COFIS

Verso un test stringente della Relatività Generale nello spazio: basi teoriche e implicazioni tecnologiche

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ASI Workshop "Studi di Osservazione dell'Universo"
Roma 25-26 Marzo 2009

Un po’ di storia e una premessa

I primi 3 “studioni” (1 anno) partiti con la Presidenza Vetrella avevano il compito di individuare le priorità nell’ambito delle rispettive comunità

Il COFIS per la prima volta introdusse la Fisica Fondamentale nello spazio tra le linee di ricerca ufficiali di ASI, con pieno diritto di cittadinanza collocandola come era naturale accanto alla Cosmologia … grazie alla lungimiranza e alla aperta culturale di Paolo de Bernardis e alla disponibilità e al supporto della unità Osservazione dell’Universo di ASI..

A conclusione di quello studio, il COFIS individuò come prioritario, per la Fisica Fondamentale, il test del principio di equivalenza con la piccola missione GG. GG fu inserita nel Piano Aersopaziale Nazionale 2006-2008 e su questa linea di budget è stato aperto uno Studio Industriale di Fase A-2 (Thales Alenia Space Italia, TO) e uno Studio scientifico per lo sviluppo di un prototipo avanzato di laboratorio (nell’ambito dell’esperimento GGG approvato in INFN). Questi studi stanno seguendo il loro corso e il loro esito sarà cruciale per eventuali sviluppi futuri

Con l’opportunità successiva degli studi triennali, sarebbe stato assurdo abbandonare la comunità della Fisica Fondamentale perché GG aveva ottenuto un primo successo… E per noi era una opportunità per approfondire le basi teoriche degli esperimenti spaziali di fisica fondamentale e guardare al di là dell’ambito della nostra specifica attività sperimentale ..

WP4000: Fundamental Physics in Space (A.M. Nobili)

COFIS

WP4100: Verifiche di precisione della gravitazione universale nello spazio: basi fisiche e dati sperimentali/osservativi A.M. Nobili

WP4110 Fisica fondamentale con i dati dei satelliti LAGEOS D. Lucchesi

WP4120 Basi teoriche di esperimenti spaziali per la verifica del Principio di Equivalenza A.M. Nobili

WP4130 La metrica del sistema solare e la natura della "Pioneer anomaly" mediante telemisure di precisione di sonde interplanetarie. L. Iess

WP4140 Stato dell'arte delle verifiche osservative di MOND a confronto con possibili test diretti R. Falomo

WP4150 Misure accelerometriche per la rimozione degli effetti inerziali negli esperimenti spaziali di radioscienza V. Iafolla

WP4200: Studi preparatori all'uso di atomi freddi nello spazio G. M. Tino

WP4210 Studio di nuovi sensori ad interferometria atomica G. M. Tino

WP4220 Studio di nuovi orologi atomici ottici G. M. Tino

WP4230 Preparazione alla missione ACES G. M. Tino

WP4240 Studio di effetti quantistici in condensati Bose-Einstein in microgravità G. M. Tino

WP4250 Aspetti teorici di gravità quantistica con atomi ultrafreddi nello spazio M. L. Chiofalo

WP4260 Studio di effetti relativistici L. Lusanna

WP4300: Studio di sorgenti, metodi di analisi dati e modelli di rumore per LISA V. Ferra

WP4310 Strategie adattative di analisi dati e studio di sorgenti gravitazionali per LISA V. Ferrari

WP4320 Modelli di rumore ed impatto sull'analisi dati di LISA G. Prodi

WP4330 Ricerca di segnali da binarie coalescenti per LISA A. Viceré

WP4340 Ricerca di segnali stocastici e impulsivi non modellati per LISA G. M. Guidi

WP4350 Evoluzione cosmica di sistemi binari di buchi neri massivi come sorgenti di onde gravitazionali per la missione LISA F. Haardt

WP4400: Nuovi esperimenti spaziali per verifiche di precisione della gravitazione universale V. Iafolla

WP4410 Progetto e design di un esperimento per la verifica diretta della teoria MOND nello spazio A. M. Nobili

WP4420 Studio di un esperimento per la misura di G con un gradiometro ad un asse V. Iafolla

WP4430 Rivisitazione critica dell'esperimento spaziale Deep Space Gravity Probe di Cosmic Vision A. M. Nobili

WP4440 Analisi dati dell'accelerometro GGG e rilevanza per l'esperimento spaziale GG F. Maccarrone

WP4500: Verso una comprensione del ruolo della turbolenza nei plasmi spaziali F. Pegoraro

WP4510 Esperimenti da satellite su fenomeni di turbolenza controllati F. Pegoraro

The Standard Model and General Relativity (I)

General Relativity (GR) and the **Standard Model** (SM) of particle physics form our current view of the physical world. GR governs physics in the macroscopic and cosmic scales; SM governs the physics of the microcosm.

GR: gravity is not a force but a manifestation of space-time curvature. The relation between space-time curvature and space-time content (mass-energy and momentum) being given by Einstein’s field equations. The theory has been extensively tested and no astronomical observation or experimental test (the most accurate of which have been performed in space) has been found to deviate from its predictions. Thus it is the best description we have of gravitational phenomena that we observe in nature.

SM: gives a unified formalism for the other three fundamental interactions (strong, weak and electromagnetic) between the fundamental particles that make up all matter. It is a quantum field theory which is consistent with both Quantum Mechanics and Special Theory of Relativity. To date, almost all experimental tests of the Standard Model have agreed with its predictions.

The Standard Model and General Relativity (II)

… however, GR and SM, despite great success in their own fields, so far could not be reconciled to form a single unified theory!

SM: particle fields are defined on a flat Minkowski space-time

GR: postulates a curved space-time which evolves with the motion of mass-energy. In addition quantum mechanics becomes inconsistent with GR near singularities….

Attempts at reconciling these theories indicate that the pure tensor gravity of GR needs modification or augmentation. New physics is needed, involving new interactions which are typically composition dependent (I.e. would violate the Equivalence Principle on which GR is based). This motivates new searches for experimental signatures of very small deviations from GR

“Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century”

“Committee on the Physics of the Universe” appointed by he National Research Council of the US National Academies.

The results of the panel’s work in the book: **”Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century”,** (National Academies press, 2003).

3rd of the eleven questions: **“Did Einstein Have the Last Word on Gravity?”**:

“Black holes are ubiquitous in the universe. The effects of strong gravity in the early universe have observable consequences. Einstein’s theory should work as well in these situations as it does in the solar system. **A complete theory of gravity should incorporate quantum effects—Einstein’s theory of gravity does not—or explain why they are not relevant.”**

“Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century”

“Dark Energy Task Force” (I)

Dark Energy Task Force (**DETF**) established in the US by the Astronomy and Astrophysics Advisory Committee and the High Energy Physics Advisory Panel to advise the Department of Energy, NASA and the National Science Foundation on future dark energy research.

DETF final report (2006)
http://www.nsf.gov/mps/ast/aaac/dark_energy_task_force/report/detf_final_report.pdf
where the Executive Summary begins as follows:

“Over the last several years scientists have accumulated conclusive evidence that the Universe is expanding ever more rapidly. Within the framework of the standard cosmological model, this implies that 70% of the universe is composed of a new, mysterious dark energy, which unlike any known form of matter or energy, counters the attractive force of gravity. Dark energy ranks as one of the most important discoveries in cosmology, with profound implications for astronomy, high-energy theory, general relativity, and string theory.

One possible explanation for dark energy may be Einstein's famous cosmological constant. Alternatively, dark energy may be an exotic form of matter called quintessence, **or the acceleration of the Universe may even signify the breakdown of Einstein's Theory of General Relativity.** With any of these options, there are significant implications for fundamental physics. “

DETF Report, Executive Summary

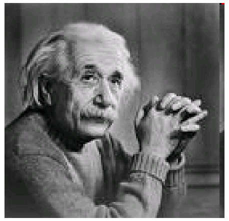
“Dark Energy Task Force” (II)

A few pages below, the Section of the DETF Report on “Goals and Methodology for Studying Dark Energy” ends with the sentence:

“Just as dark-energy science has far-reaching implications for other fields of physics, advances and discoveries in other fields of physics may point the way toward understanding the nature of dark energy; **for instance, any observational evidence for modifications of General Relativity.”**

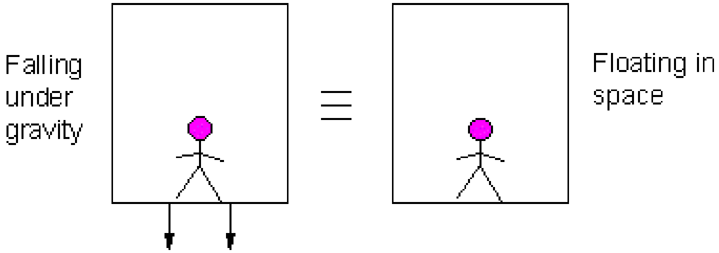
A stringent test of General Relativity (I)

Strong hint (to be “successful”…): Test GR foundations, not simply GR predictions!!!!!

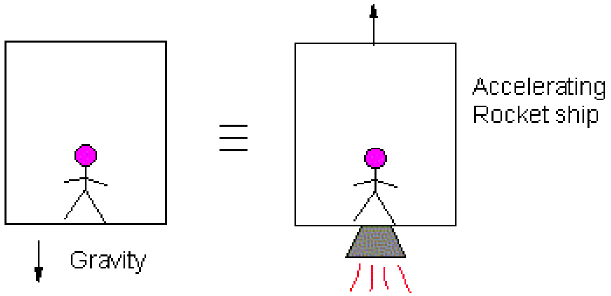


1. Einstein 1907: “hypothesis of complete physical equivalence” between a gravitational field and an accelerated frame

In a freely falling system all masses fall equally fast, hence gravitational acceleration has no local dynamical effects. Any test mass located inside the famous Einstein elevator –falling with the local acceleration of gravity g near the surface of the Earth– and zero initial velocity with respect to it, remains motionless for the time of fall.

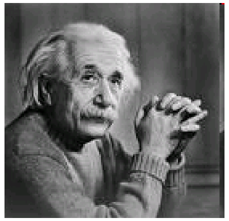


An observer inside Einstein elevator close to the Earth will not be able to tell, before hitting the ground, whether he is moving with an acceleration g in empty space, far away from all masses, or else he is falling in the vicinity of a body (the Earth) whose local gravitational acceleration is also g.



This is the Weak Equivalence Principle (WEP) (holds only locally h<<R$_\oplus$)

A stringent test of General Relativity (II)



2. Einstein Equivalence Principle (EEP) and the formulation of GR:

i) WEP is valid

ii) The outcome of any local non-gravitational experiment is independent of the velocity of the freely-falling reference frame in which it is performed (Local Lorentz Invariance)

iii) The outcome of any local non-gravitational experiment is independent of where and when in the universe it is performed (Local Position Invariance).

EEP –which assumes the WEP– is the "heart and soul" of the GR because it is the validity of this "principle" to ensure the fact that in GR the effects of gravity are replaced by a curved 4-dimensional space-time.

Einstein has moved from Newton's concept of one global reference frame with gravitational forces and the Universality of free Fall (which is the most direct experimental consequence of the Weak Equivalence Principle), to many free falling local frames without gravitational forces (also a consequence of the Weak Equivalence Principle)

… thus, the whole theory of GR is BASED on the Weak Equivalence Principle!

Test GR foundations ⇒ test the Weak Equivalence Principle

A stringent test of General Relativity (III)

WEP tests vs γ tests: a quantitative assessment of their probing power

PPN (Parametrized Post Newtonian) parameter γ:
Should be (γ-1) = 0 if GR holds
Measured with Cassini: γ-1 is zero to a few 10^{-5} (Bertotti, Iess & Tortora, 2003)

WEP tests: parameter $\eta = \frac{\Delta a}{a}$, should be $\eta = 0$ if WEP (hence, GR) holds

(η is the fractional differential acceleration between falling bodies of different composition)
Measured (torsion balances & LLR): WEP holds to about 10^{-13} (Schlamminger et al. 2008; Willimas, Turyshev & Boggs 2004)

According to Damour (1996), Damour, Piazza & Veneziano (2002):

$$\frac{\Delta \mathbf{a}}{\mathbf{a}} \simeq 10^{-5} \textbf{ to } 10^{-3} (\gamma - 1)$$

.. Current WEP tests to 10^{-13} already constrain (γ -1) below 10^{-8} or 10^{-10}!

The superior probing power of WEP tests is apparent…

Predictions of WEP violation

Within a classical framework (which does not postulate any new interaction) if gravity couples anomalously to the energy of neutrino-antineutrino exchange, its contribution to the mass-energy of the nucleus would lead (**rigorous calculation**) to an Equivalence Principle violation to the level of about 10^{-17}

Fischbach et al. 1995

Beyond the Standard Model, predictions based on string theory and the existence of dilaton lead, in a speculative scenario, to an EP violation just below 10^{-12} (for Be, Cu and Pt;Ti)

Damour, Piazza & Veneziano (2002a; 2002b)

Maximize signal, exploit weightlessness, minimize environment disturbances: the advantages of space!

With test masses in LEO (500-600 km altitude) the gain in the strength of the signal is by about 3 orders of magnitude

Weightlessness is ideal for the test masses to be sensitive to extremely tiny effects

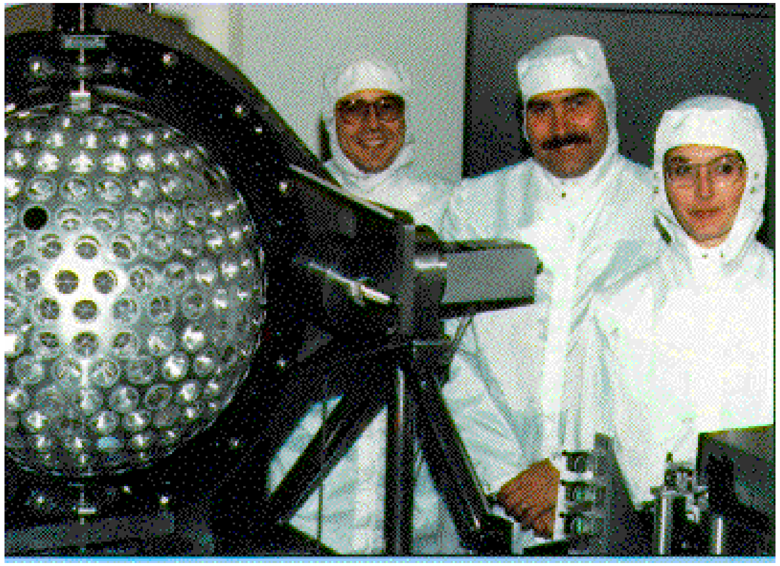
Space is (almost) empty: unlike on the ground, the s/c is an isolated system, thus minimizing disturbances from the local environment (terrain tilts, seismic noise, local mass anomalies...)

… but do we really need a spacecraft?

… we do already have test masses orbiting around the Earth!

LAGEOS/LAGEOS II: passive, compact (low A/M ratio to reduce non gravitational perturbations), cannon-ball satellites covered with corner cube laser reflectors for laser tracking from ground.

The closest possible artificial objects to the ideal “test mass” of celestial mechanics!



Orbit not so low (about 1 $R_\oplus$) the gain in signal strength is still significant…

But it does not work…

Limitations to testing the equivalence principle with satellite laser ranging
(Nobili et al., 2008)

Abstract

We consider the possibility of testing the equivalence principle (EP) in the gravitational field of the Earth from the orbits of LAGEOS and LAGEOS II satellites, which are very accurately tracked from ground by laser ranging. The orbital elements that are affected by an EP violation and can be used to measure the corresponding dimensionless parameter η are semimajor axis and argument of pericenter. **We show that the best result is obtained from the semimajor axis, and it is limited—with all available ranging data to LAGEOS and LAGEOS II—to η 2×10^{-9}, more than 3 orders of magnitude worse than experimental results provided by torsion balances. The experiment is limited because of the non uniformity of the gravitational field of the Earth and the error in the measurement of semimajor axis, precisely in the same way as they limit the measurement of the product *GM* of the Earth**. A better use of the pericenter of LAGEOS II can be made if the data are analyzed searching for a new Yukawa-like interaction with a distance scale of one Earth radius. It is found that the pericenter of LAGEOS II is 3 orders of magnitude more sensitive to a composition dependent new interaction with this particular scale than it is to a composition dependent effect expressed by the η parameter only. Nevertheless, the result is still a factor 500 worse than EP tests with torsion balances in the gravitational field of the Earth (i.e. at comparable distance)

Why?

The gravitational field of the Earth is not uniform, hence an error in the measurement of the semimajor axis mimics an EP violation

$$\eta_{\min} \simeq 3\frac{\Delta a_{meas}}{a} \simeq 2\cdot 10^{-9} \quad for \;\; LAGEOS$$

Laser tracking from ground provides an absolute distance measurement, while in testing the equivalence principle only relative measurements are needed!

Laser tracking accuracy can be improved to about 1 mm. Relative displacements with capacitance sensors already tested in the lab can reach less than a picometer!!!

No way!!!

A spacecraft is needed, totally driven by the experiment (and cheap..)

Experiment (test masses arranged to form a differential accelerometer) as passive as possible. Rely on physical design and symmetries, not on brute force!

Avoid cryogenics (not needed…)

Reduce read-out electronic noise with high frequency modulation. Provide this modulation by s/c spin axis rotation, which in turn provides passive s/c stabilization… Do not be afraid of spin … the system is isolated and co-rotating (right now we are moving at 1200 km/h !!!)

Beware of electric effects by ensuring passive discharging (in absence of weight mechanical coupling can have extremely low stiffness…Learn the lesson from GP-B…

High tech drag free control capabilities very important! …consolidate expertise built up at TAS-I for GOCE…+… all Italian…

VEGA launcher perfect for GG (low equatorial orbit), even in double launch…

1-g lab testing: a crucial tool!!!!

This is another talk, but come and visit our GGG lab at INFN Pisa-San Piero a Grado!

Future^2

GG is mature, but not yet here. What about the future^2 ?

EP tests can be performed based on interferometry of free falling cooled atoms: Peters, Chung & Chu 1999; Dimopoulos et al. 2007

…but macroscopic test masses are hard to beat:

“We have Avogadro’ s number on our side, and it is a pretty big number…”
Statement by Eric Adelberger, Eöt-Wash group, University of Washington, Seattle