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Relevance of the weak equivalence principle and experiments to test it: Lessons from the past and improvements expected in space

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ABSTRACT

Tests of the Weak Equivalence Principle (WEP) probe the foundations of physics. Ever since Galileo in the early 1600s, WEP tests have attracted some of the best experimentalists of any time. Progress has come in bursts, each stimulated by the introduction of a new technique: the torsion balance, signal modulation by Earth rotation, the rotating torsion balance. Tests for various materials in the field of the Earth and the Sun have found no violation to the level of about 1 part in 10^{13}. A different technique, Lunar Laser Ranging (LLR), has reached comparable precision. Today, both laboratory tests and LLR have reached a point when improving by a factor of 10 is extremely hard. The promise of another quantum leap in precision rests on experiments performed in low Earth orbit. The Microscope satellite, launched in April 2016 and currently taking data, aims to test WEP in the field of Earth to 10^{-15}, a 100-fold improvement possible thanks to a driving signal in orbit almost 500 times stronger than for torsion balances on ground. The 'Galileo Galilei' (GG) experiment, by combining the advantages of space with those of the rotating torsion balance, aims at a WEP test 100 times more precise than Microscope, to 10^{-17}. A quantitative comparison of the key issues in the two experiments is presented, along with recent experimental measurements relevant for GG. Early results from Microscope, reported at a conference in March 2017, show measurement performance close to the expectations and confirm the key role of rotation with the advantage (unique to space) of rotating the whole spacecraft. Any non-null result from Microscope would be a major discovery and call for urgent confirmation; with 100 times better precision GG could settle the matter and provide a deeper probe of the foundations of physics.

1. Introduction

The General theory of Relativity (GR) [1] stands on the fundamental assumption that in a gravitational field all bodies fall with the same acceleration regardless of their mass and composition, a 'fact of nature' known as the Universality of Free Fall (UFF) or the Weak Equivalence Principle (WEP). The WEP has been tested for various materials in the field of the Earth and the Sun, and no violation has been found to the level of about $\Delta a/a \simeq 10^{-13}$ [2] (Δa is the difference in acceleration between two test bodies falling in a gravitational field with mean acceleration a, referred to as the 'driving signal').

A WEP experiment is both a test of the foundation stone of GR and a search for a new long range field coupling to matter in a way that depends on composition. A confirmed violation would have the same significance as the discovery of a new force of nature. There is no firm prediction as to the level at which the violation should occur. However, the WEP is so fundamental a postulate that any experiment that can push limits by many orders of magnitude is highly significant, whether it finds an effect or not.

Substantial progress in WEP test precision has always depended on the introduction of a new technique: the torsion balance at the turn of the 20th century (Eötvös), the Sun providing a daily modulated signal source (Dicke, Braginsky in the 1960s–70s), the rotating torsion balance (Adelberger and collaborators, from the early 1990s to this date). Nowadays, laboratory experiments have run their gamut and any further progress is small and comes at slow pace. A completely different technique, Lunar Laser Ranging (LLR), tests the WEP for the Earth and Moon as bodies of different composition falling in the field of the Sun. Such tests have reached a precision similar to the torsion balance [3,4] and a 10-fold improvement requires not only mm-level laser ranging, but also a matching improvement of the physical model which describes the Earth-Moon system [5].

Today, only space experiments seem capable of a significant step forward. Just because in orbit the driving signal from Earth is stronger by a factor of almost 500 than it is for the torsion balance

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on ground, a carefully designed orbiting experiment can target a precision improved by a similar factor.

The Microscope mission, launched in April 2016 into a low altitude, sun-synchronous orbit, aims to test WEP in the field of Earth to 10^{-15} [6], a 100-fold improvement over the rotating torsion balances which can be achieved with a lower sensitivity to differential accelerations thanks to the stronger driving signal in orbit.

The guiding principle of the 'Galileo Galilei' (GG) small satellite mission [7] is to fully exploit the advantages of space as well as those of the rotating torsion balance, so as to design a balance optimized for testing the WEP at zero-g. GG aims to reach 10^{-17}: a four order of magnitude improvement over the best ground experiments and a 100-fold improvement over Microscope. For GG to achieve its target, it must be about 20 times more sensitive to differential accelerations than rotating torsion balances, which is possible by exploiting weightless conditions inside an isolated co-rotating laboratory (the spacecraft) passively stabilized by rapid 1 Hz rotation around the symmetry axis.

Today, experimental evidence pointing the way out of the current physics impasse is hard to find, and even a hint of an effect from Microscope would cause excitement and call for confirmation by new measurements with increased precision. GG could provide validation at the level of 1% and settle the matter. Recently, GG was proposed as a candidate in the European Space Agency's M5 competition for a new medium-sized science mission, and is awaiting further inquiry, having passed the first round of selection.

The paper is organized as follows.

Sec. 2 presents the WEP as an 'experimentum crucis' of modern physics. Sec. 3 presents the principles of the torsion balance experiment introduced by Eötvös for testing the equivalence between inertial and gravitational mass, a decisive progress over previous experiments with pendulums by Galileo, Newton, Bessel and others. Sect. 4 elaborates on rotation as the other key element for increased precision. Sec. 5 summarizes the state of the art of current WEP experiments and their limitations. Sec. 6 makes the case for a space experiment in low Earth orbit as the way out of such limitations. Sec. 7 discusses the key features of the Microscope space experiment aiming at 10^{-15}. Sec. 8 shows how, on a similar orbit as Microscope and without requesting cryogenic temperatures, a different experiment design allows GG to aim at a 100 times better precision, to 10^{-17}. Recent experimental results relevant to the GG mission are also reported, along with positive news from the Microscope orbiting experiment which corroborate the choice of exploiting rotation in space. Sec. 9 draws the conclusions.

2. An 'experimentum crucis' of modern physics

The UFF was established experimentally by Galileo at the turn of the 17th century using two pendulums of different composition (see [8] for a general discussion on the universality of free fall and the equivalence principle). In 1687, in the opening paragraph of the 'Principia', Newton stated the equivalence of inertial and gravitational mass and then went on to derive the equations of motion showing that all masses fall with the same acceleration under the gravitational attraction of the Earth. If inertial and gravitational mass are equivalent, UFF holds: this was the 'equivalence principle' until the early 20th century.

In 1907, Einstein made the crucial leap from Newton's principle (now referred to as the weak equivalence principle, WEP), to the strong equivalence principle, SEP (also referred to as the Einstein Equivalence Principle, EEP). In the words of Robert Dicke [9]: "*The strong equivalence principle might be defined as the assumption that in a freely falling, non-rotating, laboratory the local laws of physics take on some standard form, including a standard numerical content, independent of the position of the laboratory in space and time. It is of course implicit in this statement that the effects of gradients in the gravitational field strength are negligibly small, i.e. tidal interaction effects are negligible. . . . this interpretation of the equivalence principle, plus the assumption of general covariance is most of what is needed to generate Einstein's general relativity.*" Should experiments invalidate UFF (and the WEP), they would invalidate the SEP as well.

As experimental evidence for UFF, Einstein took the results of Eötvös ([1], p. 773), who had achieved an impressive 1000-fold improvement over previous experiments by suspending test masses of different composition on a torsion balance rather than individual pendulums.

The Standard Model of particle physics and the General theory of Relativity, taken together, form our current view of the physical world. While the former governs the physics of the microcosm, the latter governs physics at the macroscopic level. Gravity couples in the same way to all forms of mass–energy, in all bodies, regardless of composition. Such universal coupling makes gravity different from all known forces of nature described by the Standard Model, and is at the heart of the fact that the two theories have so far resisted all attempts at reconciliation into a single unified picture of the physical world. This is the crossroad physics faces at the present time, which is of vital interest not only to theorists, especially given that the nature of about 95% of the matter–energy in the Universe – the so called dark matter and dark energy – is presently unknown.

An experiment capable of testing UFF to extremely high precision can potentially break this deadlock. The situation is reminiscent of that at the end of the 19th century, when Michelson and Morley tested by very precise light interferometry the propagation of the newly discovered electromagnetic waves through the hypothetical ether [10]. Their null experimental result showed beyond question that although its existence was generally assumed, there was in fact no ether; which led to the special theory of relativity. While Michelson and Morley knew which precision their interferometer had to achieve in order to detect the relative velocity between the Earth and the ether, we do not know which precision a test of UFF-WEP should reach to detect a violation, if any. Nonetheless, the issue is so important and the potential reward so huge that many prominent experimental physicists have spent long years in such tests, renewing the effort whenever the possibility for an improvement has arisen.

A WEP experiment is both a test of the foundation stone of GR and a search for a new long-range field coupling to matter in a way that depends on composition (phenomenologically, on powers of the atomic number Z and nucleon number A). The mass–energy content (A/Z ratio; electromagnetic effects in the proton mass, in the neutron mass and in the binding energy of the nucleus; etc.) varies greatly in different atoms and the validity of WEP at very high precision – implying that all forms of mass–energy fall with the same acceleration – is a very strong constraint for all physical theories to comply with [9]. In the years leading to GR, Einstein realized that the theory could stand or fall depending on the results of a single experiment, and even went so far as proposing one himself, calling it a 'simple experiment which would have the significance of an experimentum crucis' [11].

Gravitational self-energy, neutrinos and photons, matter and antimatter, in the purely geometrical treatment of General Relativity, all obey the WEP. Conversely, a confirmed violation could provide the so far missing clue to a more comprehensive physical theory. The higher the precision of the test, the higher the chances to find new physics.

WEP tests are null experiments, by their nature among the most precise types of experiments in physics. They are conceptually simple, can rely on well proven techniques of experimental physics and do not require large apparatus or resources, which makes it easier to detect and control systematic errors. Their very high probing power has already been demonstrated in the lab to