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Gravity Control and Possible Influence on Space Propulsion:
A Scientific Study

by

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Preface

It is a well-known fact that access to space is inherently limited by the use of classical propulsion technology. Experiments and new theories have led to the questioning of whether gravitational or inertial forces can be created or modified, for example using electromagnetism. Recent physics announcements in well-established scientific journals, as well as the success of the NASA "Breakthrough in Propulsion Physics" programme, prove that this research topic is currently highly active and that the results must be taken seriously. These results raise the possibility to actively control gravity for propulsion purposes. However, it was still unknown for ESA whether these emerging theories were correct and, even if they were, if they could become viable candidates for creating propulsion breakthroughs. Therefore, the study presented in this report was initiated.

The study, on the possible influence of the control of gravitation on space propulsion systems, has been carried out in the framework of the ESA General Studies Programme. The study started in September 2002 and lasted until April 2002. The technical and scientific coordination of the work has been done by Mr Clovis de Matos. The contractual issues have been under the responsibility of Mr Christophe Carreau.

Initially, Dr. Jean Christophe Grenouilleau (working in ESA's directorate of Manned Space Flight and Microgravity at ESTEC) proposed the Study to Dr. Franco Ongaro, Head of the General Studies Programme, after preliminary discussions with Mr Clovis de Matos and Dr. Martin Tajmar. The goals of the study, which prompted a positive reaction from the evaluation board of the General Studies Programme, which argued to allocate the necessary resources to convey this work, were two-fold:

1. Evaluate the correctness of the scientific foundations underlying the field of gravity control and identify the scientific community working in the subject. Evaluate the possible influence of the control of gravitation on space propulsion systems. This has formed the core of the first part of the study.

2. Identify the critical technologies already existing or to be developed for the purpose of implementing the most promising research lines, which have been preliminarily identified in the first part of the study. Identify the role Europe is or should be playing in the field of gravity control. These issues formed the second part of the study.

To successfully achieve these goals, expertise in the field of gravitational physics and space propulsion systems was required. As it proved impossible to find both competences in a single person, two contracts were awarded, to Prof. Orfeu Bertolami from Instituto Superior Técnico, Portugal, and Dr. Martin Tajmar from the Seibersdorf Research Centre, Austria. Prof. Bertolami has impressive and long experience in the fields of Classical and Quantum Gravity, Astroparticle Physics, and Cosmology. The outstanding competences of Prof. Bertolami in those fields have been invaluable for achieving a study with high scientific value in a short time. His spirit of synthesis and his strong communication skills allowed very efficient and continuous progress in the work. Dr Martin Tajmar is a young, enthusiastic and very active Engineer Physicist, who graduated in 1999 with a Ph.D. in Field Emission Electric Propulsion from the University of Technology in Vienna. His interest and work in very advanced propulsion concepts have been a key element for the study. Forming a team where the senior and the young generation meet, and work together, was another important requirement to form a dynamic and respected working group, with the skills needed to discuss and evaluate seriously innovative ideas, and explore the leading edge of knowledge in the area of interest for our study.

Prof. Bertolami and Dr. Tajmar have provided a very complete scientific report, a database (collating, in an organised way, the major part of the bibliography already published in the field and listing key scientists and engineers currently involved), and an exhaustive power point presentation.

The process underlying the production of these items has involved a constant discussion, and multiple interactions between the contractors, and between the contractors and the Technical Officer, during numerous fruitful working meetings. We all learned a great deal in the process, not least that the control of gravitation is only relevant in the domains of activity related with microgravity, manned space flight, and fundamental physics. No fundamental breakthrough in space propulsion would be achieved through the control of gravitation. This is a surprising result, as it is counter-intuitive, and has never been seriously investigated to the author's knowledge.

The control of gravitation, if achievable, still lies far in the future. Nevertheless, this study shows that it will only be reached through the comprehension of what gravitation represents at the quantum scale. What are the quantum laws underlying the Equivalence principle? What are the gravitomagnetic properties of quantum systems? Do we have only four fundamental interactions in nature? These questions are still open; some of them are already part of the ESA fundamental physics programme, and of the CERN scientific programme. We believe that the reader will find recommendations, proposals, and original ideas in this study that complement and extend today's research programmes (space and ground-based) in the area of fundamental physics, towards the ambitious and exciting possibility of manipulating gravitation in the future. In our opinion, these are the main reasons why this study represents a very valuable and important input for ESA, in terms of the definition of the strategic scientific goals of its Scientific Programme.

As the Technical Officer, I would like to express my profound gratitude to Prof. Orfeu Bertolami and Dr. Martin Tajmar for having transformed this study into an exciting journey through interesting and serious physics, and to Dr. Franco Ongaro, Dr. Jean Christophe Grenouilleau, Prof. Martin Huber, Dr. Giacomo Cavallo, and Mr Roberto lo Verde, who made this journey possible. However, the journey has only just started.

Clovis Jacinto de Matos

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SUMMARY

Control of gravity to any degree, if ever possible, would constitute major scientific and technological progress. Present knowledge of the theory that best describes gravitational phenomena, namely *General Relativity*, provides no indication either of how to achieve any control over its strength or how to bridge any of its fundamental assumptions concerning the inertia of bodies and the way they fall in a gravitational field. Nevertheless, there is a substantial body of evidence, at least on the theoretical level, that General Relativity must be harmonized with *Quantum Mechanics* in the context of a more encompassing theory. The most promising candidate for this unification is *String Theory*, more recently usually referred to as *String/M-Theory*. In the context of string theory, 4-dimensional descendents and inspired models, a whole new lore of phenomena may arise, such as *new fundamental interactions or forces* of Nature, violations of well-established symmetries (*Lorentz* and *CPT*) with consequences regarding the extent of which the *Weak Equivalence Principle* holds and actually describes the free fall of bodies of different natures and compositions.

In this study we focus on these fundamental issues and survey possible new phenomena related with the so-called *Gravitoelectromagnetism*, the first-order approximation of General Relativity that admits recasting Einstein's equations in a form resembling Maxwell's equations. We also discuss some alternative theories of gravity whereby the strength of gravity is related with the dynamics of a still unknown field. In these models, Newton's constant corresponds to the present value of a function of this field, and in some approaches, such as for instance in *Induced Gravity Theories*, to the vacuum expectation value of the scalar field.

Throughout this report, connections with ongoing and future ESA, ESA/CNES, ESA/NASA and ESA/ISAS scientific space missions such as *MICROSCOPE, STEP, HYPER*, *LISA* and *BepiColombo* are drawn.

Our analysis of the existing proposals for the control of gravity and generation of fields that may give origin to new concepts in the launching and propulsion of spacecraft, indicates that the control of gravity is beyond our present knowledge. Furthermore, we find that control of gravity, even if it were within reach via manipulation of the inertial or gravitational masses or via the generation of gravitational fields, would have to compete with other means such as launch assist technologies or electrodynamical tethers. We show that any hypothetical control of gravity would yield only modest benefits for the launching of spacecraft, and actually no breakthrough technology in terms of propulsion. Only for the case of a vanishing gravitational mass and special orbits, such as are required for geostationary satellites, could launching be achieved with much smaller propulsion systems - which would indeed be a breakthrough in accessing space. This would, however, compete with classical launch-assist technology, which is currently many orders of magnitude more effective.

Nevertheless, given its potential in terms of knowledge and insight into the fundamental aspects of *Quantum Gravity* and gravitational properties of quantum materials, the subject deserves, in our opinion, more theoretical and experimental longer term research.

A relevant part of this study was devoted to the construction of a Database containing the most salient literature on the subject of gravity control. It contains selected publications on the subject, as well as information on the people involved in the research and on the fundamental physics associated with the topics discussed in the report. We have also set criteria for evaluating the existing ideas and proposals.

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Part I

Scientific Foundations

1 Introduction

Control of gravity to any extent would clearly represent, if ever theoretically possible and technically feasible, a major scientific and technological achievement. Present knowledge of the theory that best describes gravitational phenomena, namely *General Relativity*, gives no indication of how to achieve some control over its most salient features. For all known phenomena the strength of gravity is set by Newton's constant. Furthermore, the theory is built on the experimentally well verified assumption that all bodies fall with the same acceleration in a gravitational field. Nevertheless, there is a substantial body of evidence, at least from the theoretical point of view, that General Relativity must be harmonized with *Quantum Mechanics* so as not to lead to observable violations of the Heisenberg uncertainty principle.

In this study we survey the main features of General Relativity aiming to identify possible gaps in present knowledge and discuss certain aspects of *String/M-Theory*, currently the best candidate for a theory of *Quantum Gravity*, as well as some of its possible implications, which include violation of the underlying symmetries of low-energy physical theories. This possibility leads us to examine, in particular, to which extent fundamental symmetries of nature, such as *CPT symmetry* and *Lorentz invariance*, hold in String/M-Theory, as well as how in some superstring-inspired models one can draw conclusions about the existence of new interactions in Nature and ensuing violations of the *Weak Equivalence Principle*. Possible new phenomena in the context of *Gravitoelectromagnetism*, a first-order approximation of General Relativity that allows the recasting of Einstein's equations in a way that they resemble Maxwell's equations are also examined.

We stress that the purpose of this study is to lay down the basis for future activity on the subject of gravity control through a critical assessment of existing proposals in the context of prevailing physical theories, and from which genuinely new propulsion technology may emerge. It is rather unfortunate that the subject of gravity control has been plagued by a great number of unscientific and/or pseudo-scientific claims, which makes it rather difficult to quickly get into the most interesting and minimally rigorous proposals avoiding claims that most often invoke physical concepts such as *negative masses*, *negative energy densities*, *Mach's principle, warp drive*, etc., which are either ill-defined or cannot be seriously considered without a consistently well fundamented framework that allows for a rigorous conceptual and quantitative analysis. If from the theoretical view point the situation is not very bright, it is rather worse from the experimental side. Most often experimental claims lack serious error analysis as well as studies aiming to eliminate the more "mundane" causes for the extraordinary observations they report.

In rather general terms, we call gravity control any scheme that allows the properties of gravity to be changed by altering the strength of the gravitational coupling to matter, or leads, through the intervention of other forces, to a change in the local gravity force. This control requires one of the following conditions to be fulfilled:

1) Altering the strength of the gravitational coupling to matter due to the existence of a new fundamental interaction of Nature that would imply violation of the Weak Equivalence Principle in some regime.

2) Existence of net forces due to the interplay between gravity and electrostatic forces in shielded experimental setups, such as in the well-known Schiff-Barnhill effect.

3) Schiff-Barnhill analogous effect for magnetic fields in quantum materials and that involves the gravitomagnetic field, as first discussed by DeWitt.

4) Physically altering the vacuum properties so as to affect the relative strength of known fundamental interactions.

We will discuss these alternatives while surveying the most salient features of General Relativity, and discuss the general scientific background of the study. Furthermore, we will analyse the effect that a hypothetical degree of control over gravity would represent for propulsion and the launching of spacecraft, as well as give recommendations, analyse proposals and suggest a hierarchy of priorities.

2 General Relativity: a survey

General Relativity (GR) is a major step in the understanding of a large class of phenomena, being unavoidable in studying, for instance, the dynamics of the compact astrophysical objects such as neutron stars and black holes, and in Cosmology where the Universe itself is regarded as a whole.

In the original formulation of GR, the metric tensor, $g_{\mu\nu}$, plays a major role, being the unknown in the Einstein field equations:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \ , \tag{1}$$

where $G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R$ is the so-called Einstein tensor, Λ is the cosmological constant, G is Newton's constant, and the energy-momentum tensor is obtained through the matter Lagrangian density $\mathcal{L}_M(\phi, A_\mu, ...)$:

$$T_{\mu\nu} = -\frac{2}{\sqrt{-g}} \frac{\partial(\sqrt{-g}\mathcal{L}_M)}{\partial g^{\mu\nu}} \ . \tag{2}$$

Field equations (1) arise from the Einstein-Hilbert action plus the action describing the matter fields

$$S[g_{\mu\nu}, \phi, A_\mu, ...] = \int d^4x \sqrt{-g} \left\{ \frac{c^4}{16\pi G}(R - 2\Lambda) + \mathcal{L}_M(\phi, A_\mu, ...) \right\} \ . \tag{3}$$

The cosmological constant, although a major embarassment in current theoretical physics given its observed value, is indisputedtly an important ingredient in accounting for the cosmological data. This arises from the study of Type Ia Supernovae which, when used as standard candles, allow one to determine with some confidence important cosmological parameters. Recent analyses of the magnitude-redshift relation of about fifty Type Ia Supernovae with redshifts greater than $z \geq 0.35$ strongly suggest that we are living in an accelerating, low-matter density Universe in which a cosmological constant or a slow-varying vacuum energy of some scalar field, usually referred to as *Quintessence*, dominates [3]. This latter component amounts for a substancial part of the energy density of the Universe, $\Omega_\Lambda \simeq 0.65$, so that $\sum_i \Omega_i = 1$ with the contribution from matter (dark [1] and baryonic), $\Omega_{DM} \simeq 0.3$, $\Omega_{Baryons} \simeq 0.05$, but no contribution from the spatial curvature [7, 8, 9, 10] as predicted from *Inflation* (see eg. [11] for an extensive discussion). Of course, the above-mentioned vacuum energy density is extremely small,

$$\rho_V \equiv \frac{\Lambda c^2}{8\pi G} \lesssim 10^{-29} g\ cm^{-3} \simeq 10^{-12} eV^4 \tag{4}$$

and plays a role only on cosmological scales.

In what follows we will focus our attention on the gravitational part of the theory and therefore we will disregard for a while matter contributions to the pure Einstein-Hilbert action. In the absence of matter, this approach to GR is referred to as the Second-Order Formalism since only the metric is regarded as an independent variable. In this formulation, the symmetric affine connection $\Gamma^\lambda_{\mu\nu}$ is determined from the metricity postulate:

$$D_\lambda g_{\mu\nu} = 0 \quad , \tag{5}$$

where the covariant derivative of a covariant tensor and, particularly for the metric, is given by:

$$D_\lambda g_{\mu\nu} = \partial_\lambda g_{\mu\nu} - \Gamma^\sigma_{\lambda\mu} g_{\sigma\nu} - \Gamma^\sigma_{\lambda\nu} g_{\mu\sigma} \ . \tag{6}$$

If from a more general viewpoint one could consider a connection that allows *torsion*, this would lead to a geodesic deviation equation of the form:

$$\frac{D^2 N^\alpha}{Dt^2} + \frac{D}{Dt}\left[T^\alpha_{\beta\gamma}\frac{dx^\beta}{dt}N^\gamma\right] + R^\alpha_{\beta\gamma\delta}\frac{dx^\beta}{dt}\frac{dx^\delta}{dt}N^\gamma = 0 \quad , \tag{7}$$

[1] Most likely candidates include a linear combination of neutral supersymmetrical particles, the *neutralinos* (see eg. [4]), *axions* [5] and a *self-interacting scalar particle* [6].

where N^α is the difference of coordinates of two falling bodies, $T^\alpha_{\beta\gamma}$ is the torsion tensor which corresponds to the antisymmetric part of the connection, and $R^\alpha_{\beta\gamma\delta}$ is the Riemann tensor. This equation ought to be compared, in the weak field limit and for velocities much smaller than the velocity of light, to the Newtonian deviation equation

$$\frac{d^2N^i}{dt^2} + E^i_j N^j = 0 \tag{8}$$

where, $E_{ij} = -\partial_j g_i$, is the tidal tensor and g_i is the component of the gravitational acceleration in the i direction. Comparison of the two expressions suggests that the torsion tensor vanishes and therefore that the connection of spacetime must be symmetric. This is the so-called Levi-Civita connection, given the compatibility with the metric, Eq. (5).

From the observational point of view, GR is the theory that best accounts for available Solar System data (see e.g. [1] for an updated review). The most suitable way to address the implications of GR for Solar System gravitational phenomena is via the so-called Parametrized Post-Newtonian (PPN) formalism, where the metric is expanded in terms of the Newtonian potential, Φ, the coordinate velocity of matter, $\vec{v}$, and the velocity of the PPN coordinate system relative to a preferred frame ("mean rest frame of the Universe"), $\vec{w}$, [2]:

$$g_{00} = -1 + 2\frac{\Phi}{c^2} - 2\beta\left(\frac{\Phi}{c^2}\right)^2 + ... + (\alpha_1 + \alpha_2 - \alpha_3)\left(\frac{|\vec{w}|}{c}\right)^2 \frac{\Phi}{c^2} + ... \tag{9}$$

$$g_{0i} = -\frac{1}{2}(4\gamma + 3 + \alpha_1 - \alpha_2 + \zeta_1 - 2\xi)\frac{v_i}{c} + ... \tag{10}$$

$$g_{ij} = (1 + 2\gamma\frac{\Phi}{c^2})\delta_{ij} \tag{11}$$

where the potential created by a rest-mass density $\rho(\vec{x}, t)$ is given by

$$\Phi(\vec{x}, t) = G\int d^3\vec{x'}\frac{\rho(\vec{x'}, t)}{|\vec{x'} - \vec{x}|} \quad , \tag{12}$$

and the dots stand for higher order terms and derivatives of $\Phi(\vec{x}, t)$.

For GR, the Post-Newtonian parameters assume the following set of values:

$$\beta = \gamma = 1 \quad ; \quad \alpha_1 = \alpha_2 = \alpha_3 = \zeta_1 = ... = \xi = 0 \quad , \tag{13}$$

which fits quite well with all known gravitational data [1].

It is well known that the underlying linearized field theory associated with GR is the one corresponding to exchange of spin-2 massless particles. Indeed scalar field theories lead to no light deflection, while spin-1 field theories lead to repulsion. Full GR, on the other hand, is a global theory of spacetime and many of its most important features can only be addressed via asymptotic methods. These methods are required, for instance, for a meaningful definition of mass in GR. Indeed, a local definition of mass makes no sense in GR due to the *Equivalence Principle*, which allows the neutralizing of a gravitational field and hence any gravitational energy density by a suitable choice of the frame of reference. Furthermore, it has long been known that in GR, as in Newtonian gravity, the contribution to the energy of a system due to gravity is negative. This fact can give rise to the odd concept of *negative mass*, as a system can grow more and more compact making its gravitational binding energy more important than the sum of the masses of the particles it is made off. A system whose total mass becomes negative due to the gravitational binding energy would have striking properties. Indeed, a "gravitational dipole" consisting of bodies with positive and negative masses would be capable of accelerating itself, with no need for any propulsion system. This would occur thanks to the attraction that a positive mass body would exert on one with a negative mass and the repulsion the negative mass body would exert on one with a positive mass. However bizarre, negative mass has been repeatedly invoked in alternative propulsion proposals, even though its' scientific merits are most often not properly assessed. Negative masses were first discussed in the context of GR in 1957 by Bondi [12], who argued that Einstein's equations admit a world-wide non-singular solution describing oppositely accelerating pairs of bodies, so that each pair of bodies has one with negative gravitational (and also inertial) mass. This odd solution arises from the rather unclear assumption that energy can be negative from the start. Aiming to preclude this unobserved situation, the *Positive Energy Theorem* was proposed in the mid-sixties and was eventually demonstrated in 1979 by Schoen and Yau [13] using sophisticated differential geometry methods and by Witten in 1981 using Supergravity [14]. The theorem states that the Arnowitt-Deser-Misner (ADM) mass [15], a convenient non-local mass definition, is non-negative for an asymptotically flat spacetime that contains matter satisfying the dominant energy condition, $T_{\mu\nu}V^{\mu}V^{\nu} \geq 0$ for an arbitrary time-like four-vector V^{μ}. Physically, this condition translates, for diagonal energy-momentum tensors, $T_{\mu\nu} = diag(\rho, p_1, p_2, p_3)$, into the so-called *weak energy condition*, $\rho \geq 0$, $-\rho \leq p_a \leq \rho, a = 1, 2, 3$, where ρ is the energy density and p_a the pressure. This condition is met by known forms of matter both in normal and in extreme cosmological situations [2]. An extention of Witten's method to include non-minimally coupled scalar fields with gravity, the situation one faces, for instance, in the framework of scalar-tensor theories of gravity, was discussed in Ref. [16].

Moreover, the weak energy condition plays a central role in preventing, in the absence of torsion, closed time-like curves, being therefore ultimately responsible for causality [17, 18, 19]. Hence, this condition renders *warp drive, traversable wormholes* and *closed time-like curves* created by cosmic strings classically **impossible**. These are theoretical objects that are often invoked as alternative propulsion methods.

In what follows we discuss the observational status of the fundamental underlying symmetries of GR.

[2]It is worth pointing out that negative pressures are encountered in the context of inflationary and quintessence models, for scalar field fluids where the potential energy dominates the kinetic energy.

3 Einstein Equivalence Principle

The so-called Einstein Equivalence Principle (EEP) plays an important role in GR. It comprises three statements:

1) Universality of the free fall (Weak Equivalence Principle - WEP)

2) Independence of the rate of change of clocks of their velocities (Local Lorentz Invariance - LLI)

3) Independence of the change of rate of clocks of their spacetime positions (Local Position Invariance - LPI).

3.1 Weak Equivalence Principle

The WEP establishes a composition-independent limit on the free fall of bodies. This means that the relevant charge to describe the fall of bodies, their gravitational mass, cancels out given its equality with the inertial mass. This equality is established with great accuracy and has been tested over 400 years since Galileo in 1590, Newton in 1686, Bessel in 1832 and so on [20] until the current most stringent limit [21]:

$$\frac{|m_i - m_g|}{m_i} < 5 \times 10^{-13} \quad . \tag{14}$$

It is clear that a degree of control over gravity could be achieved if violations of the WEP could be found or somehow engineered. Hence, in order to proceed with our study, it is important to survey to what extent the WEP holds for known matter. The following elementary particles have already been experimentally scrutinized:

Photons

The deflection of light in the vicinity of the Sun by the value

$$\theta = \frac{4GM_\odot}{bc^2} = 1.75'' \frac{R_\odot}{b} \tag{15}$$

confirms, as firstly verified in 1919, that photons free fall in a gravitational field as predicted by GR. The Pound-Rebka experiment, performed in 1960, further asserts the universality of the gravitational frequency shift as expected from the WEP:

$$\frac{\Delta\nu}{\nu} = \frac{gH}{c^2} = (2.57 \pm 0.26) \times 10^{-15} \quad , \tag{16}$$

where g is the acceleration of gravity and H the height of fall.

Neutrons

The interferometric experiment of Collela, Overhauser and Werner [22] in 1975 showed that a neutron beam split by a silicon crystal travelling through distinct gravitational paths would interfere as predicted by Quantun Mechanics with a gravitational potential as given by Newtonian gravity. This is an impressive verification of the WEP to an elementary hadronic particle. We should mention that present-day technology has allowed the interferometry of atoms rising against gravity to achieve impressive sensitivity limits, of order 3×10^{-8} [23]. Quite recently an experiment for gravitational bound states of neutrons has been performed by Nesvizhevsky and collaborators [24], and a detailed discussion of this important experiment can be found in Part II of this study.

Charged Fermions (Electrons)

The WEP was tested for electrons by Witteborn and Fairbank in 1967 [25]. Electrons were allowed to fall under the action of gravity in a shielded drift-tube. A slowdown was expected and was actually observed. This surprising result is due to the electric field created by the action of gravity on electrons in the metal of the drift-tube, and was first discussed by Schiff and Barnhill in 1966 [26]. They have shown that for charged particles with mass M and charge Q, the effective gravitational acceleration resulting from the effect of electrons in the drift-tube, is given by:

$$g_{eff} = g\left[1 - \frac{m_e}{M}\frac{Q}{e}\right] \quad , \tag{17}$$

which arises because due to gravity the vanishing quantity in the drift tube is not the electric field, $\vec{E}$, but rather the sum $\vec{E} + \frac{m_e}{e}\vec{g}$.

The Witteborn and Fairbank experiment has confirmed this result within 10% for electrons

$$g_{eff} = 0.09g \quad . \tag{18}$$

It is remarkable that for positrons, the same reasoning allows one to conclude that they will fall with an acceleration

$$g_{eff} = 2g \quad . \tag{19}$$

Unfortunately, this prediction has never been fully confirmed experimentally, given the difficulty in controlling positrons for the purposes of a free-fall experiment. We regard it as highly desirable and even somewhat urgent that an experiment to verify this result be performed in the near future. In terms of scaling up the size of the free falling objects, the formula (17) shows that, already for protons, the effect is negligible.

We shall see later on that a magnetic analogue of the Schiff-Barnhill effect exists in superconductors and that this involves the gravitomagnetic field, as first pointed out by DeWitt [27].

Antiprotons and Antihydrogen

The next logical step in establishing the validity of the WEP at elementary level is to consider the free fall of antiprotons and antihydrogen. This would help in verifying to what extent gravity respects the fundamental CPT symmetry of local quantum field theories and that antiparticles fall as particles in a gravitational field. As will be seen when discussing Local Lorentz invariance, CPT symmetry may be spontaneously broken in some String/M-Theory vacua and some implications of this fact will be mentioned. Of course, observing the free fall of antiparticles is yet another test of that fundamental symmetry, even though the experimental obstacles are considerable. The subject has been extensively reviewed in Ref. [28] and the ATHENA (ApparaTus for High precision Experiments on Neutral Antimatter) group has succeeded to a certain extent in dealing with the quite difficult problem of storing antiprotons and creating an antihydrogen atom. Unfortunately, the closure of the LEAR (Low Energy Antiproton Ring) facility at CERN, in order to pursue the construction of the LHC, has made the subsequent free-fall experiment impossible (see Ref. [29] for an account of the situation up to early 1999). Meanwhile, the CPLEAR Collaboration has reported on a test of the WEP involving neutral kaons [30]. The reported limits are 6.5, 4.3 and 1.8×10^{-9}, respectively, for scalar, vector and tensor potentials originating from the Sun with the range much greater than 1 $A.U.$ acting on kaons and antikaons. However relevant, these results say nothing about new forces that couple to baryon number and therefore can be regarded as complementary at best to tests yet to be performed for antiprotons and antihydrogen.

MICROSCOPE, STEP and HYPER Missions

Ground experiments designed to verify the WEP are limited by the unavoidable microseismic activity of Earth. Space experiments offer the possibility of improving the precision of current tests by a factor of 10^6.

Most probably, the first test of the WEP in space will be carried out by the MICROSCOPE (MICROSatellite a traine Compensee pour l'Observation du Principe d'Equivalence) mission led by CNES and ESA. The drag-free MICROSCOPE satellite would be launched into a Sun-synchronous orbit at 600 km altitude and will carry two pairs of test masses. Differential displacements between the test masses of a pair will be measured by capacitive sensors. The expected precision of this room-temperature test is 1 part in 10^{15}.

The subsequent and more ambitious ESA/NASA STEP (Satellite Test of the Equivalence Principle) mission is expected to be launched in the near future into a circular, Sun-synchronous orbit at 600 km altitude. The drag-free STEP spacecraft will carry four pairs of test masses accommodated in a superfluid He-dewar at 2 K. Differential displacements between the test masses of a pair will be measured by SQUID sensors, and the expected precision with which the WEP will be tested is 1 part in 10^{18}.

Another quite interesting possibility for testing the WEP involves the interferometry of atoms. High-precision gravimetric measurements can be made via the interferometry of free-falling caesium atoms, and a precision in 7 parts per 10^9 in testing the WEP has already been achieved [31]. Ultimate precision with this method can be achieved only in space with a mission like HYPER (HYPER-precision cold atom interferometry in space). ESA's HYPER spacecraft will be in a Sun-synchronous circular orbit at 700 km altitude. Accomodated in the spacecraft will be two atomic Sagnac units comprising four-cold atom interferometers for measuring rotations and accelerations along two orthogonal planes. The resolution of the atom interferometers of HYPER could, in principle, test the WEP with a precision of 1 part in 10^{15} or 10^{16}, by comparing the rates of fall of caesium and rubidium atoms. The present experimental setup of HYPER will have to be modified in order to test the WEP [32].

It is worth mentioning that there are proposals to test the WEP by comparing the rate of fall of protons and antiprotons in a cryogenic vacuum facility that will be available at the Space Station [33]. The idea behind this Weak Equivalence Antimatter eXperiment (WEAX) consists of confining antiprotons for a few weeks in a Penning trap, a magnetic container, in a geometry in which the effect of gravity would manisfest itself as a perturbation on the motion of the antiprotons. The expected precision of the experiment is 1 part in 10^6, three orders of magnitude better than for a ground experiment.

It is clear that testing the WEP in space requires pushing current technology and imagination to its limits, and even though no significant violations of the WEP are expected, any anomalous result would provide significant insight into new and fundamental physical theories.

3.2 Local Lorentz Invariance

Invariance under Lorentz transformations, which states that the laws of physics are independent of the frame velocity, is one of the most fundamental symmetries of physics and is at the heart of all known physical theories. However, recently some evidence has been found, in the context of String/M-Theory, that this symmetry can be spontaneously broken. Naturally, this poses the challenge of verifying this possibility from the experimental point of view. It has already been pointed out that astrophysical observations of faraway sources of gamma radiation could provide hints regarding the nature of gravity-induced wave dispersion in vacuum [34, 35, 36] and therefore about the physics beyond the Standard Model (SM). Limits on the violation of Lorentz symmetry from the observations of high-energy cosmic rays with energies beyond 5×10^{19} eV, the so-called Greisen-Zatsepin-Kuzmin (GKZ) cut-off [37], have also been discussed [38, 39, 40].

It is interesting that a putative violation of Lorentz symmetry has been repeatedly considered in the literature. Indeed, a constant background cosmological vector field has been suggested as a way to introduce our velocity with respect to a presumably preferred frame of reference into the physical description [41]. It has also been suggested, based on the behaviour of the renormalization group β-function of non-abelian gauge theories, that Lorentz invariance could be just a low-energy symmetry [42]. Furthermore, higher dimensional theories of gravity that are not locally Lorentz invariant have been considered in order to obtain light fermions in chiral representations [43].

The breaking of Lorentz symmetry due to non-trivial solutions of string field theory was first discussed in Ref. [44]. These non-trivial solutions arise in the context of the string field theory of open strings and may have implications for low-energy physics. For instance, assuming that the contribution of Lorentz-violating interactions to the vacuum energy is about half of the critical density allows one to conclude that feeble tensor-mediated interactions in the range of about 10^{-4} m may exist [45]. Furthermore, Lorentz violation may induce the breaking of conformal symmetry and this together with inflation may lie at the origin of the primordial magnetic fields required to explain the observed galactic magnetic field [46]. It is natural that violations of Lorentz invariance may imply that the fundamental CPT symmetry of local quantum field theories is broken [47]. It is quite interesting that this possibility can be verified experimentally in neutral-meson [48] experiments[3], Penning-trap measurements [50] and hydrogen-antihydrogen spectroscopy [51]. Furthermore, the spontaneous breaking of CPT symmetry allows for an explanation of the baryon asymmetry of the Universe. Indeed, tensor-fermion interactions expected in the low-energy limit of string field theories give rise in the early Universe, after the breaking of the Lorentz and CPT symmetries, to a chemical potential that creates in equilibrium a baryon-antibaryon asymmetry in the presence of baryon number violating interactions [52].

Limits on the violation of Lorentz symmetry have been directly sought through laser interferometric versions of the Michelson-Morley experiment where comparisons are made between the velocity of light, c, and the maximum attainable velocity of massive particles, c_i, up to $\delta \equiv |c^2/c_i^2 - 1| < 10^{-9}$ [53]. More accurate tests can be performed via the so-called Hughes-Drever experiment [54, 55]. In this type of measurement, one searches for the time dependence of the quadrupole splitting of nuclear Zeeman levels along Earth's orbit. This technique allows the achieving of impressive limits, the most stringent being $\delta < 3 \times 10^{-22}$ [56]. Actually, a more recent assessment of these experiments reveals that more stringent bounds, up to 8 orders of magnitude, can be reached [57]. ¿From the astrophysical side, limits on the violation of momentum conservation and the existence of a preferred reference frame can be set from bounds on the parametrized post-Newtonian parameter, α_3. This parameter vanishes identically in GR (cf. Eq. (13)) and can be accurately determined from the pulse period of pulsars and millisecond pulsars [1, 58]. The most recent limit, $|\alpha_3| < 2.2 \times 10^{-20}$ [59], indicates that Lorentz symmetry holds up to this level.

The discovery of the cosmic microwave background radiation has made an analysis of how

[3] These CPT violating effects are unrelated with those due to possible non-linearities in quantum mechanics, presumably arising from quantum gravity, which were already investigated by the CPLEAR Collaboration [49].

the most energetic cosmic-ray particles would be affected by the interaction with the microwave photons mandatory. It turns out that the propagation of the ultra-high-energy nucleons is limited by inelastic collisions with photons of the microwave background radiation, unabling nucleons with energies above 5×10^{19} eV to reach Earth from further than $50 - 100$ Mpc. This is the already mentioned GZK cut-off [37]. However, events where the estimated energy of the cosmic primaries is beyond the GZK cut-off have been observed by different collaborations [60, 61, 62, 63]. It has been suggested [38] (see also [39]) that slight violations of Lorentz invariance would cause energy-dependent effects which would suppress otherwise dynamically inevitable processes, e.g. the resonant scattering reaction, $p + \gamma_{2.73K} \rightarrow \Delta_{1232}$. The study of the kinematics of this process allows the setting of quite stringent bounds on the degree of which Lorentz invariance holds as a good symmetry of Nature, $\delta < 1.7 \times 10^{-25}$ [40, 64].

Another observational anomaly related to a possible violation of Lorentz invariance refers to the detection of γ-rays with energies above 20 TeV from distant sources, such as Markarian 421 [65, 66]. These γ-rays are not expected, given their interaction with infrared background photons, to reach Earth if Lorentz invariance is an exact symmetry [67, 68, 69].

3.3 Local Position Invariance

Given that the WEP and LLI have been tested with great accuracy, experiments on the universality of the gravitational red-shift are actually a measure of the level to which the LPI holds. Hence, violations of the LPI would imply that the rate of a free falling clock would be different when compared with a standard one, for instance on the Earth's surface. Accuracy in establishing the LPI can be parametrized in the following way

$$\frac{\Delta\nu}{\nu} = (1 + \alpha)\frac{\Delta\Phi}{c^2} \quad . \tag{20}$$

¿From the already mentioned Pound-Rebka experiment (cf. Eq. (eq:1.15)), one can infer that $\alpha \simeq 10^{-2}$, and the most accurate determination of the LPI has been achieved from the comparison of hydrogen-maser frequencies on Earth and on a rocket at 10 000 km altitude, performed by Vessot and collaborators [70]. The resulting bound is

$$|\alpha| < 2 \times 10^{-4} \quad . \tag{21}$$

Further improving these limits is certainly a quite relevant scientific goal.

Before closing this Section, we should mention that Schiff [71] has conjectured on the possibility of showing that a theory of gravity should be metric solely on account of the WEP. This conjecture has, however, been shown to be unfounded in the context of the so-called $TH\epsilon\nu$ formalism for electromagnetic systems [72]. Another relevant experimental clue that metric theories of gravity, and GR in particular, are the only ones that are compatible with EEP involves the so-called *Strong Equivalence Principle*. This Principle generalizes the WEP for systems subjected to significant gravitational self-interaction. However, partial, recent experimental tests in the context of the Earth-Moon system show that no composition-dependent acceleration effects [73] are observed, which although modest, constitutes yet another proof of the robustness of GR in accounting for the observational data.

¿From the above discussion we can conclude that the fundamental principles upon which GR rests are quite solid and, even though small deviations are encountered, they are at the present state of knowledge, unlikely to give rise to effects that will have implications for the control of gravity to any extent. It should be pointed out, however, that there are important gaps in determining the validity of the WEP for antiparticles, and there are interesting phenomena associated with the free fall of charged particles.

4 New Interactions of Nature

4.1 Theoretical Framework and Phenomenological Constraints

The existence of new fundamental forces beyond the already known four fundamental interactions of Nature is an exciting possibility that will have several implications and bring important insights into the physics beyond the Standard Model. The claim in 1986 of evidence for an intermediate range interaction with sub-gravitational strength [74] has sparked great interest in theoretical explanations (see [28] for a review) and has given rise to a wave of experiments based on new ideas and to the repetition of "classical" ones using state of the art technology.

In its simplest versions, a putative new interaction or a *fifth force* would arise from the exchange of a light boson coupled to matter with a strength comparable to gravity. There are several schemes through which physics at the Planck scale could give origin to such an interaction and yield a Yukawa-type modification in the interaction energy between point-like masses. This new contribution to the interaction energy can arise, for instance, from extended supergravity theories after dimensional reduction [28, 75], from the compactification of 5-dimensional generalized Kaluza-Klein theories that include gauge interactions at higher dimensions [76] and also from string/M-Theory. On general terms, the interaction energy, $V(r)$, between two point masses m_1 and m_2, can be expressed in terms of the gravitational interaction as [4]

$$V(r) = -\frac{G_\infty \ m_1 \ m_2}{r} \ (1 + \alpha \ e^{-r/\lambda}) \ , \tag{22}$$

where $r = |\vec{r}_2 - \vec{r}_1|$ is the distance between the masses, G_∞ is the gravitational coupling for $r \to \infty$, α and λ are the strength and the range of the new interaction, respectively. Naturally, G_∞ has to be identified with the Newton's gravitational constant and the gravitational coupling becomes dependent on r. Indeed, the force associated with Eq. (22) is given by:

[4] We shall set, in this Section as well as in Sections 5 and 7, $c = \hbar = k_B = 1$, meaning that physical quantities will be given in terms of energy: $1\ m = 5.068 \times 10^{15}$ GeV^{-1}, $1\ sec = 1.519 \times 10^{24}$ GeV^{-1}, $1\ kg = 5.610 \times 10^{26}$ GeV, $1\ K = 8.617 \times 10^{-14}$ GeV and 1 GeV $= 1.602 \times 10^{-10}\ J$.

$$\vec{F}(r) = -\nabla V(r) = -\frac{G(r)\ m_1\ m_2}{r^2}\ \hat{\mathbf{r}}\ , \tag{23}$$

where

$$G(r) = G_\infty[1 + \alpha\ (1 + r/\lambda)\ e^{-r/\lambda}]\ . \tag{24}$$

The suggestion of existence of a new interaction has arisen from the recognition that the coupling α is not an universal constant, but instead a parameter depending on the chemical composition of the test masses [77]. This dependence comes about if one assumes that the new bosonic field couples to the baryon number $B = Z + N$, which is the sum of protons and neutrons. Hence the new interaction between masses with baryon numbers B_1 and B_2 can be expressed through a new fundamental constant, f, as:

$$V(r) = -f^2\ \frac{B_1\ B_2}{r}\ e^{-r/\lambda}\ , \tag{25}$$

such that the constant α can be written as

$$\alpha = -\sigma\ \left(\frac{B_1}{\mu_1}\right)\ \left(\frac{B_2}{\mu_2}\right)\ , \tag{26}$$

with $\sigma = f^2/G_\infty m_H^2$ and $\mu_{1,2} = m_{1,2}/m_H$, m_H being the hydrogen mass.

The above equations imply that in a Galileo-type experiment an acceleration difference between masses m_1 and m_2 would arise and would be given by

$$\vec{a}_{12} = \sigma\ \left(\frac{B}{\mu}\right)_{Earth}\left[\left(\frac{B_1}{\mu_1}\right)\ -\ \left(\frac{B_2}{\mu_2}\right)\right]\ \vec{F}\ , \tag{27}$$

where $\vec{F}$ is the field strength of the Earth's gravitational field.

Several experiments (see, for instance, Refs. [74, 28] for a list of the most relevant ones) have been performed in order to establish the parameters of a new interaction based on the idea of a composition-dependence differential acceleration, as described in Eq. (27), and other

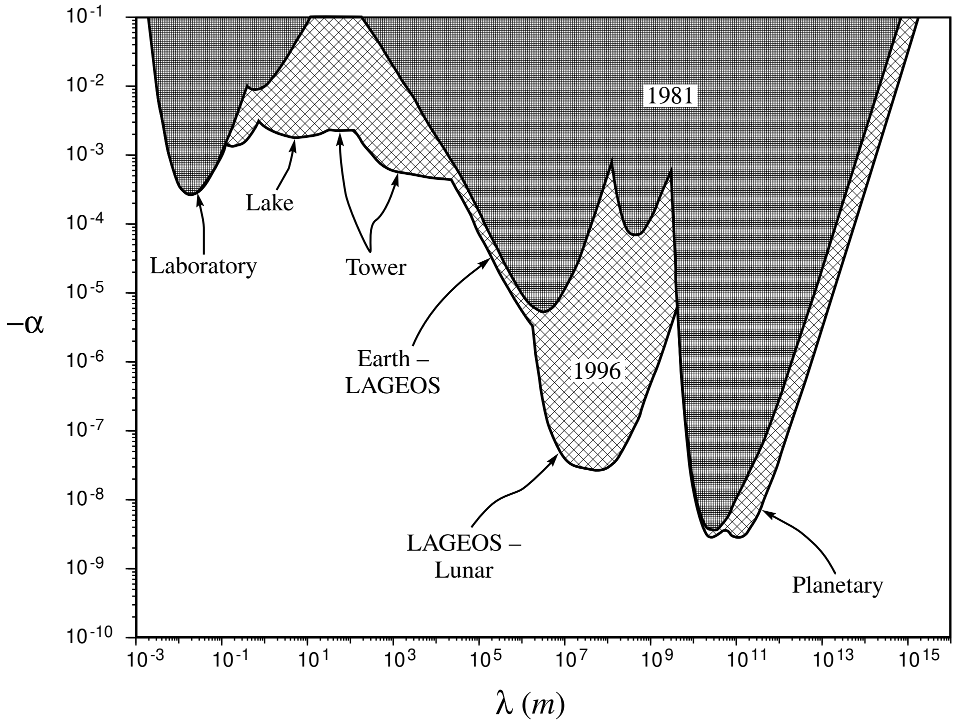

Figure 1: Experimentally Excluded Regions for the Range and Strength of New Possible Forces as shown in Ref. [74]

composition-independent effects [5]. The current experimental situation is essentially compatible with predictions of Newtonian gravity in either composition-independent or composition-dependent experiments. The bounds on parameters α and λ can be summarised as follows (Figure 1):

- Satellite tests (LAGEOS missions - see below) probing ranges of about $10^5\ m \lesssim \lambda \lesssim 10^7\ m$ indicate that $\alpha \lesssim 10^{-7}$;

- Gravimetric experiments that are sensitive in the range of $10\ m \lesssim \lambda \lesssim 10^3\ m$ suggest that $\alpha \lesssim 10^{-3}$;

- Laboratory experiments devised to measure deviations from the inverse-square law are sensitive essentially to the range $10^{-2}\ m \lesssim \lambda \lesssim 1\ m$ and constrain α to be smaller than about 10^{-4}.

[5] For instance, neutron interferometry has been suggested to investigate a possible new force that couples to neutron number [78].

It is remarkable that, for $\lambda < 10^{-3}$ m and $\lambda > 10^{13}$ m, α is essentially unconstrained so far. The former range is particularly attractive as new forces with sub-millimetric range seems to be favoured from scalar interactions in supersymmetric theories [79] and in the recently proposed theories of TeV scale quantum gravity, which are associated with the idea that extra dimensions do not necessarily have to be of Planck size [80, 81]. The range $\lambda < 10^{-3}$ m also arises from the assumption that scalar [82] or tensor interactions associated with the breaking of the Lorentz invariance in string theories [45] account for the vacuum energy up to half of the critical density, $\Omega_V < 0.5$. This range has recently been available to experimental verification. Putative corrections to Newton's law at millimetre range could have relevant theoretical and technological implications, especially if one takes into account that in certain models of extra dimensions these corrections can be, at that range, as important as usual Newtonian gravity [81, 83]. State of the art experiments rule out extra dimensions over length scales down to 0.2 mm [84].

In order to close our summary of the experimental status on the existence of new forces of nature, we should point out that, as discussed in [74], current experimental knowledge cannot explain certain anomalies such as the one claimed to exist in the Eötvös original experiment [85] and in the radiometric data from Pioneer 10/11, Galileo and Ulysses spacecraft. Indeed, these latter anomalies are associated with an unexpected constant acceleration of about $a_P = 8.5 \times 10^{-8}$ cm s^{-2} acting on the spacecraft and that is directed towards the Sun. A new interaction with $\alpha = -1 \times 10^{-3}$ and $\lambda = 200$ $A.U. = 2.98 \times 10^{13}$ m has been suggested in order to account for the anomaly [86] (see also [87]). This choice of parameters arises from the expansion of Eqs. (23) and (24) in terms of the radial distance and identification of the constant term with the observed anomalous acceleration, that is $a_P = -a_N \alpha [2(1+\alpha)]^{-1}(r/\lambda)^2$, where a_N is the Newtonian acceleration at $r = 1$ $A.U.$. More conventional explanations for this anomalous acceleration, such as gas leaks from the thrusters or non-isotropic heat radiation, have also been advanced [88, 89], although it is claimed that these are unlikely to resolve the matter [87].

A particularly auspicious opportunity to possibly help settling this relevant issue is provided by the *BepiColombo* mission. BepiColombo is a joint ESA and Institute of Space and Astronautical Science (ISAS) of Japan mission of an interdisciplinary nature to study planet Mercury and is expected to be launched by the end of the decade. The mission will consist of three spacecraft science elements, the Mercury Planetary Orbiter dedicated to planet-wide remote sensing and radio science, the Mercury Magnetospheric Orbiter on which magnetic field, wave and particle instruments will be located, and the Mercury Surface Element, a lander module for *in situ* ground study of physical, optical, chemical and minerological features. The mission will allow, through a specially equipped array of instruments, for the determination of the harmonic coefficients of Mercury's gravitational field and of the rotational state of the planet and, via precision Doppler and ranging measurements, the carrying out tests of GR with great accuracy. Indeed, BepiColombo will make possible important improvements in the measurement of the Sun's oblatness, J_2, down to 10^{-9}, of the Post-Newtonian parameters, γ, down to 2.5×10^{-6}, β, down to 5×10^{-6} and the combination, $\eta \equiv 2 - \beta + 2\gamma$, down to 2×10^{-5}, as well as improving the limit on the cosmological time variation of the gravitational coupling, $\dot{G}/G$, down to $3 \times 10^{-13}\ years^{-1}$ [90]. The accuracy in the determination of the above-mentioned parameters will most likely allow for the identification of any constant acceleration (which should then be compared to a_P discussed above) acting on the spacecraft that is unrelated with other violations of GR that are associated with alternative scalar-tensor theories of gravity (see Section **7** and Ref. [90]). Since achieving the above-mentioned precision measurements requires a great degree of control over the spacecraft tracking, which is nowadays possible thanks to progress in very high phase stability of microwave signalling, BepiColombo is a mission uniquely well suited for providing clues on the puzzle of the radiometric data from Pioneer 10/11, Galileo and Ulysses spacecraft. Thus, BepiColombo may lead, after eliminating all possible conventional explanations, to the exciting prospect of providing evidence of a new fundamental interaction of Nature or on important deviations from GR.

4.2 Carrier of a New Interaction of Nature as a Dark Matter Candidate

The carrier of a putative new interaction could, if long lived, be regarded as a suitable dark matter candidate [91, 92, 93]. Cosmological constraints on the strength and range of the new interaction are, however, very modest in comparison with the above-mentioned experimental bounds [45, 93, 94].

In many extensions of the Standard Model, the interaction between the carrier of the putative new interaction, φ, with nucleons, N, and photons is described by the Lagrangian density:

$$\mathcal{L}_{int} = c_n \frac{\varphi}{\langle \varphi_5 \rangle} m_n N \bar{N} + c_p \frac{\varphi}{\langle \varphi_5 \rangle} F_{\mu\nu} F^{\mu\nu} \quad , \tag{28}$$

where c_N and c_P are constants, $F_{\mu\nu}$ is the electromagnetic field strength, $\lambda = m_\varphi^{-1}$, m_φ being the mass of the new interaction carrier and

$$\alpha = \frac{c_n^2}{4\pi} \left(\frac{M_P}{\langle \varphi_5 \rangle} \right)^2 \quad , \tag{29}$$

where $M_P \equiv G^{-2} = 1.2 \times 10^{19}$ GeV is the Planck mass. In order to fit the experiments, $\alpha \lesssim 10^{-3}$ for $10\ m \lesssim \lambda \lesssim 10^3\ m$, and hence there are two alternatives:

$$c_n \lesssim 10^{-1}\ ; \quad \langle \varphi_5 \rangle \sim M_P \tag{30}$$

or

$$c_n \lesssim 10^{-5}\ ; \quad \langle \varphi_5 \rangle \gtrsim 10^{-5} M_P \tag{31}$$

as discussed in Ref. [95].

We stress that the existence of new forces of Nature, at a mundane scale, say $1\ mm \lesssim \lambda \lesssim few\ m$, may have an important impact on practical questions related with the launching and propulsion of spacecraft. It is crucial that the search for new fundamental interactions of

Nature continues and that theoretical relationships arising from other areas of physics, such as in String/M-Theory and braneworld scenarios [96, 97], are further developed and investigated.

4.3 Gravitational Anomalies

We close this Section by mentioning that a good number of anomalies concerning the gravitational behaviour of well-known systems and devices have been reported, especially in connection with the experimental determination of Newton's constant. The subject has been throughly reviewed in Ref. [98] and from that discussion it is evident that a good number of these claims require further experimental verification and that they lie outside the prevailing accepted physical theories. Given the fact that these anomalies are quite often invoked in schemes to control gravity, we shall quickly survey the most salient claims.

For instance, E.J. Saxl has reported a discrepancy between theory and experiment regarding the period of an electrically charged torque pendulum [99], but his results have not been confirmed [100]. A number of claims have been made and studies performed to test a progressive absorption of the gravitational force between two bodies when a medium screens one from the other. This effect is clearly a gravitational analogue of the magnetic permeability of materials, and a screening or extinction coefficient, h, was proposed by Quirino Majorana [101] in 1920 in order to measure the ability of a material with density $\rho(r)$ to shield the gravitational force between masses m_1 and m_2, an effect that can be modelled as:

$$F' = \frac{Gm_1m_2}{r^2} \exp\left[-h \int \rho(r)\ dr\right] \quad . \tag{32}$$

Naturally, h must be quite small. Several attempts to obtain this constant from general principles have been made. In connection with the magnetic analogy, Forward has pointed out that the general relativistic analogue of the magnetic permeability is given by the combination like $4\pi G/c^2 = 9.25 \times 10^{-27}\ m\ kg^{-1}$ [102] (cf. Eqs. (50) below). Weber [103] has argued that quasi-static shielding could be predicted from a general relativistic analysis of tidal phenomena, and stated that the effect should be extremely small. More recently, D. Eckhardt has shown that a lunar laser ranging experiment can set the limit, $h \leq 1.0 \times 10^{-21}\ cm^2 g^{-1}$, six orders of magnitude smaller than the geophysical constraint [104]. The most stringent laboratory limit on the gravitational shielding constant has its origin in the recent measurement of Newton's constant carried out at the Physik-Institut, Universität Zürich, which yields $h \leq 4.3 \times 10^{-14}\ cm^2 g^{-1}$ [105].

An anomaly that has been very much discussed (see references in [98]), is the result reported by Hayasaka and Takeuchi [106] on the anomalous behaviour of the weight of a spinning gyroscope. It was reported that the weight of the gyroscope decreased during rotation when the spin was oriented downwards. The effect was claimed to be proportional to the spinning velocity. More accurate experiments carried out by Nitschke and Wilmarth, Faller et al., and Quinn and Picard [107, 108, 109] have shown, however, that the effect could not be replicated.

Another anomalous result that is still covered by a mantle of controversy is due to Podkletnov and Nieminen [110] who reported on the loss of weight of a 5.5 g sample of silicon dioxide (SiO_2) suspended 15 mm above a 5.7$''$ disk of $YBa_2Cu_3O_{7-x}$, a high-temperature superconductor, that was maintained at temperatures below 77 K. For the static disk the loss of weight was found to be about 0.05%, and eventually increased to 0.3% of the sample weight when the disk was rotated. The effect reached its maximum strength at temperatures below 40 K, increased with the rotation velocity of the disk, and exhibited a resonant behaviour when the frequency of the rotational driving systems and/or suspension magnetic fields were greater than 10^5 Hz. It was claimed that several possible alternative causes have been examined and eliminated. Podesta and Bull [111] have pointed out, however, that the effect could be explained by applying an appropriate buoyancy correction to the measured force. It has been further remarked by Unnikrishnan [112] that the data of Podkletnov and Nieminen are actually not self-consistent. The same author did try to reproduce the static first Podkletnov and Nieminen experiment, but was not successful.

Podkletnov has performed a second experiment using a rotating levitating 10$''$ $YBa_2Cu_3O_{7-x}$ toroid and the same loss of weight was observed. The paper containing the results of the second experiment has been submitted and accepted for publication in the Journal of Physics D:

Applied Physics, but was subsequently put on standby by the journal given doubts concerning the co-author of the article, Petri Vuorinen, who stated that he had never worked on antigravity. Podkletnov has eventually withdrawn the paper, a few weeks before it was due to appear. NASA has carried out two attempts in 1997 to reproduce Podkletnov's results, but with no clear-cut success. The first experiment reported on the extremely difficult task of producing $12''$ disks without breaking them and on a small but detectable gravitational anomaly whose cause was discussed to be manifold [113]. In the second experiment [114], a highly accurate gravimeter was used, but *no rotation* was introduced. The group presented the preliminary results of their experiment for DC and AC magnetic fields at the Breakthrough Propulsion Physics Conference at Lewis Research Center at Cleveland, Ohio in 1997. A quite strong bound on the strength and range of any coupling between static superconductors and gravity was achieved on account of measurements of changes in acceleration that were less than 2 parts in 10^8 of the normal gravitational acceleration. Unclear aspects of the Podkletnov's papers were throughly examined [114]. A more recent attempt to reproduce Podkletnov's results introducing *rotation*, even though with not exactly the same setup, has also led to a negative outcome [115].

On the theoretical side, the literature is also rich in work on putative anomalous gravitational effects. For instance, Modanese has claimed that non-perturbative Euclidean quantum gravitational effects could account for the gravitational shielding effect reported by Podkletnov, a claim that is, in our opinion, hardly credible given the highly conjectural nature of the arguments presented [116]. In the framework of the linear approximation of Einstein's field equations, which can be written in a fashion similar to the Maxwell's equations, the so-called Gravitoelectromagnetism (GEM) which is discussed in Section **6**, Torr and Li have also claimed that the gravitoelectric field produced by a superconductor could be abnormally large due to the alignment of the spin of the lattice ions of the superconductor [117]. Nevertheless, it is hard to see how that would come about, since it is well known that the total spin found in condensed matter systems is usually quite small even after alignment. Furthermore, Torr and Li use the GEM approximation in a situation where they claim the gravitomagnetic fields actually blow up, which clearly breaks the approximation (cf. Section **6**). Similar criticism has been expressed in Ref. [118].

Another reported anomalous gravitational effect concerned the decrease in the vertical gravity of about $(7.0 \pm 2.7) \times 10^{-8}\ m\ s^{-2}$ during the first and last contact of the total eclipse of the Sun on 9 March 1997 in China [119]. After discarding the most direct possible causes for the effect, the authors have invoked a putative shielding property of gravity as a possible explanation. It is higly unclear how an effect of this type could account for the fact that around the totality of the eclipse no changes were observed. Quite recently, however, Unnikrishnan, Mohapatra and Gillies [120] have ruled out gravitational shielding as the cause of the anomaly observed by Wang et al. during the total solar eclipse. Furthermore, the authors have established a yet more stringent bound on the gravitational shielding constant $h \leq 2 \times 10^{-17}\ cm^2 g^{-1}$ and modelled the observed anomalous result as a series of unaccounted for seismic disturbances due to human activity. Actually, there is a long story of claims concerning possible gravitational anomalies during solar eclipses. However, the data are contradictory and most usually allow the establishing of quite tight bounds on h ([120] and references therein). Gravitational screening has also been invoked to explain irregularities in the trajectories of satellites when entering the Earth's shadow [121], but these claims are naturally quite difficult to confirm given the number of potential effects to which a satellite is subjected when flying close to the Earth's surface.

Finally, we mention a quite recent result reported by Podkletnov and Modanese [122]. They claim that discharges of a charged $YBa_2Cu_3O_{7-y}$ superconductor compound are accompained by the emission of radiation whose beam does not suffer noticeable attenuation on passing through different materials and exerts a short repulsive force on small movable objects. Within the measurement error, the impulse is found to be proportional to the mass of the objects and independent of their composition. The effect is presented as new and unprecedented. It is argued that a possible explanation could be found in the realm of anomalous vacuum fluctuations in quantum gravity. Naturally, an independent confirmation is absolutely necessary and it is, in our opinion, premature to engage in any theoretical modelling or efforts to understand the claim before successfully achieving its replication.

5 String/M-Theory

String theory which is presently referred to as String/M-Theory, given the unification of string theories that can be achieved in M-Theory, is currently the most promising scheme to make General Relativity compatible with Quantum Mechanics (see [123] for an extensive presentation). The spectrum of the theory contains as zero mass states, the graviton, g_{MN}, the dilaton, Φ, and an antisymmetric second-order tensor, B_{MN}. There are various schemes to extract the physics of our four-dimensional world and a major difficulty is to fix the value of the dilaton field as it does not acquire a potential at any order in string perturbation theory. Damour and Polyakov [124] have suggested considering string loop-contributions, which are actually counted by dilaton interactions, instead of a potential. In this scheme the relevant effective low-energy four-dimensional action is, after dropping the antisymmetric second-order tensor and introducing fermions, $\hat{\psi}$, Yang-Mills fields, $\hat{A}^{\mu}$, with field strength, $\hat{F}_{\mu\nu}$, in a spacetime described by the metric, $\hat{g}_{\mu\nu}$, given by:

$$S = \int_M d^4x\sqrt{-\hat{g}}B(\Phi)\left[\frac{1}{\alpha'}[\hat{R} + 4\hat{\nabla}_{\mu}\hat{\nabla}^{\mu}\Phi - 4(\hat{\nabla}\Phi)^2] - \frac{k}{4}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} - \overline{\hat{\psi}}\gamma^{\mu}\hat{D}_{\mu}\hat{\psi} + ...\right] \quad , \qquad (33)$$

where

$$B(\Phi) = e^{-2\Phi} + c_0 + c_1e^{2\Phi} + c_2e^{4\Phi} + ... \quad , \qquad (34)$$

α' is the inverse of the string tension, k is a gauge group constant and the constants c_0, c_1, ..., etc., can, in principle, be determined via computation.

In order to recover Einstein gravity, a conformal transformation must be performed with

$$g_{\mu\nu} = B(\Phi)\hat{g}_{\mu\nu} \quad , \qquad (35)$$

leading to an action where the coupling constants and masses are functions of the reescaled dilaton, ϕ,

$$S = \int_M d^4x\sqrt{-g}\left[\frac{1}{4q}R - \frac{1}{2q}(\nabla\phi)^2 - \frac{k}{4}B(\phi)F_{\mu\nu}F^{\mu\nu} - \overline{\psi}\gamma^\mu D_\mu\psi + ...\right] \quad , \tag{36}$$

from which it follows that $4q = 16\pi G = \frac{1}{4}\alpha'$ and that coupling constants and masses are now dilaton-dependent:

$$g^{-2} = kB(\phi) \quad , \quad m_A = m_A(B(\phi)) \quad . \tag{37}$$

Damour and Polyakov have then proposed the so-called *Minimal Coupling Principle* (MCP), according to which the dilaton is dynamically driven towards a local minimum of all masses (which corresponds to a local maximum of $B(\phi)$). The dependence of the masses on the dilaton implies, by virtue of the MCP, that particles fall differently in a gravitational field and hence in violation of the WEP. The estimated effect is rather small

$$\frac{\Delta a}{a} \simeq 10^{-18} \quad , \tag{38}$$

but within the precisional reach of a mission like STEP !

Verifying this prediction is clearly a quite exciting prospect as it would be a distinct experimental signature of String/M-Theory. We have no doubts that the search for violations of the WEP, as well as of the fundamental Lorentz and CPT symmetries, is an important window to string physics and should be vigorously pursued experimentally. If on the one hand, it is not altogether clear that developments in String/M-Theory will have a direct impact on the issue of gravity control, they will in any case deeply affect our understanding of gravity and most probably bring about the discovery of quite unexpected new phenomena.

GR is a fairly complex theory and relying on approximation methods (the Parametrized Post-Newtonian formalism discussed above being one of them) is quite often the only available route to extract physical predictions from the theory. Gravitoelectromagnetism (GEM) is a particularly useful approximation to compute corrections to Newtonian gravity arising from the weak-field approximation of GR. The notation of Ref. [125] will be followed throughout this Section.

One starts by considering the weak field approximation

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad , \quad |h_{\mu\nu}| << 1 \quad , \tag{39}$$

and working, for convenience, with the combination

$$\overline{h}_{\mu\nu} \equiv h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu} h \quad ; \quad h = Tr(h_{\mu\nu}) \quad . \tag{40}$$

In this approximation, Einstein's equations simplify to

$$\Box\, \overline{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu} \quad , \tag{41}$$

which admits a well-known retarded solution for matter with an energy-momentum tensor whose components are given by,

$$T^{00} = \rho c^2 \quad , \quad T^{0i} = cJ^i \quad , \tag{42}$$

namely,

$$\overline{h}_{\mu\nu} = \frac{4G}{c^4} \int d^3\vec{x}\, \frac{T_{\mu\nu}(ct - |\vec{x} - \vec{x'}|, \vec{x'})}{|\vec{x} - \vec{x'}|} \tag{43}$$

where $J^i = \rho v^i$, ρ is the mass density, v^i is the i component of the velocity and

$$\overline{h}_{00} = \frac{4}{c^2}\Phi \quad , \quad \overline{h}_{0i} = -\frac{2}{c^2} A_{gi} \quad , \quad \overline{h}_{ij} = O(c^{-4}) \quad , \tag{44}$$

so that far from the source

$$\Phi \sim \frac{GM}{x} \quad , \quad \vec{A}_g \sim G\vec{J} \times \frac{\vec{x}}{cx^3} \quad . \tag{45}$$

The spacetime metric of this matter distribution is given by

$$ds^2 = -c^2\left(1 - \frac{2\Phi}{c^2}\right)dt^2 - \frac{4}{c}(\vec{A}_g.d\vec{x})dt + \left(1 + \frac{2\Phi}{c^2}\right)\delta_{ij}dx^i dx^j \quad , \tag{46}$$

and one can define the Gravitoelectromagnetic (GEM) fields

$$\vec{E}_g = -\nabla\Phi - \frac{1}{c}\frac{\partial(\frac{1}{2}\vec{A}_g)}{\partial t} \qquad \vec{B}_g = \nabla \times \vec{A}_g \quad , \tag{47}$$

so that a sort of "Lorentz gauge" holds at lowest order

$$\frac{1}{c}\frac{\partial\Phi}{\partial t} + \nabla.(\frac{1}{2}\vec{A}_g) = O(c^{-4}) \quad . \tag{48}$$

It is interesting that the source-free GEM equations and the gravitational field equations can, in this approximation, be written in a form similar to Maxwell's equations:

$$\nabla \times \vec{E}_g = -\frac{1}{c}\frac{\partial(\frac{1}{2}\vec{B}_g)}{\partial t} \qquad \nabla.(\frac{1}{2}\vec{B}_g) = 0 \quad , \tag{49}$$

$$\nabla.\vec{E}_g = 4\pi G\rho \qquad \nabla \times (\frac{1}{2}\vec{B}_g) = \frac{1}{c}\frac{\partial \vec{E}_g}{\partial t} + \frac{4\pi G}{c}\vec{J} \quad . \tag{50}$$

The analogy with electromagnetism can be further pursued as there is a conserved "charge" (which is actually the mass) as expressed by the continuity equation:

$$\frac{\partial\rho}{\partial t} + \nabla.\vec{J} = 0 \quad . \tag{51}$$

The first relevant result emerging from this analogy is the presence of a new magnetic-type force, a Lorentz force, that has no Newtonian counterpart, and which in lowest order in $\frac{v}{c}$ and in the case $\vec{A}_g$ is time-independent. It can be written as

$$\vec{F}_g = q_E \vec{E}_g + q_B \frac{\vec{v}}{c} \times \vec{B}_g \quad , \tag{52}$$

where the gravitoelectric and gravitomagnetic "charges" are for a test particle of inertial mass, m,

$$q_E = -m \qquad q_B = -2m \quad , \tag{53}$$

which are chosen to be negative so as to more closely resemble electromagnetism. On the other hand, for a rotating body of inertial mass M,

$$q_E = M \qquad q_B = 2M \quad , \tag{54}$$

that is, these "charges" are positive as gravity is an attractive interaction.

The ratio between the charges is fixed and is ultimately related with the spin-2 nature of GR:

$$\frac{q_B}{q_E} = 2 \quad . \tag{55}$$

Naturally, GEM is a good approximation of GR in as far as one can neglect terms proportional to Φ_g^2, $\vec{A}_g^2$ and $\overline{h}_{ij}$, being reliable in dealing with bending of light related effects, for quantifying gravitational red-shift phenomena, but clearly unsuitable for accounting for perihelium effects and, of course, gravitational waves. Furthermore, GEM is meaningful only if the matter distribution evolves so as to satisfy Eq. (42) and the T^{ij} components of the energy-momentum tensor remain vanishing.

It is relevant to compare the difference in orders of magnitude between GEM and electromagnetism. Introducing the connecting constants $k_{E(B)} = 4\pi G/c^2\mu_0 q_{E(B)}/q = 7.4 \times 10^{-21}\ q_{E(B)}/q$, where μ_0 is the vacuum magnetic permeability and q is the electric charge, one can write $\vec{E}_g = k_E\vec{E}$ and $\vec{B}_g = k_B\vec{B}$, which is valid for point-like masses and uniformly distributed mass and electric charge configurations.

One of the most striking implications of GEM is the Lense-Thirring effect [126]. This is an example of the effect spacetime exerts on matter, as predicted by GR. It consists of the back-reaction caused by the rotation of a heavy object (Earth) on nearby bodies that will spin due to the dragging generated by the bigger body. Thus, the rotation velocity $\vec{\Omega}$ of a test particle, with velocity $\vec{v}$, will have in general two components, a geodetic rotation, $\vec{\Omega}_G$, and the effect of Earth's gravity and spin, $\vec{\Omega}_{LT}$, which is given in terms of the Post-Newtonian parameters γ and α_1, Newtonian potential Φ, Earth inertial momentum, I and rotation, $\vec{\omega}$ [32, 127]:

$$\vec{\Omega} = \vec{\Omega}_G + \vec{\Omega}_{LT} = (\gamma + \frac{1}{2})\frac{\vec{v}}{c} \times \nabla\Phi + \frac{1}{2}(\gamma + 1 + \frac{1}{4}\alpha_1)\frac{GI}{c^2}\frac{[\vec{\omega} - 3\hat{r}(\hat{r}.\vec{\omega})]}{r^3} \quad . \tag{56}$$

The experimental confirmation of the Lense-Thirring effect requires precise tracking of satellite orbits as performed with lasers on the LAGEOS (Laser Geodesic Satellite) missions. Astrophysical tests of the Lense-Thirring effect can also be performed through, for instance, the observation of binary systems involving a compact object like a neutron star or a black hole. The joint NASA/Italian Space Agency LAGEOS II satellite, launched in 1992, following its predecessor NASA's LAGEOS I, launched in 1976, consists of a passive satellite dedicated to high-precision laser ranging, which involves sending laser pulses to stations on Earth so as to record the round-trip travel time. Besides being able to provide relevant bounds on the existence of new interactions in Nature (see Figure 1), a NASA and a university team have recently claimed to have found the first evidence of the Lense-Thirring effect via data provided by the LAGEOS missions [32, 128].

A more ambitious project to measure the Lense-Thirring effect is NASA's Gravity Probe B satellite. Conceived after the independent suggestions of Pugh [129] and Schiff [130] who pointed out, in 1959/60, that the Lense-Thirring drag would affect the behaviour of a spinning gyroscope. This Stanford University mission is planned to circle the Earth in a polar orbit at an altitute of about 650 km and to be launched in a year or two. The goal is to monitor the precession of free-falling gyroscopes caused by the geodetic and Lense-Thirring effects over a period of a year [131]. It is remarkable that this experiment has been recently invoked as a way to get information on brane-world scenarios [132]. This comes about as in a two-brane scenario the GM effect depends heavily on the ratio of the brane separation and the radius of the anti-De Sitter five-dimensional space. For a single brane scenario, no discrepancy with the effect predicted by GR is expected [132].

ESA's HYPER mission aims to go beyond the above-mentioned missions through the precise measurement of the rotation rate of cold-atom gyroscopes and its spatial variation [33].

Before closing this Section, we should mention the important issue of the gravitational Larmor theorem. This theorem expresses Einstein's Equivalence Principle in the framework of the GEM approximation. This can be seen by considering GEM fields $\vec{E}_g$ and $\vec{B}_g$ and their relation with linear translational acceleration and angular velocity. The associated Larmor quantities are shown to be given by $\vec{a}_L = -q_E \vec{E}_g/m = \vec{E}_g$ and $\vec{\omega}_L = q_B \vec{B}_g/2mc = -\vec{B}_g/c$ [125], which means that the well-known heuristical discussion of Einstein's Equivalence Principle in terms of translational acceleration of the "Einstein elevator", found in many textbooks on GR, is somewhat incomplete as it requires the Larmor rotation as well, in order to account for the GEM field. It is worth remarking that the independence of $\vec{a}_L$ and $\vec{\omega}_L$ of the ratio of the "charges" to the masses is a clear signal of the universality of the gravitational interaction. This independence is not found in electromagnetism.

The gravitational analogue of the spin-orbit coupling and spin-spin coupling may cause measurable effects for astrophysically compact objects. For instance, spin-orbit coupling causes a rotation in the direction of the spin of the orbital plane of a neutron star around a spinning black hole; spin-spin coupling makes the orbit of a spinning neutron star different from the orbit of an elementary test particle. These orbital effects give rise to gravitational waves with distinct features and these are expected to be observed by an ESA/NASA gravitational wave detector in space, LISA (Laser Interferometer Space Antenna). The ambitious LISA mission comprises three identical spacecraft located 5×10^6 km apart, forming an equilateral triangle. This gigantic Michelson interferometer in space will be positioned so that the centre of the triangular formation lies in the ecliptic plane, 1 AU from the Sun. The interferometry will be performed by a 1 W infrared laser beam that is transmitted to the corresponding remote spacecraft via a 30 cm Cassegrain telescope. Distances fluctuations will be measured with sub-Ångstrom precision, leading to a capability to measure gravitational space strains down to $\Delta L/L = 10^{-23}$ after a year of operation, with a signal-to-noise ratio of 5 [133].

5.1 Gravitoelectromagnetism and Quantum Materials

As already mentioned, since GEM is a linear approximation of GR, it is somewhat limited and cannot be stretched to the study of gravitational waves, dynamics of compact objects, cosmology and so on. However, it is quite useful in establishing the Lense-Thirring effect, as we have seen, and the magnetic analogue of the already discussed Schiff-Barnhill effect, as first pointed out by DeWitt [27]. This effect arises from the quantum properties of a superconductor in a gravitational field. The relevant Lagrangian density is given by

$$\mathcal{L} = -m \left[g_{\mu\nu} \frac{dx^\mu}{d\tau} \frac{dx^\nu}{d\tau} \right]^{1/2} + eA_\mu \frac{dx^\mu}{d\tau} \tag{57}$$

where m and e are the mass and charge of the electron and $A_\mu = (U, \vec{A})$ is the electromagnetic gauge potential. The corresponding Hamiltonian for a single electron is, in the limit of small velocities, weak fields and after dropping the rest mass, written as

$$\mathcal{H} = \frac{1}{2m} (\vec{p} - \vec{A}_T)^2 + V \quad , \tag{58}$$

where

$$\vec{A}_T = e\vec{A} + m\vec{A}_g \tag{59}$$

and

$$V = -eU - m\Phi \quad . \tag{60}$$

For an ensemble of free electrons inside the superconductor one should sum over all electrons and also consider the electron-phonon interactions, V_{int}:

$$\mathcal{H}_{\mathcal{T}} = \sum_n \frac{1}{2m}[\vec{p}_n - \vec{A}_T(\vec{x}_n)]^2 + V(\vec{x}_n) + V_{int} \quad . \tag{61}$$

All features of the well-known BCS theory can be applied to this Hamiltonian. This allows one to conclude that whenever matter is in motion near a superconductor, as to have a non-vanishing contribution of the Lense-Thirring field, the Meissner effect requires the vanishing of the combination of $\vec{H}$ and $\vec{B}_g$ inside the superconductor, and not of $\vec{H}$ alone, as in the usual situations; that is

$$\vec{B}_T = \nabla \times \vec{A}_T = e\vec{H} + m\vec{B}_g = 0 \quad . \tag{62}$$

Since a superconductor is also a conductor, the vanishing condition of the Schiff-Barnhill field, namely $\vec{F}_T = e\vec{E} + m\vec{E}_g = 0$, must also be satisfied.

Naturally, these considerations imply that it is the flux of $\vec{A}_T$ through a superconducting ring that is quantized in units of $h/2$:

$$\oint_\Gamma (m\vec{v} + \vec{A}_T).d\vec{r} = n\frac{h}{2} \quad . \tag{63}$$

DeWitt has shown from these considerations that for an electromagnetically neutral uniformly rotating mass located axially in a superconducting circular ring, the vanishing condition will produce a Lense-Thirring field and an induced current in the ring. This is another instance of the drag effect. Detection of the resulting effect is conceptually conceived via the measurement of the magnetic field generated by a current in a region where the Lense-Thirring field is vanishingly small. In practice, however, the resulting effect is extremely small, $i \sim GmMv/ed$, for a rotating mass M, with rim velocity v and diameter d [27]. This current arises from the gravitomagnetically induced motion of electrons on the surface of the superconductor. It is worth mentioning that a covariant formulation of DeWitt's approach has been presented in Ref. [134].

Given that the generated GM field is, in such situations, quite small, one is imediately led to the question of whether the GM field can be amplified. In what follows we shall see that this seems to be impossible in the realm of GR. The existence of a "dynamo effect", a term borrowed from Magnetohydrodynamics (MHD), that is a mechanism of generation and amplification of gravitomagnetic energy from the stretching action of the velocity field on $\vec{B}_g$ might, of course, be of great importance in the study of gravity control. Given that the generation of $\vec{B}_g$ requires a flow of matter with angular velocities, it is relevant to recall that the mechanical strength of materials constrains the corresponding linear velocities to be at most as large as the velocity of sound in the material. Hence any gravitational dynamo effect generated by matter currents of a "fluid" will be limited by the above velocity bound and the resulting GM will inevitably be quite small. As we shall see shortly, conceptual limitations are also equally severe. As argued in Ref. [135], in attempting to amplify GM fields in the context of GEM, one has to assume that the matter fluid must have viscosity, so as to obtain an induction-type equation as in MHD for a fluid with velocity $\vec{v}$ and resistivity, η_e, namely

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) + \frac{1}{4\pi}\eta_e \nabla^2 \vec{B} \quad , \tag{64}$$

which, in MHD, is obtained from Ohm's Law and with negligible displacement current in the Galilean limit of Maxwell's equations.

Indeed, one can easily see that one has to go beyond a perfect fluid and generalize "Ohm's Law" in GEM, so that

$$\vec{j} = \delta(\vec{E}_g + \vec{v} \times \vec{B}_g) \quad , \tag{65}$$

where δ is a phenomenological constant. The resulting equation has, however, an important sign difference in relation to the second term in the r.h.s. of Eq. (64), which obviously precludes the possibility of an amplification mechanism. It is further argued that, ultimately, the Galilean limit of GEM is altogether troublesome, given the absence of negative masses in gravity. Even though this last point is well taken, the generality of the whole argument deserves further investigation, in our opinion.

In any case, one can conclude that mechanisms for amplifying GM fields are conceptually inconsistent in GEM. Arguments such as the one presented above are quite relevant in order to establish general criteria to quickly rule out whole classes of proposals and claims that appear in literature about possible GEM dynamo effects.

It is our opinion that the research activity on the gravitomagnetic properties of quantum materials deserves a closer look and many of its specific properties and ensuing implications must be closely and critically examined. After a survey of the existing literature, and considering some of the reported results, several questions stand out:

(i) Is it possible to align, in a substancial fashion, the field $\vec{B}_g$ likewise in ferromagnetic materials via, for instance, a rotation as in the so-called Barnett effect [136, 137, 138] ?

(ii) Is there a gravitational analogue of the converse Einstein-de Hass effect [137] that consists of increasing the free energy of a system via the action of a magnetic field antiparallel to the magnetization of a piece of iron at rest ?

(iii) Is it possible to disentangle the fields $\vec{H}$ and $\vec{B}_g$ from the quantization condition Eq. (63) so as to measure $\vec{B}_g$?

It is our belief that the answer to these questions tend to be no and that the involved GM fields would anyway be far too small for launching and propulsion purposes.

Naturally, the investigation of mechanisms to obtain sizeable GM fields should also be extended to superfluids. In this respect, it has been suggested that a net $\vec{B}_g$ would arise in a rotating ^4He superfluid gyroscope [139]. This is an interesting proposal given the absence of any electromagnetic field which allows for a direct involvement of the $\vec{B}_g$ field. However, the current picture of the phase transition into the superfluid state arising from the recent Helsinki [140] and Grenoble [141] experiments seems to agree with the Kibble mechanism for the formation of topological defects (vortices and anti-vortices) (see, for instance, the contribution of Kibble in Ref. [142]) and implies that any field associated with elementary spins or gyroscopes [143], such as $\vec{B}_g$, would be erased by the complex dynamics of the vortex network emerging from the phase transition. Actually, if any effect were to be expected, it would seem more promising to consider the ^3He system given that it is fermionic and has non-vanishing elementary spins to start with. Furthermore, the ^3He system has many important advantages from the experimental point of view, as demonstrated by the Helsinki and Grenoble experiments [140, 141].

Thus, for us it is clear that these questions merit dedicated longer term research and, at this stage of our study, we can only envisage some of the major possible obstacles. We would emphasize that some of the above-mentioned issues are current topics of research in condensate matter physics and its interplay with phase transitions in field theory and cosmology (see, for instance, Ref. [142] for extensive discussions).

6 "Vacuum Engineering"

The possibility of changing the properties of the vacuum would, of course, have dramatic physical implications. T.D. Lee has long ago coined the word *vacuum engineering* to stress that changes in the vacuum properties would have profound consequences [144]. In modern physical theories, the vacuum is regarded as the lowest energy state of a system. It has zero 4-momentum and in quantum field theories this 4-momentum states unables the construction of a Hilbert state. Since Dirac's hole theory, the vacuum can be regarded as a field with complex properties and quantum numbers. The idea that fundamental symmetries of a given theory are not shared by some vacuum states has given origin, in field theory, to the *Spontaneous Symmetry Breaking (SSB)* phenomenum, which is a major ingredient in the *Standard Model* for the Electroweak Unification. It is somewhat remarkable that in the presence of gravity, the mechanism of SSM gives rise to a major theoretical conundrum, the so-called *Cosmological Constant Problem* [145, 146] (see also Ref. [147] for an extensive review on the cosmological aspects of the problem and Refs. [148] for a discussion on the role of string duality symmetries.). The vacuum energy and its various ramifications, such as the Casimir forces, sonoluminescence and quantum field theory phenomena, have recently been extensively reviewed in Ref. [149] (see also Ref. [150]). Actually, Casimir forces are often mentioned as example of unusual phenomena associated with the quantum vacuum. Even though these feeble forces between conducting plates are a striking and somewhat unexpected manifestation of quantum field theory, it is important to stress that they are predicted by Quantum Electrodynamics and fit within the prediction of that theory to within 5% [151].

In this context, a particularly relevant question for our study concerns the possibility of altering the strength of the gravitational coupling. In many alternative theories of gravity, the gravitational coupling is given by a function of a field. In the so-called *Scalar-Tensor Theories of Gravity*, the gravitational coupling is a function of a scalar field, φ. A quite general action for these theories can be written in the following way:

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{16\pi}f(\varphi)R - g(\varphi)\partial_\mu\varphi\partial^\mu\varphi + V(\varphi)\right] + S_{Matter} \quad , \tag{66}$$

where $f(\varphi)$, $g(\varphi)$ and $V(\varphi)$ are generic functions.

Thus, for instance, the well-known Brans-Dicke theory [152] corresponds to the special choice:

$$f(\varphi) = \varphi \qquad g(\varphi) = \frac{\omega}{\varphi} \quad , \tag{67}$$

and a vanishing potential $V(\varphi)$. Notice that in the Brans-Dicke theory, the field φ has dimension of energy squared, given that its kinetic energy term is non-canonical. In this theory, it is the value of the constant ω that controls the observational differences with GR. GR is recovered in the limit $\omega \to \infty$. We point out that it is in the context of the Brans-Dicke theory that the so-called *Mach's Principle*, according to which the inertia of the bodies is due to their interaction with matter distribution in the Universe, can be operationally formulated. Indeed, in this theory the gravitational coupling is given, up to a constant, by φ^{-1}, which depends on the energy-momentum tensor of matter through the field equations. Observational bounds establish that $|\omega| \gtrsim 500$ [153] and even higher values, $|\omega| \gtrsim 4000$ [1].

Therefore, available data indicate that any deviation from GR must be very small and that any effect presumably due to Mach's Principle on a laboratory scale is ruled out. Thus, the claim by J. Woodward [154] of having experimentally generated transient fluctuations in the inertial mass of a capacitator and that, thanks to Mach's Principle, mass changes can be used as a propellantless propulsion mechanism, is hardly credible.

In Brans-Dicke theory, as well as in more general scalar-tensor theories, the gravitational coupling has a dependence on the cosmic time. Observational bounds arising from the timing of the binary pulsar PSR1913+16 set quite restrictive bounds [155]

$$\left(\frac{\dot{G}}{G}\right) = (1.0 \pm 2.3) \times 10^{-11}\ y^{-1} \quad , \tag{68}$$

but varying-G solar models [156] and measurements of masses and ages of neutron stars yield even more stringent limits [157]:

$$\left(\frac{\dot{G}}{G}\right) = (-0.6 \pm 2.0) \times 10^{-12}\ y^{-1} \quad . \tag{69}$$

Cosmological bounds are comparable to the ones set by Eq. (68) and have been reviewed in Refs. [94, 98, 158] (see Ref. [159] and references therein for a discussion on the connection with the accelerated expansion of the Universe).

In the so-called *Induced Gravity Models* [160], the functions of the fields are initially given by

$$f(\varphi) = \varphi^2 \qquad g(\varphi) = \frac{1}{2} \quad , \tag{70}$$

and the potential $V(\varphi)$ is such that it allows for the process of SSB, so that the field φ acquires a vacuum expectation value, $f(\langle 0|\varphi|0\rangle) = \langle 0|\varphi^2|0\rangle = M_P^2 = G^{-1}$. Naturally the cosmological constant is given by the interplay of the value $V(\langle 0|\varphi|0\rangle)$ and all other contributions to the vacuum energy.

Therefore, it is clear in these alternative theories of gravity that Newton's constant arises from dynamical or symmetry-breaking considerations. It is fascinating to conjecture that the φ field could be locally controlled for the purposes of propulsion. It is not clear at all if this is possible, but in any case it would require the coupling of the φ field with other fields in order to locally alter its value. This feature is encountered in some adjusting mechanisms devised to solve the problem of the cosmological constant (see eg. [145] for a list of references). Weinberg [145] has shown, however, that these mechanisms are actually unsuitable for solving the cosmological constant problem, but they nevertheless contain the required multi-field dynamics. It is worth mentioning that the graviton-dilaton system in String/M-Theory can be regarded as a scalar-tensor theory of gravity, but clearly the dynamics of this system are quite complex and have many surprising turns, as we have already seen when discussing its impact on the WEP. Of course, in the simple models we have mentioned, altering the value of the gravitational coupling would amount to achieving Planck energies in the laboratory, which is beyond any foreseeable technological developments. Nevertheless, recent speculations suggesting that the extra dimensions may be rather large [80, 81] would imply that the gravitational effects associated with these extra dimensions would arise at much lower energies, M_5, the 5-dimensional Planck mass, if one considers a single additional extra dimension. Limits on M_5 can be obtained from searches for "Kaluza-Klein" modes in accelerators and from cosmological considerations. The former yield $M_5 \gtrsim 3$ TeV [161]. Cosmological nucleosynthesis allows the setting of the bound $M_5 \gtrsim 10$ TeV [162]. A more stringent limit can be obtained in models where the fifth dimension is infinite, as this gives rise to an extra contribution to Newton's gravitational force, which must be small beyond scales above $r \gtrsim 1\ mm$ and implies that $M_5 > 10^5$ TeV (see eg. Ref. [83, 97]). A quite recent study on the conditions under which the Universe could have undergone a period of chaotic-type inflation in $N = 1$ Supergravity implies, however, a much more stringent bound, $M_5 > 1.5 \times 10^{10}$ TeV [163]. In practice, the effect of the extra dimensions, if any, would manifest itself through a contribution to Newton's law on small scales, $r \lesssim 10^{-4}\ m$, as discussed in Section **3**.

Knowledge of quantum gravity would allow one to establish whether the gravitational coupling is a running coupling constant like those of other fundamental interactions of Nature. From the point of view of String/M-Theory, the answer appears to be no given the non-renormalization theorems of *Supersymmetry*, which is a fundamental underlying principle of String/M-Theory [123]. From the point of view of 1-loop higher–derivative quantum gravity models, however, the answer is quite the opposite as these models exhibit the striking property of being asymptotically free [164]. Given the absence of a screening mechanism for gravity, asymptotic freedom may imply that quantum gravitational effects act on macroscopic and even on cosmological scales, a fact that has of course some bearing on the dark matter problem [165] and in particular on the large scale structure of the Universe [166, 167] (see, however, [94]). In any case, it seems reasonable to assume that these quantum gravity effects will show up only on cosmological scales.

Before closing this Section, we should comment on an idea that is often mentioned when discussing the impact of altering properties of the vacuum for the purposes of propulsion. In the so-called *Zero-Point Field* (ZPF) proposal, *real* QED vacuum fluctuations are considered as the origin of the Newtonian *inertia* of bodies, and can be obtained from the quantum stochastically-averaged quantity $\vec{F}_r = \langle \vec{v}_{osc} \times \vec{B}_{ZP} \rangle$, where $\vec{v}_{osc}$ is the velocity of oscillation due to the quantum fluctuations and $\vec{B}_{ZP}$ the magnetic field vacuum fluctuation [168]. This quantity is computed using techniques of quantum field theory in curved spacetime [169] and found to be proportional to the acceleration. Finally, it is argued that a connecting constant should be associated with the Newtonian inertia. It is claimed that in this framework, anisotropies introduced in the vacuum can lead to a modification of the inertial mass. Clearly, these ideas suffer from several inconsistencies, some of the most salient ones being:

(i) If one follows the reasoning of the ZPF proposal, one is led to conclude that the mass, say of the proton, has its origin in quantum vacuum fluctuations of the electromagnetic interaction. However, it is known that the mass (and spin) of hadrons is due to the non-linear strong interaction quark-gluon and gluon-gluon interactions in the non-perturbative regime of Quantum Chromodynamics. If on the other hand, the stochastic background fluctuations are assumed to be high enough that the invoked *partons* are free particles, then these partons cannot be the usual constituent quarks as their mass ratios come out wrong and hence some further sub-structure is required. Quarks and leptons are observed to be point-like to scales 10^{-18} cm [170].

(ii) To the objection that the energy associated with a real ZPF fluctuation would lead to significant spacetime curvature and an ensuing singularity, the defenders of the ZPF proposal argue that gravity should be also described as a vacuum fluctuation, an idea that has its roots in a suggestion by Sakharov [171]. Here again, it seems that the authors of the ZPF proposal disregard the fact that the induced gravity programme (see Adler [160] for an extensive review) could not be carried out since, due to the dynamical breaking of conformal invariance, non-perturbative ambiguities in the stress-energy tensor would not allow for a unique self-consistent means of computing Newton's constant and the cosmological term [172]. This is yet another example of the complexity of the difficulties one faces when dealing with the quantum aspects of gravity. Actually, the main reason behind the confidence of most theoretical physicists that String/M-Theory is the right framework in which to address the quantum gravity problem is related with the rather natural way in which some of the most fundamental questions can be addressed and eventually solved. Even if it is argued that ZPF does respect conformal invariance, one has to face the problem that ZPF does lead to a Newton force that falls as r^{-4} [173], which is clearly inconsistent. Furthermore, Eötvös-like experiments have shown with great accuracy that electrostatic energy as well as nuclear binding energy contributes to the mass. How could that be explained in terms of electromagnetic ZPF interactions ?

(iii) If one assumes that ZPF is the correct approach, how does one explain the mass of elementary neutral particles ? In the Standard Model, neutrinos and the Higgs boson are neutral particles that are believed to be elementary and there is a substantial body of evidence that the former are massive [170] .

(iv) Even if inertia can be modified as suggested in Refs. [168], most likely this will not imply any significant gain for the propulsion of spacecraft. As will be discussed in the next Section, a change in the inertia of the spacecraft will most generally imply in a change in the propellant inertia as well leading to a drop in thrust.

Hence, we conclude that the ZPF approach along the lines discussed in Refs. [168] is unlikely to provide the correct framework for understanding the complexity of the vacuum properties. Most probably, only within the realms of String/M-Theory can any significant progress be achieved in understanding the fundamental interplay between gravity and quantum fields.

7 Gravity-Controlled Propulsion

7.1 Propulsion Fundamentals

All classical propulsion systems rely on Newton's mechanics. From the reaction principle, we know that every force acting upon a body will cause a reaction force of the same intensity in the opposite direction. This is the basis for the conservation of momentum, which is illustrated in Figure 2.

According to Newton's second law, the force, $\vec{F}$, generated by the propellant is the time derivative of its linear momentum and given the loss of propellant mass at a constant exhaust velocity, which is the case in most of the situations,

$$\vec{F} = \frac{d\vec{P}}{dt} = \frac{dm_p}{dt}\ \vec{v}_p = -|\dot{m}_p|\ \vec{v}_p \quad . \tag{71}$$

One can see that higher exhaust velocities $\vec{v}_p$ create the same force at a lower mass flow rate $\dot{m}_p$ and therefore less propellant is used. This gives us information on how effectively the propellant is used. Another characteristic parameter is the so-called specific impulse, I_{sp}, which is the propellant velocity divided by the standard gravitational acceleration $g_0 = 9.81 m/s^2$. It is usual to use this expression for comparing different propulsion systems:

$$I_{sp} = \frac{v_p}{g_0} \quad . \tag{72}$$

Chemical propulsion systems use the energy stored in the propellant to create a hot gas

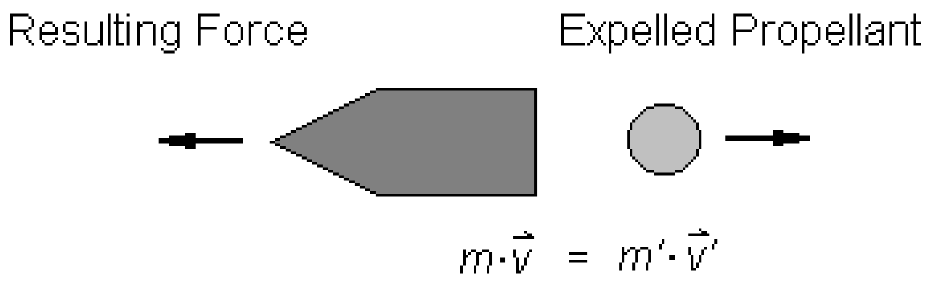

Figure 2: Momentum Conservation

Propulsion System		**Specific Impulse [s]**	**Max. Thrust [N]**
Chemical	Solid	$250-310$	10^7
	Liquid	$300-500$	10^7
Magnetohydrodynamic		< 200	10^5
Nuclear	Fisson	$500-860$	10^6
	Fusion	$10,000-100,000$	10^5
	Antimatter	$60,000$	10^2
Electric	Electrothermal	$150-1,200$	10^1
	Electrostatic	$1,200-10,000$	3×10^{-1}
	Electromagnetic	$700-5,000$	10^2
Propellantless	Photon Rocket	3×10^7	10^{-3}

Table 1: Typical Propulsion Performance

which is exhausted by a nozzle. In this situation, the achievable exhaust velocity is limited by the energetic reaction from the propellants. In another concept, so-called *electric propulsion*, electrical power from the spacecraft can be used to accelerate a propellant, either by heating or using ionized propellant via electric and/or magnetic fields. Much higher exhaust velocities and thus more effective use of propellant can be achieved. *Nuclear power* can also be used to heat up a working fluid, which is again expelled by a nozzle giving a very high specific impulse and thus high thrusts due to the very high energy density of nuclear materials. Another propulsion concept worth mentioning uses the atmosphere as a working fluid and acceleration is achieved by electromagnetic means. This concept is referred to as *magnetohydrodynamic propulsion* or simply MHD. A list of the different propulsion systems and their associated specific impulses as well as their maximum thrusts is shown in Table 1; a thorough discussion can be found in Refs. [174, 175].

Already in these classical propulsion systems, the mass of the propellant is an important parameter influencing performance. Neglecting the influence of the nozzle or the ambient atmosphere, the propellant velocity for a simple chemical thruster can be expressed as [174]

$$v_p \simeq \sqrt{\frac{2\gamma}{(\gamma-1)}\frac{RT_c}{\mu_p}} \quad , \tag{73}$$

where γ is the adiabatic index, R is the universal gas constant, T_c the temperature in the combustion chamber and μ_p the molar mass of the propellant in units of kg/mol. The lighter the expelled gas, the higher will be the propellant velocity and therefore the specific impulse ($I_{sp} \propto v_p \propto \mu_p^{-1/2}$). However, a lighter gas also reduces the mass flow rate $\dot{m}_p$. From the basic thrust equation, $F = \dot{m}_p v_p$, including the scaling law for v_p, we see that the thrust will then scale as $F \propto m_p^{1/2}$ (of course, only if the chamber temperature T_c stays constant). This is a very general and important result, which applies to all propulsion systems. For instance, a nuclear thermal rocket uses hydrogen as propellant, the lightest gas, to obtain a high specific impulse (about 700 s). In order to increase the thrust, oxygen can be injected in the back of the nozzle to create water vapour. Water is much heavier than hydrogen and therefore the specific impulse will be reduced (down to 300 s) but the thrust increased (according to the above scaling laws). By simply changing the mixing ratio between oxygen and hydrogen, thrust and specific impulse can be varied over a wide range.

Another example is electric propulsion. The propellant gas is ionized and accelerated, for instance, through an electrostatic field. The thruster characteristics can be written as

$$v_p = \sqrt{\frac{2qU}{m_p}} \quad , \tag{74}$$

$$F = I\sqrt{\frac{2m_pU}{q}} \quad , \tag{75}$$

where q is the ion's charge, U the applied potential and I the current. Our previously derived scaling relationships for thrust and propellant velocity with respect to the propellant (in this case ion) mass can be clearly seen. A typical propellant gas is Xenon (atomic mass 131). If Argon (atomic mass 40) would be used instead, the specific impulse would *increase* by 1.8 and the thrust would *decrease* by 0.55. By changing the propellant mass, in this case both the specific impulse and thrust can be varied. We shall use these scaling laws for a further discussion about hypothetical inertial mass modification and its implications for present propulsion systems.

The amount of propellant needed for a given mission is derived from the trajectory analysis and is typically expressed as the change of velocity required from the spacecraft, Δv. The total requirement consists of several components,

$$\Delta v = \Delta v_g + \Delta v_{drag} + \Delta v_{orbit} - \Delta v_{initial} \quad , \tag{76}$$

namely the Δv_g to overcome the gravitational potential (e.g. from the Earth's surface to the required orbit), Δv_{drag} due to drag from the atmosphere, Δv_{orbit} giving the velocity increment to reach a certain orbit and $\Delta v_{initial}$ the initial velocity. For example, if we launch from the Earth's surface and want to reach a Low Earth Orbit (LEO) at 100 km, the first factor is calculated by equating the difference in gravitational potential energy between Earth's surface and the 100 km orbit and the kinetic energy

$$\frac{mv^2}{2} = GMm\left(\frac{1}{r_{initial}} - \frac{1}{r_{final}}\right) \quad , \tag{77}$$

hence

$$\Delta v_g = \sqrt{2GM\left(\frac{1}{r_{initial}} - \frac{1}{r_{final}}\right)} \quad , \tag{78}$$

where m is the mass of the launcher, M the Earth's mass, $r_{initial}$ and r_{final} are the radii at Earth's surface and at a LEO, respectively. Notice that Eq. (78) changes if the Equivalence Principle is violated (cf. discussion below). By setting $r_{initial} = 6400\ km$ and $r_{orbit} = 6500\ km$, we obtain a $\Delta v_g = 1.4\ km/s$. To stay in LEO, the centrigufal force has to balance the gravitational pull

$$\frac{mv^2}{r} = \frac{GMm}{r^2} \quad , \tag{79}$$

where r is the radius from the centre of the Earth to LEO. We can now express the Δv_{orbit} requirement

Mission	**Description**	**Typical** Δv [km/s]
Planetary	Deep-space robotic missions	10
Human Planetary Exploration	Fast, direct trajectory	$30-200$
$100-1,000$ $A.U.$	Interstellar precursor mission	100
$10,000$ $A.U.$	Mission to Oort Cloud	$1,000$
Slow Interstellar	4.5 $light-years$ in 40 years	$30,000$
Fast Interstellar	4.5 $light-years$ in 10 years	$120,000$

Table 2: Mission Propulsion Requirements as discussed in Ref. [176]

$$\Delta v_{orbit} = \sqrt{\frac{GM}{r}} \quad . \tag{80}$$

For a LEO with say, $r = 6500\ km$, we obtain $\Delta v_{orbit} = 7.8\ km/s$, starting from Earth's surface. Due to the Earth's rotation, $\Delta v_{initial} \simeq 0.4\ km/s$, the atmospheric drag adds another $\Delta v_{drag} = 0.1\ km/s$. The total requirement is therefore $\Delta v_{LEO} = (1.4 + 0.1 + 7.8 - 0.4)\ km/s = 8.9\ km/s$. We can now see that this requirement can be reduced by

- launching from a less massive planet,
- from a higher initial orbit to reduce the Δv_g, or
- reducing the drag by optimizing the structure.

Once in LEO, the Δv requirement for further targets such as planets is mostly influenced by the time required to reach the destination and its distance. For example, a robotic mission to Mars can last a year or more; for manned exploration, on the other hand, the trip time needs to be reduced to a few months only, which increases the Δv requirement significantly. Typical mission requirements are listed in Table 2. Of course, launching from a less massive planet, such as the Moon, or even from interplanetary space, reduces the Δv requirement as well.

The propellant mass necessary to meet the Δv requirement can be calculated using the integral of Eq. (71), the so-called Tsiolkovski equation:

$$m_p = m_0 \left[1 - \exp\left(-\frac{\Delta v}{v_p}\right)\right] \tag{81}$$

where m_p is the propellant mass and m_0 the initial spacecraft mass including structure, payload and propellant. Eq. (81) can be rewritten as

$$\Delta v = v_p \ln\left(\frac{m_0}{m}\right) \tag{82}$$

where $m = m_0 - m_p$ is the mass of the spacecraft excluding propellant.

A special case is the *laser propulsion* concept, which uses photons for propulsion purposes. The force exerted on a spacecraft by a laser beam can be calculated from

$$F = \frac{P}{c} = \frac{h\nu}{c}\kappa \tag{83}$$

where P is the laser power, h Plank's constant, ν the frequency of the laser light, c the speed of light and κ the repetition rate per second. Hence, a laser of 1 MW would produce a force of 3.3 mN per second. This mechanism converts electric energy directly into kinetic energy and does not require any onboard propellant. Devices with these features are referred to as *propellantless propulsion systems.* Tsiolkovski's equation does not apply in this case, and the specific-impulse concept is somewhat misleading in this situation. Nevertheless, due to the speed of the photons, which are the working fluid in this propulsion system, the specific impulse is 3×10^7 seconds.

7.2 Influence of Gravity Manipulation on Propulsion Systems

In the following discussion we shall consider a series of hypothetical devices capable of manipulating the inertia (influencing current propulsion systems) or generating a gravitational field (new propulsion concept using gravity control). As already discussed, no such devices are known. Nevertheless, all possible combinations (during launch and in space) are going to be analysed and their influence on propulsion systems or as a force generator discussed. As already analysed in the Section on Gravitoelectromagnetism (GEM), non-Newtonian gravitational fields can be induced from gravitomagnetic fields to generate gravitoelectric fields, and if one assumes that a device is developed to magnify these effects by about twenty orders of magnitude, the schemes discussed below would be worth a serious and concrete analysis. Here we consider two possible scenarios: a gravitoelectric field similar to that generated by a coil, or a gravitoelectric-dipolar type field. The gravitomagnetic field itself can also be used for propulsion purposes.

7.2.1 Inertial Mass Modification

Let us assume a device that can change the inertial mass of bodies in its interior, such as a launcher. If the spacecraft were to fire conventional chemical rockets or electric propulsion thrusters, how would this device affect performance ? We define an inertial mass modification factor δ and introduce it into the equations for the specific impulse and force for chemical thrusters:

$$I_{sp} = \frac{v_p}{g_0} \simeq \frac{1}{g_0}\sqrt{\frac{2\gamma}{(\gamma-1)}\frac{RT_c}{\mu_p \delta}} \propto \delta^{-1/2} \quad , \tag{84}$$

and hence

$$F = \delta \dot{m}_p v_p \propto \delta^{1/2} \quad . \tag{85}$$

We note that these are the same scaling laws previously discussed. Hence, hypothetical inertial mass modification is similar to choosing propellant with a different molar mass. These laws are similar for all other classical propulsion systems. The only advantage could be that by manipulating inertial mass, the chamber temperature T_c is really not changing. This might not be the case when choosing a lighter propellant in chemical thrusters (e.g. H_2/O_2 instead of Kerosin/O_2). If T_c is lower, the specific impulse drops as well.

How is the Δv requirement influenced ? The kinetic energy now has to be multiplied by the factor δ and one derives the modified equations:

$$\Delta v_g = \sqrt{2GM\left(\frac{1}{r_{initial}} - \frac{1}{r_{final}}\right)\frac{1}{\delta}} \propto \delta^{-1/2} \quad , \tag{86}$$

and

$$\Delta v_{orbit} = \sqrt{\frac{GM}{r}\frac{1}{\delta}} \propto \delta^{-1/2} \quad . \tag{87}$$

Hence, an inertial mass reduction would actually *increase* the Δv requirement ! For the extreme case of $\delta = 0$, the launcher would not move any more ($F = 0$) and accordingly the Δv requirement would be infinite. Thus, for $0 < \delta < 1$, thrust F would increase while the specific impulse I_{sp} would decrease (Figure 3). This is similar to using a heavier propellant, e.g. solid boosters with aluminia oxides instead of H_2/O_2 chemical thrusters.

An interesting result is that Tsiolkovski's Eq. (81) is not affected at all by a modification of the inertial mass. Indeed, to a good approximation one can neglect Δv_{drag} and $\Delta v_{initial}$, so that the total $\Delta v \propto \delta^{-1/2}$. Furthermore, since $m_p \to m_p\delta$, $m_0 \to m_0\delta$, from the scaling $v_p \to v_p\delta^{-1/2}$ one can see that all δ factors in Eq. (81) cancel out. Therefore, whatever the inertial mass modification, the amount of propellant will not be changed, or in other words the change in propulsion performance is always counterbalanced by the change in the Δv requirement !

Finally, we examine whether the trip time would be changed by an inertial mass modification. The acceleration is defined by Newtons's second law. From our scaling analysis, we conclude that

$$a = \frac{\dot{m}_p\delta}{m_p\delta}\sqrt{\frac{2\gamma}{(\gamma-1)}\frac{RT_c}{\mu_p\delta}} \propto \delta^{-1/2} \quad . \tag{88}$$

The time, τ, to reach the required velocity change is linked to the Δv requirement by the acceleration a:

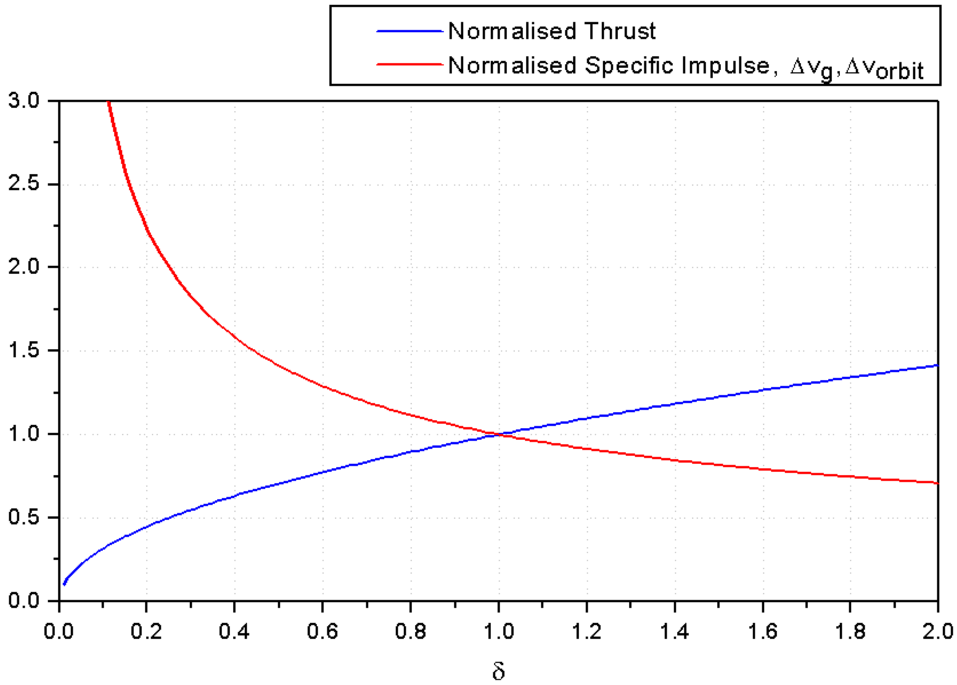

Figure 3: Influence of Inertial Mass Modification on Propulsion Performance and Δv Requirement

$$\tau = \frac{\Delta v}{a} \quad . \tag{89}$$

Since $a \propto \delta^{-1/2}$ and $\Delta v \propto \delta^{-1/2}$, both factors cancel out and we conclude that also the trajectory and time scale would not be changed at all !

We therefore conclude that a modification of the inertial mass is *not* of interest for propulsion. As we have shown, *neither trip time nor propellant mass are affected* by a change in the inertial mass.

7.2.2 Gravitational Mass Modification

We turn now to the analysis of the modification of the gravitational mass. Such modification does not influence propulsion performance (thrust, specific impulse); only parts of the Δv requirement are affected in this case. By using the gravitational mass modification factor, $\varepsilon \equiv m_g/m_i$, we obtain

$$\Delta v_g = \sqrt{2GM\varepsilon\left(\frac{1}{r_{initial}} - \frac{1}{r_{final}}\right)} \propto \varepsilon^{1/2} \quad , \tag{90}$$

and

$$\Delta v_{orbit} = \sqrt{\frac{GM}{r}\varepsilon} \propto \varepsilon^{1/2} \quad . \tag{91}$$

Neglecting as before Δv_{drag} and $\Delta v_{initial}$, we obtain, $\Delta v \propto \varepsilon^{1/2}$, approximately. The modified Tsiokovski's equation can then be written as

$$m_p = m_0\left[1 - \exp\left(-\frac{\Delta v \varepsilon^{1/2}}{v_p}\right)\right] \quad . \tag{92}$$

According to Eq. (89), the time to reach the Δv requirement would also scale as $\tau \propto \varepsilon^{1/2}$. The trajectory would then change in this case. Nevertheless, since the acceleration of the spacecraft does not change, the overall trip time would not change significantly. If the gravitational mass would be reduced, that is $\varepsilon < 1$, the Δv requirement would drop and less propellant mass would be required.

For a satellite orbiting the Earth, our modified definition of Δv_{orbit} in Eq. (91) also increases the time it takes to make a full orbit (less speed to cycle the Earth). This may not be important for launching interstellar probes, but affects for instance, remote sensing or Geostationary Orbit (GEO) satellites, which require the circling of the Earth with a certain speed for mapping and telecommunication purposes. In such cases the full Δv_{orbit} ($\epsilon = 1$) would have to be applied with no reduction, which then in turn causes an unstable orbit since the centrifugal force would be higher than the gravitational pull. To counterbalance this effect, two different strategies are possible:

1. Launch of the spacecraft with the gravitational mass manipulator (GMM) activated. Once in orbit, de-activate the GMM and apply full Δv_{orbit} using a propulsion system. The centrifugal force is then balanced by the gravitational pull.

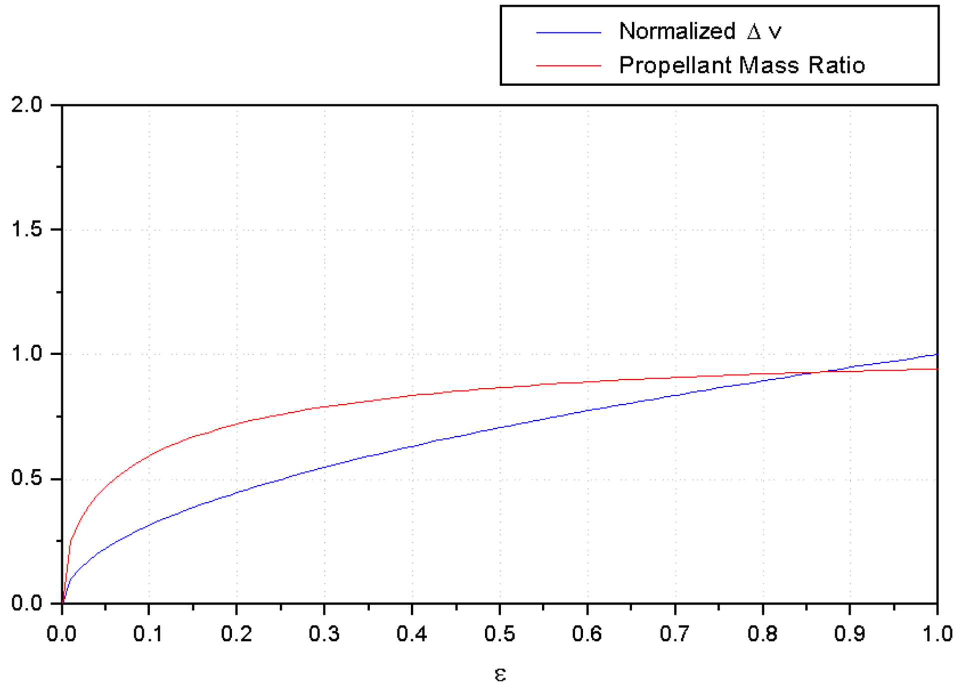

Figure 4: Influence of Gravitational Mass Manipulation on Propellant Consumption and Δv Requirement

2. GMM is always active and use propulsion system to counterbalance the higher centrifugal force to stay in orbit.

As an example we consider a scientific satellite for a planetary target ($\Delta v = 10\ km/s$) with a chemical thruster ($v_p = 3500\ m/s$). In this case we do not need a full Δv_{orbit} and our above-mentioned concerns do not apply. Figure 4 plots the Δv and propellant mass ratio (m_p/m_0) reduction as a function of ε. For a very high shielding of say $\varepsilon = 0.05$, only half of the propellant would be required. Of course, shielding very close to $\varepsilon = 0$ would reduce the propellant consumption to zero and a very direct trajectory to the target would be possible. However, as already pointed out, there is no breakthrough in terms of overall trip time.

Let us now assume the extreme case in which the gravitational mass vanishes and thus Δv_g is zero. The Δv requirement, still including the full Δv_{orbit} for typical LEO satellites, would then change from (76) to

$$\Delta v = \Delta v_{drag} + \Delta v_{orbit} - \Delta v_{initial} \quad . \tag{93}$$

Using again our 100 km LEO example from the Section on propulsion fundamentals, the case of $\Delta v_g = 0$ would reduce the total Δv requirement from the initial 8.9 km/s by 1.4 km/s, that is down to 7.5 km/s. So a launcher, although with less propellant, is still required. The higher the original Δv_g, the higher the possible reduction in the total Δv. GEO satellites with a high altitude of 42,160 km could be reduced in this case from a total Δv of about 13 km/s to 3 km/s which would require a much smaller propulsion system, drastically reducing launch costs. Only in the case where Δv_{orbit} is not important (e.g. interplanetary spacecraft), can we assume a full reduction to

$$\Delta v = \Delta v_{drag} - \Delta v_{initial} \quad . \tag{94}$$

If the spacecraft is close to the Equator, then $\Delta v_{initial} \simeq 0.4$ km/s from the spinning Earth is higher than $\Delta v_{drag} \simeq 0.1$ km/s and so it would start lifting by itself. That could lead to a completely new launch strategy and would certainly be a breakthrough.

How far are we away from such a possible breakthrough? As discussed in Section **3.1**, experimental verification of the Weak Equivalence Principle indicates that $\varepsilon = 1 \pm 5 \times 10^{-13}$ (cf. Eq. (14)). On the other hand, string theory predicts that $\varepsilon = 1 \pm 10^{-18}$ (cf. Eq. (38)). Obviously, these values do not influence propulsion at all. As previously outlined, significant deviations from $\varepsilon = 1$ are not forseen, unless, for instance, the behaviour of antiparticles in a gravitational field is substantially different from that of particles.

Even if situations exist where $\varepsilon \neq 1$ can be engineered, they would have to compete with concepts such as electric propulsion, which can already lower propellant consumption by 90% with much higher propellant velocities. There are also technologies and concepts available that can reduce the Δv requirement and trip time. One example is to reduce the gravitational potential Δv_g simply by launching from a mountain or to supply a higher initial velocity $\Delta v_{initial}$

by launching from an airplane [6]. NASA, for instance, is developing an initial acceleration rail for future spacecraft that uses superconducting magnetic levitation (MAGLIFTER) to fire the rocket engine after the spacecraft has reached a speed of 300 m/s. An extreme concept was put forward by Arthur C. Clarke [177] who proposed the building of an ultra-high tower, which he named the *space elevator,* for lifting spacecraft to orbits as high as 100 km.

7.2.3 Dipolar Gravitoelectric Field

Generation of an artificial gravitational field would imply new concepts for propulsion systems, but not a breakthrough. This field can be obtained through the interaction with an external gravitational field like Earth's. Firstly, we shall analyse the interaction of an artificially created dipolar gravitoelectric field with the Earth's gravitational field. As can be seen in Figure (5), such a field configuration could be used to generate a torque orientating the spacecraft parallel with the planet's gravitational field. In analogy with electromagnetism, we can write

$$\vec{\tau}_g = \vec{\mu}_g \times \vec{g} \quad , \tag{95}$$

where $\vec{\tau}_g$ is the torque, $\vec{\mu}_g$ the gravitoelectric dipole momentum, and $\vec{g}$ the Earth's gravitational field. Since much simpler conventional concepts are available, we shall not ellaborate on this idea. The simplest concept available is the so-called gravity boom [178], which is used in almost all small satellites. It consists of a test mass along a deployable boom attached to the spacecraft. Due to the gravitational gradient, the boom always points the satellite towards Earth. In addition to its simplicity, such a device requires no power.

7.2.4 Wire-like Gravitomagnetic Field

Through the use of a "wire-like" gravitoelectric field or a gravitomagnetic field, one could generate a gravitational analogue of the Lorentz force. This could be used as a propulsion system

[6] The Pegasus rocket from Orbital Sciences Corporation is currently being launched from a Boing 747 aircraft to reduce the Δv requirement.

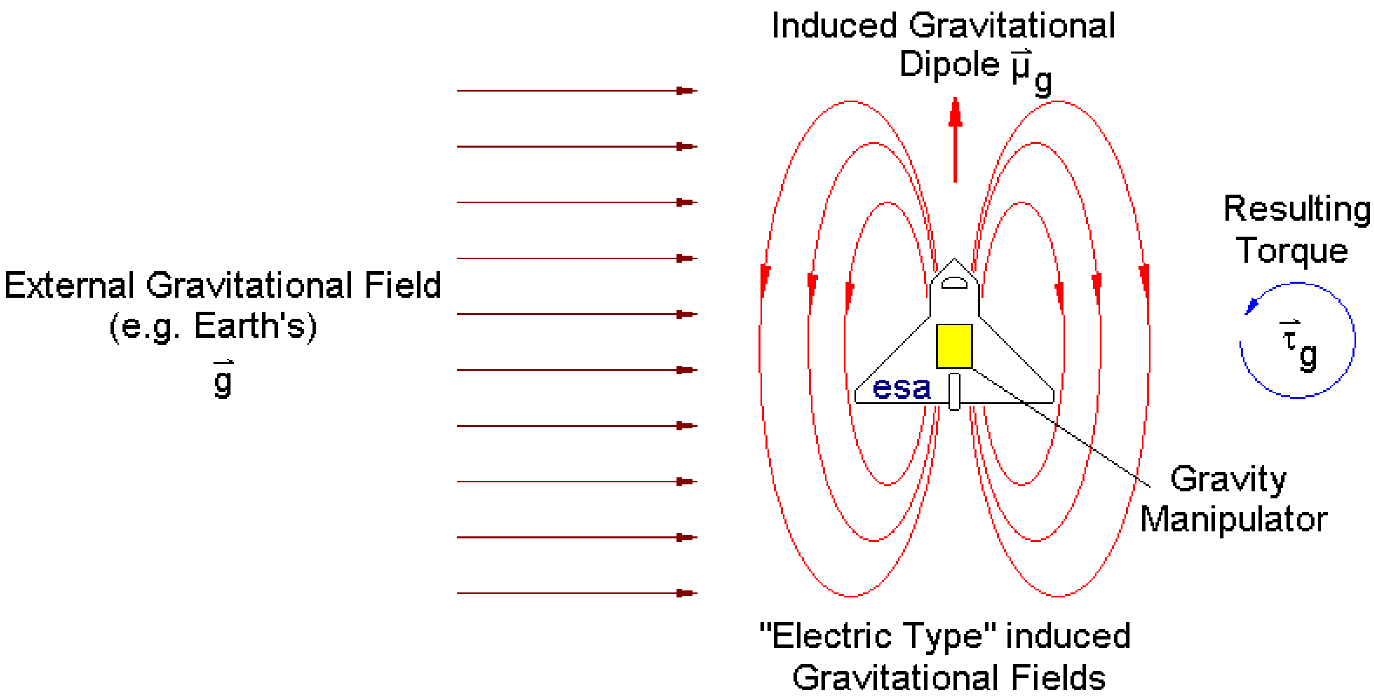

Figure 5: Dipolar Gravitoelectric Field - Propulsion System

(see Figure 6) interacting with a planet's gravitomagnetic field. By using Gravitoelectromagnetism, one can conceive of a gravitational analogue of an electrodynamic tether. The force F produced by a wire in a gravitational field can be expressed as

$$F = \frac{B_g}{c} I_m l \quad , \tag{96}$$

where B_g is the gravitomagnetic field (for Earth $B_g/c = 2GM_{\oplus}\omega/3R_{\oplus}c^2 = 3.3 \times 10^{-14}\ rad/s$), $I_m = dm/dt$ is the mass current, and l the length of the wire. For $I_m = 3000\ kg/s$ (for example by pumping liquid metal through a tube), a length of 1 km and the Earth's gravitomagnetic field, this force is equal to 0.1 μN. Comparing this unrealistic concept (huge I_m) with an electrodynamical tether used for satellites, with a typical power consumption of only 2.4 kW, a force of 0.36 N is produced in LEO. Therefore, a gravitational analogue adds no extra benefit to current tether technology.

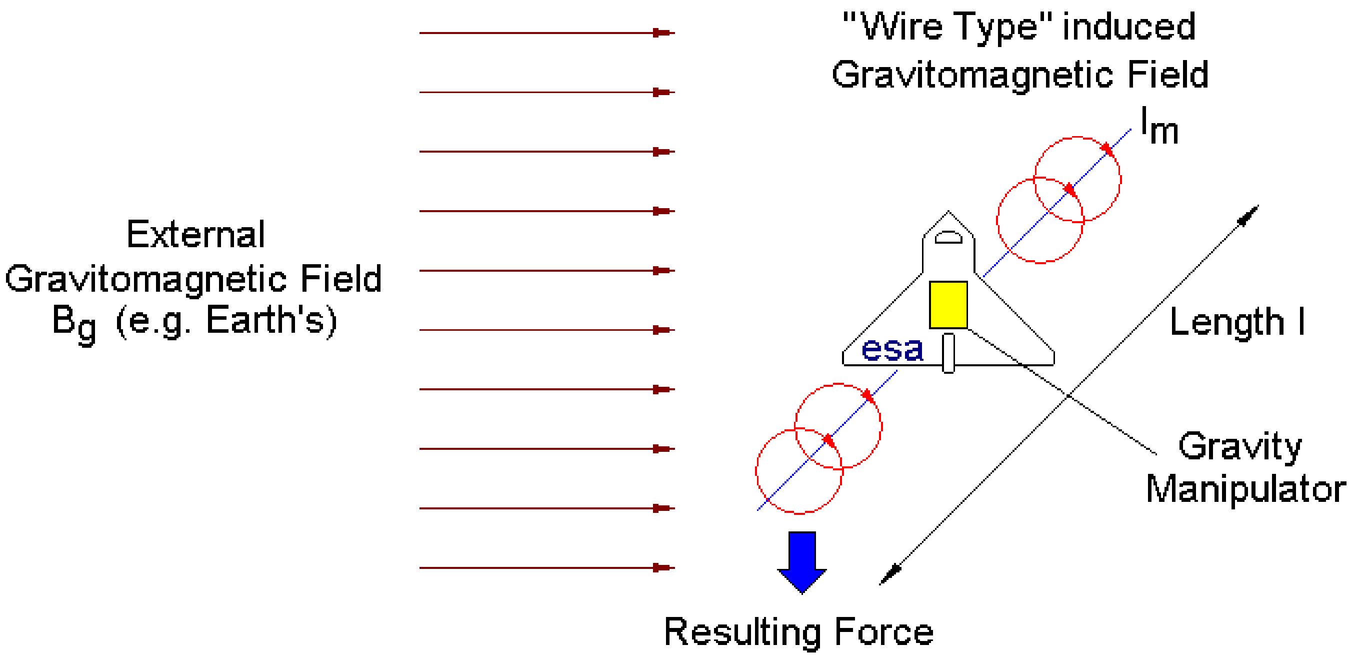

Figure 6: Wire-like Gravitoelectric Field - Propulsion System

7.2.5 Discussion

In our analysis, we have only considered propulsion devices based on the reaction principle, since we have previously rulled out exotic concepts such as negative masses, warp drive or transversable wormholes. Remarkably, our study reveals that control of gravity, even if it were achievable, does not imply a breakthrough for propulsion.

The modification of inertial mass has no influence at all, and the modification of gravitational mass would have to compete with classical launch-assist technologies such as launching from an airplane, the top of a mountain, or in an extreme case, from an ultra-high tower. The use of gravitomagnetic or gravitoelectric fields for propulsion does not bring any extra benefit compared with classical electrodynamical tethers or gravity booms.

Only for the case of GEO satellites and a complete reduction of gravitational mass is a significant breakthrough foreseen, since no propulsion system would then be required for launching under these special circumstances. A summary of our conclusions can be found in Table 3.

	F	I_{sp}	Δv	m_p/m_0	Comparison with Present Technology
Inertial Mass Modification (by Factor δ)	$\delta^{1/2}$	$\delta^{-1/2}$	$\delta^{-1/2}$	-	Has no influence at all
Gravitational Mass Modification (by Factor ε)	-	-	$\varepsilon^{1/2}$	$1-\exp\left(-\frac{\Delta v \varepsilon^{1/2}}{v_p}\right)$	• Requires very high shielding $\varepsilon \simeq 0$ • Electric Propulsion already saves up to 90% of propellant • Launch from ultra-high tower or aircraft can save Δv too
Dipolar Gravito-electric/magnetic Field	Only Torque	-	-	-	Gravity-booms are simple and require no power at all
Wire-like Gravitomagnetic Field	10^{-7} N	-	-	-	Electrodynamical tethers have much higher thrusts

Table 3: Summary of Influence on Propulsion Systems and Gravitoelectromagnetic Propulsion Systems

8 Evaluation of Existing Literature and Programmes

Control of gravity is a topic which is discussed and speculated about in a broad range of publications, including journal papers, conference proceedings and even patents. Part of this study involved developing a Database containing all important literature, as well as listing key people working in the field. A ranking methodology was set up to evaluate existing material and to guide research that we regarded as worthwhile pursuing in the future. In addition, a number of national and industrial programmes on the control of gravity, some of them in Europe, are reviewed.

8.1 Review of Existing Gravity-Control Programmes

Several exploratory research programmes have been established to look at emerging theories in physics and to test them experimentally. This Section highlights the major programmes that have been set up by agencies and industry.

European scientists and industry are well involved in this type of exploratory research. Most notably, Project Greenglow involving BAe Systems and Rolls-Royce in the UK funds Universities at about the same level as NASA does in their Breakthrough Propulsion Physics Project. The Swedish Defense Material Administration is currently also planning to launch an exploratory research programme next year, aiming to bring together European and US scientists. Starlabs of Belgium, a privately funded research centre supported by the high-tech industry, was also getting involved in gravity-control research before filing for bankrupcy after the stock market crash in summer 2001. European Internet communities (such as the Jean-Louis Naudin Labs) also actively contribute to this unconventional topic of research.

8.1.1 NASA Breakthrough Propulsion Physics Project

In 1996, NASA established the Breakthrough Propulsion Physics Project, the first of its kind, to investigate breakthroughs in space transportation with respect to

- propulsion that requires no propellant mass,
- propulsion that attains the maximum transit speeds physically possible, and
- breakthrough methods in energy production to power such devices.

This programme is part of the Advanced Space Transportation Plan (ASTP), formulating a comprehensive strategy for advancing propulsion in the next 25 years. The project started with a workshop in 1997, aiming to assess emerging theories in physics that could ultimately lead to such breakthroughs. In 1999, several research proposals were selected for initial funding following a peer-review evaluation. Out of 80 proposals, the following tasks were selected:

- An Experimental Test of a Dynamic Mach's Principle Prediction (Prof. John Cramer, University of Washington): This is an independent verification of experiments from James Woodward, indicating a unidirectional force generated by proper excitation of piezo crystals. Woodward claims that Mach's Principle (explaining that the inertial mass of any object is due to the gravitational interaction of the object with the rest mass of the Universe) is responsible for this force generation.
- The Use of Surfaces in Systems to Exploit Quantum Vacuum Energy - A Theoretical Study Using QED Coupled with an Experimental Study Using MEMs (Microelectromechanical) Devices (Dr. Jordan Maclay, Quantum Fields LLC): This research task focuses on measuring the predictions about forces generated by vacuum fluctuations (e.g. Casimir forces) in different geometries and comparing them with theory.
- Search for Effects of an Electrostatic Potential on Clocks in the Frame of Reference of a Charged Particle (Dr. Harry Ringermacher, Kronotran Enterprises): A theory has been developed introducing a torsion tensor into theories of gravity. An experiment is going to be carried out measuring a frequency spectral line shift of a proton inside a 10 kV electric field and comparing it with the prediction from the theory.
- Exploration of Gravity Modification by Josephson Junction Effects in Magnetized High-Tc Superconducting Oxides (Glen Robertson, Dr. Ron Litchford, NASA Marshall Spaceflight

Center): As part of this task, an extremely sensitive torsional gravity balance is being constructed to measure gravity modification effects by radio-frequency-pumped type-II superconductor test masses.

- Detection of Superluminal Propagation at Low or Near Resonance Frequencies and the Dynamics of the Forerunners (Dr. K. Malloy, University of New Mexico): Under special circumstances photons can travel through an inverted medium with phase, group, energy, and signal velocities all exceeding the velocity of light in vacuum. Experiments will be carried out to examine such effects.

In the previous sections of this study we have analysed the underlying physics of most of these claims and have found no evidence that they are likely to lead to any significant progress in the control of gravity. Nevertheless, this does not exclude a possible breakthrough in propulsion for reasons other than gravity control. We should stress that some of these claims can be shown to be inconsistent with well-established observational facts accounted for by known physical theories.

The Breakthrough Propulsion Physics (BPP) Project is headed by Marc Millis, after an interim period of management in the summer of 2001 by Peter Ouzt. Funding for the period 1996-2000 was 685k$ (about 770 kEuro, as of December 2001) excluding overheads. A BPP research consortium is now being established and should be in place in the first quarter of 2002. This research consortium will make collaboration with universities and industry easier and provide the administrative functions needed to manage the large number of geographically dispersed BPP research participants. The consortium will have an advisory council to facilitate member participation, conduct surveys, solicitations, and prioritization of candidate research, and maintain an electronic database of research proposals and results. The Ohio Aerospace Institute (OAI) will administer the consortium. Its next call for research proposals will be issued after the first quarter of 2002. The consortium will issue formal research solicitations every other year thereafter.

8.1.2 BAe Systems Project Greenglow

In 1997, Project Greenglow was established by BAe Systems in the UK as a response to the NASA Breakthrough Propulsion Physics initiative. Headed by Dr. Ron Evans from BAe Systems, it is a speculative research programme aiming to investigate propellentless propulsion and anomalous gravitational effects. All experimental research is being carried out at UK Universities. Rolls-Royce is member of the industrial team providing additional funding. The funding level for this year is about £100.000 (about 160 kEuro, in December 2001). Greenglow's main research activities are as the follows:

- Gravitational Theory (Prof. Robin Tucker, Lancaster University)
- Podkletnov Experiment - Superconductor Coupling of Gravity (Dr. Clive Woods, Sheffield University)
- Microwave Thrust Generation (Prof. Paul Smith, Dundee University)
- Casimir Force Experiment (Dr. Clive Speake, Birmingham University)
- Goals & Metrics (Prof. Colin McInnes, Glasgow University)
- "What-if" Design Study (Prof. John Allen, Kingston University)

8.1.3 DoE Breakthrough Energy Physics Research Programme

Within the US Department of Energy (DoE), the Breakthrough Energy Physics Research Programme (BEPR) was established as a joint exploratory research effort, managed by the Office of Advanced Energy Concepts. The BEPR Programme aims to research, develop, and validate emerging theories, new ideas, and anomalous effects that can lead to breakthroughs in energy and transportation. Specific goals are to develop:

- efficient and/or massive energy storage systems,
- energy-conversion mechanisms with extremly high conversion efficiencies,

- propulsion mechanisms that significantly improve transportation efficiency,
- integrated power conditioning, management, and control systems that improve energy and transportation.

The final draft of the programme definition is currently under review by DoE senior management, and funding is not expected to be available before October 2002.

8.1.4 US Air Force

Since the 1970s, the Air Force has been sponsoring speculative research, also in the area of propulsion relevant to the topic of gravity control. Dr. Franklin Mead from the propulsion directorate has been in charge of most of the studies, including survey and experimental work (e.g. on possible new coupling phenomena). His interest has recently shifted to "classical" laser propulsion.

The United States Air Force Academy, under the direction of Dr. Timothy Lawrence, is currently supporting the NASA Breakthrough Propulsion Physics Program in an advisory role. They intend to perform independent analysis and experiments of other concepts supported within the programme. Their goal is to achieve experimental results that are state of the art, in for instance, the measurement of thrusts at the microNewton level with acceptable error bars, which is the current standard for electric propulsion.

More recent efforts are focused on investigating the Heavyside magnetic stress tensor force.

8.1.5 Internet Communities

In addition, many privately funded programmes have been established, and information about their experimental activities and "theories" is available over the Internet. The major problem is the great lack of scientific credibility (e.g. no peer review), extraordinary claims (e.g. reactionless propulsion, deviation from Newton's laws, etc.). However, they do contain a great pool of ideas and material which, after careful study, could be worthy of investigation. Examples of these research organizations include:

- The Gravity Society (http://www.gravity.org): Collects mainly material on how superconductivity could be used to control gravity,
- Quantum Cavorite (http://www.inetarena.com/∼noetic/pls/gravity. html):

  Reviews experiments and theories largely dealing with superconductivity and gravity, as well as transient mass shifts claimed by Prof. James Woodward as due to Mach's Principle,
- Jean-Louis Naudin Labs (http://jnaudin.free.fr): Wealth of experimental data on home-built devices claiming extraordinary performance.

Our study reveals, however, that the vast majority of the ideas being pursued lack a serious scientific background and contradict well-established experimental facts in gravitational physics, condensed matter and quantum field theory.

8.2 Database and Ranking Criteria Definition

In this study a Database was developed (in Microsoft ACCESS 2000) containing important papers in the area of gravity-controlled spacecraft propulsion and relevant related literature. The papers were scanned and are available in Adobe PDF format on a CD together with the Database programme. In order to judge the papers' credibility, a ranking criterion was defined, and additional comments are also included in the Database.

Since the material gathered contains both papers that are very focused on the topic as well as references on broader related issues, the final ranking is based on a combination of two criteria, one scientific and one expressing relevance for the study.

8.2.1 Scientific Criteria

To indicate the scientific credibility of a paper, a number from 0 - 5 has been assigned, where 5 is the highest rank and 0 the lowest. Consensual and universally accepted judging parameters are used to set the ranking:

- Quality of publishing: Peer-reviewed papers in world-recognized journals with high impact get a higher mark than conference publications. Preprints are considered higher quality (due to constant observation by the scientific community) than patents which do not have to prove the correctness of their concept.
- Correctness: A paper that is based on clearly wrong assumptions, wrong derivations or mistakes in their calculations receive the lowest marking.
- Originality: Papers advancing present knowledge of physics or presenting important experimental observations are considered more important than papers showing simple relations or not containing any novel concepts or ideas.

Examples:

0 ... Patent based on wrong assumption.

1 ... Conference/preprint paper containing a wrong derivation, but the idea can in principle be developed further.

2 ... Conference paper speculating on new theoretical developments, with some potential in principle.

3 ... Peer-reviewed paper in a recognized journal reporting an experimental observation of a new gravity coupling phenomenon which has not been independently verified.

4 ... Peer-reviewed paper showing important relations and bounds but does not add new material to the subject.

5 ... Peer-reviewed paper reporting a high order of magnitude effect on generating non-Newtonian gravitational fields, or showing experimental deviations from classical predictions.

8.2.2 Relevance for Study Criteria

This parameter links the scientific quality of the paper to the topic of this study, namely the control of gravity, by adding a ranking from A to E after the scientific ranking:

A ... Not relevant, e.g. papers that do not deal with the gravity control subject in particular.

B ... Relevant only to a very limited extent.

C ... Relevant in principle, but completely out of reach in the near future.

D ... Relevant in principle, but too small to be utilised with present technology.

E ... Very relevant and possibly exploitable.

The Annex to this report contains more detailed information about the content of the Database, as well as the necessary instructions for its use.

8.3 Identification of the Most Promising Topics for Future Research

Even though our analysis of the existing proposals on the control and manipulation of gravity reveals that none of the claims are convincing, and furthermore that, even if they were they would bring just a modest gain in terms of the launching of spacecraft and no general breakthrough for propulsion, we have nevertheless identified at least three subjects that, in our opinion, deserve further theoretical and experimental investigation. They are:

- Possible violations of the Weak Equivalence Principle related to corrections to General Relativity or Newtonian gravity due to String/M-Theory, large extra-dimensions or unknown effects associated with the coupling of gravity to antiparticles and charged particles. As discussed in this report, forthcoming ESA, ESA/CNES and ESA/NASA missions such as MICROSCOPE, STEP and HYPER will play a crucial role in the clarification of these issues. Laboratory tests are, of course, of fundamental importance also. An experiment involving the gravitational behaviour of antiparticles contained in a specially built Penning-trap located on the Space Station is, in our opinion, also highly desirable.

- Possible new interactions of Nature may exist in connection with String/M-Theory, large extra-dimensions and other proposals for the unification of the known fundamental interactions of Nature. It is particularly relevant in this respect that the observed anomalous acceleration apparently acting on the Pioneer 10/11, Galileo and Ulysses spacecraft can be explained in terms of a new interaction of Nature. The ESA/ISAS BepiColombo mission to planet Mercury can most probably provide some relevant insight into this topic.

- Gravitational anomalies claimed to be observed in quantum materials, although controversial and theoretically puzzling, should be further investigated so as to definitively settle the matter. As discussed in this report, gravitoelectromagnetic fields generated in mundane situations are tiny and their use, even for manoeuvring spacecraft under microgravity conditions, is still elusive.

Part II

Implementation of Future Activities:

A Set of Recommendations

9 Recommendation Guidelines

Research on the control of gravity has always been regarded as esoteric and speculative. Proposals to control gravity are most often elusive and invariably covered by an aura of controversy. It has been the purpose of this study to lay down the scientific basis of current knowledge on gravity and to survey its various branches in terms of the most advanced research in experimental and theoretical physics so as to critically assess the existing literature on the control of gravity. People working in space-related research and technology tend to treat gravity as an outside condition that is lost in outer space and can be used to boost satellite orbits and trajectories, but is not really understood in its most fundamental aspects. We hope that this study, however limited, may help in a modest way to change this state of affairs. Even though the main focus of this study has been to examine mechanisms for "switching-off" and manipulating gravity, the complexity of the subject has led us to embark necessarily on a study of the basics of this fundamental interaction of Nature. The next Section is a summary of our findings regarding the scientific foundations of this study, but it is important to realise from the beginning that whatever scheme to control gravity may exist in the future, if any at all, it will necessarily involve rather complex and as yet unknown physics. Therefore, our study turned quite naturally into a fundamental physics study and it became evident that our task was to search for the unknown aspects of the fundamental theories of physics and push the experimental cornerstones of General Relativity and its quantum generalizations to the limit. Furthermore, we have also considered propulsion in the framework of a hypothetical change in the main features of gravity, as well as the implications of some gravitoelectromagnetic effects encountered in the first-order approximation of General Relativity.

In the next Sections our recommendations for the implementation of future activities addressing the underlying physics of any possible development towards the goal of controlling gravity are presented and discussed. The aim is to cover the three research topics identified in the first part of this study, namely the search for violations of the Weak Equivalence Principle for antiparticles and charged particles, the search for a possible fundamental new interaction of Nature, and the study in the laboratory of possible gravitational anomalies in quantum materials. Before presenting these recommendations, however, we will summarize our conclusions regarding the scientific foundations of our study.

10 Highlights of the Scientific Foundations of the Study

10.1 Summary

In the first part of our study on the control of gravity we have laid down the scientific foundations that would have to be taken into account in future research activities on the subject. We have pointed out that any scheme to alter the strength of the gravitational coupling to matter or lead, through the intervention of other forces, to a change in the local gravity force would have to fulfil at least one of the following conditions:

(1) Altering the strength of the gravitational coupling to matter due to the existence of a new fundamental interaction of Nature implying violations of the Weak Equivalence Principle.

(2) Existence of net forces due to the interplay between gravity and electrostatic forces in shielded experimental configurations, as found in the well-known Schiff-Barnhill effect.

(3) Analogous effect for magnetic fields in quantum materials involving the gravitomagnetic field.

(4) Physically altering the vacuum properties so as to change the relative strength of known fundamental interactions.

Aiming to critically assess existing proposals and to consider lines of research that could lead to the identification of as yet unknown phenomena we have then surveyed the following topics:

- General Relativity
- Einstein Equivalence Principle
    - Weak Equivalence Principle
    - Local Lorentz Invariance
    - Local Position Invariance
- New Interactions of Nature

- String/M-Theory
- Gravitoelectromagnetism and Quantum Materials
- "Vacuum Engineering"
- Gravity-Controlled Propulsion.

From our survey, we have drawn a set of critical conclusions:

- Schemes involving heterodox concepts such as *negative masses*, *negative energy densities*, *Mach's principle, warp drive*, etc. defy well-tested conventional physical wisdom and cannot be seriously considered.
- Gravitational anomalies related to shielding effects (usually claimed to be observed during total eclipses), reduction of weight due to rotation of quantum materials and amplification of gravitomagnetic fields are almost entirely ruled out. Anomalous effects that have not been examined or reproduced so far will be discussed below.
- The Weak Equivalence Principle holds with great accuracy and expected violations, such as the one emerging from string theory, are far too small to lead to any workable scheme to control gravity. The same can be said about Lorentz and CPT symmetries. Violations due to as yet unknown fundamental interactions of Nature will be discussed below.
- Local Position Invariance is rather poorly established in comparison to the Weak Equivalence Principle and Local Lorentz Invariance. Clock experiments in space are the most promising way to further improve the level of accuracy of this fundamental symmetry. We shall discuss this issue later.
- Schemes to alter vacuum properties and the relative strength of the known fundamental interactions of Nature are beyond current theoretical knowledge and out of reach with foreseeable technological developments.

- Regarding propulsion, we have used the *redutio per absurdum* method to show that if gravity could be modified then the following conclusions would ensue:

  (1) If modification of gravity were through any scheme that would diminish the inertial mass of a spacecraft, then thrust would be lost as the propellant mass would be diminished as well.

  (2) If modification of gravity were through a scheme that would affect the gravitational mass, then some gain would be achieved even though it would be rather modest as gravity is just one of the components of the so-called Δv requirement to reach orbit. However, one could certainly envisage a change in the philosophy for reaching space as a vanishing gravitational mass could drastically reduce launcher requirements.

  (3) Dipolar gravitoelectric field or wire-like gravitomagnetic field-assisted propulsion schemes lead to irrelevant thrust *vis-a-vis* to conventional devices such as deployable booms or electrodynamical tethers.

  (4) Control of gravity would bring a somewhat modest gain in terms of launching of spacecraft and no breakthrough for propulsion.

  (5) The topic of gravity control should *not* be pursued with respect to propulsion applications, *but* rather within the realm of fundamental-physics programmes and microgravity applications.

  Despite the fact that our set of conclusions is rather negative in terms of existing proposals regarding the control and manipulation of gravity, we have nevertheless identified at least three issues that we believe deserve further theoretical and experimental investigation, and these are discussed in the following subsection.

10.2 Promising Topics for Future Research

- In searching for violations of the Weak Equivalence Principle, dedicated experiments for examining unknown effects associated with the coupling of gravity to antiparticles and charged particles should be urgently considered. This research would be complementary to forthcoming ESA, ESA/CNES and ESA/NASA missions such as MICROSCOPE, STEP and HYPER. Laboratory experiments to test the gravitational behaviour of antiparticles contained in a specially built Penning-trap are thus crucial. Repetition of these experiments at the International Space Station (the WEAX proposal discussed below) is also equally important and can bring important advances. Clock-comparison experiments using the International Space Station as a base are also of great relevance.

- Possible new interactions of Nature may exist in connection with String/M-Theory, large extra-dimensions and other proposals for the unification of the known fundamental interactions of Nature. As described in the scientific foundations of this study, the parameters describing a possible new interaction are its strength, α, and its range, λ. The windows of opportunity correspond to the regions in this two-dimensional space that are not yet excluded by experiments. As already discussed, they correspond to $\lambda \lesssim 10^{-3}\ m$ and $\lambda \gtrsim 10^{13}\ m$, regions where α is still essentially unconstrained. We shall discuss a possible ground experiment to examine the sub-millimetre range and emphasise the fundamental role that ESA can play in a programme to study the long-range region. It should be recalled in this respect that the particularly relevant observation that the detected anomalous acceleration acting on the Pioneer 10/11, Galileo and Ulysses spacecraft can be explained in terms of a new interaction of Nature. It is also of particular importance that missions in progress and under development by ESA in collaboration with other space agencies are considered also for their relevance in the search for a new possible fundamental interaction of Nature. The current ESA/NASA Cassini-Huygens and the future ESA/ISAS BepiColombo mission to the planet Mercury could provide important information in this context. Further examination of conventional explanations for the observed anomalies should be carried out, especially in terms of modelling the electrical power generation and thermal dissipation histories of the spacecraft involved.

- Gravitational anomalies claimed to be observed in quantum materials, although controversial and theoretically surprising, should be investigated, even though the gravitoelectromagnetic fields generated in known schemes are tiny and their use for manoeuvering of spacecraft under microgravity conditions is still elusive.

In the next section we will discuss these fundamental questions and lay down a set of recommendations for future research activities, as well as suggesting a hierarchy of priorities.

11 Recommendations for Missions in Progress and Under Development

The current ESA Fundamental Physics and Microgravity Programmes represent an impressive effort to tackle a number of issues in contemporary physics and provide an extremely fertile proving ground for various points associated with the scientific foundations of our study. These include ESA, ESA/CNES, ESA/ISAS and ESA/NASA missions in progress and under development such as *Cassini/Huygens*, *SOHO*, *Rosetta*, *MICROSCOPE, STEP, HYPER*, *LISA*, *BepiColombo* and the *International Space Station.*

11.1 Galileo and Ulysses

Reported anomalies in the radiometric data from the Pioneer 10/11, Galileo and Ulysses spacecraft seem to be associated with an unexpected constant acceleration towards the Sun of about $a_P = 8.5 \times 10^{-8}\ cm\ s^{-2}$ acting on the spacecraft [86, 87]. Conventional explanations for this anomalous acceleration include gas leaks from the thrusters or non-isotropic heat radiation [88, 89]. However, these explanations have been seriously criticized [87]. A new fundamental interaction with strength $\alpha = -1 \times 10^{-3}$ and range $\lambda = 200\ A.U. = 3.98 \times 10^{13}\ m$ could account for the anomaly [86, 87]. This is a quite exciting possibility, but the issue will not be settled before several questions have been carefully studied for all of these missions [86, 87]. These issues include the dynamics of the solar radiation pressure on the spacecraft, the history of electrical power generation and dissipation on the spacecraft, louver dissipation, etc. In the case of Galileo [180] in its Earth-Jupiter orbit, it is claimed that it was impossible to separate the effects of solar radiation from an anomalous acceleration [86]. In the case of Ulysses [181], analysis of the radiation pressure on its out-of-the-ecliptic journey, from 5.4 $A.U.$ near Jupiter in February 1992 to the perihelium at 1.3 $A.U.$ in February 1995, indicated it varied with distance. Orbit solution required periodic updating of solar radiation pressure and the inferred solar constant is about 40% larger at the perihelium than at Jupiter, which is inconsistent. This led Anderson et al. [86] to conclude that Ulysses was subject to an unmodelled acceleration towards the Sun of $(12 \pm 3) \times 10^{-8}\ cm\ s^{-2}$. On the basis of these facts we suggest that:

- A re-analysis of the available telemetric and radiometric data from these missions and further study possible unaccounted effects such as solar radiation pressure, ageing of the spacecraft, and so on be carried out.

We estimate that 1 man-year is required to carry out this task, and the costs associated with the data processing.

We will now turn our attention to the various missions in progress and in prospect so as to clarify their role in the development of a strategy for systematically examining the possible existence of a new long range force of Nature or new gravitational physics.

11.2 Missions in Progress

11.2.1 SOHO

SOHO [182], was designed for the observation of the Sun and is stationed $1.5 \times 10^{6}\ km$ away from Earth on its sunward side. It was launched in 1995 and was meant to operate until 1998, but, given its success, its lifetime has been prolonged till 2003. Being situated at about 1 $A.U.$, it is not particularly interesting in terms of the search for a new interaction since, as previously discussed, LAGEOS missions[7] have set quite stringent limits on the strength of any new interaction at this range, namely, $\alpha \lesssim 10^{-7}$ (cf. Section 4.1 on the scientific foundations of this study).

11.2.2 Cassini-Huygens

The Cassini-Huygens [185] mission aims to fully explore the Saturnian system, including atmosfere, rings magnetosphere, and a large number of its moons, namely Titan and the icy satellites.

[7] At the time of writing, a discussion has appeared in the literature on the impact of the planned LAGEOS III - LARES mission [183] for the detection of the gravitomagnetic Lense - Thirring drag of inertial frames (see Section 6 of the scientific foundations of this study) [184].

A relevant aspect of the Cassini-Huygens mission is the study of the interaction between the various elements of the Saturnian system.

The Cassini-Huygens spacecraft was launched on 15 October 1997 and has performed flybys of Venus (1998 and 1999), Earth (August 1999) and Jupiter (December 2000) [186] and is expected to reach Saturn on 1 July 2004 and Titan in November 2004. By then its heliocentric distance will be about 9.5 *A.U.* The effect of a putative new force will be about 90 times stronger than the one felt by SOHO.

Our set of recommendations for these missions in progress is then as follows:

- Perform detailed analyses of the available tracking data, specially for the Cassini-Huygens mission.
- Thermal behaviours of the spacecraft should be compared with what is expected from the available thermal models.
- Power production and consumption histories should be carefully studied to check whether anomalies due to unknown effects are present.

11.3 Missions under Development

11.3.1 Rosetta

ESA's international Rosetta mission [187] has a goal of *rendezvous*ing with comet 46 P/Wirtanen through an eight-year journey until its final destination at a heliocentric distance of about 3.25 *A.U.* Rosetta will be launched in January 2003 by an Ariane-5 from Kourou in French Guiana. In order to reach its destination, orbital energy will be derived via one Mars and two Earth gravity assists. Manoeuvering of this nature will be also required in a proposed dedicated mission like Sputnik-5, which is going to be discussed later. Even though the effect of a new force of Nature at that heliocentric distance will give origin to a 2.6×10^{-6} effect when compared with Newtonian gravity, considering the parameters suggested by Anderson and collaborators

[86], it should be recalled that the Rosetta mission is expected to last for two successive years and in its fartherst distance from the Sun it will be at 5.5 $A.U.$.

11.3.2 BepiColombo

A particularly relevant opportunity to further investigate the intriguing small acceleration, $8.5 \times 10^{-8}\ cm\ s^{-2}$, towards the Sun is provided by the BepiColombo mission [90]. Given the expected high degree of control over its tracking and its ability to measure the Sun's oblatness and the Post-Newtonian parameters, γ, β, and the combination, $\eta \equiv 2 - \beta + 2\gamma$, with great accuracy, this mission could shed some light on this fundamental question.

For achieving this goal our recommendations for the missions under development are the following:

- Analysis and simulation of the spacecraft's trajectory should be carried out with the highest possible accuracy from launch to final destination.
- Means for monitoring power production and consumption should be installed and carefully modelled. The spacecraft should be equipped with a set of thermal detectors at sensitive spots, specially by the solar panels.

11.3.3 LISA

Even though the LISA (Laser Interferometer Space Antenna) mission [133] has been designed for totally different purposes, the suggestion by Scheffer [89] of using the three spacecraft of the LISA system to study the Pioneer 10/11 anomaly is rather intriguing. One could in principle dismiss this claim as the LISA system will be bound in an interior elliptic orbit at about 1 $A.U.$, whereas the Pioneers are in unbound hyperbolic orbits 20 $A.U.$ away. However, the instrumentation that will be available at the LISA system will be so accurate in terms of relative positioning and laser focusing that the suggestion should, in our opinion, be carefully considered.

11.4 Dedicated Mission "Sputnik-5"

In our opinion, the importance of establishing the existence of a long new fundamental interaction of Nature does justify a dedicated mission. Given its similarities with previous soviet Sputnik missions, and the purpose of looking for signatures for a fifth force of Nature, we suggest calling this mission Sputnik-5.

Given the time constraint and the resources available for this study, we can only outline the main aspects of such as a dedicated mission. We would like to stress, however, that besides its intrinsic scientific value, a Sputnik-5 type-mission is consistent, in many respects, with various ESA strategic objectives for the near future, including:

- Fundamental physics is the area with the smallest budget in the ESA Scientific Programme compared to the two other main areas of Solar System Exploration and Astronomy. Sputnik-5 can be regarded as a modest mission and its cost would fit within the financial constraints.
- Given that the core of the Sputnik-5 mission involves tracking it during as long an operational lifetime as possible, an independent and fully operational European deep-space tracking capability would be highly beneficial for the mission. Elements of this system are already taking shape with the antennas in Spain and near Perth in Western Australia that will be soon operational. A third element of this system, namely a 64 m radio antenna in Sardinia, is expected to be operational in 2005-2006.

In addition, there is presently no European fundamental physics mission in space.

The Sputnik-5 spacecraft would ideally be spherically shaped or at least highly symmetrical. The main purpose of the mission consists of acquiring accurate tracking data and monitoring its performance in energy terms to exclude any intrinsic and known Solar System scale astronomical effects on its trajectory. Any observed anomaly in its trajectory could then be directly attributed to a new force. Our previous discussions of the missions in progress and under development illustrated the importance of the thermal behaviour of the spacecraft in allowing any observed anomaly to be attributed to a single external cause. Sputnik-5 must therefore have a simple design and be conceived to allow knowledge of its thermal state at any time, a requirement that is often absent in current space missions. Geometrical simplicity implies that the spacecraft will on average be equally exposed to external conditions. The spacecraft also requires good reflective features to still allow its tracking, when onboard power supplies are exhausted. Sputnik-5 would be ideally a very long duration mission and hence its energy sources should be intrinsic and compact. Nuclear powered batteries are the most obvious choice, but launch restrictions and cost may rule out this option.

Data for a scenario for a rather modest mission have been obtained from a simulation performed by Robin Biesbroek from Jaqar - Space Engineering [191]. The main requirement was to achieve an elliptic heliocentric orbit with the highest possible aphelion at a relatively low cost. After excluding the low-cost Rockot launcher, which is unable to reach heliocentric orbits and the more expensive Ariane-5 launcher, one is led to consider a Soyuz-Fregat launch. The highest possible aphelion one can achieve with this launcher is about 3 $A.U.$, with an aphelion velocity, $v_{inf} = 6.8\ km/s$, with a satellite of 300 kg in a period of 1061 days. The orbit can be extended by the use of gravity assists. Two gravity assists (GAs) could take the spacecraft out to 5.2 $A.U.$, i.e. close to Jupiter (see Figure 7). The main features of this mission would be the following:

Launch: 2 October 2007: with a Soyuz-Fregat launcher of a launch mass of 442 kg.

First Mars GA: 6 February 2008: Powered GA ($\Delta v = 7308\ m/s$). Aphelion raised to 3.7 $A.U.$ (1:2 resonant orbit with Mars).

Second Mars GA: 24 November, 2011: Unpowered GA. Aphelion raised to 5.2 $A.U.$ (1:3 resonant orbit with Mars and next arrival at 4 August, 2017).

Satellite dry mass: 350 kg for $I_{sp} = 317\ s$ (using onboard chemical thrusters).

A lower cost alternative might be the Russian Dneps launcher with attached VARYAG upper-stage, whose performance is slightly lower than that of Soyuz.

To go beyond 5 $A.U.$ a large launcher such as a Proton or Ariane-5, or perhaps the Indian GSLV, would be required for a straightforward mission. A complex mission design like that of Cassini-Huygens would allow a much higher aphelion to be reached, but this would imply greater technical complexity. Besides the positioning, orbit control and communication systems, nuclear batteries seem to be an inevitable choice for powering the spacecraft. It should be stressed that a mission reaching the highest possible aphelion is most relevant in terms of achieving the proposed scientific goal of measuring an acceleration towards the Sun as detected by the Galileo, Ulysses and Pioneer 10/11 spacecraft.

11.5 STEP and MICROSCOPE

Ground experiments to verify the Weak Equivalence Principle are limited by the unavoidable microseismic activity of Earth. Space experiments offer the possibility of improving the precision of current tests by a factor of 10^6.

The ambitious ESA/NASA STEP (Satellite Test of the Equivalence Principle) mission [188] carrying four pairs of test masses accommodated in a superfluid He-dewar at 2 K should allow testing the Weak Equivalence Principle to 1 part in 10^{18} using SQUID sensors to measure differential displacements between the pair of test masses. In this respect a good strategy,in our opinion, would be to consider:

- Pairs of masses of different compositions so also to test possible composition-dependent couplings of the test masses to a new interaction and/or effect.
- The same considerations apply to the MICROSCOPE (MICROSatellite a traine Compensee pour l'Observation du Principe d'Equivalence) mission [189].

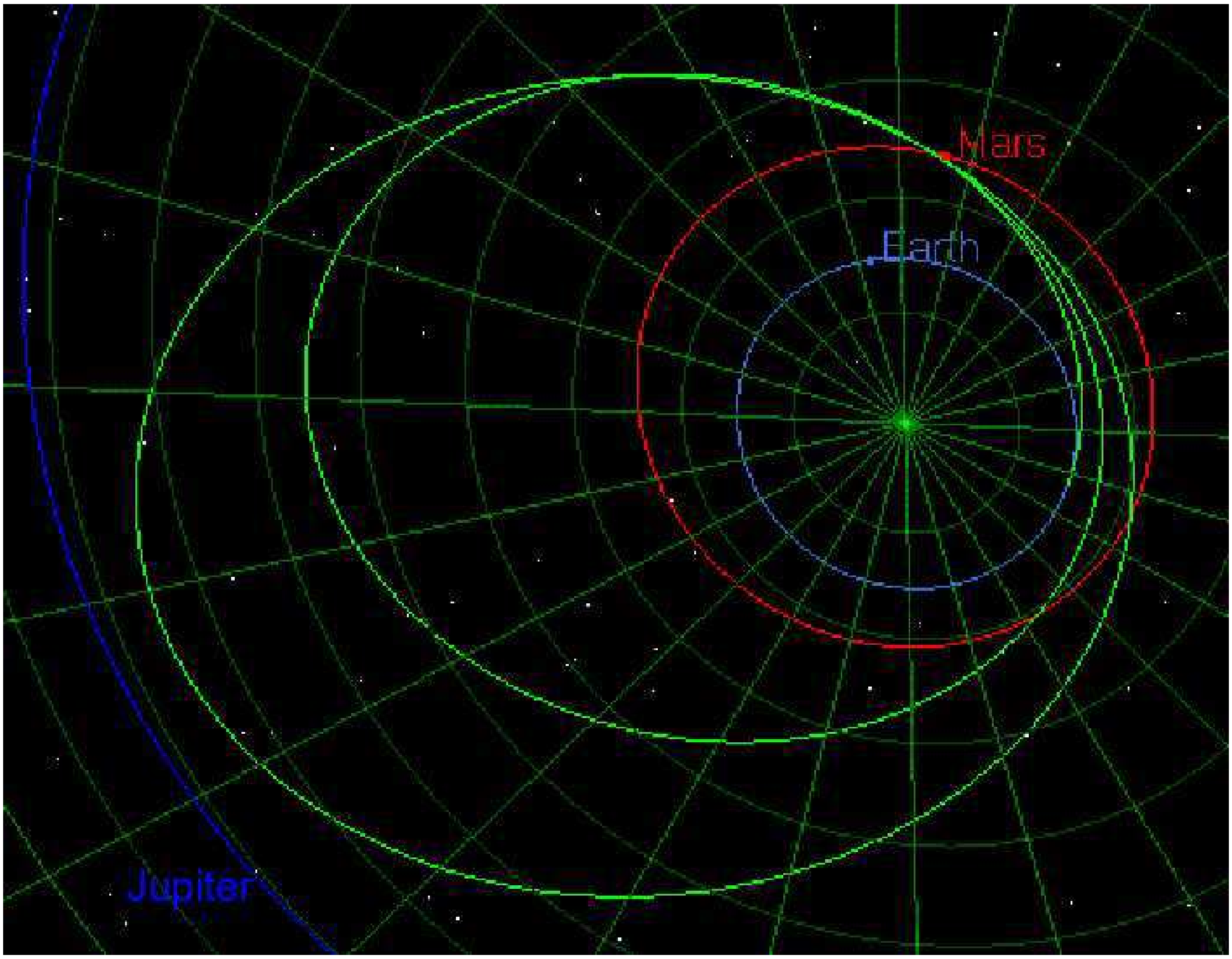

Figure 7: Example of a Trajectory Simulation.

11.6 International Space Station

11.6.1 Weak Equivalence Antimatter eXperiment (WEAX)

The International Space Station (ISS) will be equipped with a cryogenic vacuum facility that would be suitable for comparing the free fall of protons and antiprotons [33]. The idea involves the confinement of antiprotons for a few weeks in a Penning trap in a geometric configuration where the effect of gravity would manisfest itself through a perturbation on the motion of the antiprotons. The expected precision of the experiment is 1 part in 10^6. Given that this would correspond to a three orders of magnitude improvement compared with a ground measurement, the experiment should, in our opinion, have high priority.

Giving its importance for a multitude of applications in advanced experimental physics, we will briefly describe the main features of a Penning trap. This device allows the storage of charged particles (ions) through the superposition of a magnetic field and a static electric field. The magnetic field prevents the charged particles from escaping perpendicularly to the applied magnetic field lines, as ions travel on cyclotron-like orbits. Confinement in the direction of the magnetic field is achieved via an electrostatic potential between electrodes. The resulting ion motion can be described by three uncoupled harmonic oscillations (reduced cyclotron, axial, and magnetron oscillation). The magnetic field is produced by a superconducting magnet, while the electric field is produced by a set of cylindrical electrodes.

In order to store positive ions, the potential difference, U, has to be negative. The voltage U is tuned so that an harmonic potential is obtained. Figure (8) is a sketch of the Penning trap as shown in Ref. [190]. The traps can be optimized for different purposes. For instance, they can be equipped with a nickel ring, which produces an inhomogeneity in the magnetic field to enable the detection of spin-flips of the electron (respectively, the ion). In another type of trap, the magnetic field is left homogeneous, which guaranties narrow linewidths of the Larmor and cyclotron resonances.

There is quite a rich literature and considerable experimental knowledge regarding the construction of this device; descriptions and information can be found at:

http://google.yahoo.com/bin/query?p=penning+trap

It should be stressed that the ATHENA group [192, 193] at CERN (see below) has successsfully captured about a million antiprotons in a large-scale Penning trap at the already closed LEAR (Low Energy Antiproton Ring) facility at CERN in 1996 [194]. Furthermore, about 65% of the the captured antiprotons have subsequently been electron cooled to energies below 1 eV and stored for about an hour. At this energy, the annihilation rate is dramatically reduced and the antiprotons could be observed in an ultrahigh vacuum environment.

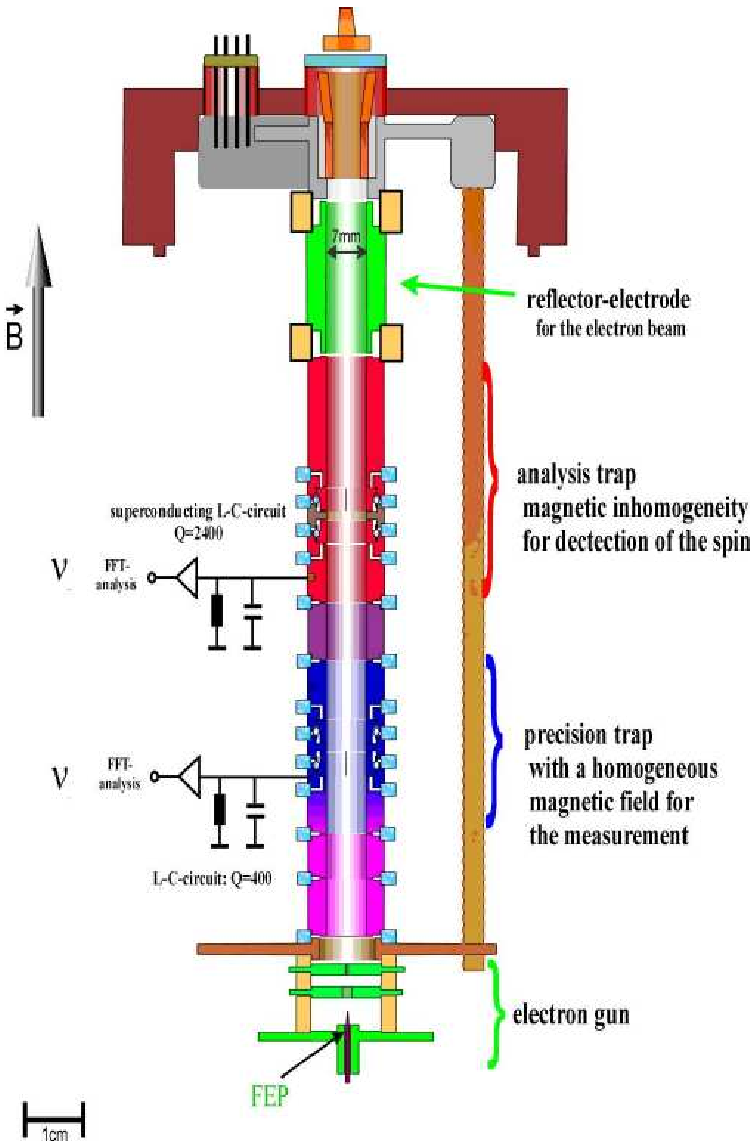

Figure 8: Scheme of a Penning trap device as described in Ref. [190]

We regard an experiment along the lines of WEAX as particularly relevant as it will allow several key experimental concepts to be put to the test, as well as allowing the ultimate goal of establishing to what extent the Weak Equivalence Principle holds for antiparticles to be achieved. In our view, therefore, the following tasks should be carried out in the future:

- It is yet to be proven that it is possible to successfully deploy highly sensitive experimental devices such as dedicated Penning traps in a working environment in space [8]. Hence this

[8]The mass spectrometer AMS (Alpha Spectrometer in Space) [195] was the first large and highly sensitive

step has to be planned and seriously considered.

- It is crucial that the ISS be equipped with a rich ensemble of scientific instruments to exploit its multi-purpose scientific nature.

11.6.2 Clock-comparison Experiments

Space-based clock-comparison experiments can, as discussed in the scientific foundations of our study, provide the most accurate limits on the validity of Local Position Invariance. Furthermore, it has recently been pointed out [196] that this type of experiment can also provide Planck-scale sensitivity, i.e. 1 part in 10^{18}, for many parameters that measure violations of Lorentz and CPT symmetries in the Lorentz violating extension of the Standard Model (cf. Section 3.2 of Scientific Foundations of this study) [198]. This arises because certain Zeeman hyperfine transitions are shifted if Lorentz and CPT symmetries are violated. Clock-comparison experiments using H masers, laser-cooled ^{133}Cs clocks or ^{87}Rb clocks could yield impressive limits on the violation of those fundamental symmetries. Some of these could be even more stringent than bounds obtained from ultra-high-energy cosmic rays, namely, 1.7×10^{-25} [40]. Furthermore, given that a satellite orbital period is typically much smaller than the sidereal day, the time required for data collection is much reduced. It is estimated that a clock-comparison experiment on the ISS could be completed 16 times faster than a Earth-based one, since the orbital period of the ISS is about 92 minutes [196]. The PHARAO (Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbit) project aims at developing in space an atomic clock based on cooled vapour of cesium atoms. The model for this clock is the ground-based atomic fountain type, which is recognized as the most accurate cesium clock in the world. An airborne prototype was built and tested in low-gravity environment during the first parabolic flight campaign of the new zero-gravity Airbus in Spring 1997. Subsenquently, CNES and a group of laboratories has been planning a new generation of atomic clocks to be built at the ISS by 2005 [197]. The accuracy target is 10^{-16}. It should be realized that this will, for instance, allow accurate measurements of the gravitational redshift to be performed and will be crucial

particle physics instrument to be taken into space. The experience and the scientific know-how acquired in the process has been of great value for the scientific community.

in future space missions for the detection of gravitational waves and for the realization of global time scale and positioning systems.

Hence, we regard it as a high priority to plan and perform clock-comparison experiments for different types of clocks (H masers, laser-cooled ^{133}Cs, ^{87}Rb clocks) at the ISS.

12 Ground Experiments

12.1 Gravitomagnetic Field in Quantum Materials

If a superconducting ring is rotated, a magnetic field is generated inside. This is the well-known London moment [206], arising from the quantization of the canonical momentum of the Cooper-pairs. Measurements of this magnetic field inside a rotating superconducting shell match the theoretical predictions only with an error margin of a few percent. In the most precise experiment conducted up to now, Tate et al. [207] used a thin Niobium superconducting ring with a SQUID device (measurement device for very small magnetic fields), reporting a definite disagreement between the measured and calculated Cooper-pair mass (out of the magnetic flux measurement) of 0.01%.

As proposed in Ref. [139] and dating back to the work of DeWitt [27], the canonical momentum used for these calculations can be extended to include the gravitomagnetic field as well. We may then relate the experimental disagreement to an additional gravitomagnetic field generated together with the magnetic field. By using Tate and collaborators results, a gravitomagnetic field of the order of 10^{-8} $rad.s^{-1}$ is required to explain the anomaly (see Figure 9). This is certainly above any classical coupling phenomena and requires further investigation. Of course, it can turn out that a refinement of the corrections to the Cooper-pair mass will give a better match between experiment and theory, which would reduce the magnitude of any possibly involved gravitomagnetic field. However, at the present stage, this is still an open question.

We therefore recommend the following step-by-step approach in order to investigate these phenomena:

Confirmation of Disagreement between Calculated and Measured Magnetic Field

Tate et al. [207] have used a thin Niobium superconducting layer for their experiment. This prohibits the Meissner effect and requires the more general Ginzburg-Landau theory to interpret the experiments [139]. Thus, as a first stage, a thick rotating superconducting ring

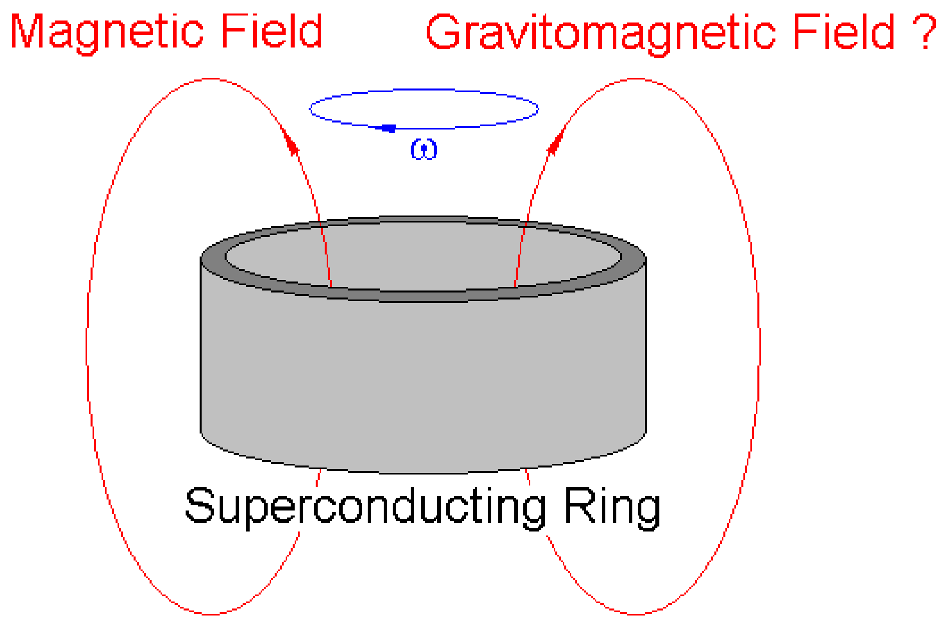

Figure 9: Magnetic and Possible Gravitomagnetic Fields Generated by a Rotating Superconductive Ring

should be used as in early experiments of Hildebrandt [208], but now using a state-of-the-art SQUID magnetic flux sensor in order to determine a similar discrepancy between measured and predicted magnetic flux. This would make the detection of a discrepancy much easier. In Hildebrandt's setup, a magnetic field of the order of 10 nT was measured. The Tate and collaborators experiment suggests that the measurement accuracy needs to be improved by at least 3 orders below this value. Commercially available SQUID magnetic field sensors have a measurement range down to pT, which seems to be sufficient. Several distinct superconducting materials should be used to check for any variation in the measurement results. If unsuccessful, we recommend pursuing the approach of Tate and collaborators and using a thin-film Niobium superconductor to verify the reported discrepancy in the Cooper-pair mass.

For such a task, we estimate about 2 man-years of effort and facility costs of 100 kEuro.

The activity described can be carried out in any superconducting laboratory in universities or research centres. The proposed setup is not trivial, but can be quite easily manufactured in workshops.

Investigation of Possibly Involved Gravitomagnetic Fields

If the above-mentioned discrepancy persists after performing the previous experiments, we recommend investigating whether gravitomagnetic fields are indeed involved. In principle, there are two different ways to measure such a component:

(i) By inducing a gravitoelectric field (e.g. by rapidly slowing down the rotating superconductor ring), which could be measured with accelerometers, or

(ii) By measuring the gravitomagnetic component directly via observation of the torque on spinning gyroscopes.

The first method is probably more accessible because commercial off-the-shelf accelerometers are widely available. We should expect the gravitoelectric and gravitomagnetic fields to be of similar magnitude, and hence an accelerometer capable of operating in the range of 10^{-8} g is required. Low-cost off-the-shelf accelerometers such as the SENSOREX QA 700 [210] are currently used for electric-propulsion thrust balances in the μN range, which could be used during initial testing. Higher sensitive accelerometers such as the ONERA STAR, which is under development for MICROSCOPE [209], or the Lacoste-Romberg gravimeters [211], are capable of measurements in the 10^{-9} g range. Although sufficiently accurate, these instruments are large compared with a superconducting ring and might be difficult to integrate into the experiment.

For the second method, a rotating gyroscope needs to be place at the centre of the superconducting ring. If a gravitomagnetic field is present, the spinning gyroscope would experience a torque along its axis of rotation, which could be detected using laser-beam reflection (see Figure 10). Several design issues are discussed in Ref. [212]. Obviously, the biggest challenge is the mounting of the gyroscope and the mechanism to spin it up, so that a high accuracy for the torque detection is maintained.

It is clear that a detailed description of those experiments requires additional investigation on experimental limitations and proper design. We estimate that such an investigation would

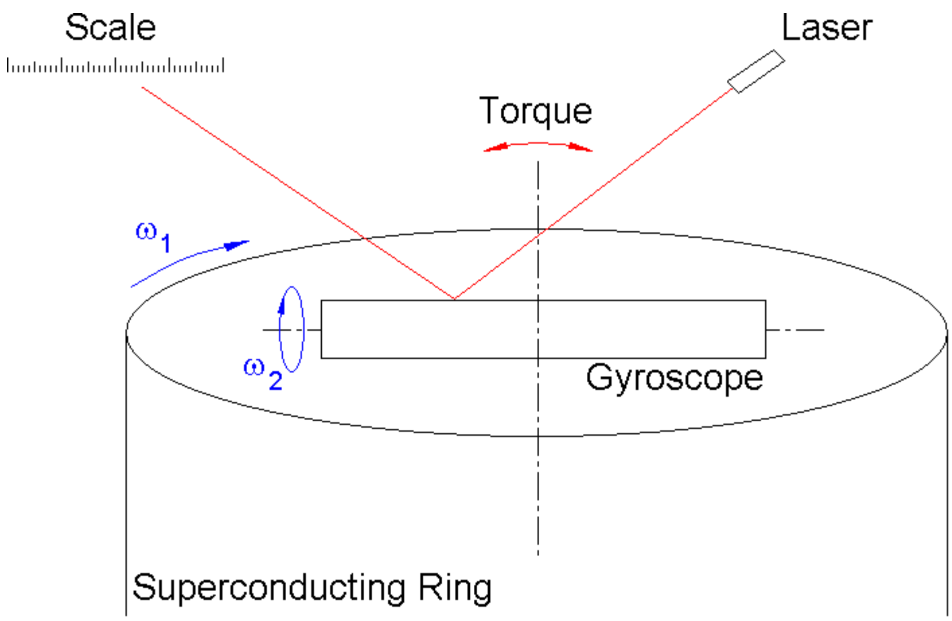

Figure 10: Possible Measurement Technique for Detecting a Gravitomagnetic Field in a Rotating Superconducting Ring

require 1 man-year of effort. After the experimental constraints are established, the above-described investigation into gravitomagnetic fields could be carried out with similar costs to the previous step.

In principle, this second step should be carried out at the same research site that built the setup in step one. Since relatively high orders of magnitudes can be investigated with off-the shelf measurement components, there is no need to delegate this task to institutions with great experience in investigating small gravitational anomalies (like geophysical institutions). Nevertheless, experience in measuring very small forces is of crucial importance. Therefore, teaming up a superconducting research laboratory with a group experienced in small force measurements would be beneficial. This team could be from the same university or research centre.

12.2 ATHENA and Recent Quantum Gravity Experiments

The ATHENA (AnTiHydrogEN Apparatus) experiment [192, 193] at CERN aims to produce antihydrogen atoms at low energies, magnetically trap them and compare their energy levels with the ones of hydrogen (see eg. [199]). Another experiment team in the USA, ATRAP [200], has been working to achieve the same scientific goal. This methodology will eventually allow the high-resolution spectroscopy required to test the fundamental CPT symmetry of local quantum field theories with great accuracy to be developed. The CERN experiment also aims to test the gravitational acceleration of antimatter. Recently, impressive progress has been made in capturing antiprotons in especially designed Penning traps, and their subsequent cooling to a few meV and storage for hours in a small volume. Positrons have been accumulated in large numbers in similar traps, and low-energy positron or positronium (electron-positron bound state) beams have been generated. Since techniques for the trapping and cooling of neutral atoms have also been developed, the conditions for the production of antihydrogen at rest are available. This would involve the merging of two cold charged plasmas made up of antiprotons and positrons and allowing for the spontaneous or stimulated radiative recombination. The antiproton source is the Antiproton Decelerator (AD) at CERN delivering 100 MeV/c particles. Achieving lower energies requires the use of electromagnetic traps. About 1% of the AD antiprotons are caught inside a cylindrical multisector trap of about 40 cm of length and 2.4 cm diameter, and then cooled down to cryogenic temperatures by the electron cooling method using the experience acquired during the operation period of LEAR [201]. Further cooling of the antiprotons with an electron plasma would then allow for the combination with positrons to obtain antihydrogen. At this stage, high-precision spectroscopic methods could be used to compare the results with the usual hydrogen atom. Knowledge of the $1s-2s$ transition with a lifetime of the excited state of 122 ms and a natural linewidth of 5 parts in 10^{16} could allow verification of matter-antimatter properties to 1 part in 10^{16}. Given that the ATHENA group has developed the best available Penning traps for this task, any experiment along the lines of WEAX to study the gravitational properties of antiprotons in the ISS will critically depend, as discussed above, on this device, and hence will have necessarily to team up with the ATHENA group. We regard establishing these links as a high priority. We mention that some of the proposers of WEAX are actually also working at ATHENA. Thus, in our view, it is crucial that:

- Institutional and scientific planning of an experiment along the lines of WEAX is performed. This would imply establishing links with the ATHENA group at CERN and starting to consider the quite difficult task of getting workable amounts of antimatter on board the ISS to carry out a test of the CPT symmetry in space.

Quite recently, Nesvizhevsky and collaborators have reported on the evidence for gravitational bound states of neutrons [24]. The conceptual aspects of the experiment were developed long ago, in 1978 [202]. Subsequent steps towards the goal of the final experiment can be found in Ref. [203]. The experiment consists of letting ultracold neutrons (from a source at the Institute Laue-Langevin reactor in Grenoble) fall towards a horizontal mirror under the influence of the Earth's gravitational field. This potential confines the motion of the neutrons, which do not move continuously in the vertical direction, but rather jump from one height to another as predicted by quantum mechanics. This impressive experiment complements the Collela, Overhauser and Werner experiment [22] in which neutrons were split and allowed to interfere under the effect of gravity, even though in this situation the neutrons were not quantum states [9]. It is reported that the minimum energy is $1.4 \times 10^{-12}\ eV$, corresponding to a vertical velocity of $1.7\ cm/s$. A more intense beam and an enclosure mirrored on all sides could lead to an energy resolution down to $10^{-18}\ eV$.

The prospect of a variation of this experiment involving antineutrons aiming to verify the CPT symmetry is quite exciting, but naturally the intensity of the antineutron beams, which would require an accelerator, would be several orders of magnitude smaller, rendering the experiment virtually impossible. Indeed, antineutrons could be obtained from the decay of anti-Λs, baryons with non-vanishing strangeness number, that is $\overline{\Lambda} \to \overline{n}\,\overline{\pi}^0$ with branching ratio

[9] A version of this experiment for establishing bounds on the parameters of a new interaction of Nature was discussed in Ref. [78].

of 35% [170]. Production of $\overline{\Lambda}$ particles would require, for instance, a J/Ψ factory, whose decay into $\Lambda\overline{\Lambda}$ has a branching ratio of about 1.3×10^{-3} [170]. Thus, an antineutron would require about 4.5×10^{4} J/Ψ mesons. It should be remembered that the antineutrons obtained would then have to be cooled down before being sent to bounce off a mirror under the action of gravity and then detected. These operations would considerably degrade the overwhelming majority of the antineutrons produced. Perhaps a variation of this experiment could be perfomed for nuclear bound states such as $p\overline{n}$ or $pp\overline{n}$, even though to our knowledge these bound states have not yet been produced.

On the other hand, an upgraded version of the experiment of Nesvizhevsky and collaborators so to allow for an energy resolution of $\Delta E = 10^{-18}$ eV can allow for a modest bound on the Weak Equivalence Principle [204].

Thus, regarding this crucial experiment we regard it as particularly important that:

- Higher energy resolution is achieved.

13 European Research on Gravity Control

13.1 High-Risk and Speculative Research

Traditionally, there are important gaps between invention and innovation. This is especially true for exploratory research (like verification of reported gravitational anomalies not supported by presently known physics) or unconventional ideas. A few years ago, the Advanced Technology Program (ATP) was launched by the US National Institute of Standards and Technology (NIST), focusing on the advantages of high-risk research and investigating these gaps. One of their projects, the Managing Technical Risk Project [205], summarises the gap as follows:

- *Financial gap*: This refers to the gap between research funds available to support both the creation of the idea and the initial demonstration that it works. In reality, only a few sources exist that can bridge this gap, namely "angel investors" (like wealthy individuals), venture-capital firms or mostly military seed money.
- *Research gap*: After initial demonstration of the working concept, there is still a certain research gap that may require additional breakthroughs until a basis for a commercial product is formed.
- *Information or thrust gap*: The technologist from the potential funding source knows what is scientifically interesting and what is technically feasible. In the event of failure, the technologist risks a loss of reputation. This is a very important point, which drastically reduces the chances for very novel concepts and exploratory research.

There are a number of high-risk, high-potential payoff research initiatives coming from non-space sectors such as biology and medicine (e.g. cancer, AIDS drugs). Space activities, due to the limited accessibility to space and the many launch failures in the past, represent a very conservative business. The most prominent recent attempt to change this was NASA's Faster-Cheaper-Better philosophy from former Administrator Daniel Goldin during the 1990s.

One key component in this philosophy is the NASA New Millennium Program, where high-risk technology components are selected for flight qualification to lower the risk for future missions.

It was in this period that the Breakthrough-Propulsion-Physics project was launched in 1996, and the NASA Institute for Advanced Concepts (NIAC) was founded in 1998. The NIAC calls for proposals focusing on revolutionary concepts (propulsion and others) which can give a dramatic boost to ongoing NASA programmes. Also, the US military has long experience in giving seed money to sponsor exploratory research. In addition to the Air Force advanced studies and activities mentioned in Section 9, the Defense Advanced Research Projects Agency (DARPA) also has supporting high-risk research and exploiting emerging technologies as its prime mission.

Although innovative in non-space business areas such as aerospace (e.g. Airbus fly-by-wire) or mobile phones, Europe is traditionally less innovative in funding space-related exploratory research. Nevertheless, there are some high-risk projects despite BAe System's Project Greenglow. One of them is the CNES μSat programme. The first microsatellite DEMETER will monitor ionospheric perturbations that may be related to earthquakes. There is only some empirical evidence and no physical theory that could explain such a link, but nevertheless, if such a relationship is revealed, it would be a very powerful early-warning tool for earthquakes. This is a classical example of high-risk payoff.

ESA started a high-risk technology programme called SMART (Small Missions for Advanced Research in Technology) as a response to NASA's New Millennium Program. The first mission, SMART-1, is due for launch in March 2003. Also, an innovation task force was established in the Agency in October 2000 to make recommendations for high-risk/high-payoff developments to be funded under the next ESA Technology Research Programme (TRP) cycle [213]. However, very-high-risk projects like gravity control or exploratory research are not considered within these programmes.

13.1.1 Possible Examples of Speculative Research

There are several experimental claims for new interactions or unknown effects related to gravity in the literature. Although often unexplained by current theories of physics, such claims should be ruled out experimentally. The likely negative outcomes would even be useful for the community in order not to continue to follow the identified research line. As an example, we shall describe three such claims.

Podkletnov-Type Superconductor Experiments

As discussed in the scientific foundations of this study, Podkletnov has reported on two controversial claims. In the first one, he reports a 0.05% weight loss of a sample put above a superconducting disc levitating above a solenoid. The weight loss increased to 0.3% when the superconductor was rotated [122] using two additional solenoids [122]. All three solenoids were excited with an AC current ranging from 50-106 Hz. In a second experiment, a current was first induced in the superconducting disc during cooling down; afterwards the solenoids were excited with a MHz AC current [214]. Even higher shielding effects of up to 2.1% were reported. Several groups have tried to reproduce his experiments, but were not successful. However, all replications were not done with exactly the same setup used by Podkletnov (which were somewhat poorly described in his papers). For instance, NASA has only investigated the weight loss of samples above a superconducting disk levitating over a DC current solenoid [216], or a superconducting disk under EM radiation which was not rotating or levitating [217]. In an attempt carried out at the University of Sheffield, permanent rotating magnets were used instead of a soleniod with AC currents for levitating the superconducting disk, and this setup could achieve only kHz rather than MHz frequencies [115]. Hence, although some effort has been devoted to replicating Podkletnov's results, not quite all factors were properly reproduced. We therefore recommend that further attempts to reproduce Podkletnov results be carried out, preferably by getting more information from Podkletnov himself so that the matter is definitely clarified.

A second type of claim concerns the generation of a gravitational impulse due to a high-voltage discharge on a superconducting sphere [215]. A pendulum was placed in an evacuated glass tube outside the experimental apparatus. In the case of a discharge, the pendulum was excited indicating a relationship with the discharge voltage and the pendulum mass. This reported pendulum movement persisted even after moving it several hundred metres away and behind a brick wall. The paper contains a number of measurements and also an extensive discussion of theoretical explanations and possible experimental errors. This is a good example of a high-pay-off claim, described in some detail, with an obvious lack of theory. We recommend an investigation of this phenomenon as part of a high-risk research programme.

Investigation of Charge-Mass-Acceleration Relationship

There are several reports in the literature describing a relationship between charge, mass and acceleration. For instance, Woodward has shown that a sharply accelerated test sample induced a charge in the target. There was a linear relationship between the induced charge and the mass of the test sample [218]. A similar measurement was obtained with a rotating cylinder, instead of an accelerated test sample [219].

Another claim of the same nature can be found in a patent by Yamashita and Toyama [220] (cf. the evaluation criteria used in the Database constructed in the context of this study, Section 9.2). Those authors have reported a change in the weight of a charged rotating cylinder and a similar relationship as found by Woodward [220]. To our knowledge, no independ attempts to replicate these results have been performed so far. These claims are extraordinary and one could wonder how could such a relationship could have escaped experimental detection. In any case, these experiments require independent replication and further analysis of their experimental errors. We therefore recommend a low-cost investigation in the context of the General Programmatic Recommendations.

13.2 General Programmatic Recommendations

In line with the main findings of this study, we recommend the following programmatic actions:

- Further work on the subject of gravity control should be pursued in the fundamental physics/science and microgravity framework, and not with respect to propulsion.
- Due to the high flow of information on the subject, evaluation of the current developments in the subjects discussed in this study and updating of the database should be done on a regular basis (e.g. every 2 years).
- Building and exploring partnerships with CERN in Geneva, Institute Laue-Langevin in Grenoble and NASA (and any other institution of interest) for carring out the experiments we have here suggested. For instance, a re-evaluation of the trajectory analyses from the Galileo and Pioneer missions would certainly require the sharing of NASA tracking data. Antimatter particle experiments require the infrastructure of CERN.
- Constructive teaming up with NASA to enable European participation in the Breakthrough Propulsion Physics Call for Proposals. This would take advantage of an already well established infrastructure and peer-review process, as well as sharing costs and risks.
- Organizing regular workshops and sponsoring interdisciplinary networks in order to stimulate theoretical and experimental advancements in this area of research.
- Exploring internal funding sources to pursue the identified research lines and possible speculative research (most likely within the framework of ESA's innovation task force).

13.3 Summary of Recommendations and Outlook

We will now summarize our set of recommendations for the three lines of research that have been identified in the scientific foundations of our study and that have been extensively discussed.

As far as the search for a new long-range interaction of Nature ($\lambda \gtrsim 10^{13}\ m$) is concerned, our recommendations comprise suggestions for ongoing missions, for missions under development and a dedicated mission, Sputnik-5:

- Tracking data for the Galileo and Ulysses spacecraft should be further studied and alternative explanations for the observed anomalous acceleration should be re-analysed.

- Tracking data from missions in progress should be analysed to establish whether there is any sign of the anomalous acceleration, specially for the Cassini-Huygens mission. In the case of a positive indication, a thorough search for conventional explanations should be carried out.

- Missions under development should be designed so as to allow simple detection of any anomalous long-duration acceleration. This implies that trajectory simulations should be carried out with the highest possible accuracy, and furthermore that means are available to allow the thermal state of the spacecraft to be accurately known at any time. This last requirement translates into endowing spacecraft with a comprehensive set of thermal detectors.

- Any dedicated mission for the study of a new long-range fundamental interaction of Nature should have a simple and highly symmetrical design and be planned to reach the farthest possible aphelion.

In terms of the search for a new short-range interaction ($\lambda \gtrsim 10^{-5}\ m$), we have suggested that the energy resolution of the recent quantum gravity experiment of Nesvizhevsky and collaborators be improved to $10^{-18}\ eV$, which corresponds to neutrons spending their whole lifetime within the experimental apparatus.

As far as the search for violations of the Weak Equivalence Principle for antiparticles and charged particles is concerned and further improving the level of determination of Local Lorentz Invariance and Local Position Invariance, we have suggested that:

- Support is given for the concrete planning of an experiment for examining the behaviour of antiprotons in a specially built Penning trap to be placed at the ISS, the WEAX proposal. For achieving this goal, the establishing of links with the ATHENA group at CERN is a fundamental step.

- Extention of the PHARAO project for the construction and placing of atomic fountain clocks on the ISS, thereby including other types of high precision clocks in orbit.

Our recommendations for ground experiments, aimed at being complementary to missions under development to test General Relativity with greater and greater precision, comprise:

- Systematic study of the origin of the discrepancy between the predicted Cooper-pair mass in the BCS theory and the observed one, aiming to establish whether this discrepancy can be explained via some yet unknown mechanism involving the gravitomagnetic field in quantum materials.

Finally, in terms of general programmatic recommendations we propose that the following suggestions be considered:

- ESA should establish a small team for keeping track of upcoming progress in the subjects discussed throughout this study. We believe that the control of gravity, if ever possible, will most likely emerge from the pool of ideas arising from quantum generalizations of General Relativity, String/M-theory, etc. Furthermore, since developments in theoretical and experimental physics are evolving quickly, a continuous updating of this study is, in our view, the most effective way of avoiding that relevant developments go unnoticed by decision makers at the Agency.

- ESA should, in our opinion, sponsor regular meetings on the subjects discussed in this study. Gatherings such as the CERN-ESA-ESO meetings are quite useful, but given their scope, subjects like unconventional propulsion methods, gravitational anomalies, etc. tend to be outside their main line of interest, thereby missing the opportunity to attract a good number of interested people. The meetings we are suggesting here should, in our view, be essentially interdisciplinary on the one hand, but focussed, innovative and peer-review-oriented on the other.

It is somewhat difficult to outline a set of conclusions to a study that has left the object of its analysis essentially unanswered. Control of gravity remains still in the realms of science fiction. Our study has failed to change this state of affairs and has left open the question of whether such control will ever be possible. More modestly, we have instead ruled out many schemes and proposals that were in conflict with well-known scientific facts. Furthermore, we have delved into the fringes of the known theories of physics to the limits of our knowledge, and humbly pointed out the most likely type of physics investigation that may lie ahead. Surprisingly, we have found that, however astonishing the answer may be, control of gravity would have a rather modest impact on the technology we use nowadays to reach space and would imply no breakthrough at all for the known methods of propulsion. Thus, it seems that reality has the upper hand over fiction, at least for a while. This could be expected to be the outcome of any serious scientific study, and ours could not be any different, however, that we did not aim to put a ban on imagination, but rather make it totally clear that, as far as the control of gravity is concerned, the dream must be much more spectacular than anything we can currently envisage and probably will be able to imagine until the last obstacle to the solution crumbles.

...

Something begins, and already it is no longer the beginning, but something else, propelling us into the heart of the thing that is happening. If we were suddenly to stop and ask ourselves, ‘Where are we going ?’, or ‘Where are we now ?’, we would be lost, for at each moment we are no longer where we were, but have left ourselves behind, irrevocably, in a past that has no memory, a past endlessly obliterated by a motion that carries us into the present.

...

And no matter how small, each and every possibility remains. Even a motion reduced to an apparent absence of motion. A motion, for example, as minimal as breathing itself ...

White Spaces

Paul Auster

(Selected Poems, Faber & Faber 1998)

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Annex:

Database Documentation