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The Zero-Point Field and the NASA Challenge to Create the Space Drive

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Abstract — This NASA Breakthrough Propulsion Physics Workshop seeks to explore concepts that could someday enable interstellar travel. The effective superluminal motion proposed by Alcubierre (1994) to be a possibility owing to theoretically allowed space-time metric distortions within general relativity has since been shown by Pfenning and Ford (1997) to be physically unattainable. A number of other hypothetical possibilities have been summarized by Millis (1997). We present herein an overview of a concept that has implications for radically new propulsion possibilities and has a basis in theoretical physics: the hypothesis that the inertia and gravitation of matter originate in electromagetic interactions between the zero-point field (ZPF) and the quarks and electrons constituting atoms. A new derivation of the connection between the ZPF and inertia has been carried through that is properly covariant, yielding the relativistic equation of motion from Maxwell's equations. This opens new possibilites, but also rules out the basis of one hypothetical propulsion mechanism: Bondi's "negative inertial mass" appears to be an impossibility.

Keywords: zero-point field — interstellar travel — inertia — gravitation

Introduction

The objective of this NASA Breakthrough Propulsion Physics Workshop is to explore ideas ranging from extrapolations of known technologies to hypothetical new physics which could someday lead to means for interstellar travel. One concept that has generated interest is the proposal by Alcubierre (1994) that effectively superluminal motion should be a possibility owing to theoretically allowed space-time metric distortions within general relativity. In this model, motion between two locations could take place at effectively hyperlight speed without violating special relativity because the motion is not ***through*** space at $v > c$, but rather within a space-time distortion: somewhat like the "stretching of space itself' implied by the Hubble expansion. Alcubierre's concept would indeed be a "warp drive." Unfortunately Pfenning and Ford (1997) demonstrated that, while the theory may be correct in principle, the necessary conditions are physically unattainable. In "The Challenge to Create the Space Drive" Millis (1997) has summarized a number of other possibilities for radically new propulsion methods that could someday lead to interstellar travel if various hypothetical physics concepts should prove to be true. Seven different propulsion concepts were presented: three involved hypothetical collision sails and four were based on hypothetical field drives.

The purpose of this paper is to discuss a new physics concept that no longer falls in the category of "purely hypothetical," but rather has a theoretical foundation and is relevant to radically new propulsion schemes: the zero-point field (ZPF) as the basis of inertia and gravitation. On the basis of this concept we can definitively rule out one of the hypothesized propulsion mechanisms since the existence of negative inertial mass is conclusively shown to be an impossibility. On the other hand, a differential space sail becomes a distinct possiblity. More importantly, though, the door is theoretically open to the possibility of manipulation of inertia and gravitation of matter since both properties are shown to stem at least in part from electrodynamics. This raises the stakes considerably as Arthur C. Clarke (1997) writes in his novel, 3001 referring to the ZPF-inertia concept of Haisch, Rueda and Puthoff (1994; hereafter HRP):

> An "inertialess drive," which would act exactly like a controllable gravity field, had never been discussed seriously outside the pages of science fiction until very recently. But in 1994 three American physicists did exactly this, developing some ideas of the great Russian physicist Andrei Sakharov.

The Zero-Point Field From Planck's Work

In the year 1900 there were two main clouds on the horizon of classical physics: the failure to measure the motion of the earth relative to the ether and the inability to explain blackbody radiation. The first problem was resolved in 1905 with the publication of Einstein's "Zur Elektrodynamik bewegter Korper" in the journal ***Annalen der Physik,*** proposing what has come to be known as the special theory of relativity. It is usually stated that the latter problem, known as the "ultraviolet catastrophe," was resolved in 1901 when Planck, in "Über das Gesetz der Energieverteilung im Normalspektrum" in the same journal, derived a mathematical expression that fit the measured spectral distribution of thermal radiation by hypothesizing a quantization of the average energy per mode of oscillation, $\epsilon = h\nu$.

The actual story is somewhat more complex (cf. Kuhn, 1978). Since the objective is to calculate an electromagnetic spectrum one has to represent the electromagnetic field in some fashion. Well-known theorems of Weyl allow for an expansion in countably many infinite electromagnetic modes (*e.g.* Kurokawa, 1958). Every electromagnetic field mode behaves exactly as a linear harmonic oscillator. The Hamiltonian of a one-dimensional oscillator has two terms, one for the kinetic energy and one for the potential energy:

$$H = \frac{p^2}{2m} + \frac{Kx^2}{2}. \tag{1}$$

The classical equipartition theorem states that each quadratic term in position or momentum contributes $kT/2$ to the mean energy (*e.g.* Peebles, 1992). The mean energy of each mode of the electromagnetic field is then $< \mathrm{E} >= kT$. The number of modes per unit volume is $(8\pi\nu^2/c^3)d\nu$ leading to the Rayleigh-Jeans spectral energy density $(8\pi\nu^2/c^3)kTd\nu$ with its v^2 divergence (the ultraviolet catastrophe).

In his "first theory" Planck actually did more than simply assume $\epsilon = hv$. He considered the statistics of how "P indistinguishable balls can be put into N distinguishable boxes." (Milonni, 1994) So Planck anticipated the importance of the fundamental indistinguishability of elementary particles. With those statistics, the average energy of each oscillator becomes $< \mathrm{E} >= \epsilon/(\exp(\epsilon/kT) - 1)$. Assuming that $\epsilon = h\nu$ together with the use of statistics appropriate to indistinguishable energy elements then led to the spectral energy distribution consistent with measurements, now known as the Planck (or blackbody) function:

$$\rho(\nu, T)d\nu = \frac{8\pi\nu^2}{c^3}\left(\frac{h\nu}{e^{h\nu/kT} - 1}\right) d\nu. \tag{2a}$$

Contrary to the cursory textbook history, Planck did not immediately regard his $\epsilon = h\nu$ assumption as a new fundamental law of physical quantization; he viewed it rather as a largely ad *hoc* theory with unknown implications for fundamental laws of physics. In 1912 he published his "second theory" which led to the concept of zero-point energy. The average energy of a thermal oscillator treated in this fashion (cf. Milonni, 1994 for details) turned out to be $< E >= h\nu/(\exp(h\nu/kT) - 1) + h\nu/2$ leading to a spectral energy density:

$$\rho(\nu, T)d\nu = \frac{8\pi\nu^2}{c^3}\left(\frac{h\nu}{e^{h\nu/kT} - 1} + \frac{h\nu}{2}\right) d\nu. \tag{2b}$$

The significance of this additional term, $h\nu/2$, was unknown. While this appeared to result in a v^3 ultraviolet catastrophe in the second term, in the context of present-day stochastic electrodynamics (SED; see below) that is intepreted as not to be the case, because this component now refers not to measurable excess radiation from a heated object, but rather to a uniform, isotropic background radiation field that cannot be directly measured because of its homogeneity. Planck came to the conclusion that the zero-point energy would have no experimental consequences. It could be thought of as analagous to an arbitrary additive constant for potential energy. Nernst (1916), on the other hand, took it seriously and proposed that the Universe might actually contain enormous amounts of zero-point energy.

Work on zero-point energy in the context of classical physics was essentially abandoned at this stage as the development of quantum mechanics, and then quantum electrodynamics (QED), took center stage. However the parallel concept of an electromagnetic quantum vacuum soon emerged.

The Zero-Point Field From Quantum Physics

For a one-dimensional harmonic oscillator of unit mass the quantum-mechanical Hamiltonian analagous to Eq. (1) may be written (cf. Loudon, 1983)

$$\hat{H} = \frac{1}{2}(\hat{p}^2 + \omega^2 \hat{q}^2), \tag{3}$$

where p and $\hat{q}$ are momentum and position operators respectively. Linear combination of the p and q result in the ladder operators, also known as destruction (or lowering) and creation (or raising) operators respectively:

$$\hat{a} = (2\hbar\omega)^{-1/2}(\omega\hat{q} + i\hat{p}), \tag{4a}$$

$$\hat{a}^\dagger = (2\hbar\omega)^{-1/2}(\omega\hat{q} - i\hat{p}). \tag{4b}$$

The application of the destruction operator on the nth eigenstate of a quantum oscillator results in a lowering of the state, and similarly the creation operator results in a raising of the state:

$$\hat{a}|n\rangle = n^{1/2}|n-1\rangle, \tag{5a}$$

$$\hat{a}^\dagger|n\rangle = (n+1)^{1/2}|n+1\rangle, \tag{5b}$$

It can be seen that the number operator has the $|n\rangle$ states as its eigenstates as

$$\hat{N}|n\rangle = \hat{a}^\dagger\hat{a}|n\rangle = n|n\rangle. \tag{5c}$$

The Hamiltonian or energy operator of Eq. (3) becomes

$$\hat{H} = \hbar\omega\left(\hat{N} + \frac{1}{2}\right) = \hbar\omega\left(\hat{a}^{\dagger}\hat{a} + \frac{1}{2}\right). \tag{6}$$

The ground state energy of the quantum oscillator, $|0\rangle$, is greater than zero, and indeed has the energy $\frac{1}{2}\hbar\omega$,

$$\hat{H}|0\rangle = E_0|0\rangle = \frac{1}{2}\hbar\omega|0\rangle, \tag{7}$$

and thus for excited states

$$E_n = \left(n + \frac{1}{2}\right)\hbar\omega. \tag{8}$$

Now let us turn to the case of classical electromagnetic waves. Plane electromagnetic waves propagating in a direction k may be written in terms of a vector potential $\mathbf{A_k}$ as

$$\mathbf{E_k} = i\omega_{\mathbf{k}}\{\mathbf{A_k}\mathrm{exp}(-i\omega_{\mathbf{k}}t + i\mathbf{k}\cdot\mathbf{r}) - \mathbf{A}^*_{\mathbf{k}}\mathrm{exp}(i\omega_{\mathbf{k}}t - i\mathbf{k}\cdot\mathbf{r})\}, \tag{9a}$$

$$\mathbf{B_k} = i\mathbf{k}\times\{\mathbf{A_k}\mathrm{exp}(-i\omega_{\mathbf{k}}t + i\mathbf{k}\cdot\mathbf{r}) - \mathbf{A}^*_{\mathbf{k}}\mathrm{exp}(i\omega_{\mathbf{k}}t - i\mathbf{k}\cdot\mathbf{r})\}, \tag{9b}$$

Using generalized mode coordinates analogous to momentum ($P_{\mathbf{k}}$) and position ($Q_{\mathbf{k}}$) in the manner of Eqs. (4ab) above one can write $\mathbf{A_k}$ and $\mathbf{A}^*_{\mathbf{k}}$ as

$$\mathbf{A_k} = (4\epsilon_0 V\omega^2_{\mathbf{k}})^{-\frac{1}{2}}(\omega_{\mathbf{k}}Q_{\mathbf{k}} + iP_{\mathbf{k}})\hat{\varepsilon}_k, \tag{10a}$$

$$\mathbf{A}^*_{\mathbf{k}} = (4\epsilon_0 V\omega^2_{\mathbf{k}})^{-\frac{1}{2}}(\omega_{\mathbf{k}}Q_{\mathbf{k}} - iP_{\mathbf{k}})\hat{\varepsilon}_k, \tag{10b}$$

where $\hat{\varepsilon}_k$ is the polarization unit vector and V the cavity volume. In terms of these variables, the single-mode phase-averaged energy is

$$< E_{\mathbf{k}} >= \frac{1}{2}(P^2_{\mathbf{k}} + \omega^2_{\mathbf{k}}Q^2_{\mathbf{k}}). \tag{11}$$

Note the parallels between equations (10) and (4) and equations (11) and (3). Just as mechanical quantization is done by replacing position, x, and momentum, p, by quantum operators x and **p**, so is the "second" quantization of the electromagnetic field accomplished by replacing **A** with the quantum operator A, which in turn converts E into the operator E, and B into B. In this way, the electromagnetic field is quantized by associating each k-mode (frequency, direction and polarization) with a quantum-mechanical harmonic oscillator. The ground-state of the quantized field has the energy

$$< E_{\mathbf{k},0} >= \frac{1}{2}(P^2_{\mathbf{k},0} + \omega^2_{\mathbf{k}} Q_{\mathbf{k},0})^2 = \frac{1}{2}\hbar\omega_{\mathbf{k}} \tag{12}$$

that originates in the non-commutative algebra of the creation and annihilation operators. It is as if there were on average half a photon in each mode.

Zero-Point Field In Stochastic Electrodynamics

A common SED treatment (cf. Boyer, 1975 and references therein; also the comprehensive review of SED theory by de la Peña & Cetto 1996) has been to posit a zero-point field (ZPF) consisting of plane electromagnetic waves whose amplitude is ***exactly*** such as to result in a phase-averaged energy of $\hbar\omega/2$ in each mode $(\mathbf{k}, \sigma)$, where we now explicitly include the polarization, a. After passing to the continuum such that summation over discrete modes of propagation becomes an integral (valid when space is unbounded or nearly so) this can be written as:

$$\mathbf{E}^{ZP}(\mathbf{r},t) = \mathrm{Re}\sum_{\sigma=1}^{2}\int d^3k\hat{\varepsilon}_{\mathbf{k},\sigma}\left[\frac{\hbar\omega_{\mathbf{k}}}{8\pi^3\epsilon_0}\right]^{\frac{1}{2}}\exp(i\mathbf{k}\cdot\mathbf{r} - i\omega_{\mathbf{k}}t + i\theta_{\mathbf{k},\sigma}), \tag{13a}$$

$$\mathbf{B}^{ZP}(\mathbf{r},t) = \mathrm{Re}\sum_{\sigma=1}^{2}\int d^3k(\hat{k}\times\hat{\varepsilon}_{\mathbf{k},\sigma})\left[\frac{\hbar\omega_{\mathbf{k}}}{8\pi^3\epsilon_0}\right]^{\frac{1}{2}}\exp(i\mathbf{k}\cdot\mathbf{r} - i\omega_{\mathbf{k}}t + i\theta_{\mathbf{k},\sigma}), \tag{13b}$$

where $\theta_{\mathbf{k},\sigma}$ is the phase of the waves. The stochasticity is entirely in the phase of each wave: There is no correlation in phase between any two plane electromagnetic waves k and **k'**, and this is represented by having the $\theta_{\mathbf{k},\sigma}$ phase random variables independently and uniformly distributed between 0 and 2π.

Davies-Unruh Effect

In connection with "Hawking radiation" from evaporating black holes, Davies (1975) and Unruh (1976) determined that a Planck-like component of the ZPF will arise in a uniformly-accelerated cordinate system with constant proper acceleration **a** (where $|\mathbf{a}| = $ a) having an effective temperature,

$$T_a = \frac{\hbar a}{2\pi ck}. \tag{14}$$

This temperature is negligible for most accelerations. Only in the extremely large gravitational fields of black holes or in high-energy particle collisions can this become significant. This effect has been studied using both quantum field theory (Davies, 1975; Unruh, 1976) and in the SED formalism (Boyer, 1980). For the classical SED case it is found that the spectrum is quasi-Planckian in T_a. Thus for the case of no true external thermal radiation $(T = 0)$ but including this acceleration effect (T_a), equation (2b) becomes

$$\rho(\nu, T_a)d\nu = \frac{8\pi\nu^2}{c^3}\left[1 + \left(\frac{a}{2\pi c\nu}\right)^2\right]\left[\frac{h\nu}{2} + \frac{h\nu}{e^{h\nu/kT_a} - 1}\right]d\nu, \qquad (15)$$

where the acceleration-dependent pseudo-Planckian component is placed after the $h\nu/2$ term to indicate that except for extreme accelerations (*e.g.* particle collisions at high energies) this term is very small. While these additional acceleration-dependent terms do not show any spatial asymmetry in the expression for the ZPF spectral energy density, certain asymmetries do appear when the electromagnetic field interactions with charged particles are analyzed, or when the momentum flux of the ZPF is calculated. The ordinary plus a^2 radiation reaction terms in Eq. (12) of HRP mirror the two leading terms in Eq. (15).

Newtonian Inertia From ZPF Electrodynamics

The HRP analysis resulted in the apparent derivation of Newton's equation of motion, $F = ma$, from Maxwell-Lorentz electrodynamics as applied to the ZPF. In that analysis it appeared that the resistance to acceleration known as inertia was in reality the electromagnetic Lorentz force stemming from interactions between a charged particle (such as an electron or a quark) and the ZPF, *i.e.* it was found that the stochastically-averaged expression $< \mathbf{v}_{osc} \times \mathbf{B}^{ZP} >$ was proportional to and in the opposite direction to the acceleration $\mathbf{a}$. The velocity $\mathbf{v}_{osc}$ represented the internal velocity of oscillation induced by the electric component of the ZPF, $\mathbf{E}^{ZP}$, on the harmonic oscillator. For simplicity of calculation, this internal motion was restricted to a plane orthogonal to the external direction of motion (acceleration) of the particle as a whole. The Lorentz force was found using a perturbation technique; this approach followed the method of Einstein and Hopf (1910a, b). Owing to its linear dependence on acceleration we interpreted this resulting force as Newton's inertia reaction force on the particle.

The analysis can be summarized as follows. The simplest possible model of a structured particle (which, borrowing Feynman's terminology, we referred to as a parton) is that of a harmonically-oscillating point charge ("Planck oscillator"). Such a model would apply to electrons or to the quarks constituting protons and neutrons for example. (Given the peculiar character of the strong interation that it increases in strength with distance, to a first approximation it is reasonable in such an exploratory attempt to treat the three quarks in a proton or neutron as independent oscillators.) This Planck oscillator is driven by the electric component of the ZPF, $\mathbf{E}^{ZP}$, to harmonic motion, $\mathbf{v}_{\mathbf{osc}}$, assumed for simplicity to be in a plane. The oscillator is then forced by an external agent to undergo a constant acceleration, $\mathbf{a}$, in a direction perpendicular to that plane of oscillation, *i.e.* perpendicular to the $\mathbf{v}_{osc}$ motions. New components of the ZPF will appear in the frame of the accelerating particle having a similar origin to the terms in equation (15). The leading term of the acceleration-dependent terms is taken; the electric and magnetic fields are transformed into a constant proper acceleration frame using well-known relations. The Lorentz force arising from the acceleration-dependent part of the B^{ZP} acting upon the Planck oscillator is calculated. This is found to be proportional to the imposed acceleration. The constant of proportionality is interpreted as the inertial mass, m_i, of the Planck oscillator. The inertial mass, m_i, is a function of the Abraham-Lorentz radiation damping constant of the oscillator and of the interaction frequency with the ZPF,

$$m_i = \frac{\Gamma h \nu_0^2}{2\pi c^2}, \tag{16}$$

where we have written ν_0 to indicate that this may be a resonance rather than the cutoff assumed by HRP. Since both Γ and ν_o are unknown, we can make no absolute prediction of mass values in this simple model. Nevertheless, if correct, the HRP concept substitutes for Mach's principle a very specific electromagnetic effect acting between the ZPF and the charge inherent in matter. Inertia is an acceleration-dependent electromagnetic (Lorentz) force. Newtonian mechanics would then be derivable in principle from Maxwell electrodynamics. Note that this coupling of the electric and magnetic components of the ZPF via the technique of Einstein and Hopf is very similar to that found in ordinary electromagnetic radiation pressure.

The Relativistic Equation of Motion and ZPF Electrodynamics

The physical oversimplification of an idealized oscillator interacting with the ZPF as well as the mathematical complexity of the HRP analysis are understandable sources of skepticism, as is the limitation to Newtonian mechanics. A relativistic form of the equation of motion having standard covariant properties has been obtained (Rueda & Haisch, 1997a,b). To understand how this comes about, it is useful to back up to fundamentals.

Newton's third law states that if an agent applies a force to a point on an object, at that point there arises an equal and opposite force back upon the agent. Were this not the case, the agent would not experience the process of exerting a force and we would have no basis for mechanics. The law of equal and opposite contact forces is thus fundamental both conceptually and perceptually, but it is legitimate to seek further underlying connections. In the case of a stationary object (fixed to the earth, say), the equal and opposite force can be said to arise in interatomic forces in the neighborhood of the point of contact which act to resist compression. This can be traced more deeply still to electromagnetic interactions involving orbital electrons of adjacent atoms or molecules, *etc.*

A similar experience of equal and opposite forces arises in the process of accelerating (pushing on) an object that is free to move. It is an experimental fact that to accelerate an object, a force must be applied by an agent and that the agent will thus experience an equal and opposite reaction force so long as the acceleration continues. It appears that this equal and opposite reaction force also has a deeper physical cause, which turns out to also be electromagnetic and is specifically due to the scattering of ZPF radiation. Rueda and Haisch (1997a,b) demonstrate that from the point of view of the pushing agent there exists a net momentum flux (related to the Poynting vector) of ZPF radiation transiting the accelerating object in a direction necessarily opposite to the acceleration vector. The scattering opacity of the object to the transiting flux creates the back reaction force customarily called the inertia of the object. Inertia is thus a special kind of electromagnetic drag force, namely one that is acceleration-dependent since only in accelerating frames is the ZPF perceived as asymmetric. In stationary or uniform-motion frames the ZPF is perfectly isotropic with a zero net Poynting vector.

The relativistic form of the equation of motion results because, from the point of view of the agent, the accelerating object has a velocity dependent proper volume due to length contraction in the direction of motion which modifies the amount of scattering of ZPF flux that takes place within the object.

The physical interpretation that springs from this analysis is the following. In stationary or uniform-motion frames the interaction of a particle with the ZPF will result in random oscillatory motions. Fluctuating charged particles will produce dipole scattering of the ZPF which may be parametrized by an effective scattering spectral coefficient $\eta(\omega)$ that depends on frequency. Owing to the relativistic transformations of the ZPF, in an accelerated frame the interactions between a particle and the field acquire a definite direction, *i.e.* the "scattering" of ZPF radiation generates a directional resistance force. This directional resistance force is proportional to and directed against the acceleration vector for the subrelativisitic case and it proves to have the proper relativistic generalization.

Gravitation

If inertial mass, m_i, originates in ZPF-charge interactions, then, by the principle of equivalence so must gravitational mass, m,. In this view, gravitation would be a force originating in ZPF-charge interactions analogous to the HRP inertia concept. Sakharov (1968) was the first to conjecture this interpretation of gravity. If true, gravitation would be unified with the other forces: it would be a manifestation of electromagnetism.

The general relativistic mathematical treatment of gravitation as a space-time curvature works extremely well. However if it could be shown that a different theoretical basis can be made analytically equivalent to space-time curvature, with its prediction of gravitational lensing, black holes, ***etc.*** this may reopen the possibility that gravitation should be viewed as a force.

The following points are worth noting: (I) space-time curvature is inferred from the propagation of light; (2) general relativity and quantum physics are at present irreconcilable, therefore something substantive is either wrong or missing in our understanding of one or both; (3) the propagation of gravitational waves is not rigorously consistent with space-time curvature. (The issue revolves around whether gravitational waves can be made to vanish in a properly chosen coordinate system. The discovery of apparent gravitational energy loss by the Hulse-Taylor pulsar provides indirect evidence for the existence of gravitational waves. Theoretical developments and calculations have not yet been performed to examine whether an approach based on the Sakharov (1968) ideas would predict gravitational waves, but the coordinate ambiguities of GR should not appear in a ZPF-referenced theory of gravitation.)

There were some early pioneering attempts, inspired by Sakharov's conjecture, to link gravity to the vacuum from a quantum field theoretical viewpoint (by Amati, Adler and others, see discussion and references in Misner, Thorne and Wheeler [1973]) as well as within SED. The first step in developing Sakharov's conjecture in any detail within the classical context of nonrelativistic SED was the work of Puthoff (1989). Gravity is treated as a residuum force in the manner of the van der Waals forces. Expressed in the most rudimentary way this can be viewed as follows. The electric component of the ZPF causes a given charged particle to oscillate. Such oscillations give rise to secondary electromagnetic fields. An adjacent charged particle will thus experience both the ZPF driving forces causing it to oscillate, and in addition forces due to the secondary fields produced by the ZPF-driven oscillations of the first particle. Similarly, the ZPF-driven oscillations of the second particle will cause their own secondary fields acting back upon the first particle. The net effect is an attractive force between the particles. The sign of the charge does not matter: it only affects the phasing of the interactions. Unlike the Coulomb force which, classically viewed, acts directly between charged particles, this interaction is mediated by extremely minute propagating secondary fields created by the ZPF-driven oscillations, and so is enormously weaker than the Coulomb force. Gravitation, in this view, appears to be a long-range interaction akin to the van der Waals force.

The ZPF-driven ultrarelativistic oscillations were named ***Zitterbewegung*** by Schrodinger. The Puthoff analysis consists of two separate parts. In the first, the energy of the ***Zitterbewegung*** motion is equated to gravitational mass, m_g (after dividing by c^2). This leads to a relationship between m_g and electrodynamic parameters that is identical to the HRP inertial mass, m_i, apart from a factor of two. This factor of two is discussed in the appendix of HRP, in which it is concluded that the Puthoff m, should be reduced by a factor of two, yielding $m_i = m$, precisely.

The second part of Puthoff's analysis is more controversial. He quantitatively examines the van der Waals force-like interactions between two driven oscillating dipoles and derives an inverse square force of attraction. This part of the analysis has been challenged by Carlip (1993), to which Puthoff (1993) has responded, but, since problems remain (Danley, 1994), this aspect of the ZPF-gravitation concept requires further theoretical development, in particular the implementation of a fully relativistic model.

Clearly the ZPF-inertia and the ZPF-gravitation concepts must stand or fall together, given the principle of equivalence. However, that being the case, the Sakharov-Puthoff-type gravity concept does legitimately refute the objection that "the ZPF cannot be a real electromagnetic field since the energy density of this field would be enormous and thereby act as a cosmological constant, **A**, of enormous proportions that would curve the Universe into something microscopic in size." This cannot happen in the Sakharov-Puthoff view. This situation is clearly ruled out by the elementary fact that, in this view, the ZPF cannot act upon itself to gravitate. Gravitation is not caused by the mere presence of the ZPF, rather by secondary motions of charged particles driven by the ZPF. *In this view it is impossible for the ZPF to give rise to a cosmological constant.* (The possibility of non-gravitating vacuum energy has recently been investigated in quantum cosmology in the framework of the modified Born-Oppenheimer approximation by Datta [1995].)

The other side of this argument is of course that as electromagnetic radiation is not made of polarizable entities, one might naively no longer expect deviation of light rays by massive bodies. We speculate, however, that such deviation will be part of a fully relativistic theory that besides the ZPF, properly takes into account the polarization of the Dirac vacuum when light rays pass through the particle-antiparticle Dirac sea. It should act, in effect, as a medium with an index of refraction modified in the vicinity of massive objects. This is very much in line with the original Sakharov (1968) concept. Indeed, within a more general field-theoretical framework one would expect that the role of the ZPF in the inertia and gravitation developments mentioned above will be played by a more general quantum vacuum field, as was already suggested in the HRP appendix.

Summary of Four Types of Masses and Impossibility of Negative Mass

The proposed ZPF perspective associates very definite charged particle-field interactions with each of the four fundamental masses: inertial mass, active *vs.* passive gravitational mass and relativistic rest mass. It is important to be clear on the origin and interrelation of these "masses" when considering something as fundamental as the possibility of altering inertial (or gravitational) mass.

Inertial mass is seen as the reaction force due to the asymmetry of the perceived ZPF in any accelerated frame. A flux of ZPF radiation arises in an accelerated frame. When this flux is scattered by the charged particles (quarks or electrons) within any object a reaction force is generated proportional to the acceleration and to the proper volume of the object. This immediately rules out any science-fiction-like possibility of "negative mass" (not to be confused with anti-matter) originally hypothesized by Bondi (1957). If an observer moves to the right, the perceived motion of the surroundings must be to the left. There is no other rational possibility. Thus the flux scattering which is the physical basis of inertia must be directed against the motion, since the (accelerated) motion is into the flux: an object being accelerated must push back upon the accelerating agent, because from the point of view of the object, the radiation is coming toward it, which in turn points back upon the accelerating agent.

Active gravitational mass is attributed to the generation of secondary radiation fields as a result of the ZPF-driven oscillation. Passive gravitational mass is attributed to the response to such secondary radiation fields. Finally, the relativistic rest mass in the $E = mc^2$ relation reflects the energy of the ZPF-induced ***Zitterbewegung*** oscillations. Mass is the manifestation of energy in the ZPF acting upon charged particles to create forces.

The Need for a Quantum Derivation

Clearly a quantum field theoretical derivation of the ZPF-inertia connection is highly desireable. Another approach would be to demonstrate the exact equivalence of SED and QED. However as shown convincingly by de la Peña and Cetto (1996), the present form of SED is not compatible with QED, but modified forms could well be, such as their own proposed "linear SED." Another step in the direction of reconciling SED and QED is the proposed modification of SED by Ibison and Haisch (1996), who showed that a modification of the standard ZPF representation (Eqs. 13a and 13b) can exactly reproduce the statistics of the electromagnetic vacuum of QED. This gives us confidence that the SED basis of the inertia and gravitation concepts is a valid one.

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