition, the Higgs boson, the particle predicted by the Standard Model, has yet to be discovered. It is widely expected that the Large Hadron Collider (LHC) at CERN will be able to probe the nature of electroweak symmetry breaking and verify the prediction of the Higgs boson in the near future. In addition to this long-anticipated discovery, one hopes to find new physics beyond the Standard Model at the LHC. The new physics could explain the hierarchy of scales and resolve the naturalness problems associated with the Standard Model. Physics beyond the Standard Model is required to explain dark matter and the matter-antimatter asymmetry of the Universe. Furthermore, the Standard Model does not offer an explanation for the observed spectrum of fermion masses and their mixing angles. The exact conservation of the charge-conjugation and parity (CP) symmetries in strong interactions appears mysterious in the Standard Model, because it requires the exact cancellation of two seemingly unrelated contributions to the measurable quantity θ , which *a priori* can take any value between 0 and 2π . New physics is expected to shed light on this mystery as well.

Theoretical models of the kinds of new physics that can solve the problems above typically involve new interactions, some of which could manifest themselves as violations of the equivalence principle, variation of fundamental constants, modification of the inverse square law of gravity at short distances, Lorentz symmetry breaking, as well as large-scale gravitational phenomena. Each of these manifestations

offers an opportunity for space-based experimentation and, hopefully, a major discovery.

Our objective is to emphasize the uniqueness and advantages of space as an experimental site when addressing the challenges above and, thereby, to demonstrate that the space-based laboratory research in fundamental physics is a unique area of space science that offers the best possible science investigations to be done from space.

In this section we discuss the current status of space-based research in fundamental physics, including gravitational experiments, the search for new physics beyond the Standard Model, efforts at direct detection of gravitational waves and their use as a probe of physics in the strong gravitational limit, and also cosmology, astroparticle, and atomic physics.

2.1. Search for a new theory of gravity and cosmology with experiments in space

The recent remarkable progress in observational cosmology has subjected the general theory of relativity to increased scrutiny by suggesting a non-Einsteinian model of the Universe’s evolution. From a theoretical standpoint, the challenge is even stronger — if gravity is to be quantized, general relativity will have to be modified. Furthermore, recent advances in the scalar-tensor extensions of gravity^{6–11} have motivated searches for very small deviations from Einstein’s theory, at the level of three-to-five orders of magnitude below the level currently tested by experiment.^{12,13} For many of the modern gravitational experiments, space is an essential laboratory that, in combination with modern technologies, offers unique conditions that are much purer than those achievable in the best ground-based laboratories.^{14,15}

We discuss below a number of laboratory experiments that benefit from the space deployment.

2.1.1. Test of Einstein’s equivalence principle

Einstein’s equivalence principle (EP)^{6,7,16,17} is at the foundation of Einstein’s general theory of relativity; therefore, testing the principle is very important. The EP includes three hypotheses: (i) local Lorentz invariance (LLI), (ii) local position invariance (LPI), and (iii) universality of free fall (UFF). Using these three hypotheses Einstein deduced that gravity is a geometric property of space–time.¹⁸ One can test both the validity of the EP and of the field equations that determine the geometric structure created by a mass distribution. We shall discuss below two different “flavors” of the principle: the weak and the strong forms of the EP that are currently tested in various experiments performed with laboratory testmasses and with bodies of astronomical sizes.¹⁷

The *weak form of the EP* (the WEP) states that the gravitational properties of strong and electroweak interactions obey the EP. In this case the relevant test-body

differences are their fractional nuclear-binding differences, their neutron-to-proton ratios, their atomic charges, etc. Furthermore, the equality of gravitational and inertial masses implies that different neutral massive test bodies will have the same free fall acceleration in an external gravitational field, and therefore in freely falling inertial frames the external gravitational field appears only in the form of a tidal interaction.¹⁹ Apart from these tidal corrections, freely falling bodies behave as if external gravity was absent.²⁰

General relativity and other metric theories of gravity assume that the WEP is exact. However, extensions of the Standard Model of particle physics that contain new macroscopic range quantum fields predict quantum exchange forces that generically violate the WEP because they couple to generalized “charges” rather than to mass/energy as does gravity.^{6–11}

Currently, the most accurate results in testing the WEP were reported by ground-based laboratories.^{17,21} The most recent result^{22,23} for the fractional differential acceleration between beryllium and titanium test bodies was given as $\Delta a/a = (1.0 \pm 1.4) \times 10^{-13}$. Significant improvements in the tests of the EP are expected from dedicated space-based experiments.

The composition independence of acceleration rates of various masses toward the Earth can be tested to many-additional-orders-of-magnitude precision in space-based laboratories, down to levels where some models of the unified theory of quantum gravity, matter, and energy suggest a possible violation of the EP.^{6–11} Interestingly, in some scalar-tensor theories, the strength of EP violations and the magnitude of the fifth force mediated by the scalar can be drastically larger in space compared with that on the ground,^{24–26} which further justifies a space deployment. Importantly, many of these theories predict observable violations of the EP at various levels of accuracy, ranging from 10^{-13} down to 10^{-16} . Therefore, even a confirmation of no EP violation will be exceptionally valuable, placing useful constraints on the range of possibilities in the development of a unified physical theory.

Compared with Earth-based laboratories, experiments in space can benefit from a range of conditions including free fall and significantly reduced contributions due to seismic, thermal, and many other sources of non gravitational noise (see App. A). As a result, there are many experiments proposed to test the EP in space. We present below a partial list of these missions. Furthermore, to illustrate the use of different technologies, we present only the most representative concepts.

The MicroSCOPE missionⁱ is a room temperature EP experiment in space relying on electrostatic differential accelerometers.²⁷ It is currently under development by CNES^j and ESA, and is scheduled for launch in 2010. The design goal is to achieve a differential acceleration accuracy of 10^{-15} . MicroSCOPE’s electrostatic

ⁱMicro-Satellite à traînée Compensée pour l’Observation du Principe d’Equivalence (MicroSCOPE). For more details, see <http://microscope.onera.fr>

^jCentre National d’Etudes Spatiales (CNES) — the French Space Agency. See website: <http://www.cnes.fr>

differential accelerometers are based on flight heritage designs from the CHAMP, GRACE, and GOCE missions.^k

The Principle of Equivalence Measurement (POEM) experiment²⁸ is a ground-based test of the WEP, now under development. It will be able to detect a violation of the EP with a fractional acceleration accuracy of 5 parts in 10^{14} in a short (a few days) experiment and 3–10-fold better in a longer experiment. The experiment makes use of optical distance measurement (by TFG laser gauge²⁹) and will be advantageously sensitive to short-range forces with a characteristic length scale of $\lambda < 10$ km. SR-POEM, a POEM-based proposed room temperature test of the WEP during a suborbital flight on a sounding rocket, was recently also presented.³⁰ It is anticipated to be able to search for a violation of the EP with a single-flight accuracy of one part in 10^{16} . Extension to higher accuracy in an orbital mission is under study. Similarly, the Space Test of Universality of Free Fall (STUFF)³¹ is a recent study of a space-based experiment that relies on optical metrology and proposes to reach an accuracy of one part in 10^{17} in testing the EP in space.

The Quantum Interferometer Test of the Equivalence Principle (QuITE)³² is a proposed test of the EP with cold atoms in space. QuITE intends to measure the absolute single-axis differential acceleration with an accuracy of one part in 10^{16} , by utilizing two colocated matter wave interferometers with different atomic species.¹ It will improve the current EP limits set in similar experiments conducted in ground-based laboratory conditions^{33,34,m} by nearly seven-to-nine orders of magnitude. Similarly, the ICE project,ⁿ supported by CNES in France, aims to develop a high-precision accelerometer based on coherent atomic sources in space,³⁵ with an accurate test of the EP being one of the main objectives.

The Galileo Galilei (GG) mission^{36,37} is an Italian space experiment^o proposed to test the EP at room temperature with an accuracy of one part in 10^{17} . The key instrument of GG is a differential accelerometer made up of weakly coupled coaxial, concentric test cylinders rapidly spinning around the symmetry axis and sensitive in the plane perpendicular to it. GG is included in the National Aerospace Plan of the Italian Space Agency (ASI) for implementation in the near future.

The Satellite Test of Equivalence Principle (STEP) mission^{38–40} is a proposed test of the EP to be conducted from a free-falling platform in space provided by

^kSeveral gravity missions were recently developed by the German National Research Center for Geosciences (GFZ). Among them are CHALLENGING Minisatellite Payload (CHAMP), GRACE (Gravity Recovery and Climate Experiment Mission; together with NASA), and GOCE (Global Ocean Circulation Experiment; together with ESA and other European countries). See http://www.gfz-potsdam.de/pb1/op/index_GRAM.html

^lCompared to the ground-based conditions, space offers a factor-of-nearly- 10^3 improvement in the integration times in observation of the free-falling atoms (i.e. progressing from ms to s). The longer integration times translate into the accuracy improvements (see discussion in Sec. 2.6.3).

^mIts ground-based analog, called the “Atomic Equivalence Principle Test (AEPT),” is being built at Stanford University. AEPT is designed to reach a sensitivity of one part in 10^{15} .

ⁿInterférométrie à Source Cohérente pour Applications dans l’Espace (ICE). See <http://www.ice-space.fr>

^oGalileo Galilei (GG) website: <http://eotvos.dm.unipi.it/nobili>

a drag-free spacecraft orbiting the Earth. STEP will test the composition independence of gravitational acceleration for cryogenically controlled test masses by searching for a violation of the EP with a fractional acceleration accuracy of one part in 10^{18} . As such, this ambitious experiment will be able to test very precisely for the presence of any new nonmetric, long-range physical interactions.

In its *strong form the EP* (SEP) is extended to cover the gravitational properties resulting from gravitational energy itself.¹⁷ In other words, it is an assumption about the way that gravity begets gravity, i.e. about the nonlinear property of gravitation. Although general relativity assumes that the SEP is exact, alternate metric theories of gravity such as those involving scalar fields, and other extensions of gravity theory, typically violate the SEP. For the SEP case, the relevant test body differences are the fractional contributions to their masses by gravitational self-energy. Because of the extreme weakness of gravity, SEP test bodies must have astronomical sizes.

Currently, the Earth–Moon–Sun system provides the best solar system arena for testing the SEP. Lunar laser ranging (LLR) experiments involve reflecting laser beams off retroreflector arrays placed on the Moon by the Apollo astronauts and by an unmanned Soviet lander.^{16,17} Recent solutions using LLR data give $(-0.8 \pm 1.3) \times 10^{-13}$ for any possible inequality in the ratios of the gravitational and inertial masses for the Earth and Moon. This result, in combination with laboratory experiments on the WEP, yields a SEP test of $(-1.8 \pm 1.9) \times 10^{-13}$ that corresponds to the value of the SEP violation parameter of $\eta = (4.0 \pm 4.3) \times 10^{-4}$, where $\eta = 4\beta - \gamma - 3$ and both β and γ are post-Newtonian parameters.^{17,41–45}

With the new APOLLO^P facility (jointly funded by NASA and NSF; see details in Refs. 46 and 47), the LLR science is going through a renaissance. APOLLO's 1-mm-range precision will translate into order-of-magnitude accuracy improvements in the test of the WEP and SEP (leading to accuracy at the level of $\Delta a/a \lesssim 1 \times 10^{-14}$ and $\eta \lesssim 2 \times 10^{-5}$ respectively), in the search for variability of Newton's gravitational constant (see Sec. 2.1.2), and in the test of the gravitational inverse square law (see Sec. 2.1.3) on scales of the Earth–Moon distance (the anticipated accuracy is 3×10^{-11}).⁴⁷

The next step in this direction is interplanetary laser ranging,^{48–53} for example to a lander on Mars. The technology is available to conduct such measurements with a-few-picoseconds timing precision which could translate into centimeter-class accuracies achieved in ranging between the Earth and Mars. The resulting Mars Laser Ranging (MLR) experiment could test the weak and strong forms of the EP with an accuracy at the 3×10^{-15} and 2×10^{-6} levels respectively, to measure the PPN parameter γ (see Sec. 2.1.4) with an accuracy below the 10^{-6} level, and to test the gravitational inverse square law at ~ 2 AU distances with an accuracy of 1×10^{-14} , thereby greatly improving the accuracy of the current tests.⁵¹ MLR could

^PThe Apache Point Observatory Lunar Laser-ranging Operations (APOLLO) is the new LLR station that was recently built in New Mexico and successfully initiated operations in 2006.

also advance research in several areas of science, including remote sensing geodesic and geophysical studies of Mars.

Furthermore, with the recently demonstrated capabilities of reliable laser links over large distances (e.g. tens of millions of kilometers) in space,^{48–50} there is a strong possibility of improving the accuracy of gravity experiments with precision laser ranging over interplanetary scales.^{51–53} Science justification for such an experiment is strong, the required technology is space-qualified and some components have already flown in space. By building MLR, our very best laboratory for gravitational physics will be expanded to interplanetary distances, representing an upgrade in both the scale and the precision of this promising technique.

The experiments above are examples of the rich opportunities offered by the fundamental physics community to explore the validity of the EP. These experiments could potentially offer up-to five-orders-of-magnitude improvement over the accuracy of the current tests of the EP. Such experiments would dramatically enhance the range of validity for one of the most important physical principles, or they could lead to a spectacular discovery.

2.1.2. *Test of the variation of fundamental constants*

Dirac’s 70-year-old idea of cosmic variation of physical constants has been revisited with the advent of models unifying the forces of Nature based on the symmetry properties of possible extra dimensions, such as the Kaluza–Klein-inspired theories, Brans–Dicke theory, and supersymmetry models. Alternative theories of gravity¹⁸ and theories of modified gravity⁵⁴ include cosmologically evolving scalar fields that lead to variability of the fundamental constants. Furthermore, it has been hypothesized that a variation of the cosmological scale factor with the epoch could lead to temporal or spatial variation of the physical constants, specifically the gravitational constant, G , the fine-structure constant, α , and the electron–proton mass ratio (m_e/m_p).

In general, the constraints on the variation of fundamental constants can be derived from a number of gravitational observations, such as the test of the universality of free fall, the motion of the planets in the solar system, stellar and galactic evolutions. They are based on the comparison of two time scales, the first (gravitational time) dictated by gravity (ephemeris, stellar ages, etc.) and the second (atomic time) determined by a nongravitational system (e.g. atomic clocks).^{55,56} For instance, planetary and spacecraft ranging, neutron-star-binary observations, paleontological and primordial nucleosynthesis data allow one to constrain the relative variation of G .^{57,58} Many of the corresponding experiments could reach a much higher precision if performed in space.

A possible variation of Newton’s gravitational constant G could be related to the expansion of the Universe depending on the cosmological model considered. Variability in G can be tested in space with a much greater precision than on the Earth.^{16,57,58} For example, a decreasing gravitational constant, G , coupled

with angular momentum conservation is expected to increase a planet's semimajor axis, a , as $\dot{a}/a = -\dot{G}/G$. The corresponding change in the orbital phase grows quadratically with time, providing strong sensitivity to the effect of \dot{G} .

Space-based experiments using lunar and planetary ranging measurements are currently the best means of searching for very small spatial or temporal gradients in the values of G .^{16,17} Thus, recent analysis of LLR data strongly limits such variations and constrains a local (~ 1 AU) scale expansion of the solar system as $\dot{a}/a = -\dot{G}/G = -(5 \pm 6) \times 10^{-13} \text{ yr}^{-1}$, including that due to cosmological effects.^{41,59} Interestingly, the achieved accuracy in \dot{G}/G implies that, if this rate is representative of our cosmic history, then G has changed by less than 1% over the 13.4 Gyr age of the Universe.

The ever-extending LLR data set and increase in the accuracy of lunar ranging (i.e. APOLLO) could lead to significant improvements in the search for variability of Newton's gravitational constant; an accuracy at the level of $\dot{G}/G \sim 1 \times 10^{-14} \text{ yr}^{-1}$ is feasible with LLR.⁵¹ High-accuracy timing measurements of binary and double pulsars could also provide a good test of the variability of the gravitational constant.^{60,61}

The current limits on the evolution of α are established by laboratory measurements, studies of the abundances of radioactive isotopes and those of fluctuations in the cosmic microwave background, as well as other cosmological constraints (for-review see Refs. 57 and 58). Laboratory experiments are based on the comparison either of different atomic clocks or of atomic clocks with ultrastable oscillators. They also have the advantage of being more reliable and reproducible, thus allowing better control of the systematics and better statistics compared with other methods. Their evident drawback is their short time scales, fixed by the fractional stability of the least precise standards. These time scales usually are of the order of a month to a year, so that the obtained constraints are restricted to the instantaneous variation today. However, the shortness of the time scales is compensated by a much higher experimental sensitivity.

There is a connection between the variation of the fundamental constants and a violation of the EP; in fact, the former almost always implies the latter.⁹ For example, should there be an ultralight scalar particle, its existence would lead to variability of the fundamental constants, such as α and m_e/m_p . Because masses of nucleons are α -dependent, by coupling to nucleons this particle would mediate an isotope-dependent long-range force.^{8,9,57,58,62-64} The strength of the coupling is within a few of orders of magnitude from the existing experimental bounds for such forces; thus, the new force can potentially be measured in precision tests of the EP. Therefore, the existence of a new interaction mediated by a massless (or very-low-mass) time-varying scalar field would lead to both variation of the fundamental constants and violation of the WEP, ultimately resulting in observable deviations from general relativity.

⁹Note that the converse is not necessarily true: the EP may be violated without any observable variation of fundamental constants.

Following the arguments above, for macroscopic bodies, one expects that their masses depend on all the coupling constants of the four known fundamental interactions, which has profound consequences concerning the motion of a body. In particular, because the α dependence is *a priori* composition-dependent, any variation of the fundamental constants will entail a violation of the universality of free fall.^{57,58} This allows one to compare the ability of two classes of experiments — clock-based and EP-testing ones — to search for variation of the parameter α in a model-independent way.⁶¹ EP experiments have been superior performers. Thus, analysis of the frequency ratio of the 282 nm $^{199}\text{Hg}^+$ optical clock transition to the ground state hyperfine splitting in ^{133}Cs was recently used to place a limit on its fractional variation of $\dot{\alpha}/\alpha \leq 1.3 \times 10^{-16} \text{ yr}^{-1}$.⁶⁵ At the same time, the current accuracy of the EP tests¹⁷ already constrains the variation as $\Delta\alpha/\alpha \leq 10^{-10} \Delta U/c^2$, where ΔU is the change in the gravity potential. Thus, for ground-based experiments (for which the variability in the gravitational potential is due to the orbital motion of the Earth) in one year the quantity U_{Sun}/c^2 varies by 1.66×10^{-10} , and so a ground-based clock experiment must be able to measure fractional frequency shifts between clocks to a precision of a part in 10^{20} in order to compete with EP experiments on the ground.⁶¹

On the other hand, sending atomic clocks on a spacecraft to within a few solar radii of the Sun where the gravitational potential grows to $10^{-6}c^2$ could, be a competitive experiment if the relative frequencies of different on-board clocks could be measured to a precision better than a part in 10^{16} . Such an experiment would allow a direct measurement of any α variation, thus further motivating the development of space-qualified clocks. With their accuracy surpassing the 10^{-17} level in the near future, optical clocks may be able to provide the needed capabilities to directly test the variability of the fine-structure constant (see Sec. 2.6.1 for details).

SpaceTime is a proposed atomic clock experiment designed to search for a variation of the fine-structure constant with a detection sensitivity of $\dot{\alpha}/\alpha \sim 10^{-20} \text{ yr}^{-1}$ and will be carried out on a spacecraft that flies to within six solar radii of the Sun.^{58,66} The test relies on an instrument utilizing a triclock assembly that consists of three trapped-ion clocks based on mercury, cadmium, and ytterbium ions that are placed in the same vacuum, thermal, and magnetic field environment. Such a configuration allows a differential measurement of the frequency of the clocks, and the cancellation of perturbations common to the three. For alkali atoms, the sensitivity of different clocks, based on atoms of different Z , to a change in the fine-structure constant displays specific signatures. In particular, the Casimir correction factor, $F(\alpha Z)$, leads to the differential sensitivity in the alkali microwave hyperfine clock transition frequencies. As a result, different atomic systems with different Z display different frequency dependencies on a variation of α through the αZ -dependent terms. A direct test for a time variation of α can then be devised through a comparison of two clocks, based on two atomic species with different atomic number, Z . This is a key feature of the SpaceTime instrument which, in conjunction with the individual sensitivity of each atomic species to an α variation, can produce clear

and unambiguous results. Observation of any frequency drift between the three pairs of clocks in response to the change in gravitational potential, as the triclock instrument approaches the Sun, would signal a variation in α .

Clearly, a solar fly-by on a highly eccentric trajectory with very accurate clocks and inertial sensors makes for a compelling relativity test. A potential use of highly accurate optical clocks (see Sec. 2.6.1) in such an experiment would likely lead to additional accuracy improvement in the tests of α and m_e/m_p , thereby providing a good justification for space deployment.⁶⁸ The resulting space-based laboratory experiment could lead to an important discovery.

2.1.3. Search for new physics via tests of the gravitational inverse square law

Many modern theories of gravity, including string, supersymmetry, and brane-world theories, have suggested that new physical interactions will appear at short ranges. This may happen, in particular, because at submillimeter distances new dimensions can exist, thereby changing the gravitational inverse square law^{69,70} (for a review of experiments, see Ref. 71). Similar forces that act at short distances are predicted in supersymmetric theories with weak scale compactifications,⁷² in some theories with very-low-energy supersymmetry breaking,⁷³ and also in theories of very-low-quantum gravity scale.^{74,75} These multiple predictions provide strong motivation for experiments that would test for possible deviations from Newton's gravitational inverse square law at very short distances, notably on ranges from 1 mm to 1 μm .

Recent ground-based torsion balance experiments⁷⁶ tested the gravitational inverse square law at separations between 9.53 mm and 55 μm , probing distances less than the dark energy length scale $\lambda_d = \sqrt[4]{\hbar c/u_d} \approx 85 \mu\text{m}$, with energy density $u_d \approx 3.8 \text{ keV/cm}^3$. It was found that the inverse square law holds down to a length scale of 56 μm and that an extra dimension must have a size less than 44 μm (similar results were obtained by Ref. 77). These results are important, as they signify the fact that modern experiments reached the level at which dark energy physics can be tested in a laboratory setting; they also provided a new set of constraints on new forces,⁷⁸ making such experiments very relevant and competitive with particle physics research.

Sensitive experiments searching for weak forces invariably require soft suspension for the measurement degree of freedom. A promising soft suspension with low dissipation is superconducting magnetic levitation. Levitation in 1g, however, requires a large magnetic field, which tends to couple to the measurement degree of freedom through metrology errors and coil nonlinearity, and stiffen the mode. The high magnetic field will also make suspension more dissipative. The situation improves dramatically in space. The g level is reduced by five to six orders of magnitude, so the test masses can be supported with weaker magnetic springs, permitting the realization of both the lowest resonance frequency and the lowest dissipation. The microgravity conditions also allow for an

improved design of the null experiment, free from the geometric constraints of the torsion balance.

The Inverse Square Law Experiment in Space (ISLES) is a proposed experiment whose objective is to perform a highly accurate test of Newton's gravitational law in space.^{79–81} ISLES combines the advantages of the microgravity environment with superconducting accelerometer technology to improve the current ground-based limits in the strength of violation^{82–84} by four to six orders of magnitude in the range below 100 μm . The experiment will be sensitive enough to probe large extra dimensions down to 5 μm and also to probe the existence of the axion,^r which, if exists, is expected to violate the inverse square law in the range accessible by ISLES.

The recent theoretical ideas concerning new particles and new dimensions have reshaped the way we think about the Universe. Thus, should the next generation of experiments detect a force violating the inverse square law, such a discovery would imply the existence of either an extra spatial dimension or a massive graviton, or the presence of a new fundamental interaction.⁹¹

While most attention has focused on the behavior of gravity at short distances, it is possible that tiny deviations from the inverse square law occur at much larger distances. In fact, there is a possibility that noncompact extra dimensions could produce such deviations at astronomical distances⁹² (for a discussion see Sec. 2.1.4).

By far the most stringent constraints on a test of the inverse square law to date come from very precise measurements of the Moon's orbit about the Earth. Even though the Moon's orbit has a mean radius of 384,000 km, the models agree with the data at the level of 4 mm! As a result, analysis of the LLR data tests the gravitational inverse square law to 3×10^{-11} of the gravitational field strength on scales of the Earth–Moon distance.⁴⁷

Interplanetary laser ranging could provide conditions that are needed to improve the tests of the inverse square law on the interplanetary scales.⁵¹ MLR could be used to perform such an experiment that could reach the accuracy of 1×10^{-14} at 2 AU distances, thereby improving the current tests by several orders of magnitude.

Although most of the modern experiments do not show disagreement with Newton's law, there are puzzles that require further investigation. The radiometric tracking data received from the Pioneer 10 and 11 spacecraft at heliocentric distances between 20 and 70 AU have consistently indicated the presence of a small, anomalous Doppler drift in the spacecraft carrier frequency. The drift can be interpreted as being due to a constant Sun-ward acceleration of $a_P = (8.74 \pm 1.33) \times 10^{-10} \text{ m/s}^2$ for each particular craft.^{93–96} This apparent violation of the inverse square law has become known as the Pioneer anomaly.

^rThe axion is a hypothetical elementary particle postulated by Peccei–Quinn theory in 1977 to resolve the strong-CP problem in quantum chromodynamics (QCD); see details in Ref. 87–90.

The possibility that the anomalous behavior will continue to defy attempts at a conventional explanation has resulted in a growing discussion about the origin of the discovered effect, including suggestions for new physics mechanisms^{97–106} and proposals for a dedicated deep space experiment.^{107–109,s} A recently initiated investigation of the anomalous signal using the entire record of the Pioneer spacecraft telemetry files in conjunction with the analysis of much-extended Pioneer Doppler data may soon reveal the origin of the anomaly.^{110,111}

Besides the Pioneer anomaly, there are other intriguing puzzles in the solar system dynamics still awaiting a proper explanation, notably the so-called fly-by anomaly,^{112–114} which occurred during Earth gravity assists performed by several interplanetary spacecraft.

2.1.4. *Tests of alternative and modified gravity theories with gravitational experiments in the solar system*

Given the immense challenge posed by the unexpected discovery of the accelerated expansion of the Universe, it is important to explore every option to explain and probe the underlying physics. Theoretical efforts in this area offer a rich spectrum of new ideas (some of them are discussed below) that can be tested by experiment.

Motivated by the dark energy and dark matter problems, long-distance gravity modification is one of the radical proposals that have recently gained attention.^{115–117} Theories that modify gravity at cosmological distances exhibit a strong coupling phenomenon of extra graviton polarizations.^{118,119} This strong coupling phenomenon plays an important role for this class of theories in allowing them to agree with solar system constraints. In particular, the “brane-induced gravity” model¹²⁰ provides a new and interesting way of modifying gravity at large distances to produce an accelerated expansion of the Universe, without the need for a nonvanishing cosmological constant.^{121,122} One of the peculiarities of this model is the way one recovers the usual gravitational interaction at small (i.e. noncosmological) distances, motivating precision tests of gravity on solar system scales.

The Eddington parameter γ , whose value in general relativity is unity, is perhaps the most fundamental parametrized-post-Newtonian (PPN) parameter,^{18,42} in that $\frac{1}{2}(1 - \gamma)$ is a measure, for example, of the fractional strength of the scalar gravity interaction in scalar-tensor theories of gravity.^{6,7} Currently, the most precise value for this parameter, $\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$, was obtained using radio-metric tracking data received from the Cassini spacecraft¹²³ during a solar conjunction experiment. This accuracy approaches the region where multiple tensor-scalar gravity models, consistent with the recent cosmological observations,¹²⁴ predict a lower bound for the present value of this parameter at the level of $1 - \gamma \sim 10^{-6} - 10^{-7}$.^{6–11,125,126} Therefore, improving the measurement of this

^sFor details, see the webpage of the Pioneer Explorer Collaboration at the International Space Science Institute (ISSI), Bern, Switzerland: <http://www.issi.unibe.ch/teams/Pioneer>

parameter^t would provide crucial information to separate modern scalar-tensor theories of gravity from general relativity, probe possible ways of gravity quantization, and test modern theories of cosmological evolution.

Interplanetary laser ranging could lead to a significant improvement in the accuracy of the parameter γ . Thus, precision ranging between the Earth and a lander on Mars during solar conjunctions may offer a suitable opportunity (i.e. MLR).^u If the lander were to be equipped with a laser transponder capable of reaching a precision of 1 cm, a measurement of γ with an accuracy of a part in 10^6 is possible. To reach accuracies beyond this level one must rely on a dedicated space experiment.⁵¹

The Gravitational Time Delay Mission (GTDM)^{131,132} proposes to use laser ranging between two drag-free spacecraft (with spurious acceleration levels below 1.3×10^{-13} m/s²/√Hz at 0.4 μHz) to accurately measure the Shapiro time delay for laser beams passing near the Sun. One spacecraft would be kept at the L1 Lagrange point of the Earth–Sun system, with the other one being placed on a 3:2 Earth-resonant, LATOR-type orbit (see Ref. 133–136 for details). A high-stability frequency standard ($\delta f/f \lesssim 1 \times 10^{-13}$ 1/√Hz at 0.4 μHz) located on the L1 spacecraft permits accurate measurement of the time delay. If requirements on the performance of the disturbance compensation system, the timing transfer process, and high-accuracy orbit determination are successfully addressed,¹³² then determination of the time delay of interplanetary signals to 0.5 ps precision in terms of the instantaneous clock frequency could lead to an accuracy of 2 parts in 10^8 in measuring the parameter γ .

The Laser Astrometric Test of Relativity (LATOR)^{133–137} proposes to measure the parameter γ with an accuracy of a part in 10^9 , which is a factor of 30,000 beyond the currently best Cassini 2003 result.¹²³ The key element of LATOR is a geometric redundancy provided by the long-baseline optical interferometry and interplanetary laser ranging. By using a combination of independent time series of gravitational deflection of light in the immediate proximity to the Sun, along with measurements of the Shapiro time delay on interplanetary scales (to a precision better than 0.01 picoradians and 3 mm, respectively), LATOR will significantly improve our knowledge of relativistic gravity and cosmology. LATOR’s primary measurement, precise observation of the non-Euclidean geometry of a light triangle that surrounds the Sun, pushes to unprecedented accuracy the search for cosmologically relevant scalar-tensor theories of gravity by looking for a remnant scalar field in today’s solar system. LATOR could lead to very robust advances in the tests of fundamental physics — it could discover a violation or extension of general relativity or reveal the presence of an additional long-range interaction.

^tIn addition, any experiment pushing the present upper bounds on another Eddington parameter β , i.e. $\beta - 1 = (0.9 \pm 1.1) \times 10^{-4}$ from Refs. 16 and 17, will also be of interest.

^uIn addition to Mars, a Mercury lander^{127,128} equipped with a laser ranging transponder would be very interesting as it would probe a stronger gravity regime while providing measurements that will not be affected by the dynamical noise from the asteroids.^{129,130}

If implemented, the missions discussed above could significantly advance research in fundamental physics; however, due to lack of dedicated support none of these experiments could currently be performed in the US. The recent trend of allowing “laboratory” fundamental physics to compete for funding with “observational” disciplines of space science may change the situation and could help NASA to enhance its ongoing space research efforts, so that the space agency will be doing the best possible science in space — a truly noble objective.

2.2. *Detection and study of gravitational waves*

Gravitational waves, a key prediction of Einstein’s general theory of relativity had not yet been directly detected. The only indirect evidence for the existence of gravitational waves came from binary pulsar investigation, the discovery that led to the 1993 Nobel Prize in physics.

Gravitational wave observatories in space will provide insight into the structure and dynamics of space and time. They will also be able to detect the signatures of cosmic superstrings or phase transitions in the early Universe and contribute to the study of the dark energy that dominates the evolution of the Universe. Space-based gravitational wave observatories, such as the planned Laser Interferometer Space Antenna (LISA),^v will offer access to a range of the gravitational wave frequency spectrum that is not accessible on the Earth. It promises to open a completely new window into the heart of the most energetic processes in the Universe, with consequences fundamental to both physics and astronomy. LISA is a joint NASA-ESA mission that expects to detect gravitational waves from the merger of massive black holes in the centers of galaxies or stellar clusters at cosmological distances, and from stellar mass compact objects as they orbit and fall into massive black holes. LISA will measure the signals from close binaries of white dwarfs, neutron stars, or stellar mass black holes in the Milky Way and nearby galaxies.

LISA will consist of an array of three spacecraft orbiting the Sun, each separated from its neighbor by about 5 million km. Laser beams will be used to measure the minute changes in distance between the spacecraft induced by passing gravitational waves. For this purpose, the spacecraft have to be drag-free, a requirement common for many fundamental physics missions. The preparatory LISA Pathfinder^w mission is aimed at demonstrating the ability to achieve free-fall conditions at the required levels of accuracy.

Studies of gravitational waves can provide potentially powerful insight into large-distance modified-gravity theories. The main reason is that in all such theories the graviton carries three extra polarizations (for details, see Ref. 138), which follows

^vThe Laser Interferometric Space Antenna (LISA) is an international space mission whose development is currently funded through a collaborative agreement between NASA and ESA. See the websites <http://lisa.nasa.gov/> and <http://www.lisa-science.org>, and resources therein.

^wLISA Pathfinder is a technology demonstration for the future LISA mission. See <http://sci.esa.int/science-e/www/area/index.cfm?fareaid=40>

from similar properties,^{139,140} of the massive graviton.¹⁴¹ This is in contrast to the normal massless graviton in general relativity, which carries only two helicities. In addition, in such theories the dispersion relation of the graviton is no longer that of a massless spin-2 particle, but rather acquires nontrivial frequency dependence.¹³⁸ As a result, both emission and propagation properties of the gravitational waves are altered in modified-gravity theories. LISA and future gravitational wave missions will be able to address these important questions and provide the insight needed to explore these possibilities.

Although of extreme importance, research in gravitational waves does not enjoy stable funding. NASA support for research in this area is conducted via the Beyond Einstein Program^x which was approved by the US Congress in 2004 and is managed by the Astrophysics Division of NASA's Science Mission Directorate. The program was recently assessed by the Beyond Einstein Program Assessment Committee (BEPAC), formed by the Space Studies Board and the Board on Physics and Astronomy of the National Academy of Sciences (NAS) with the purpose of assessing the five proposed Beyond Einstein missions [Constellation-X, LISA, Joint Dark Energy Mission (JDEM), Inflation Probe, and Black Hole Finder probe] and of recommending which of these five missions should be developed and launched first.^y In its recently released Report,^z BEPAC recommended NASA to immediately proceed with the development of the JDEM mission, while also investing additional funds in LISA technology development and risk reduction.

Although the NAC's assessment effectively postpones LISA's launch toward the end of the next decade, it urges NASA to develop LISA-enabling technologies, many of which are common to other fundamental physics missions. As such, these BEPAC recommendations will have a major impact on the entire field of space-based research in fundamental physics in the next decade.

2.3. Precision research in cosmology

The current model of the Universe includes critical assumptions, such as an inflationary epoch in primordial times, and peculiar settings, such as the fine-tuning in the hierarchy problem, which call for a deeper theoretical framework. In addition, the very serious vacuum and/or dark energy problems and the related cosmological phase transitions lead researchers to areas beyond general relativity and standard quantum field theory. Observations of the early Universe are an important tool for constraining physics beyond the Standard Model and quantum gravity. This work led to the discovery of the fluctuations in the cosmic microwave background (CMB) made by the NASA COBE mission — an experiment that revolutionized the entire field of cosmology and led to the 2006 Nobel Prize in physics.

^xNASA Beyond Einstein Program: <http://universe.nasa.gov>

^yFor details see <http://www7.nationalacademies.org/ssb/BeyondEinsteinPublic.html>

^z"NASA's Beyond Einstein Program: An Architecture for Implementation," Committee on NASA's Einstein Program: An Architecture for Implementation, National Research Council. For details see <http://www.nap.edu/catalog/12006.html>

The 2005 Report by the CMB Task Force^{aa} identified two types of observations that are critical for cosmological research: (1) study of the polarization of the CMB anisotropies and (2) direct detection of primordial gravitational waves with second- or third-generation missions. Some of the relevant observations can be made by space missions inspired by the astronomy community. Other observations will be made by space missions inspired by the fundamental physics community. It seems to be quite natural that the former missions should be under the purview of astronomy, while the latter missions should fall under the purview of fundamental physics.

The recently discovered baryon acoustic oscillations¹⁴² together with the CMB and supernovae data provide additional, very important constraints for possible models and scenarios. The 2006 Report from the Dark Energy Task Force (DETF)^{bb} explicitly mentions the significance of various tests of general relativity, especially as they relate to dark energy.¹⁴³ The report also highlights the synergy between observational and experimental methods to benefit modern research in cosmology. Just as dark energy science has far-reaching implications for other fields of physics, advances and discoveries made in laboratory fundamental physics may point the way toward understanding the nature of dark energy. For instance, such a pointer could come from observing any evidence of a failure of general relativity.

The strong coupling phenomenon (discussed in Sec. 2.1) makes modified-gravity theories predictive and potentially testable at scales that are much shorter than the current cosmological horizon. Because of the key role that nonlinearities play in relativistic cosmology, namely those of its scalar sector, their presence leads to potentially observable effects in gravitational studies within our solar system. Thus, it is possible to test some features of cosmological theories in space-based experiments performed at spacecraft-accessible distances.⁹²

There is a profound connection between cosmology and possible Lorentz symmetry violation^{144–146} (see also Sec. 2.5). Spontaneous breaking of the Lorentz symmetry implies that there exists an order parameter with a nonzero expectation value that is responsible for the effect. For spontaneous Lorentz symmetry breaking one usually assumes that sources other than the familiar matter density are responsible for such a violation. However, if Lorentz symmetry is broken by an extra source, the latter must also affect the cosmological background. Therefore, in order to identify the mechanism of such a violation, one has to look for traces of similar symmetry breaking in cosmology, for instance in the CMB data.^{cc} In other words, should a violation of the Lorentz symmetry be discovered in experiments but not supported by observational cosmology data, such a discrepancy would indicate

^{aa}See the webpage of the Task Force of CMB at the NSF, <http://www.nsf.gov/mps/ast/tfcr.jsp>, and also “Report from the Task Force on CMB Research (TFCR),” July 11, 2005. http://www.nsf.gov/mps/ast/tfcr_final_report.pdf

^{bb}Dark Energy Task Force (DETF) website at the NSF: <http://www.nsf.gov/mps/ast/detf.jsp>

^{cc}Analyses of the CMB for Lorentz violation have already begun.¹⁴⁷ This provides a systematic classification of all operators for Lorentz violation and uses polarimetric observations of the CMB to search for associated effects. Lorentz symmetry violation can also have important implication for cosmology via CPT violation and baryogenesis.^{148,149}

the existence of a novel source of symmetry breaking. This source would affect the dispersion relation of particles and the performance of the local clocks, but leave no imprint on the cosmological metric. Such a possibility emphasizes the importance of a comprehensive program for investigating all possible mechanisms of breaking of the Lorentz symmetry, including those accessible by experiments conducted in space-based laboratories.

Because of the recent important discoveries, the area of observational cosmology is receiving some limited multiagency support from NASA, DOE, and NSF. However, no support is available for laboratory experiments in this discipline. NASA's support for research in cosmology comes through the Beyond Einstein Program, but it is limited to observational aspects, providing essentially no support to relevant solar system laboratory experiments.

2.4. Space-based efforts in astroparticle physics

Astroparticle physics touches the foundation of our understanding of the matter content of the Universe. One can use cosmic rays, high-energy photons, and neutrinos to test the fundamental laws of Nature at energies well beyond the reach of terrestrial experiments. The results can play an important role in the future development of the fundamental theory of elementary particles. Many observations require going to space because the atmosphere stops the cosmic messengers, such as X-rays. In other cases, for example that of ultrahigh-energy cosmic rays, the advantage the space missions offer is in observing a large segment of the Earth's atmosphere, which can be used as part of the detector. We will discuss below some examples of how the astroparticle physics can benefit from going to space.

2.4.1. Detection of ultrahigh-energy cosmic rays and neutrinos from space

Ultrahigh-energy cosmic rays (UHECR's), with energies in excess of 10^{20} eV and beyond, have been observed by the AGASA,^{dd} HiRes,^{ee} and Pierre Auger^{ff} experiments. Understanding the origin and propagation of these cosmic rays may provide a key to fundamental laws of physics at the highest energy scales, several orders of magnitude beyond the reach of particle accelerators. The propagation of cosmic rays through space will test both the fundamental symmetry of space-time and the Lorentz invariance.

Detection of UHE neutrinos will mark the beginning of a new era in astronomy and will allow mapping of the most extreme objects in the Universe, such as supermassive black holes, active galactic nuclei, and, possibly, cosmic strings and other topological defects.

^{dd}The Akeno Giant Air Shower Array (AGASA) experiment. See <http://www-akeno.icrr.u-tokyo.ac.jp/AGASA>

^{ee}The High Resolution Fly's Eye (HiRes) experiment. See <http://hires.phys.columbia.edu>

^{ff}The Pierre Auger Cosmic Ray Observatory. See <http://www.auger.org>

By comparing the rates of upgoing and downgoing neutrino-initiated air showers, one can measure the neutrino-nucleon cross section at a center-of-mass energy as high as 10^6 GeV, orders of magnitude beyond the reach of collider experiments.^{85,86} There are differing theoretical predictions for this cross section; its measurement can probe fundamental physics at the highest scales.^{85,86}

Space-based instruments, such as the proposed EUSO^{gg} and OWL,^{hh} can use a large segment of the Earth's atmosphere as a medium for detecting cosmic rays and neutrinos. These observations can test the fundamental laws of physics at the highest energy frontier. They also provide information about the most extreme objects in the Universe, such as supermassive black holes.

2.4.2. Identifying the dark matter particles by their properties

There is now overwhelming evidence that most of the matter in the Universe is not made of ordinary atoms, but, rather, of new, yet-undiscovered particles (see Ref. 153 for a review). The evidence for dark matter is based on several independent observations, including the anisotropies of the CMB radiation, gravitational lensing, optical observations of the galactic rotation curves, and X-ray observations of clusters. None of the Standard Model particles can be dark matter. Hence, the identification of dark matter will be a discovery of new physics beyond the Standard Model.

One of the most popular theories for physics beyond the Standard Model is supersymmetry (SUSY). A class of supersymmetric extensions of the Standard Model predicts dark matter in the form of either the lightest supersymmetric particles (LSP's) (see Ref. 154 for a review) or SUSY Q balls.^{155–159} Another theoretically appealing possibility is dark matter in the form of axions.^{87–90} An axion is a very weakly interacting field that accompanies the Peccei–Quinn solution to the strong CP problem.ⁱⁱ There are several other dark matter candidates that are well motivated by theoretical reasoning.

The right-handed or sterile neutrinos can be the cosmological dark matter.^{160–169} The existence of such right-handed neutrino states is implied by the discovery of the active neutrino masses. Although it is not impossible to explain the neutrino masses otherwise, most models introduce gauge singlet fermions that give the neutrinos their masses via mixing. If one of these right-handed states has a mass in the range of $\sim 1–50$ keV, it can be the dark matter.^{jj} Several indirect

^{gg}The Extreme Universe Space Observatory (EUSO). See <http://www.euso-mission.org>

^{hh}The Orbiting Wide-angle Light collectors (OWL). See <http://owl.gsfc.nasa.gov>

ⁱⁱThe existence of the axion is suggested by models attempting to solve symmetry problems of the Standard Model.^{87–90} The axion would violate the $1/r^2$ law of gravity at short distances and would thus be detectable experimentally.

^{jj}The LSND experiment claimed^{170–173} to observe a sterile neutrino with a much smaller mass ($m \sim \text{eV}$) and a much larger mixing angle ($\sin^2 \theta \sim 10^{-1}$) than those needed for dark matter ($m \sim \text{keV}$, $\sin^2 \theta \sim 10^{-9}$). The LSND neutrino would pose some serious problems for cosmology. Recent results from the MiniBooNE experiment¹⁷⁴ have refuted the LSND claim.

astrophysical clues support this hypothesis. Indeed, if sterile neutrinos exist, they can explain the long-standing puzzle of pulsar velocities.^{175–180} In addition, the X-rays produced in decays of the relic neutrinos could increase the ionization of the primordial gas and can catalyze the formation of molecular hydrogen at redshifts as high as 100. Since molecular hydrogen is an important cooling agent, its increased abundance could play an important role in the formation of the first stars.^{181–184} Sterile neutrinos can also help the formation of supermassive black holes in the early Universe, as well as explain the matter–antimatter asymmetry.^{185,186} The consensus of these indirect observational hints makes a stronger case for the sterile dark matter.¹⁸⁷

Depending on the properties of dark matter particles, they can be identified by one of several techniques. In the case of LSPs, their annihilations in the center of our galaxy can produce gamma rays. Thus, the search for gamma rays from the galactic center with instruments such as GLAST^{kk} may lead to the discovery of this form of dark matter.¹⁸⁸ The spectrum, the flux, and the distribution of these gamma rays can be used to distinguish the SUSY signal from the alternatives. The LSP annihilations are also expected to produce an identifiable flux of antiprotons and antideuterons.¹⁸⁹ Superheavy dark matter can be discovered by the proposed EUSO or OWL if the heavy particles decay producing the UHECR's, as suggested by some theories.

If dark matter is made up of sterile neutrinos with mass in the keV range,^{160–169} their decays into the lighter left-handed neutrinos and X-rays offer an opportunity to discover dark matter using a high-resolution X-ray spectrometer. Since this decay is a two-body process, the decay photons produce a narrow spectral line, Doppler-broadened due to the motion of dark matter particles. For the most plausible masses, one expects a line between 1 and 50 keV, with a width of about 1 eV. To detect this line and distinguish it from the gaseous lines, one needs an instrument with a good energy resolution. Current limits are based on the observations of Chandra and XMM-Newton.^{190–200} A dedicated search by the Suzaku telescope is under way. Further ideas for space-based experiments searching for sterile neutrinos are being investigated. In particular, the recently proposed X-ray telescope in space, EDGE,^{ll} would be able to search for dark matter in the form of sterile neutrinos.

Ongoing efforts in the search for dark matter particles include a number of underground detectors, as well as GLAST. The search for dark matter must cover a number of avenues because different candidate particles have different interactions. NASA has a unique opportunity to initiate and lead the work in this very important area of space-based research, by funding missions such as EDGE, which could potentially result in a major discovery. Similar opportunities for a significant discovery exist in other areas of astroparticle physics.

^{kk}The Gamma-ray Large Area Space Telescope (GLAST). See <http://glast.gsfc.nasa.gov>

^{ll}The Explorer of Diffuse emission and Gamma-ray burst Explosions (EDGE). See <http://projects.iasf-roma.inaf.it/edge/EdgeOverview.htm>

2.5. Search for physics beyond the standard model with space-based experiments

The Standard Model coupled to general relativity is thought to be the effective low-energy limit of an underlying fundamental theory that unifies gravity and the matter sector at the Planck scale. This underlying theory may well include Lorentz violation^{201–204} which could be detectable in space-based experiments.²⁰⁵ If one takes the Standard Model and adds appropriate terms that involve operators for Lorentz invariance violation,²⁰⁶ the result is the Standard Model extension (SME), which has provided a phenomenological framework for testing Lorentz invariance,^{207–216} and also suggested a number of new tests of relativistic gravity in the solar system.²¹⁷ Compared with their ground-based analogs, space-based experiments in this area can provide improvements by as much as six orders of magnitude. Several general reviews of the SME and corresponding efforts are available (for a review, see Refs. 218–227). Recent studies of the “aether theories”^{228–230} have shown that these models are naturally compatible with general relativity,¹⁸ but predict several nonvanishing Lorentz-violation parameters that could be measured in experiment.

A discovery of an electron electric dipole moment (e-EDM) would be unequivocal proof of new physics beyond the Standard Model. An EDM in an eigenstate of angular momentum is possible only if both parity (P) and time reversal (T) are violated, where T violation is, by the CPT theorem, the equivalent of CP violation. No EDM of any particle or system has yet been observed: all known CP violations (in the decays of the B and K^0 systems) are consistent with the Standard Model’s Cabbibo–Kobayashi–Maskawa (CKM) mechanism. The CKM mechanism directly affects only the quark sector, and the CKM-generated e-EDM is extremely small. It is estimated^{231,232} to be about 10^{-10} – 10^{-5} (depending upon assumptions about the number of neutrino generations and their masses) of the current e-EDM experimental limit of 2.6×10^{-48} C-m (1.6×10^{-27} e-cm).^{233–236} By improving the present e-EDM limit, constraints would be placed on many SME’s and possibly on current models of neutrino physics.²³⁷

We will discuss below examples of space-based experiments testing for physics beyond the Standard Model.

2.5.1. Probing the special theory of relativity in space-based clock comparison experiments

Searches for extensions of special relativity on a free-flying spacecraft or on the International Space Station (ISS) are known as “clock comparison” experiments.^{mmm}

^{mmm}The clocks referred to here take several forms, including atomic and optical clocks, masers, and electromagnetic cavity oscillators. Some clocks may be cesium and rubidium atomic clocks, enhanced to exploit fully the low-gravity environment of space. Each produces an exceptionally stable oscillating signal from energy-level transitions in alkali atoms. Other ISS-based clocks may include masers generating stimulated microwave signals, and microwave cavities creating resonant radiation in small superconducting cavities.

The basic idea is to operate two or more high-precision clocks simultaneously and to compare their rates correlated with orbit parameters such as velocity relative to the microwave background and position in a gravitational environment. The SME allows for the possibility that comparisons of the signals from different clocks will yield very small differences that can be detected in experiment.

Tests of special relativity and the SME were proposed by the Superconducting Microwave Oscillator (SUMO) group, those from the Primary Atomic Reference Clock in SPACE (PARCS),^{238–240} and the Rubidium Atomic Clock Experiment (RACE),²⁴¹ originally slated for operation on the ISS in the 2005–07 time frame. SUMO, a cryogenic cavity experiment,²⁴² was to be linked with PARCS to provide differential redshift and Kennedy–Thorndike measurements and improved local oscillator capability.²⁴⁰ Unfortunately, for programmatic reasons the development of these experiments was canceled by NASA in 2004.ⁿⁿ Currently, an experiment called the Atomic Clock Ensemble in Space (ACES) is aiming to do important tests of the SME. ACES is a European mission^{243–245} in fundamental physics that will operate atomic clocks in the microgravity environment of the ISS with fractional frequency stability and accuracy of a few parts in 10^{16} . It is jointly funded by ESA and CNES and is being prepared for a flight to the ISS in 2013–14²⁴⁶ for a planned mission duration of 18 months.

Optical clocks (see Sec. 2.6) offer an improved possibility of testing the time variations of fundamental constants at a high-accuracy level.^{247–251} Such measurements interestingly complement the tests of local Lorentz invariance (LLI)²⁵² and of the universality of free fall to experimentally establish the validity of the EP. The universality of the gravitational redshift can be tested at the same accuracy level by two optical clocks in free flight in a varying gravitational potential. Constancy and isotropy of the speed of light can be tested by continuously comparing a space clock with a ground clock. Optical clocks orbiting the Earth combined with a sufficiently accurate time and frequency transfer link can improve present results by more than three orders of magnitude.

In general relativity, continuous space–time symmetries, such as the Lorentz symmetry, are part of gauge invariance, and as such their violation can only be understood as the low-energy limit of some underlying spontaneous breaking.^{144–146} Any order parameter that spontaneously breaks Lorentz invariance will also couple to gravity, ultimately distorting the geometry of space–time, thereby severely constraining the value of that parameter. A consistent Lorentz-breaking inevitably requires either going beyond the usual order parameters (which are different from ordinary cosmic fluids) or going beyond general relativity at large distances. Such

ⁿⁿSee the 2003 Report “Factors Affecting the Utilization of the International Space Station for Research in the Biological and Physical Sciences,” submitted by the NRC Space Studies Board’s Task Group on Research on the ISS (The National Academies Press, 2003), and especially the list of the fundamental physics experiments to be flown on the ISS in the period of 2002–2008, on p. 75 of <http://books.nap.edu/books/N1000492/html>

a connection suggests that there must be a strong correlation between detection of Lorentz violation and results of relevant cosmological observations. If no such correlation is found, then any discovery of Lorentz violation would indicate the existence of new physical sources or new gravitational dynamics at large distances. Therefore, a consistent breaking of Lorentz-invariance is rather a profound effect that, if detected by an experiment, must be studied together with cosmological observations to determine its nature (see Sec. 2.3 for additional details).

2.5.2. Search for the electron's electric dipole moment

Electron EDM experiments are a sensitive test for non-Standard Model sources of CP violation.²⁵³ New, non-CKM sources of CP violation, which directly affect leptons and which can give rise to a large e-EDM, are predicted by the SME and are within the reach of modern experiments. A non-CKM source of CP violation is thought to be necessary for generating the observed matter-antimatter asymmetry in the Universe.^{254,255} Within the range of future experiments, e-EDMs are predicted to arise from couplings to new particles and with nonstandard sources of CP violation. These particles are, in some models, candidates for dark matter, or part of the mechanism for generating the observed excess of matter over antimatter, or part of the mechanism for generating neutrino mass. In fact, potentially observable e-EDMs^{231,232,256} are predicted by supersymmetry,²⁵⁷ multi-Higgs models, left-right-symmetric models, lepton flavor-changing models, technicolor models,²⁵⁸ and TeV scale quantum gravity theories.⁶⁹ Split supersymmetry²⁵⁹⁻²⁶¹ predicts an e-EDM within a few orders of magnitude of the present experimental limit and up to the present experimental limit. Merely improving the present e-EDM limit would place constraints on these SME's and possibly on current models of neutrino physics.²³⁷

Cold-atom-based experiments may be used to search for an e-EDM. As a first step a ground-based demonstration of a Cs fountain e-EDM experiment has been carried out at LBNL.²⁶² Similar to an atomic clock, a cold-atom-based e-EDM experiment is more sensitive in the microgravity environment of space than on the ground. Such an experiment may improve the current sensitivity to the e-EDM by several orders of magnitude.

Direct measurement of any SME effects would herald a new era, fundamentally changing the perspective on the fabric of special relativity. The effect of such a discovery would include permanent changes in cosmology, high-energy physics, and other fields.

The current research efforts in this area are limited to ground-based laboratory work supported by the NSF. All NASA funding previously available to the space-based efforts described above was terminated after the 2004 cancellation of the "Microgravity and Fundamental Physics" program (see App. B for details); no NASA support for research in this area is currently available.

2.6. *Cold atom physics, new frequency standards and quantum technologies*

Studies of the physics of cold atoms and molecules have recently produced sensational scientific results and important inventions. The field of atomic, molecular, and optical physics has had an incredibly productive decade, marked by Nobel Prize awarded for discoveries in laser cooling (1997), Bose–Einstein condensation and atom lasers (2001), laser-based precision spectroscopy, and the optical frequency comb technique (2005).

Quantum principles are at the core of many advanced technologies used in high-accuracy experiments in fundamental physics. One of the areas where the progress will certainly bring societal and technological benefits is the area of condensed quantum matter. The new phenomenon of interest is seen only at extremely low temperatures, or at very high densities, when particles such as electrons in some metals, helium atoms, or alkali atoms in atomic traps, form a pattern not in “real” space, but rather in momentum space. This “condensation” into momentum space is known as Bose–Einstein condensation (BEC), which in strongly interacting systems, such as liquid helium, results in a complex phenomenon known as superfluidity. BEC in the “paired” electrons in some metals results in superconductivity, which has already revolutionized many technologies to date and is poised to produce many new applications in the future.

While gravitational and relativistic physics examine the most fundamental laws describing the Universe on the large scale, it is equally important to look at the tiny building blocks of matter and how they manifest the same fundamental laws. New techniques allow us to use laser light to cool and probe the properties of individual atoms as a starting point for exploration. Working with individual atoms as test laboratories, researchers stand at the bridge between the smallest pieces of matter and the complex behavior of large systems.

Furthermore, conducting these experiments in space allows one to remove the influence of gravity and manipulate matter freely, without having to counteract specimens “falling” within the instruments. It is possible 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 the Earth. This unique realization of an atom nearly at rest in free space allows longer observation times and enables measurements with higher precision (see the discussion of the experiments relying on cold-atom-based technologies in sections above).

We present below several impressive examples of the new generation of quantum technologies and discuss their role for space-based experimental research in fundamental physics.

2.6.1. *Highly accurate optical clocks*

Precision physics, particularly precision frequency measurements, has recently shown substantial progress with the introduction of new types of atomic clocks.

Recent advances in accuracy that have turned the clocks into powerful tools in the development of applications in time and frequency metrology, universal time scales, global positioning and navigation, geodesy, gravimetry, and others.

Present-day trapped-ion clocks are capable of a stability at the 10^{-15} level over a few hours of integration time.²⁶³ Such performance allows simultaneous one-way (down-) and two-way (up- and down-) links between space and ground, with a greatly reduced tropospheric noise contribution. These clocks are lightweight, have no lasers, cryogenics, or microwave cavities and are similar to the traveling wave tube that is already on board many spacecraft.

Microwave atomic clocks with similar performance have also been space-qualified²⁶⁴ and are being prepared for a flight on the ISS.^{243–245} In fact, the current accuracy of fountain clocks is already at the 5×10^{-16} level and is expected to improve in the near future.

Optical clocks have already demonstrated fractional frequency stability of a few parts in 10^{17} at 1 s of integration time. The performance of these clocks has strongly progressed in recent years, and accuracies below one part in 10^{17} are expected in the near future.²⁶⁵ Access to space provides conditions for further improving the clock performance, potentially reaching the 10^{-18} – 10^{-19} stability and accuracy level.^{266–269} In addition, the operation of optical clocks in space provides new scientific and technological opportunities,^{3,68} with far-reaching societal benefits.

High-precision optical clocks can measure the gravitational redshift with a relative frequency uncertainty of a few parts in 10^{18} , demonstrating a new, efficient way of mapping the Earth's gravity field at the centimeter level. The universality of high-accuracy time transfer is another important aspect of an optical clock. In particular, it is feasible that a few space-based high-precision clocks will provide a universal high precision time reference for users both ground-based and in space — a highly accurate clock synchronization and time transfer that cannot be achieved from the ground. There will be a strong impact on various disciplines of Earth sciences that will greatly benefit from the use of clocks, including studies of relativistic geodesy, Earth rotation, climate research, ocean research, earthquakes, tsunamis, and many others.

There are several benefits of space deployment for the latest generation of atomic clocks. Thus, it is known that thermal noise and vibration sensitivity are the two factors limiting the performance of the optical local oscillator.^{270,271} By operating the clock in a quiescent space environment one can use longer cavity spacers to reach better short term stability for the local oscillator. That will have a direct impact on spectral resolution as better spectral resolution will lead to smaller systematic errors.

2.6.2. Femtosecond optical frequency combs in space

The optical frequency comb (OFC) is a recently discovered method that enables comparison of the frequency stability of optical clocks at the level of

$\delta f/f \sim 10^{-19}$.²⁷² In the optical domain, using a frequency comb a group at NIST observed a beat note frequency stability at the 3×10^{-17} level between Al^+ and Hg^+ ions.²⁶⁵ Where the stability of the microwave-to-optical link is concerned, with the help of a mode-locked femtosecond laser emitting a series of very short laser pulses with a well-defined repetition rate, an OFC can be generated that makes it possible to compare the microwave frequency of atomic clocks (about 10^{10} Hz) with optical frequencies (about 10^{15} Hz) with an accuracy of one part in 10^{15} .^{65,273}

The OFC technique will lead to further improvements of Kennedy–Thorndike tests²⁷⁴ and also tests of the universality of the gravitational redshift.²⁷⁵ The OFC has aided the development of better optical clocks. With reduced vibration-related problems in the space environment, further improvements can be made in the traditional optical-cavity-based speed-of-light tests (see discussion in Sec. 2). Instead of using two orthogonally oriented cavities to test the angle-dependent (Michelson–Morely) and angle-independent terms (Kennedy–Thorndike, velocity-dependent terms), using an optical clock one can do these tests with one cavity, while using the clock itself as the absolute reference. The fact that this would be an all-optical test is an additional benefit of the method.

As an example of a possible experiment, one could use a rotating wide-bandwidth optical cavity. As the cavity rotates in space, with its axis pointing to different gravitational sources, one can measure possible frequency shifts in blue, green, and red, or even all the way to microwave (group delay) frequencies, all in one setup. These measurements could give an extra constraint with respect to the optical carrier frequency and improve the experimental sensitivity.²⁷⁷ There are other promising nonfrequency comb proposals, for instance those based on high finesse cavities.^{278–283}

OFC's offer a unique opportunity of simultaneous time-keeping and distance ranging. Traditionally laser ranging involves measuring the delay of pulses reflected or transponded from the ranging target.^{oo} Use of the highly coherent light associated with modern femtosecond combs would allow interferometry, supplemented by pulse delay ranging.²⁸⁴ The idea of absolute distance measurement within an optical fringe based on a comb can be easily implemented in space due to a significantly lower contribution from any dispersive medium there. Substantial improvement in laser ranging would aid studies of relativistic gravity in the solar system as well as astrometry, geodesy, geophysics, and planetology.³

2.6.3. *Atomic quantum sensors*

Atomic quantum sensors based on matter-wave interferometry are capable of detecting very small accelerations and rotations (see discussion in Refs. 285–288). The present-day sensitivity of atom interferometers used as accelerometers

^{oo}Lunar ranging from a reflector placed by lunar astronauts has, since the early 1970's, improved from several tens of centimeters to a level now of about a millimeter; see Refs. 16, 47 and 46.

is $\delta a \sim 10^{-9} \text{ m/s}^2/\sqrt{\text{Hz}}$, and as gyroscopes, $\delta\omega \sim 6 \times 10^{-10} \text{ rad/s}/\sqrt{\text{Hz}}$.²⁸⁹ These instruments reach their ultimate performance in space, where the long interaction times achievable in a freely-falling laboratory improve their sensitivity by at least two orders of magnitude (for a review, see Ref. 290). Possibilities of improvements in the measurement techniques with differential atom interferometry, including those beyond the standard quantum limit, are also investigated.²⁹¹

Cold atom sensors in space may enable new classes of experiments, such as testing the gravitational inverse square law at distances of a few microns, the universality of free fall, and others. Matter-wave interferometer techniques may lead to radically new tests of the EP using atoms as nearly perfect test masses,³² measurements of the relativistic frame-dragging precession,²⁹² the value of G ,^{293,294} and other tests of general relativity.²⁹⁵ Furthermore, cold atom quantum sensors have excellent sensitivity for absolute measurement of gravity, gravity gradients and magnetic fields, as well as Earth rotation, and therefore find application in Earth sciences and in Earth-observing facilities.²⁹⁶ Miniaturized cold atom gyroscopes and accelerometers may lead to the development of autonomous navigation systems not relying on satellite tracking.²⁹⁷⁻³⁰¹

Today, a new generation of high performance quantum sensors (ultrastable atomic clocks, accelerometers, gyroscopes, gravimeters, gravity gradiometers, etc.) is surpassing previous state-of-the-art instruments, demonstrating the high potential of these techniques based on the engineering and manipulation of atomic systems. Atomic clocks and inertial quantum sensors represent a key technology for accurate frequency measurements and ultraprecise monitoring of accelerations and rotations.³ New quantum devices based on ultracold atoms will enable fundamental physics experiments testing quantum physics, physics beyond the Standard Model of fundamental particles and interactions, special relativity, gravitation, and general relativity.³⁰³ Because of the anticipated strong impact of these new devices on the entire area of precision measurements, the development of quantum technologies for space applications has also seen increased activity.^{PP}

In addition, studies of ultracold atoms, molecules, and degenerate quantum gases (BEC, Fermi gases, and Bose-Fermi mixtures) are steadily progressing.³⁰⁴⁻³⁰⁶ BEC provides gases in the sub-nanokelvin range, with extremely low velocities (i.e. at the micron-per-second level), which are ideally suited for experiments in a microgravity environment. Similarly, Fermi gases have no interactions at low temperatures, which is very important for potential tests of the EP in space-based experiments. The atom chip technology and compact interferometers now under development may provide a low-power, low-volume source for atomic quantum sensors.³⁰⁷

In summary, it is clear that in recognition of such impressive progress and also because of its uniquely strong potential for space applications, research on cold atoms

PPFor instance, a recent European workshop on “Quantum Mechanics for Space,” held at ONERA, Châtillon, France, during 30 Mar.–Apr. 2005. See <http://qm-space.onera.fr> and the related proceedings issue.³⁰²

and quantum technologies would greatly benefit from NASA (and, hopefully, multi-agency) support; the current European effort in this area are an excellent example.⁹⁹ We emphasize that coordinated multiagency support could lead to significant progress in developing quantum technologies for space applications and would benefit the entire discipline of space-based research in fundamental physics.

3. Discussion and Recommendations

The recent technological progress and the availability of the quiescent environment of space have placed fundamental physics in a unique position to address some of the pivotal questions of modern science. The opportunity to gather important new knowledge in cosmology, astronomy, and fundamental physics stems from recent discoveries suggesting that the basic properties of the Universe as a whole may be intimately related to the physics at the very smallest scale that governs elementary particles such as quarks and other constituents of atoms.

The science investigations presented in this paper are focusing on the very important and challenging questions that physics and astronomy face today. Space deployment is the common factor for these investigations; in fact, their science outcomes are more significant if the experiments are performed in space rather than on the ground.

Because of the significant discovery potential offered by the space-based laboratory research in fundamental physics, it would be beneficial to set aside some dedicated multiagency funding to stimulate the relevant research-and-development efforts. Investments in this area of fundamental physics are likely to lead to major scientific advances and to the development of new technologies and applications that will strengthen national economic competitiveness and security.¹⁰⁰

Our specific recommendations are:

3.1. *Include fundamental physics in the NAS' Decadal Survey in Astronomy and Astrophysics*

We recommend that the upcoming National Academy of Sciences' Decadal Survey in Astronomy and Astrophysics⁸⁸ include space-based research in fundamental physics as one of its focus areas. As new scientific discoveries and novel experimental approaches cut across the traditional disciplinary boundaries, the next survey

⁹⁹The ESA has recently established two programs to develop atomic clocks and atom interferometers for future missions in space: ESA-AO-2004-100, "Space Optical Clocks," coordinated by S. Schiller; and ESA-AO-2004-064/082, "Space Atom Interferometers," coordinated by G. M. Tino.

¹⁰⁰Note that NASA was not included to receive a funding increase as a result of the American Competitiveness Initiative (ACI) (see <http://www.ostp.gov/html/ACIBooklet.pdf>). ACI provided additional authorization of US\$160 million for basic science and research for FY 2007 to other agencies.

⁸⁸In addition, the upcoming NAS' Decadal Survey in Physics should have a strong responsibility for recommendations to NASA on space-based research in fundamental physics.

should make physics an equal partner for strategic planning of future efforts in space. The space-based research community in fundamental physics is ready to contribute to this important strategic planning process for the next decade, as evidenced by “Quantum to Cosmos” meetings.

3.2. Establish an interagency fundamental physics task force

For the near term, we recommend that the Astronomy and Astrophysics Advisory Committee (AAAC)^{tt} establish an interagency “Fundamental Physics Task Force (FPTF)” to assess benefits of space-based efforts in the field, to identify the most important focus areas and objectives, and to suggest the best ways to organize the work of the agencies involved.³⁰⁸

The FPTF can help the agencies identify actions that will optimize near- and intermediate-term synergistic fundamental physics programs carried out at NSF, NASA, DOE, and other federal agencies,^{uu} and ensure progress in the development and implementation of a concerted effort toward improvement of our understanding of the fundamental laws of physics.

Given the scientific promise of “Quantum to Cosmos” and also its interdisciplinary nature, it is the right time for the National Science and Technology Council’s Committee on Science^{vv} to include the new program under the jurisdiction of the Interagency Working Group (IWG) on the “Physics of the Universe” and to ask the IWG to examine the investments required to support the new area of space-based laboratory research in fundamental physics and to develop priorities for further action.

3.3. Establish a NASA-led program dedicated to space-based efforts in fundamental physics

In the intermediate term, we recommend that NASA establish a program dedicated to space-based efforts in fundamental physics and quantum technologies. The new program, tentatively named “Quantum to Cosmos” (Q2C), would complement NASA’s “Beyond Einstein” program^x and could also offer a “space extension” to NSF and DOE ground-based research efforts by providing unique opportunities for high-accuracy investigations in fundamental physics.

The program would focus on high-precision tests of relativistic gravity in space, searches for new physics beyond the Standard Model, direct detection and studies

^{tt}The Astronomy and Astrophysics Advisory Committee (AAAC). See details at <http://www.ucolick.org/~gdi/aaac> and also the NFS AAAC webpage <http://www.nsf.gov/mps/ast/aaac.jsp>

^{uu}The 2006 “Quantum to Cosmos” (Q2C) workshop (see meeting details at <http://physics.jpl.nasa.gov/quantum-to-cosmos>) demonstrated that, in addition to NASA, NSF, and DOE-SC, agencies like the Department of Commerce’s National Institute of Standards and Technology (DOC/NIST) do benefit from laboratory physics research in space and, thus, could also sponsor the FPTF (see discussion in Ref. 308).

^{vv}National Science and Technology Council (NSTC) at the Executive Office of the President of the United States. See <http://www.ostp.gov/nstc>

of gravitational waves, searches for dark matter, discovery research in astroparticle physics, and experiments in precision cosmology. It would also develop and utilize advanced technologies needed for space-based experiments in fundamental physics, such as laser transponders, drag-free technologies, atomic clocks, optical frequency combs and synthesizers, atom and matter-wave interferometers, and many others.

The new program would allow NASA to fully utilize the science potential of the ISS by performing carefully planned fundamental physics experiments on board the space station — which would be a direct response to the 2005 designation of the ISS as a national laboratory.^{ww}

With its strong interdisciplinary research focus such a program would broadly cut across agencies, academia, and industry while also overlapping the interests of several federal agencies, namely NASA, NSF, DOE/SC, DOC/NIST, NIH, and others. We believe that this program will allow the US to regain a leadership position in fundamental physics worldwide.

3.4. Enrich and broaden NASA's advisory structure with space-based laboratory fundamental physics

We observe that the ESA's FPAG^g is a good example of how to engage the fundamental physics community in space-related research activities, enrich and deepen the space enterprise, and also broaden the ESA's advocacy base. NASA would benefit from access to a similar group of science advisors. The recently formed NASA Advisory Committee (NAC)^{xx} does not have representation from the fundamental physics community, nor does the Astrophysics subcommittee^{yy} of the NAC. Therefore, we propose:

- To include members of the fundamental physics community in the NAC and/or NAC's Astrophysics subcommittee. Include fundamental physics in the Astrophysics Division of the SMD and provide adequate representation in the advisory structure.
- To consult with the ESA on the possibility of appointing US *ex-officio* members to the ESA's FPAG. Such participation could facilitate development of ongoing (i.e. LPF, LISA) and future fundamental physics missions.

^{ww}The 2005 NASA Authorization Act designated the US segment of the ISS as a national laboratory and directed NASA to develop a plan to increase the utilization of the ISS by other federal entities, the research community, and the private sector; see http://www.nasa.gov/mission_pages/station/science/nlab. The majority of NASA's ISS research effort is focused on supporting the human exploration of space program, with only about 15% going toward other activities. There is currently no NASA support for performing fundamental physics aboard the ISS. Thus, the designation of the ISS as a national laboratory rings untrue as long as major research areas, such as fundamental physics, are excluded from participating. The recent NASA Request for Information for Earth and Space Science Payloads on the ISS could be an important first step in the right direction.

^{xx}The NASA Advisory Committee (NAC). For details see webpage at <http://www.hq.nasa.gov/office/oer/nac>

^{yy}Webpage of the NAC's Astrophysics subcommittee: <http://science.hq.nasa.gov/strategy/subcomm.html>

We believe that the recommendations presented above will benefit space-based research in fundamental physics and quantum technologies, the area of research with its unique science and strong technological potential.

Acknowledgments

We would like to express our gratitude to our many colleagues who have either collaborated with us on this manuscript or shared with us their wisdom. We specifically thank Eric G. Adelberger, Peter L. Bender, Curt J. Cutler, Gia Dvali, John L. Hall, Wolfgang Ketterle, V. Alan Kostelecký, Kenneth L. Nordtvedt, Douglas D. Osheroff, Craig Hogan, William D. Phillips, E. Sterl Phinney, Thomas A. Prince, Irwin I. Shapiro, Jun Ye, and Frank Wilczek, who provided us with valuable comments, encouragement, support, and stimulating discussions while this document was in preparation.

We are grateful to our European colleagues who benefited us with their insightful comments and suggestions regarding the manuscript. In particular, our gratitude goes to Orfeu Bertolami, Robert Bingham, Philippe Bouyer, Luigi Cacciapuoti, Thibault Damour, Hansjoerg Dittus, Ulrich Johann, Claus Lämmerzahl, Ekkehard Peik, Serge Reynaud, Albrecht Ruediger, Christophe Salomon, Stephan Schiller, Mikhail Shaposhnikov, Guglielmo Tino, Andreas Wicht, and Peter Wolf.

We thank our colleagues at JPL for their encouragement, support, and advice regarding this manuscript. We especially appreciate the valuable contributions from Roger A. Lee, Moshe Pniel, Michael W. Werner, and Jakob van Zyl of the Astronomy and Physics Directorate, Robert J. Cesarone of the Architecture and Strategic Planning Office of the Interplanetary Network Directorate, and also William M. Folkner and James G. Williams. Our gratitude also goes to Michael H. Salamon of NASA and Nicholas White of GSFC, who kindly provided us with many insightful comments and valuable suggestions on various aspects of the manuscript.

The work described here, was in part carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Appendix A. Advantages of Carrying out Physics Research in Space

Historically, experiments in fundamental physics focused on laboratory efforts involving ground-based, underground, and more recently, balloon experiments. Scientific progress in these experiments depends on clever experimental strategy and the use of advanced technologies needed to overcome the limits imposed by the environment typically present in Earth-based laboratories. As a result, the use of sophisticated countermeasures needed to eliminate or reduce contributions from various noise sources increases the overall cost of the research. Oftentimes the conditions in the Earth-based laboratories cannot be improved to the required levels of purity.

Although very expensive, access to space offers conditions that are not available on the Earth but are pivotal for many pioneering investigations exploring the limits of modern physics. We assert that, for many fundamental physics experiments, especially those aiming at exploring gravitation, cosmology, and atomic physics, while achieving the uttermost measurement precision, and increasingly so for high energy and particle astrophysics, a space-based location is the ultimate destination.

Considering fundamental physics experiments, our solar system is a unique laboratory that offers plenty of opportunities for discovery. A carefully designed space-based experiment can take advantage of a number of factors that significantly improve its accuracy; some of these factors are listed below.

A.1. Access to significant variations of gravitational potential and acceleration

Some general-relativistic effects (such as the gravitationally induced frequency shift) vary with the potential. Space enables far more precise tests because the change in potential can be much greater, and at the same time less affected by noise, than in any ground-based experiments. Other effects (for example, those resulting from a violation of the EP or of local Lorentz and position invariances (see Secs. 2.5 and 2.1) vary with the magnitude or direction of the acceleration. These, and the range of frequencies at which they can be made to occur in the experiment frame, can greatly exceed the values accessible in corresponding ground-based tests.

The strongest gravity potential available in the solar system is that provided by the Sun itself. Compared with terrestrial conditions, the Sun offers a factor of ~ 3000 increase in the strength of gravitational effects. The corresponding gravitational acceleration near the Sun is nearly a factor of 30 larger than that available in ground-based laboratories.

Placing an experimental platform in heliocentric orbit provides access to conditions that are not available on the ground. For instance, a highly eccentric solar orbit with apoapsis of 5 AU and periapsis of 10 solar radii offers more than two orders of magnitude in variation of the solar gravity potential and four orders of magnitude in variation in the corresponding gravitational acceleration, clearly not available otherwise. Smaller benefits may be achieved at a lower cost in Earth orbit.

In addition, the ability to precisely track very long arcs of trajectories of test bodies in the solar system is another great advantage of space deployment.

A.2. Greatly reduced contribution of nongravitational sources of noise

Compared with Earth-based laboratories, experiments in space can benefit from a range of conditions, especially those of freefall, and also with significantly reduced contributions due to seismic, thermal, and other sources of nongravitational noise.

Microgravity environments ranging from $10^{-4} g$ to $10^{-6} g$ achieved with free-falling platforms enable new laser-cooling physics experiments and high-accuracy

tests of gravity with colocated clocks. A long duration in a controlled free fall environment and drag-free operations benefit many experiments. It is expected that the next-generation optical atomic clocks will reach their full potential of accuracy only in space (see Sec. 2.6.1).

Purely geodesic orbits that are achieved with drag-free spacecraft and for which effects of nongravitational forces are reduced to 10^{-10} – $10^{-14}g$ levels compared with terrestrial conditions are needed for precision tests of gravity and direct detection of gravitational waves.

A.3. Access to large distances, velocities, and separations; availability of remote benchmarks and inertial references

Laser retroreflectors on the Moon, radio transponders on Mars, and radio science experiments on board remote spacecraft have vastly improved the accuracy of tests of relativistic gravity. In the near future, optics- and atom-based quantum technologies could provide even higher accuracy for the next generation of interplanetary laser ranging experiments.

Formation flying technologies, with spacecraft separated by distances from hundreds of meters to millions of kilometers, enable larger apertures, more complex focal plane assemblies, and longer interferometric baselines than are possible on the Earth. For example, a gravitational wave observatory with a baseline of several million km is possible only in space, opening a window for the study of low-frequency gravitational waves.

Availability of an inertial reference frame is oftentimes one of the most critical requirements for precision tests of gravity. Modern-day precision star-trackers and spacecraft attitude control systems allow the establishment of inertial reference and, thus, the carrying out experiments in the inertial or quasi-inertial environment of the solar system.

A.4. Access to vacuum conditions of space

Space deployment provides for a significant reduction of atmospheric interference with the propagation of optical, radio, and X-ray signals. In fact, absence of air allows perfect optical “seeing” and avoids particle annihilation in antimatter searches. Thus, space conditions allow for small point spread functions (PSF’s) (due to the absence of atmospheric blurring) and PSF stability (due to the thermally stable environment only available in space) needed for many precision measurements. As a result, the space vacuum allows the construction of instruments with unique architectures enabled by highly accurate optical metrology, including image-forming instruments with large apertures and long-baseline interferometers.

A.5. Availability of critical technologies

Development of technologies needed for many fundamental physics experiments is a very challenging task; however, recent years have seen the maturation of a significant

number of key technologies that were developed to take advantage of the unique conditions available in space. Among them are high-precision accelerometers, drag-free control using He-proportional thrusters or small ion thrusters as actuators, ultrastable lasers in space, He dewars, cryocoolers, superconducting detectors, high-precision displacement sensors, magnetic spectrometers, small trapped-ion clocks, lightweight H-maser clocks and atomic clocks using laser-cooled atoms. Many of these technologies have been space-qualified and some have already been flown in space, thereby paving the way for the development of many fundamental physics experiments.

Many of the advanced space technologies developed for gravitational experiments can be directly applied to other space sciences, including astrophysics, cosmology, astroparticle and atomic physics. Such technological cross-pollination allows other science disciplines to take advantage of space deployment opportunities, thereby stimulating the progress in many areas of space research.

Appendix B. Fundamental Physics in Space: Lessons from the Past and Prospects for the Future

In the past, NASA had recognized the potential and importance of fundamental physics research conducted in space. In particular, the program on “Microgravity and Fundamental Physics” that was established in 1996 was focused primarily on research to be conducted on the ISS, thereby contributing to the science justification for the space station.^{zz} After the publication of *Roadmap for Fundamental Physics in Space* in 1999,^{aaa} the NAC^{xx} endorsed the Roadmap and recommended broader support dedicated to fundamental physics.

Following the initial success of NASA’s “Microgravity and Fundamental Physics” program and in recognition of the emergence of fundamental physics as a space discipline not served by other commissions, the Committee on Space Research (COSPAR) established Commission H: Fundamental Physics in Space in 1996.^{bbb} Since the time of its inception, the contributions from Commission H at the biannual COSPAR meetings have been growing steadily.

As for NASA efforts in the field, a suite of missions and space-based experiments representing many areas of physics were developed and planned for flight in the period of 2002–08.^{mmm} However, in 2004, following the NASA reorganization in a response to the US New Space Exploration Initiative, Code U became part of the new NASA Exploration Systems Mission Directorate (ESMD). With no clear alignment with the

^{zz} Among the most successful outcomes of this program that existed during 1996–2004 were the Lambda Point Experiment (LPE; 1992), the Confined Helium eXperiment (CHeX, 1997), Critical Fluid Light Scattering (ZENO; 1991, 1994), and Critical Viscosity Xenon (CVX; 1997). See details at <http://funphysics.jpl.nasa.gov> and <http://funphysics.jpl.nasa.gov/technical/lcemp/zeno.html>

^{aaa} An electronic version of *Roadmap for Fundamental Physics in Space* is available at <http://funphysics.jpl.nasa.gov/technical/library/roadmap.html>

^{bbb} See COSPAR’s webpage, <http://www.cosparhq.org>, for information about Commission H on Fundamental Physics in Space.

ESMD's objectives, Code U's fundamental physics budget was decimated within four months and the entire program was terminated in September 2006.

In contrast, the ESA's science program, through persistent efforts by the fundamental physics community,³⁰⁹ has an established "Fundamental Physics Program" highlighted by development of several missions which are nearing flight-ready status.^{ccc} The ESA's recently initiated Cosmic Vision 2015–25 program seeks to respond to the most important and exciting scientific questions that European scientists want to address by space missions in the time frame 2015–25.^h In fact, Cosmic Vision marks a significant breakthrough for fundamental physics: for the first time, a major space agency has given full emphasis in its forward planning to missions dedicated to exploring and advancing the limits of our understanding of many fundamental physics issues, including gravitation, unified theories, and quantum theory.^{310,ddd} NASA would benefit from a similar bold and visionary approach. Proposals submitted to the call for "Astrophysics Strategic Mission Concept Studies" of ROSES^{eee} could lead to such an opportunity and potentially result in a dedicated space-based laboratory experiment in fundamental physics.

B.1. *Dedicated missions to test relativistic gravity*

There are two distinct approaches to organizing research in fundamental physics in space — either a dedicated space mission to perform an experiment or a smaller-scale-experiment as a part of a planetary exploration mission. We discuss below these approaches in some detail.

NASA has successfully launched two PI-led missions devoted to experimental tests of general relativity, namely Gravity Probe A^{fff} and Gravity Probe B.

The first convincing measurement of the third of Einstein's proposed tests of general theory of relativity — the gravitational redshift — was made in 1960 by Pound and Rebka. The Pound–Rebka experiment was based on Mössbauer effect measurements between sources and detectors spanning the 22.5 m tower in the Jefferson Physical Laboratory at Harvard. In 1976, Gravity Probe A exploited the much higher "tower" enabled by space; a suborbital Scout rocket carried a hydrogen maser to an altitude of 10,273 km and a novel telemetry scheme allowed comparison with hydrogen masers on the ground. The clocks confirmed Einstein's prediction to 70 ppm. More than 30 years later, this remains the most precise measurement of the gravitational redshift.¹⁸

^{ccc}Notably, the MicroSCOPE and ACES missions.

^{ddd}In October 2007 several candidate missions were selected for consideration for launch in 2017/18. See <http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=41438>. Although no fundamental physics mission was chosen at that time, the Cosmic Vision opportunity strongly motivated the work in the entire area of space-based experimental research.

^{eee}NASA Research Opportunities in Space and Earth Sciences (ROSES-2007). See details at <http://nspires.nasaprs.com>.

^{fff}See http://en.wikipedia.org/wiki/Gravity_Probe_A

Gravity Probe B was launched on April 20, 2004. The goal of this experiment is to test two predictions of general relativity by means of measuring the spin direction of gyroscopes in orbit about the Earth. For the 642-km-high GP-B orbit, GR predicts two gyroscope precessions, the geodetic effect with a rate of 6.606 arcsec per year and the frame-dragging effect with a rate of 39 milliarcsec per year. A polar orbit is chosen so the two effects would occur at right angles and could be independently resolved. The science instrument was housed in the largest helium dewar ever flown in space. The helium lifetime set the experiment duration; the orbital setup and science data phase lasted 17.3 months, exceeding requirements.

GP-B was the first spacecraft with six-degrees-of-freedom active control: translation, attitude, and roll. He boil-off gas proportional thrusters provided control actuation enabling the “drag-free” control system to reduce cross track acceleration to $10^{-11} g$. The requirements on charge control, magnetic shielding, and pressure were all met with margin. Flight data confirm that the GP-B gyroscope disturbance drift rates were more than a factor of a million times smaller than the best modeled navigational gyroscopes. The small size of the relativity effects under test imposed extreme requirements on the mission; their successful demonstration in space has yielded and will yield many benefits to future fundamental physics missions in space. Final results are pending the completion of the data analysis scheduled for early 2008.

B.2. Missions of opportunity on planetary missions

In addition to the development of dedicated missions, another practical way to conduct fundamental physics experiments is to fly advanced instruments as Missions of Opportunity (MO’s) on planetary missions and the ISS.

The LLR experiment that was initiated in 1969 by the Apollo 11 astronauts placing laser retroreflectors on the lunar surface¹⁷ is an excellent example of a successful MO. The resulting fundamental physics experiment is still active today and is the longest-running experiment in the history of space science (see Sec. 2.1.2).

One can further improve LLR-enabled science by delivering to the Moon either new sets of laser retroreflector arrays or laser transponders pointed at the Earth, or both types of instruments.⁵¹ A geographic distribution of new instruments on the lunar surface wider than the current distribution would be a great benefit; the accuracy of the lunar science parameters would increase several times. A bright transponder source on the Moon would open LLR to dozens of satellite laser ranging stations which cannot detect the current weak signals from the Moon. This would greatly benefit LLR — the living legacy of the Apollo program — and would also enhance the science outcome of the new lunar exploration efforts.

Highly accurate measurements of the round-trip travel times of laser pulses between an observatory on the Earth and an optical transponder on Mars could lead to major advances in gravitation and cosmology, while also enhancing our knowledge of the Martian interior. The technology is available to conduct such measurements with picosecond-level timing precision, which could translate into

millimeter-class accuracies achieved in ranging between the Earth and Mars. Similar to its lunar predecessor, the resulting Mars Laser Ranging experiment could become an excellent facility to advance fundamental physics.

Other examples of successful MO's are the recently conducted gravity experiment on the Cassini mission performed on its way to Jupiter during one of the solar conjunctions¹²³ and a similar experiment that is planned for the ESA's Bepi-Colombo mission to Mercury.³¹¹

In general, research in fundamental and gravitational physics will greatly benefit from an established mechanism to participate on planetary missions as MO's that will offer sorely needed space deployment opportunities.

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