Gravity Control and Possible Influence on Space Propulsion:

A Scientific Study

Part I

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SUMMARY

Control of gravity to any degree, if ever possible, would constitute a major scientific and technological progress. Present knowledge of the theory that best describes gravitational phenomena, namely General Relativity, provides no indication neither on how to achieve any control of its strength nor 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 theoretical level, that General Relativity must be harmonized with Quantum Mechanics in the context of a more encompassing theory. The theory that stands out as 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 to the extent of which the Weak Equivalence Principle holds and actually describe the free fall of bodies of different nature and composition. In this study we shall 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 shall also discuss some alternative theories of gravity where the strength of gravity is related with the dynamics of a still unknown field. In these models, Newton's constant correspond 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.

Throught out this study, connections with ongoing and future scientific space ESA, ESA/CNES, ESA/NASA and ESA/ISAS missions such as *MICROSCOPE*, *STEP*, *HYPER*, *LISA* and *Bepi-Colombo* will be 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 generation of gravitational fields, would have to compete with other means such as launch assist technologies or electrodynamical tethers. We show that an hypothetical control of gravity would yield only modest benefits on the launch of spacecraft, and actually no breakthrough technology in what concerns propulsion. Only for the case of a vanishing gravitational mass and special orbits such as required for geostationary satellites, launching could be achieved with much smaller propulsion systems - which would 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 control of gravity. In this Database the selected publications on the subject can be found as well as information on the people involved in research related with the control of gravity and on the fundamental physics related with the topics discussed in the report. We have also set a criteria of evaluation for the existing ideas and proposals.

Part I

Scientific Foundations

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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, hints no indication on how to achieve some control of its most salient features. The strength of gravity is drawn from phenomenology and to all known phenomena it 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 not to lead to observable violations of the Heisenberg uncertainty principle. In this study we shall 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 to a theory of Quantum Gravity, as well as some of its possible implications which include the violation of the underlying symmetries of low-energy physical theories. This possibility leads us to examine, in particular, up 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 on the existence of new interactions of Nature and ensued violations of the Weak Equivalence Principle. Possible new phenomena in the context of Gravitoelectromagnetism, a first order approximation of General Relativity, that allows recasting Einstein's equations in a fashion they resemble Maxwell's equations will also be examined.

We stress that the purpose of this study is to lie 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 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 more "mundane" causes for the extraordinary observations they report.

On rather general terms, we call gravity control any scheme that allows changing the properties of gravity via altering the strength of the gravitational coupling to matter or lead, through the intervention of other forces, to a change of the local gravity force. This control requires either 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 in violations 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 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 to affect the relative strength of known fundamental interactions.

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

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

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

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

The cosmological constant, although being a major embarassment in current theoretical physics in what respects expectation and its observed value, is beyond dispute an important ingredient to account for the cosmological data. This arises from the study of Type Ia Supernovae which, when used as standard candles, allow 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 abovementioned 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 shall draw our attention to the gravitational part of the theory and therefore we shall disregard for 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, in particular of 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 view point one could consider a connection that allows torsion, this would lead to a geodesic deviation equation with the following form

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

¹Most 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 velocities much smaller than the velocity of light, to the Newtonian deviation equation

$$\frac{d^2N^i}{dt^2} + E_j^i N^j = 0 (8)$$

where, $E_{ij} = -\partial_j g_i$, is the tidal tensor and g_i is the component of the gravitational acceleration in *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 eg. [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]:

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

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

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

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:

$$\beta = \gamma = 1 \; ; \; \alpha_1 = \alpha_2 = \alpha_3 = \zeta_1 = \dots = \xi = 0 \; ,$$
 (13)

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

It is well known that the underlying linearized field theory associated to 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 neutralizing a gravitational field and hence any gravitational energy density by a suitable choice of a frame of reference. Furthermore, it is known for a long time that in GR, as in Newtonian gravity, the contribution to the energy of a system due to gravity is negative. This fact can give origin 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 accelerate itself off, with no need of any propulsion system. This would arise thanks to the attraction that a positive mass body would exert on a negative mass one and the repulsion the negative mass body would exert on the positive mass one. However bizarre, negative masses have been repeatedly invoked in alternative propulsion proposals, even though its scientific merits are most often not properly assessed. Negative masses have been firstly 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 has one of the bodies 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 mid sixties and was eventually shown 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, $T_{\mu\nu} = diag(\rho, p_1, p_2, p_3)$, in 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**. We mention that these theoretical objects are often invoked as alternative propulsion methods.

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

²It is relevant 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 on their velocities (Local Lorentz Invariance -LLI)
- 3) Independence of the change of rate of clocks on 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] till 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 of gravity could be achieved if violations of the WEP could be found or somehow engineered. Hence, in order to proceed our study it is important to survey to which 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 mention that present day technology has allowed the interferometry of atoms rising against gravity to achieve impressive sensitivity limits, such as 3×10^{-8} [23]. We mention that quite recently an experiment for gravitational bound states of neutrons has been performed by Nesvizhevsky and collaborators [24]. The reader can find a detailed discussion of this important experiment in Part II of this study.

Charged Fermions (Electrons)

The WEP was tested for electrons by Witteborn and Fairbank in 1967 [25]. Electrons were let to fall under the action of gravity in a shielded drift-tube. A slow-down 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 as 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

$$g_{eff} = 0.09g$$
 . (18)

It is remarkable that for positrons, the same reasoning allows concluding 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 purpose of a free fall experiment. We regard as highly desirable and even somewhat urgent that an experiment to verify this result is performed in the near future. In what regards 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 it does exist a magnetic analogue of the Schiff-Barnhill effect 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 verifying to which extent gravity respects the fundamental CPT symmetry of local quantum field theories and 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 to 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 up to a certain degree to deal with the quite difficult problem of storaging antiprotons and creating an antihydrogen atom. Unfortunately, the closure of the LEAR (Low Energy Antiproton Ring) facility at CERN, so to pursue the construction of the LHC, has rendered the subsequent free fall experiment impossible (see Ref. [29] for an account of the situation up to early 1999). We mention that meanwhile, the CPLEAR Collaboration has reported on a test of the WEP envolving 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 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 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 the Centre Nationale d'Etudes Spatiales and ESA. The drag-free MICROSCOPE satellite will be launched in 2004 in 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 reached only in space as in a mission like HYPER (HYPER-precision cold atom interferometry in space). The ESA's HYPER spacecraft will be in a Sun-synchronous circular orbit at 700 km altitude. Accomodated in the spacecraft there 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 comparison of the rate of fall of caesium and rubidium atoms. 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 of this Weak Equivalence Antimatter experiment (WEAX) consists in confining antiprotons for a few weeks in a Penning trap, a magnetic container, in a geometry wherein 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 10⁶, three orders of magnitude better than 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

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 basis 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 on the nature of gravity-induced wave dispersion in vacuum [34, 35, 36] and therefore on 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 rather 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 Refs. [44]. These non-trivial solutions arise in the context of the string field theory of open strings and may have relevant 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] experiments³, 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 comparison 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 the latter type of measurement, one searches for the time dependence of the quadrupole splitting of nuclear Zeeman levels along Earth's orbit. This technique allows achieving impressive limits, the most stringent $\delta < 3 \times 10^{-22}$ [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 mandatory the analysis on how the most energetic cosmic-ray particles would be affected by the interaction

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

with the microwave photons. 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 $5 \times 10^{19}~eV$ to reach Earth from further than $50-100~{\rm Mpc}$. 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 processes, otherwise dynamically inevitable, e.g. the resonant scattering reaction, $p + \gamma_{2.73K} \rightarrow \Delta_{1232}$. The study of the kinematics of this process allows setting 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 with 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 up to which the LPI holds. Hence, violations of the LPI would imply that rate of a free falling clock would be different when compared with a standard one, for instance on 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 10000 km altitude as 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 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 fact towards a proof 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, it constitutes in 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 origin to effects that will have implications in 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 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 origin 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

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

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:

⁴We 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: $1 m = 5.068 \times 10^{15} \, \text{GeV}^{-1}$, $1 \sec = 1.519 \times 10^{24} \, \text{GeV}^{-1}$, $1 kg = 5.610 \times 10^{26} \, \text{GeV}$, $1 K = 8.617 \times 10^{-14} \, \text{GeV}$ and $1 \, \text{GeV} = 1.602 \times 10^{-10} \, J$.

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

where

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

The suggestion of existence of a new interaction has arisen from the recognition that the coupling α was 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:

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

such that the constant α can be written as

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

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

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

where \vec{F} is the field strength of the Earth 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

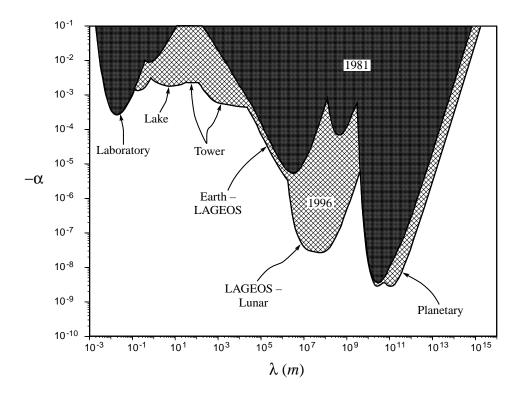


Figure 1: Experimentally excluded regions for the range and strength of new possible forces as shown in Ref. [74]

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 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 deviced 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} .

⁵For instance, neutron interferometry has been suggested in order 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, that are associated with the idea that extra dimensions do not have to be necessarily of Planck size [80, 81]. The range $\lambda < 10^{-3}~m$ also arises from the assumption that scalar [82] or tensor interactions associated to the breaking of the Lorentz invariance in string theories [45] account for the vacuum energy up to half of the critical density, $\Omega_V < 0.5$. It is remarkable that this range has been recently available to experimental verification. Putative corrections to Newton's law at millimeter range could have relevant theoretical and technological implications, specially 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 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 on the radio metric 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. = 2.98×10^{13} m has been suggested in order to account for the anomaly [86] (see also [87]). This choice of parameters arise 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. . We mention that 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 settle this quite relevant issue arises from the Bepi-

Colombo mission. BepiColombo is a joint ESA and Institute of Space and Astronautical Science (ISAS) of Japan mission of interdisciplinary nature to study planet Mercury and 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 well equipped array of instruments, for the determination of the harmonic coefficients of Mercury's gravitational field, of the rotational state of the planet and, via precision Doppler and ranging measurements, to carry out tests of GR with great accuracy. Indeed, BepiColombo will make possible important improvements on the measurement of 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 abovementioned 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 abovementioned precision measurements requires a great degree of control of the spacecraft tracking, which is nowdays possible thanks to progress in very high phase stability of microwave signaling, BepiColombo is an uniquely well suited mission for settling the puzzle of the radio metric data from Pioneer 10/11, Galileo and Ulysses spacecraft. Thus, BepiColombo may lead, after eliminating all possible conventional explanations, to the exciting prospect of confirming the discovery of a new fundamental interaction of Nature.

4.2 Carrier of a new interaction of Nature as a dark matter candidate

We further remark that 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 abovementioned 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:

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

or

$$c_n \lesssim 10^{-5} \; ; \quad \langle \varphi_5 \rangle \gtrsim 10^{-5} M_P$$
 (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 of new fundamental interactions of

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

4.3 Gravitational Anomalies

We close this Section mentioning that a good number of anomalies concerning the gravitational behaviour of well known systems and devices have been reported, specially 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 quite often these anomalies are 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 on the period of an electrically charged torque pendulum [99], however his results have not been confirmed [100]. A number of claims and studies have been performed to test a progressive absorption of the gravitational force between two bodies when a medium screened 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:

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

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 quasistatic 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 on 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]), was 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 is 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 $10'' Y B a_2 C u_3 O_{7-x}$ toroid and the same loss of weight was observed. The publication with the results of the second

experiment have been submitted and accepted for publication in the Journal of Physics D: Applied Physics, but subsequently put into 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 manyfold [113]. In the second experiment [114], a highly accurate gravimeter was used, however 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 in changes in acceleration that were less than 2 parts in 10⁸ 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 presented arguments [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 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 March 9th, 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 highly 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 the gravitational shielding as the cause of the anomaly observed by Wang et al. during the total solar eclipse. Furthermore, the authors have established an yet more stringent bound on the gravitational shielding constant $h \leq 2 \times 10^{-17}~cm^2g^{-1}$ and modelled the observed anomalous result as a series of unaccounted seismic disturbances due to human activity. Actually, there is a long story of claims concerning possible gravitational anomalies during Sun eclipses. However, data are contradictory and most usually allow stablishing a quite tight bounds on h ([120] and references therein). Gravitational screening has also been invoked to explain irregularities in the trajectory of satellites when entering in the shadow of the Earth [121], but these claims are naturally quite difficult to confirm given the number of potential effects a satellite is subjected when flying close to 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 coumpound are accompained by the emission of radiation whose beam does not suffer noticeable attenuation 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 on their composition. The effect is presented as new and unprecedented. It is argued that a possible explanation should 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 engaging in any theoretical modelling and effort 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 4-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 to consider string loop-contributions, that are actually counted by dilaton interactions, instead of a potential. In this scheme the relevant effective low-energy 4-dimensional action is, after dropping the antisymmetric second order tensor and introducing fermions, $\hat{\psi}$, Yang-Mills fields, \hat{A}^{μ} , with field strength, $\hat{F}_{\mu\nu}$, in a spacetime described by the metric, $\hat{g}_{\mu\nu}$, given by:

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

where

$$B(\Phi) = e^{-2\Phi} + c_0 + c_1 e^{2\Phi} + c_2 e^{4\Phi} + \dots \quad , \tag{34}$$

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

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

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

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

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

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

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

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

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

but within the precision 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 from one hand, it is not altogether clear that developments in String/M-Theory will have a direct impact on the issue of gravity control, it will in any case deeply affect our understanding of gravity and most probably bring about quite unexpected new phenomena.

6 Gravitoelectromagnetism

GR is a fairly complex theory and quite often relying on approximation methods (the Parametrized Post-Newtonian formalism discussed above being one of them) is the only available route to extract physiccal 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 considering the weak field approximation

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

and work, 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 the mass density, v^i the *i* component of the velocity and

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

so that far from the source

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

The spacetime metric of this matter distribution is given by

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

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

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

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:

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

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

The analogy with electromagnetism can be further carried out 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, 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 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 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 to account for perihelium effects and, of course, gravitational waves. Furthermore, GEM is meaningful only if the matter distribution evolves so 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 of GEM and electromag-

netism. 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, 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 in 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]:

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

The experimental confirmation of the Lense-Thirring effect requires precise tracking of satellites orbits as performed with lasers in 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 precission laser ranging, which involve sending laser pulses to stations on Earth so to record the round-trip travel time. Besides being able to provide relevant bounds on the existence of new interactions of 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 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 dragging would affect the behaviour of a

spinning gyroscope. This Stanford University project is planned to orbit around Earth in a polar orbit at an altitute of about 650 km and to be launched in a year or two. The goal of the mission is to monitor the precession of free falling gyroscopes caused by the geodetic and Lense-Thirring effect 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 abovementioned missions through the precise measurement of the rotation rate of cold-atom gyroscopes and its spatial variation [33].

Before closing this Section let us 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 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], meaning that the well known heuristical discussions of Einstein's Equivalence Principle in terms of translational acceleration of the "Einstein elevator" found in many textbooks of GR, is somewhat incomplete as it requires the Larmor rotation as well, in order to account for the GM field. It is worth remarking that the independence of \vec{a}_L and $\vec{\omega}_L$ on the ratio of the "charges" to the masses is a clear signature of the universality of the gravitational interaction. This independence is not found in electromagnetism.

We mention that the gravitational analogue of the spin-orbit coupling and spin-spin coupling may cause measurable effects for astrophysical 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 turns the orbit of a spinning neutron star different from the orbit of an elementary test particle. It is remarkable that these orbital effects give origin to gravitational waves with distinct features and these are expected to be observed by ESA/NASA gravitational wave detector in space, LISA (Laser Interferometer Space An-

tenna). The ambitious LISA mission comprises three identical spacecraft located $5 \times 10^6~km$ apart forming an equilateral triangle. This gigantic Michelson interferometer in space will be located so that the centre of triangular formation will lie 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 to 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].

6.1 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

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

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

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 nearby a superconductor, so 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 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, this considerations imply that it is the flux of \vec{A}_T through a superconducting ring that is quantized in units of h/2:

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

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

vanishing small. In practise, 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 current situations, quite small, one imediately is led to the question 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 the Magnetohydrodynamics (MHD), that is a mechanism of generation and amplification of gravitomagnetic energy from stretching the action of the velocity field on \vec{B}_g might be, of course, 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 sound velocity 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 be inevitably quite small. As we shall see in a while, 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 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 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, that is

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

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, in our opinion, further investigation.

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, in 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 that 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 in 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 to measure \vec{B}_g ?

It is our believe that the answer to these questions tend to be negative and even otherwise, the involved GM fields would be far too small for the purpose of launching and propulsion.

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 gyroscopes [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, 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 imply that any field associated to 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, it is clear for us that these questions deserve a dedicated longer term research and, at this stage of our study, we can only envisage some of the major possible obstacles. We emphasize that some of the abovementioned 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).

7 "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 rather remarkable that in the presence of gravity, the mechanism of SSM gives origin 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 been recently extensively reviewed in Ref. [149] (see also Ref. [150]). Actually, Casimir forces are often mentioned as a prototype of esotherical phenomenum 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 prediction of that theory 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:

$$f(\varphi) = \varphi$$
 $g(\varphi) = \frac{\omega}{\varphi}$, (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 which 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 are 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 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 laboratory scale is ruled out. Thus, the claim by J. Woodward [154] of having experimentally generated transient fluctuations on 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]

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

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

$$\left(\frac{\dot{G}}{G}\right) = (-0.6 \pm 2.0) \times 10^{-12} \ y^{-1} \ .$$
 (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 that in these alternative theories of gravity Newton's constant arise 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 to couple the φ field to other fields in order to locally alter its value. This feature is encountered in some adjusting mechanisms deviced 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 to solve the cosmological constant problem, but they contain nevertheless the required multifield 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 is quite complex and have many surprising turns as we have already seen when discussing its impact to the WEP. Of course, in the simple models we have mentioned, altering the value of the gravitational coupling would

amount achieving Planck energies at laboratory, which is beyond any forseable technological developments. Nevertheless, recent speculations suggesting that the size of the extra dimensions may be rather large [80, 81] would imply that the gravitational effects associated to 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 searchs of "Kaluza-Klein" modes in accelerators and from cosmological considerations. The former yield $M_5 \gtrsim 3$ TeV [161]. Cosmological nucleosynthesis allows setting 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 origin to an extra contribution to Newton's gravitational force, which must be small beyond scales above $r \gtrsim 1$ mm and imply 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, in 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 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 establishing whether the gravitational coupling is a running coupling constant likewise the coupling constants of the other fundamental interactions of Nature. From the point of view of String/M-Theory, the answer appears to be negative 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 which 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 at cosmological scales.

Before closing this Section let us 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 which 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 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. Let us mention the most salient ones:

- 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 on 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 so 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 substructure is required. Quarks and leptons are observed to be point-like to scales $10^{-18} \ cm$ [170].
- ii) To the objection that the associated energy to a real ZPF fluctuation would lead to a significant spacetime curvature and an ensued 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 of 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 an unique self-consistent way to compute Newton's constant and the cosmological term [172]. This is yet another example of the complexity of 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 to address the quantum gravity problem is related with the rather natural way some of the most fundamental questions can be addressed and eventually solved. Even if it is argued that ZPF do 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 also contribute 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 to 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 substancial 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 in any significant gain in the propulsion of spacecraft. As it will be discussed in the next Section, a change in the inertia of the spacecraft will most generally imply in a change of 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 realm of String/M-Theory that any significant progress can be achieved in the understanding of the fundamental interplay between gravity and quantum fields.

8 Gravity Controlled Propulsion

8.1 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 uses less propellant. This gives us information on how effective 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 with each other:

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

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

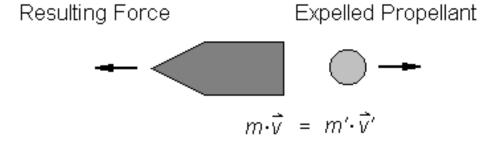


Figure 2: Momentum Conservation

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, the so-called electric propulsion, electric 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 a 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 refers the use of 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 different propulsion systems and their associated specific impulse as well as their maximum thrust 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 written as [174]

$$v_p \simeq \sqrt{\frac{2\gamma}{(\gamma - 1)} \frac{RT_c}{\mu_p}} \quad ,$$
 (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 vapor. Water is much heavier than hydrogen, 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. Thruster characteristics can be written as

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

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

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 further discussion on an 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 required change of velocity from the spacecraft, Δv . The total

requirement consists of several components,

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

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 of the 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 $\Delta v_g = 1.4 \ km/s$. To stay in a 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 center of the Earth to a LEO. We can now express the Δv_{orbit} requirement

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

Mission	Description	Typical $\Delta v [\mathrm{km/s}]$
Planetary	Deep space robotic missions	10
Human Planetary Exploration	Fast, direct trajectory	30 - 200
100 - 1,000 A.U.	Interstellar precursor mssion	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]

For a LEO say, r=6500~km, we get $\Delta v_{orbit}=7.8~km/s$, 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 to reduce the drag by optimizing the structure.

Once in a 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 duration needs to be minimized 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 planetary-type, such as the Moon or even in 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 from a laser beam can be calculated by

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

where P is the laser power, h the 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 is the working fluid in this propulsion system, the specific impulse is 3×10^7 seconds.

8.2 Influence of Gravity Manipulation on Propulsion Systems

In the following discussion we shall consider a series of hypothetical devices capable of manipulating the inertia (with influence in 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 will be 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 generate these effects by about twenty orders of magnitude, the schemes that are going to be discussed below would be worth a serious and concrete analysis. Here we consider two possible scenarios: a gravitoelectric field similar to the one generated by a coil, or a gravitoelectric-dipolar type field. Also the gravitomagnetic field itself can be used for propulsion purposes.

8.2.1 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 for 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 has now 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 oxydes 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 on 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 is the inertial mass modification, the amount of propellant will not be changed, or in other words, the change in the propulsion performance is always counterbalanced by the change in the Δv requirement!

Finally, we examine if 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

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

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

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

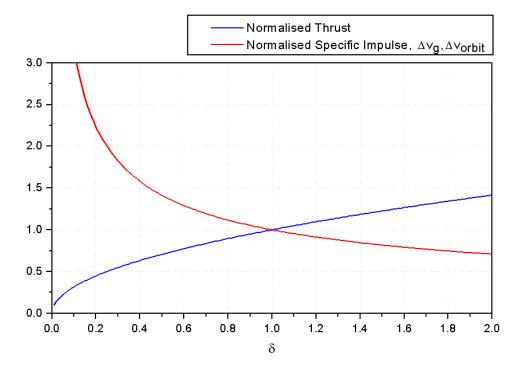


Figure 3: Influence of Inertial Mass Modification on Propulsion Performance and Δv Requirement

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

8.2.2 Gravitational Mass Modification

We turn now to the analysis on 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 get

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

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 needs to make a full orbit (less speed to cycle the Earth). This is may not be important for launching interstellar probes, but affects for instance, remote sensing or Geostationary Orbit (GEO) satellites which require cycling Earth with a certain speed for the purpose of mapping and telecommunication. 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, desactivate GMM and apply full Δv_{orbit} using a propulsion system. The centrifugal force is then balanced by the gravitational push.
- 2. GMM is always active and use propulsion system to counterbalance the higher centrifugal force to stay in orbit.

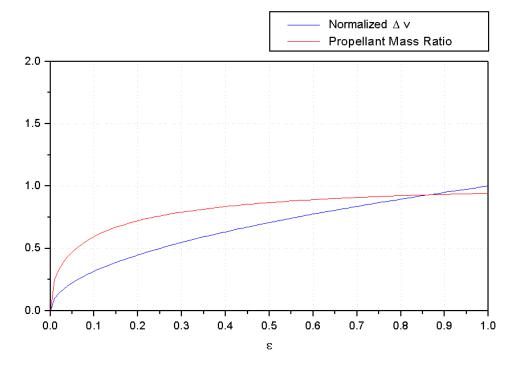


Figure 4: Influence of Gravitational Mass Manipulation on Propellant Consumption and Δv Requirement

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 the overall trip time.

Let us assume the extreme case where 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 of the total Δv . GEO satellites with a high altitude of 42, 160 km could reduce in this case from a total Δv of about 13 km/s to 3 km/s which would require a much smaller propulsion system reducing launch costs drastically. Only in the case where Δv_{orbit} is not important (e.g. interplanetary spacecraft), we can 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 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 on a gravitational field is substantially different from the one 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 lower the propellant consumption already by 90% with much higher propellant velocities. There are also technologies and concepts available which 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 reached a speed of 300 m/s. An extreme concept was put

⁶The Pegasus rocket from Orbital Sciences Corporation is currently being launched from a Boing 747 aircraft for reduction of the Δv requirement.

forward by Arthur C. Clarke [177] who proposed to built an ultra-high tower, which was named $space\ elevator$, for lifting spacecraft to orbits as high as $100\ km$.

8.2.3 Dipolar Gravito-Electric Field

Generation of an artificial gravitational field, would imply in 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 it can be seen in Figure (5), such field configuration could be used to generate a torque orientating the spacecraft parallel to the planet 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 does not require any power at all.

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

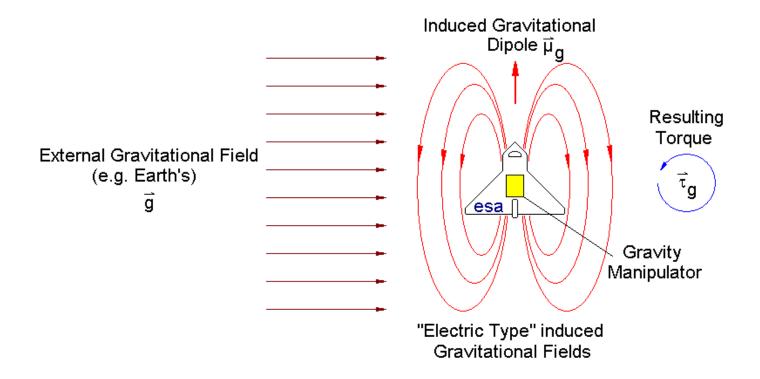


Figure 5: Dipolar Gravitoelectric Field - Propulsion System

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

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 a LEO. Therefore, a gravitational analogue adds no extra benefit to current tether technology.

8.2.5 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

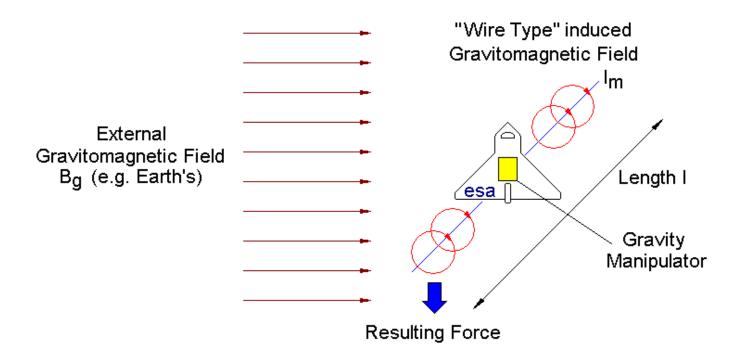


Figure 6: Wire-like Gravitoelectric Field - Propulsion System

transversable wormholes. Remarkably, our study reveals that control of gravity, even if it were achievable, does not imply in 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, top of a mountain, or in an extreme case, from an ultra-high tower. The use of gravitomagnetic or gravitoelectric fields for propulsion do not bring any extra benefit compared to classical electrodynamical tethers or gravity booms.

We present in Table 3 a summary of our conclusions.

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

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

9 Evaluation of Existing Literature and Programmes

Control of gravity is a topic which is discussed and speculated in a broad range of means including journal papers, conference proceedings and even patents. Part of this study consisted in 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 worthwile pursuing in the future. In addition, a number of national and industrial programmes are reviewed who coordinate research activities on the control of gravity, some of them in Europe.

9.1 Review of Existing Gravity Control Programmes

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

European scientists and industry are well involved in this type of exploratory research. Most notably, Project Greenglow from BAE Systems and Rolls-Royce in the UK fund 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 gather European and US scientists. Starlabs of Belgium, a privately funded research center supported by the high-tech industry, was also getting involved in gravity control research before filling for bankrupcy after the stock market crash in summer 2001. Also European Internet communities (such as the Jean-Louis Naudin Labs) do actively contribute to this unconventional topic of research.

9.1.1 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 introducting 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): Within this task, an extremely sensitive torsional gravity balance is 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 the light in vacuum. Experiments will be carried out to examine such effects.

We have analysed in the previous sections of this study 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 due to other reasons than gravity control. We stress that some of these claims can be shown to be inconsistent with well established observational facts accounted by known physical theories.

The Breakthrough Propulsion Physics (BPP) Project is headed by Marc Millis with an interim period in the summer of 2001 by Peter Ouzt. Funding so far was 685k\$ (about 770 kEuro, as of December 2001) covering the period from 1996-2000 excluding overheads. A BPP research consortium is being established and should be in place in the first Quarter of 2002. This research consortium will make easier collaboration with universities and industry and provide the administrative functions to manage the large number of geographically dispersed participants in BPP research. The consortium will consist of an advisory council to enable 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.

A next call for research proposals will be issued from this consortium and will be announced after the first Quarter of 2002. The consortium will issue formal research solicitations every other year from that point.

9.1.2 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. The project is 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 carried out at Universities in the UK. 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 the following:

- 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)

9.1.3 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 include

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

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

The final draft of the programme definition is currently under review at DoE senior management, funding is not expected to start before October 2002.

9.1.4 US Air Force

Since the 1970s, the Air Force is sponsoring speculative research, also in the area of propulsion relevant to the topic of gravity control. Dr. Franklin Mead from the propulsion directorate was in charge of most studies performed including survey and experimental work (such as on possible new coupling phenomena). His interest shifted recently towards "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 in the programme. Their goal is to achieve experimental results that are regarded as 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.

9.1.5 Internet Communities

In addition, many privately funded programmes were established, and information about their experimental activities and "theories" is available over the Internet. The major problem is a 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, under careful study, could be worthwile to investigate. As an example of some of these research organizations we mention:

- 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 homebuilt devices claiming extraordinary performance.

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

9.2 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 with respect to their credibility, a ranking criteria was defined. In addition to the actual ranking, comments are also included into the Database.

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

9.2.1 Scientific Criteria

This parameter will be used to indicate the credibility of a paper. A number from 0 - 5 has been assigned to quantify this criteria, 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-wide recognized journals with high impact parameter 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 which 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 without containing any nouvel concept or idea.

Examples:

- 0 ... Patent based on wrong assumption.
- 1 ... Conference/preprint paper containing a wrong derivation, however, the idea can be developed further in principle.
- 2 ... Conference paper speculating on new theoretical developments with some potential in principle.
- 3 ... Peer-review paper from a standard journal reporting an experimental observation of a new gravity coupling phenomena which has not been independently verified.
- 4 ... Peer-review paper showing important relations and limits but do not add new material to the subject.

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

9.2.2 Relevance for Study Criteria

This parameter shall link the scientific quality of the paper to the topic of this study, namely the control of gravity. This is done through an added letter from A to E after the scientific criteria. The letter parameter is defined as follows:

- A ... Not relevant, e.g. papers which do not deal with the gravity control subject in particular.
 - B ... Relevant only to a far 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.

Thus we conclude the discussion on the guiding principles used for the construction and organization of the Database. The reader will find in the Annex of this report all the information about the content of the Database as well as the necessary instructions for its use.

9.3 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 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 the following:

• 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 as well. An experiment involving the gravitational behaviour of antiparticles contained in a specially built Penning-trap located at the Space Station is, in our opinion, also highly desirable.

- Possible New Interactions of Nature may exist in connection to 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 the planet Mercury could most probably bring 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 to definetly settle the matter. As discussed in this report, gravitoelectromagnetic fields generated in mundane situations are tiny and their use, even for manoeuvring of spacecraft under microgravity conditions, is still elusive.

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Annex:

Database Documentation