STEP, The Satellite Test Of The Equivalence Principle

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Abstract

STEP (the Satellite Test of the Equivalence Principle) will advance experimental limits on violations of Einstein's equivalence principle (EP) from their present sensitivity of 2 parts in 10^{13} to 1 part in 10^{18} through multiple comparison of the motions of four pairs of test masses of different compositions in an earth-orbiting drag-free satellite. Dimensional arguments suggest that violations, if they exist, should be found in this range, and they are also predicted by many of the leading attempts at unified theories of fundamental interactions (e.g. string theory), as well as cosmological theories involving dynamical dark energy. Discovery of a violation would constitute the discovery of a new force of nature and provide us with a critical signpost toward unification. A null result would be just as profound, because it would close off any possibility of a natural-strength coupling between standard-model fields and the new light degrees of freedom that nearly all such theories generically predict (e.g., dilatons, moduli, quintessence). STEP should thus be seen as the intermediate-scale component of an integrated strategy for fundamental physics experiments that already includes particle accelerators (at the smallest scales) and supernova probes (at the largest). The former may find indirect evidence for new fields via their missing-energy signatures, and the latter may produce direct evidence through changes in cosmological equation of state, but only a gravitational experiment like STEP can go further and reveal how or whether such a field couples to the rest of the standard model. It is at once complementary to the other two kinds of tests, and a uniquely powerful probe of fundamental physics in its own right.

Historical Overview

The Satellite Test of the Equivalence Principle (STEP) will probe the underlying foundation of Einstein's theory, the (local) equivalence of gravitational and inertial mass, ofter called the weak equivalence principle. The equivalence principle (EP) originated in Newton's clear recognition (1687) of the strange experimental fact that mass fulfills two conceptually independent functions in physics, as both the source of gravitation and the seat of inertia. Einstein's "happiest thought" (1907) was the realization that the local equivalence of gravitational and inertial mass tells us something very deep about gravity: it tells us that the phenomenon of gravitation does not depend on the properties of matter (for it can be transformed away by moving to the same accelerated frame, regardless of the mass or composition of the falling object). Rather, the phenomenon of gravity must spring from the properties of spacetime itself. Einstein eventually identified the property of spacetime that is responsible for gravitation as its curvature. General relativity, our currently accepted "geometrical" theory of gravity, thus rests on the validity of the EP. But it is now widely expected that general relativity must break down at some level, in order to be united with the other fields making up the standard model of particle physics. It therefore becomes crucial to test the EP as carefully as possible. Historically, there have been four distinct ways of testing equivalence: (1) Galileo's free-fall method, (2) Newton's pendulum experiments,

(3) Newton's celestial method (his dazzling insight that moons and planets could be used as test masses in the field of the sun) and (4) Eotvos' torsion balance. Of these, (3) and (4) are at present the most exact: the celestial method now makes use of lunar laser ranging to place limits on the relative difference in acceleration toward the sun of the earth and moon of $3*10^{-13}$ [1], and constraints of 0.3+- $1.8*10^{-13}$ come from modern state-of-the-art torsion balance experiments[2]. But both these methods have reached an advance level of maturity and is unlikely that they will advance significantly beyond the 10^{-13} level in the near term. STEP is conceptually a return to Galileo's free-fall method, but one that uses a 7000 km high "tower" that constantly reverses its direction to give a continuous periodic signal, rather than a quadratic 3 s drop. A free-fall experiment in space has two principal advantages over terrestrial torsion-balance tests: a larger driving acceleration (sourced by the entire mass of the earth) and a quieter environment, particularly if drag-free technology is used. These and other factors will enable STEP to improve existing constraints on EP violation by five to six orders of magnitude, from $2*10^{-13}$ to 10^{-18}.

Experimental Design

The STEP design calls for four pairs of concentric test masses forming four differential accelerometers. The baseline mass pairs are composed of Pt-Ir alloy, Nb and Be in a "cyclic condition" to eliminate possible sources of systematic error (the total acceleration difference between A-B, B-C and C-A must be zero for three mass pairs AB, BC and CA). Results from extensive theoretical discussions in the 1990s suggest that EP violations are likely to be tied to at least one of three potential determinative factors that can be connected to a general class of string-inspired models: baryon number, neutron excess and nuclear electrostatic energy [3, 4]. The test masses are constrained by superconducting magnetic bearings to move in one direction only; they can be nearly perfectly centered by means of gravity gradient signals, thus avoiding the pitfall of most other free-fall methods (unequal initial velocities and times of release). Their accelerations are monitored with very soft magnetic "springs" coupled to a cryogenic SQUID-based readout system. STEP will used the same SQUIDs that were successfully demonstrated in flight by the Gravity Probe B Mission, GP-B[5]. Many of the other key STEP technologies, including test mass positioning, charge measurement and UV discharge systems, drag-free control algorithms and proportional helium thrusters using boiloff from the dewar as propellant were also successfully flown on GP-B. Prototypes of key components are in advanced stages of development.

The science instrument comprised of the 4 differential accelerometers is housed in a 220 liter superfluid helium dewar which provides the main structure of the spacecraft as shown in figure 1. Payload and spacecraft (service module) electronics are housed above the dewar in an enclosure shielded by a sunshield and solar array. A 550 km high, sun synchronous orbit mitigates thermal disturbances.

Theoretical Motivation

Theoretically, the range $10^{-13} < \partial a/a < 10^{-18}$ is extremely interesting. This can be seen in at least three ways. The simplest argument is a dimensional one. New effects in any theory of quantum gravity must be describable at low energies by an effective field theory with new terms like $\beta(m/m_{QG}) + O(m/m_{QG})^2$ where β is a dimensionless coupling parameter not too far from unity and m_{QG} is the quantum-gravity energy scale, which could be anywhere between the grand unified theory (GUT) scale $m_{GUT} \sim 10^{16}$ GeV and the Planck scale $m_{Pl} \sim 10^{19}$ GeV. In a theory

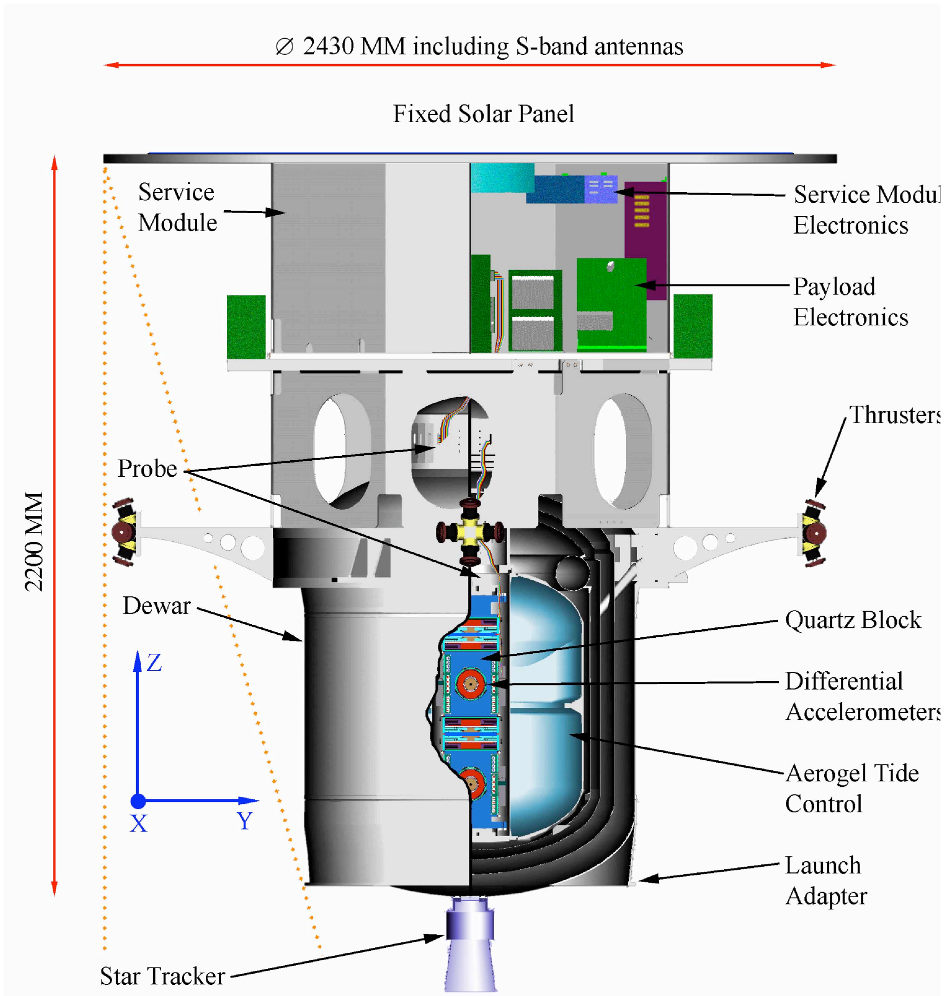

Figure 1. STEP Spacecraft as defined by NASA and ESA funded Phase A and Industrial Studies. Total mass equals 700 kg.

combining gravity with the Standard Model, m could plausibly lie anywhere between the mass of an ordinary nucleon ($m_{nuc} \sim 1$ GeV) and that of the Higgs boson ($m_H \sim 100$ GeV). With these numbers one finds that EP-violating effects should appear between $(m_{nuc}/m_{Pl}) \sim 10^{19}$ and $(m_H/m_{GUT}) \sim 10^{14}$, the range of interest. This makes STEP a potential probe of quantum gravity [6].

The dimensional argument, of course, is not decisive. A second approach is then to look at the broad range of specific theories that are sufficiently mature to make quantitative predictions for EP violation. There are two main categories. On the high-energy physics side, EP violations occur in many of the leading unified theories of fundamental interactions, notably string theories based on extra spatial dimensions. In the low-energy limit, these give back classical general relativity with a key difference: they generically predict the existence of a four-dimensional scalar dilaton partner to Einstein's tensor graviton, and several other gravitational-strength scalar fields known as moduli. In the early universe, these fields are naturally of the same order as the gravitational field, and some method has to be found to get rid of them in the universe we observe. If they survive, they will couple to Standard Model fields with the same strength as gravity, producing drastic violations of the EP. One conjecture is that they acquire large masses and thus correspond to very short-range interactions, but this solution, though widely accepted, entails grave difficulties (the Polonyi or "moduli problem") because the scalars are so copiously produced in the early universe that their masses should long ago have overclosed the universe, causing it to collapse. Another possibility involves a mechanism whereby a massless "runaway dilaton" (or moduli) field is cosmologically attracted toward values where it almost, but not quite, decouples from matter; this results in EP violations that lie in the same range as that identified above and can reach $\sim 10^{14}$[7]. Similar comments apply to another influential model, the TeV "little string" theory [8].

The second category of specific EP-violating theories occurs at the opposite extremes of mass and length, in the field of cosmology. The reason is the same, however: a new field is introduced whose properties are such that it should naturally couple with gravitational strength to Standard Model fields, thus influencing their motion in violation of the EP. The culprit in this case is usually dark energy, a catch-all name for the surprising but observationally unavoidable fact that the expansion of the universe appears to be undergoing late-time acceleration. Three main explanations have been advanced for this phenomenon: either general relativity is incorrect on the largest scales, or there is a cosmological constant (whose value is extremely difficult to understand) – or dark energy is dynamical. Most theories of dynamical dark energy (also known as quintessence) involve one or more species of new, light scalar fields that could violate the EP [9]. The same thing is true of new fields that may be responsible for producing cosmological variations in the electromagnetic fine-structure constant α[10].

In all or most of these specific theories, EP violations are suggested to appear in the STEP range, $10^{-18} < \partial a/a < 10^{-13}$. To understand the reasons for this, it is helpful to look at the third of the arguments alluded to above for regarding this range as a particularly rich and interesting one from a theoretical point of view. This line of reasoning shares some of the robustness of the dimensional argument, in that it makes the fewest possible assumptions beyond the Standard Model, while at the same time being based upon a convincing body of detailed calculations. Many authors have done work along these lines, with perhaps the best known being that of Carroll in 1998 [11], which we follow in outline here. Consider the simplest possible new field: a scalar ϕ (as motivated by observations of dark energy, or alternatively by the dilaton or supersymmetric moduli fields of high-energy unified theories such as string theory). Absent some protective symmetry (whose existence would itself require explanation), this new field ϕ couples to Standard Model fields via dimensionless coupling constants β_k (one for each SM field) with values not too far from unity. Detailed but standard calculations within the Standard Model (modified only to incorporate ϕ) show that these couplings are tightly constrained by existing limits on violations of the EP. The current bound of order $\partial a/a < 10^{-12}$ translates directly into a requirement that the dominant coupling factor (the one associated with the gauge field of quantum chromodynamics or QCD) cannot be larger than $\beta_{QCD} < 10^{-6}$. This is very small for a dimensionless coupling constant, though one can plausibly "manufacture" dimensionless quantities of this size (e.g. $\alpha^2/16\pi$), and many theorists would judge that anything smaller is almost certainly zero. Now STEP will be sensitive to violations as small as 10^{-18}. If none are detected at this level, then the corresponding upper bounds on β_{QCD} go down like the square root of $\partial a/a$; i.e., to $\beta_{QCD} < 10^{-9}$, which is no longer a natural coupling constant by any current stretch of the imagination. For perspective, recall the analogous "strong CP" problem in QCD, where a dimensionless quantity of order 10^{-8} is deemed so unnatural that a new particle, the axion, must be 4 invoked to drive it toward zero. This argument does not say that EP violations inside the STEP range are inevitable; rather it suggests that violations outside that range would be so unnaturally fine-tuned as to not be worth looking for. As Ed Witten has stated, "It would be surprising if ϕ exists and would not be detected in an experiment that improves bounds on EP violations by 6 orders of magnitude" [12]. Only a space test of the EP has the power to force us to this conclusion.

The fundamental nature of the EP makes such a test a "win-win" proposition, regardless of whether violations are actually detected. A positive detection would be equivalent to the discovery of a new force of nature, and our first signpost toward unification. A null result would imply either that no such field exists, or that there is some deep new symmetry that prevents its being coupled to Standard Model fields. A historical parallel to a null result might be the Michelson-Morley experiment, which reshaped physics because it found nothing. The "nothing" finally forced physicists to accept the fundamentally different nature of light, at the cost of a radical revision of their concepts of space and time. A non-detection of EP violations at the 10^{-18} level would strongly suggest that gravity is so fundamentally different from the other forces that a similarly radical rethinking will be necessary to accommodate it within the same theoretical framework as the Standard Model based on quantum field theory. STEP should be seen as the integral "intermediate-scale" element of a concerted strategy for fundamental physics experiments that also includes high-energy particle accelerators (at the smallest scales) and cosmological probes (at the largest scales). Accelerators such as the Large Hadron Collider (LHC) may provide indirect evidence for the existence of new fields via their missing-energy signatures. Astronomical observatories such as the SuperNova Acceleration Probe (SNAP) may produce direct evidence of a quintessence-type cosmological field through its bulk equation of state. But only a gravitational experiment such as STEP can go further and reveal how or whether that field couples to the rest of the standard model. It is at once complementary to the other two kinds of tests, and a uniquely powerful probe of fundamental physics in its own right

Flight Readiness

STEP originated in 1972 and a ground-based version was built and operated at Stanford University with NASA and NSF support[5]. In 1989, with NASA Code U backing, STEP was proposed to the ESA M2 AO as a joint US/European mission. It was one of four from across the whole range of ESA science awarded a Phase A Study, and ranked second in the final 1993 M2 selection. Further studies followed, but with delays which led French and Italian STEP team members to advance competing European-led missions, most notably MICROSCOPE[13], a low-cost lower-accuracy room-temperature version of STEP proposed to CNES by our ONERA colleagues in 1997. MICROSCOPE is currently scheduled for 2011 launch. It has two, rather than four, pairs of test masses, capacitive in place of superconducting readout, and aims at an EP sensitivity of 10^{-15}.

From 1992 on NASA Code U provided enhanced instrument development funding for STEP. In 1998, STEP successfully passed the dual Science Concept Review (SCR), Requirements

Definition Review (RDR) selection process used to determine whether a Code U program should enter the queue for flight. The RDR committee (Chair: J. Salzman) concluded: "Our overall findings, based on all the information in hand, is that the STEP Project Team has: 1) an excellent understanding of the PI's science requirements, 2) a viable experiment concept to satisfy those requirements, 3) an in-depth knowledge of the critical techniques and technologies necessary to implement that concept in a successful space flight experiment, 4) a reasonable approach to bring those techniques and technologies to the level of maturity required to eventually secure ATP for the Project's implementation phase."

In 1999, STEP was one of the six from 43 proposals selected for Phase A Study under SMEX 8/9. The study, joint with JPL, was highly beneficial and many of its findings are reflected in the current baseline design. It was not selected for flight. In the July 2002 HQ de-briefing, the principal reason given was that the technology, though well-advanced, was not yet at TRL levels compatible with the short time-period of a SMEX.

Two things have transformed the situation since then: (1) the successful launch and operation of GP-B (with STEP team members closely involved) brought on orbit demonstration of many key technologies (e.g. SQUID performance, electrical centering, extreme superconducting shielding); (2) with NASA MSFC we defined in 2004 a STEP Technology Development Program for the non-GP-B technologies. This program, focusing on the fabrication and test of an engineering unit accelerometer, has answered many of the remaining technical challenges.

STEP proposed to the most recent SMEX AO (NNH07ZDA003O) and was reviewed by three panels: an external peer review for Scientific Merit, an external peer review for Scientific Implementation, and a NASA Langley Center review for Technical, Management and Cost. While the program was not selected due to the Langley panel that rated it high risk, the two external peer reviews were extremely positive[14]. The panels' findings are as follows:

STEP SMEX Scientific Merit Evaluation

Major Strengths

- There is an exceptionally strong scientific case for the goal of this project.
- No planned experiment would match, much less exceed, the sensitivity of STEP.
- The design will likely yield a successful mission.
- Testing the WEP more deeply than in the past is a prescription for discovering new fundamental physics

Major Weaknesses

- None

STEP SMEX Scientific Implementation Evaluation

Major Strengths

- The STEP instrument, which is designed to meet the science goals, has a long history and has received repeated scrutiny.
- The instrument is cryogenic, providing many advantages.
- Spurious signals are mitigated by appropriate operation of the spacecraft.
- The proposed instrument can be built with technologies described.
- The data returned will directly address the science goals and, with most of the mission devoted to instrument characterization and calibration, the instrument is likely to provide

the necessary data quality.
- The probability of success seems high

Major Weaknesses
- None

Guided by extensive peer review and with significant investment by NASA and ESA, STEP is primed to advance into a flight program. That STEP should fly is perhaps best summed up by the National Academy of Sciences report *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century 2003*[15]: "Improvement by a factor of around 10^5 could come from an equivalence principle test in space. … at these levels, null experimental results provide important constraints on existing theories, and a positive signal would make for a scientific revolution."

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