ZERO-POINT FIELDS, GRAVITATION AND NEW PHYSICS

A Report by

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Abstract

Research over the last decade has shown that problems exist about how to reconcile the zero-point fields that follow from quantum mechanics with the energy conditions built into classical gravitational theories such as general relativity. Here, these problems are identified, and possible resolutions are suggested. The inference from the material presented here is that research into zero-point physics is justified and should continue to be supported. However, a catalog is given detailing 11 topics wherein past research has run into difficulties. These difficulties are in principle surmountable, and there is given a list of 6 topics that are theoretically and practically important for future pursuit.

1 Introduction

In recent years, it has been suggested that the electromagnetic zero-point field (zpf) is not merely an artefact of quantum mechanics, but a real entity with major implications for gravity, astrophysics and technology. This view is shared by a number of researchers, including Boyer (1980), McCrea (1986), Puthoff (1987) and Rueda and Haisch (1998a). The present work is a report on research into the zpf during the last decade, with recommendations about where investigations should be directed in the future.

The theoretical basis for believing in a real zpf is simple. A one-dimensional harmonic oscillator has states which can be raised or lowered in units n of $\hbar\omega$ where $\hbar$ is Planck's constant divided by 2π and ω is the frequency. In terms of the momentum operator $\hat{p}$ and the position operator $\hat{q}$, the Hamiltonian (energy) of the system is $\hat{H} = \left(\hat{p}^2 + \omega^2\hat{q}^2\right)/2$. The excited states have energy $E_n = (n + 1/2)\,\hbar\omega$, a relation which is known to lead to acceptable results in quantum-mechanical calculations for $n \geq 0$. However, if the kinetic energy of the system (or alternatively the temperature) goes to zero, there remains a zero-point energy of $\hbar\omega/2$. This, summed over frequencies, represents a zero-point field with a large energy density.

The countervailing approach to modern physics is via Einstein's theory of general relativity. This is supported by the so-called $(3 + 1)$ classical solar-system tests, as well as data from binary pulsars and gravitational lensing. According to general relativity, all forms of energy produce gravitational effects.

The quantum and classical pillars of modern physics are not architecturally campatible: the (electromagnetic) zero-point field does not appear to produce the expected classical gravitational effects.

This report aims to elucidate this contratemps. Section 2 is an account of research in both the quantum and gravitational domains, where contradictions are highlighted. Section 3 is a catalog of problems that are outstanding. There are many of these, so Section 4 is a list of recommendations about where future research efforts should be focussed. Section 5 is a conclusion, and there follows an up-to-date bibliography.

2 Recent Work on the Electromagnetic ZPF

This section presents an objective discussion of the most significant work that has been done on the zpf and its implications for gravity in the last decade. The emphasis is on how a quantum-mechanical electromagnetic zpf can be reconciled with a classical theory of gravity such as general relativity.

Haisch, Rueda and Puthoff (1994) argued that the elementary constituents of matter, such as electrons and quarks, when accelerating through the electromagnetic zero-point field, experience a Lorentz-type force. This force acts against the acceleration, and the authors identified this as giving rise to inertia. The calculations leading to this conclusion are lengthy, but the main result is simple: a particle acquires an inertial mass

$$m_i = \frac{\Gamma \hbar \omega_c^2}{2\pi c^2} \quad . \tag{1}$$

Here Γ is the Abraham-Lorentz damping constant, $\hbar \equiv h/2\pi$ as above, c is the speed of light, and ω_c is a cutoff frequency.

The last is not fixed by theoretical considerations. From the physical side, one might expect ω_c to correspond to the size of the particle, and its inability to respond to oscillations of the zpf with wavelengths of arbitrary smallness. Provided ω_c is large enough (or the wavelength small enough), the Lorentz invariance of the zpf spectrum will not be measurably affected. One could, of course, relate ω_c to the Planck frequency:

$$\omega_P = \left(\frac{c^5}{\hbar G} \right)^{1/2} \quad . \tag{2}$$

Here G is the Newtonian gravitational constant, which since c and $\hbar$ also appear is commonly taken to indicate that $\omega_P$is a fundamental limit on frequency set by quantum gravity. This argument, as pointed out by Wesson (1992a) and others, is logically suspect. The same dimensional argument, applied to the mass, would imply that the Universe should be dominated by particles with the Planck mass of order 10^{-5} gm. This is manifestly not the case. Wisely, Haisch, Rueda and Puthoff (1994) avoid the identification of ω_c with ω_P.

Another physical constant which the authors leave out of their discussion is Λ, the cosmological constant (loc. cit., p. 693). This parameter is present in Einstein's field equations of general relativity because the metric tensor g_{ij} on which the theory is based acts like a constant under covariant (curved-space) differentiation, so a term like Λg_{ij} will not affect the consequences of the field equations. (To this extent, it is like the gauge-invariance manifested by Maxwell's equations of electromagnetism.) Then Einstein's field equations in full read

$$R_{ij} - \frac{Rg_{ij}}{2} + \Lambda g_{ij} = \frac{8\pi G}{c^2} T_{ij} \, (i,j = 0, 123) \quad . \tag{3}$$

Here R_{ij} is the Ricci tensor, R is the Ricci scalar, and T_{ij} is the energy-momentum tensor. The last depends in general on the 4-velocity of the matter $u^i = dx^i/ds$ (where s is the 4D interval or proper time) and properties of the matter. For a perfect fluid with density ρ and pressure p,

$$T_{ij} = \left(\rho + \frac{p}{c^2}\right) u_i u_j - \frac{p}{c^2} g_{ij} \quad . \tag{4}$$

Now Λ in textbooks is commonly regarded as a kind of force per unit mass, which from the Schwarzschild metric is given by $\Lambda rc^2/3$ (here we take Λ to have dimension length^{-2}). However, (3) and (4) show that Λ can also be regarded as describing a density and pressure for the vacuum, given by

$$\rho_v = \frac{\Lambda c^2}{8\pi G} = -\frac{p_v}{c^2} \quad . \tag{5}$$

That is, the equation of state of the vacuum in Einstein's theory is the inflationary universe one $\rho_v + p_v/c^2 = 0$. Also, the fluid decribed by (5) behaves to all physical intents as a zero-point field.

It is well known that the zero-point fields predicted by particle physics are many orders more intense than the cosmological Λ-field, a puzzle which is usually termed the cosmological constant problem (see Weinberg 1989, Ng

1992 and Wesson 1999 for reviews). This is basically a contradiction between a particle-physics prediction and an astrophysical observation. There are several possible resolutions of it, but the consensus is that the zpf's associated with the interactions of particles must in some way cancel, perhaps due to the operation of a physical principle such as supersymmetry (see Wesson 1999, p. 33). From the viewpoint of the electromagnetic zpf and the origin of inertia as discussed by Haisch, Rueda and Puthoff (1994), something similar must necessarily happen. Otherwise, the energy-density of the zpf would curve spacetime (as does Λ) to a degree which is incompatible with astrophysical observations such as the dynamics of galaxies and the lensing of QSOs. The authors in fact avoid this and related problems by arguing that it is only the perturbation of the zpf which produces gravity and curvature; and that the zpf itself does not gravitate or produce a Λ-type field.

Cosmological and astrophysical constraints on the zpf were derived by Wesson (1991) using a model of Puthoff (1987; 1989a,b). The latter model envisioned the electromagnetic zpf as an Olbers-type field that is continuously absorbed and regenerated by charged particles within the observable part of the universe. The latter can be assumed to have uniform density and (if finite) pressure, in which case (3) reduce to the Friedmann equations:

$$8\pi G\rho = \frac{3kc^2}{R^2} + \frac{3\dot{R}^2}{R^2} - \Lambda c^2$$

$$\frac{8\pi Gp}{c^2} = \frac{-kc^2}{R^2} - \frac{\dot{R}^2}{R^2} - \frac{2\ddot{R}}{R} + \Lambda c^2 \qquad . \tag{6}$$

Here $R = R(t)$ is the scale factor, k is the curvature constant ($k = \pm 1$ or 0) and an overdot represents differentiation with respect to the time t. The joining of a quantum-mechanical zpf to classical models in Einstein's theory which obey (6) is technically problematical, and the original model of Puthoff was criticized in connection with its application to general relativity and its derivation of a quasi-Newtonian law of gravity (Santos 1991, Wesson 1992b, Carlip 1993). However, the reformulation of the model by Wesson (1991) is technically sound. This is not to say, though, that its implications for cosmology and astrophysics are benign. For example, it is difficult to see how an electromagnetic zpf does not leak energy into wavelength bands on which conventional astrophysics has much data. There is excellent data on the isotropy and intensity of the 3K microwave background, good constraints on the infrared, optical and ultraviolet backgrounds, and usable data on the X-ray and γ-ray backgrounds (for a review see Overduin and Wesson 1992). One wonders how the zpf is so isolated as not to produce any notable perturbations in these wavebands. A related question, which we have touched on above, concerns the gravitational effect of the zpf. If one requires that its mass density not exceed the critical (Einstein-deSitter) density, its spectrum must have a cutoff at a wavelength $\lambda_c \geq 0.2$ mm, which would destroy its Lorentz invariance in a practical way since wavelengths of this type are readily observable using conventional astrophysical techniques. This constraint can, however, be reinterpreted to mean that the view of Puthoff, Haisch and Rueda is correct and that the zpf does not gravitate.

Rueda and Haisch (1998 a,b) revisited the issues discussed above, removing certain ad hoc aspects of the particle-field interaction, but reaching similar results. In particular, they reiterated that inertia is a kind of electromagnetic drag that affects charged particles undergoing acceleration through the (electromagnetic) zpf, and connected this again to the existence of a gravity-like force as originally envisioned by Sakharov (1968). They concentrated on rectilinear motion with uniform constant acceleration, which results in hyperbolic orbits, but also considered more general motion. They also pointed out that their model for the origin of inertia is Machian, in the sense that a local particle acquires its (inertial) mass through an interaction with a global field.

The history of Mach's principle is long, and there are several different formulations of it in the literature (see Wesson 1978, 1999 for reviews). Though it is widely conceded that Einstein's theory of general relativity is not Machian, there is a consensus among researchers that an extension of that theory would be appealing if it gave an account of the properties of particles in terms of some cosmological field. Theories of this type have been proposed by Dirac, Hoyle and Narlikar, Canuto and coworkers, and Wesson and coworkers.

In the approach of the last-mentioned authors, the (inertial) rest mass of a particle is treated as a coordinate in a dimensionally-extended spacetime, where the two physically natural (but mathematically equivalent) choices are

$$\ell_g = \frac{Gm}{c^2} \qquad , \qquad \ell_p = \frac{h}{mc} \qquad . \tag{7}$$

These choices correspond to what in 4D scale-covariant theories of gravity are called gravitational and particle units. In a fully-covariant, dimensionally-extended theory based on Riemannian geometry, these choices are seen as representing convenient coordinate frames. There are many theories with extended dimensionality, notably Kaluza-Klein theory (5D), superstrings (10D) and supergravity (11D). The choice of dimensionality depends on which aspects of particle physics one wishes to explain alongside gravity. Most work has been done on Kaluza-Klein theory, which since its origin in the 1920s has accummulated a vast literature (Kaluza 1921; Klein 1926; for a review of modern 5D theory, see Overduin and Wesson 1997). In the current approach, so-called <u>induced-matter theory</u>, the Einstein field equations (3) for 4D with matter are replaced by the 5D field equations with vacuum:

$$R_{AB} = 0 \qquad\qquad (A, B = 0, 1, 2, 3, 4) \quad . \tag{8}$$

These 15 equations break down into sets of 10, 4 and 1. The first set is just Einstein's equations (3), but now with matter <u>derived</u> from the field equations by virtue of the extra metric coefficient and derivatives with respect to the extra coordinate. [It is now widely conceded that one should not insist on a circular topology for the extra dimension or insist on setting derivatives with respect to the extra coordinate to zero, as in the original Kaluza-Klein theory, since these assumptions lead to the hierarchy and cosmological-constant problems to do with particle masses and the value of Λ, as alluded to elsewhere.] The second set of 4D equations given by the 5D ones (8) has been known for a long time to be just Maxwell's equations of electrodynamics. The last (or 4-4) equation in (8) is a conservation equation for the scalar field in the extended metric (g_{44}). The field equations (8) are in agreement with the classical tests of relativity and cosmological data (Will 1993; Kalligas, Wesson and Everitt 1995) and cosmological data (Wesson 1999). The identification (7) for mass makes the theory Machian. The field equations (2.7) are non-linear, leading to a rich field of solutions for the fields.

Both of the latter characteristics were mentioned by Rueda and Haisch (1998) as attributes of their approach to the origin of inertia by accelerated motion through vacuum. This approach can be based on stochastic electrodynamics or SED, which briefly is an alternative approach using classical field theory to results derived from quantum field theory (for a review see De La Peña and Cetto 1996). However, as described above, a Machian theory of non-linear fields can also be approached through dimensionally-extended Riemannian geometry as used in modern Kaluza-Klein or KK theory (for a review see Wesson 1999). The choice between SED and KK - or other theories - depends on academic concerns to do with consistency and practical concerns to do with testability. We will return to these issues below.

Haisch and Rueda (1999a) returned to the issue of non-linearities, arguing that the observed masses of particles (e.g., the electron mass at 512 keV) are due to resonances in the electromagnetic zpf. They also suggested that the scattering of the zpf by a charged particle takes place at the Compton wavelength defined by the second relation in (7); and that this leads to the de Broglie relation characterizing the wave description of the particle in terms of $\lambda_{deB} = h/p$ (where p is the momentum). This extension of their previous work is interesting; but in terms of making contact with the testable aspects of wave-mechanics, needs to be extended to a full discussion of the wave function and how its modulus defines the probability of finding a particle at a given place in a given potential.

Haisch, Rueda and Puthoff (1998) discussed further aspects of their approach to the zpf, including its possible practical application to spacecraft propulsion (see below) and the concept of negative mass. The latter idea may sound unusual. However, it should be recalled that a negative-energy field is potentially a way of cancelling the enormous positive energy densities of particle physics, and would lead to a cosmological model of the Milne type. The Milne model (Wesson 1991) is a solution of the Friedmann equations (6) with zero <u>net</u> density and pressure, zero cosmological constant, and a scale factor varying as the time t. Its interval is given in spherical polar coordinates by

$$ds^2 = c^2dt^2 - t^2\left[\frac{dr^2}{(1+r^2)} + r^2\left(d\theta^2 + \sin^2\theta d\phi^2\right)\right] \quad . \tag{9}$$

This metric can be changed by a coordinate transformation to flat spacetime (see Wesson 1999), so the model is a logical one to consider from the viewpoint of a zpf-dominated universe. It has the practical advantage of avoiding the horizon problem posed by the isotropy of the 3K microwave background, since it has no horizon.

However, Haisch, Rueda and Puthoff (1998) argued that the concept of negative inertial mass is unacceptable within their formalism of the zpf, basically because inertia is the resistance of a charged particle to acceleration in the zpf, and so cannot be reversed. As the authors note, this runs counter to the work by Bondi (1957), which showed that negative inertia is a viable proposition. On a more recent note, Bonnor (1989) has discussed the various types of mass which enter the laws of physics, and concluded that negative mass does not violate any of the standard postulates, including the weak equivalence principle.

A dichotomy therefore becomes apparent: one can either argue that the zpf does not gravitate at all, or one can argue that it does gravitate but is cancelled by another field of negative energy density.

Haisch, Rueda and Puthoff (1998) also mentioned several other effects which are in principle measurable. The Davis-Unruh effect really follows from work by Hawking on the match between quantum field theory and general relativity, originally applied to black holes. In terms of a particle which undergoes an acceleration a, the theory predicts that an observer on such a particle would measure an ambient temperature

$$T = \frac{\hbar a}{2\pi ck} \quad , \tag{10}$$

where k is Boltzmann's constant and the other parameters have been defined. However (10) was derived without the zpf formalism, and in most astrophysically-accessible situations is unmeasurably small.

The same is not true of the Casimir effect. This is commonly derived on the basis of a wave-mechanical argument, wherein two parallel plates exclude modes with wavelengths larger than the plate separation, producing a decrease in energy between the plates compared to their external environment, or equivalently a force of attraction between the plates (Casimir 1948; Sparnaay 1958; De Witt 1975, 1989; Milonni, Cook and Goggin 1988). This reasoning is actually generic, applying not only to electromagnetism but also to other wave phenomena such as gravity. However, the Casimir effect has only been measured in the laboratory for the electromagnetic interaction. The best experiment, which supersedes earlier questionable ones, was carried out by Lamoreaux (1997). Due to the difficulty of aligning plane plates, he used a plate and a sphere. The results confirmed the predicted (distance)$^{-4}$ dependency of the Casimir force to an accuracy of 5%.

This result is unique in the realm of vacuum physics. However, it should be recalled that the excluded-mode derivation is generic (De Witt 1975, 1989). This leaves an opportunity for more detailed interpretations, including ones which are not dependent on the assumption of an electromagnetic zpf.

In a series of collected papers, Haisch and Rueda (1997a,b; 1998, 1999b) discussed possible experimental and technological applications of the zpf. Of these articles, the one presented at the NASA conference on spacecraft propulsion offers the most intriguing suggestions for future space drives (Haisch and Rueda 1997a). One cannot but agree with other workers in the field that conventional spacecraft limited to velocities $v < c$ are an impractical way of exploring space beyond our solar system. If the (electromagnetic) zpf exists, then it represents an untapped source of energy; and in conjunction with modern quantum field theory wherein virtual particles can come into and go out of existence below the limits set by Heisenberg's uncertainty principle, the opportunity exists in principle for new forms of travel. Indeed, that communication at $v > c$ is possible is already presaged by quantum-interference experiments and the Aharanov-Bohm effect. One should, however, be careful to note that concrete models of propogation at $v > c$ are theory-dependent. The zpf formalism, non-localized quantum field theory, and Kaluza-Klein theory all in principle allow communication with $v > c$. But the precise mode depends on the theory adopted, so any practical application would appear destined to wait on a clearing of the theoretical waters.

3 Outstanding Problems

It is clear from the considerations of the preceding section that certain problems exist in the matching of a quantum-mechanical zero-point field to classical general relativity (or a replacement for the latter). Therefore, it is useful to collect, in the same order as they were discussed above, the main issues of contention:

1. The origin of inertia is a long-standing problem in physics and the idea that the rest mass of a particle like an electron is purely electromagnetic in origin has a history of more than a century. However, one can question why electromagnetism is supposed to play a fundamental role in inertia compared to the other (known) three interactions of physics.

2. There is no generally agreed theory of quantum gravity, but the existence of the constants c, G and h (as used liberally in the zpf approach) raises the question of why their dimensional products of length, time and mass are not natural parameters of the theory, and not represented (especially in terms of the Planck mass) in the real world.

3. The cosmological constant, with dimensions of length^{-2} or time^{-2} (depending on whether it is combined with c^2), plays no role in the zpf approach. But astrophysical observations of QSO lensing, and cosmological observations of the effective density of the universe as measured by the dynamics of galaxies, indicate that Λ is finite and positive.

4. The so-called cosmological-constant problem highlights the mismatch between the most widely accepted theories of particle physics (the standard model) and gravitation (general relativity), but one might expect that the zpf approach would provide a natural resolution of this problem.

5. To avoid intense curvature, the zpf either does not gravitate <u>or</u> is cancelled by another field of opposite sign. The proponents of the zpf prefer the former view, but studies have shown the acceptability of the latter view. There certainly <u>are</u> negative fields in physics (e.g. gravitational potential energy); so the fiat of a non-gravitational zpf may appear <u>ad hoc</u> to some workers.

6. The idea that it is only <u>perturbations</u> of the zpf which are important has merit. But attempts to derive a quasi-Newtonian law of gravity from such perturbations have been criticized; and even if this were the case, such a simple law cannot reproduce the $(3+1)$ classical tests of general relativity in the solar system, or the data which indicate gravitational radiation as predicted by Einstein's theory from binary pulsars. This is a major problem: <u>the zpf approach is intuitive but restrictive, and one wonders how it can tackle the extensive data which support general relativity</u>.

7. Mach's principle is well-regarded by many researchers, who acknowledge that while desirable it is not incorporated in Einstein's theory of general relativity. One might reasonably expect that the zpf approach would give a more clear-cut rationale for this principle.

8. Dimensionality of the equations of physics is a major issue today. It is worthwhile recalling that special relativity was made mathematically concrete by Minkowski, who realized that time and space could be put on the same footing by simply defining ct as a new coordinate. The zpf approach uses 4D spacetime as a basis. However, there is no uniqueness about 4D; and, mainly motivated by a wish to understand the properties of particles, there is currently much work underway on $N(>4)D$ field theory. (This incorporates Kaluza-Klein theory, superstrings and supergravity.) One can raise the question of whether the assumption of $N = 4$ does not unreasonably constrain the zpf approach.

9. The Davis-Unruh effect is derived on the basis of quantum field theory in a curved spacetime described by general relativity. This presents a two-sided problem: if the effect exists, it should be deriveable in a straightforward way from the zpf approach; but it has never been observed, so another view (dependent on which physics one adopts) is that it does not exist and is therefore not an effect that needs to be addressed in the zpf approach.

10. The Casimir effect (contrary to the preceding) exists, and has been measured. This is a strong argument in favour of the existence of a real zpf. However, a practical effect can derive from several theories, and there is controversy about the underlying mechanism.

11. If the (electromagnetic) zpf is real, it does in principle provide a new source of energy that has potential applications to technology, and particularly spacecraft propulsion. Now one could argue that current understanding of the zpf is similar to the understanding of electromagnetism in the 1800's, insofar as the equations were written down but nobody had built a radio. However, one could also argue that the physics of the zpf is based on known laws and is mathematically fairly straightforward, so that a practical application should be deliverable in relatively short order.

4 Recommendations for Research

The problems described in the preceding section are in principle surmountable; but they are extensive. Therefore, in this section, issues will be identified that are academically important but expected practically to yield to analysis.

1. The status of the cosmological constant needs to be addressed. Astrophysical data indicate that it is finite, and if so it represents a fundamental length or frequency which should be incorporated into the zpf approach.

2. The existence of a real (electromagnetic) zpf is conceptually distinct from the (questionable) existence of a quasi-Newtonian law of gravity derived from zpf perturbations. It is recommended that future work concentrate on the physics of the zpf and not on a quasi-Newtonian form of gravitation.

3. As an extension of the comments of the preceding paragraph, it should be acknowledged that a large body of data exists which supports the standard gravitational theory of general relativity. It is essential that some effort be made to match zpf theory and Einstein theory.

4. The Davis-Unruh effect, since it is derived from quantum field theory in curved space and has never been measured, is not something with which the zpf approach should be concerned, and discussion of it should therefore be dropped.

5. The Casimir effect <u>is</u> central to the zpf argument. However, the magnitude of the force is topology-dependent. Therefore, theoretical studies should be made on the Casimir effect for various configurations, as a precursor to practical measurements of the force which might be of technological value.

6. Following from the experimental verification of the Casimir effect, work should be continued to identify technological applications of a zpf. Conventional spacecraft are pre-obsolete in regard to interstellar exploration, so alternatives should be investigated.

5 Conclusion

Zero-point fields are predicted by interactions which are well described by quantum mechanics, but the energies involved do not manifest themselves either in terms of the curvature of spacetime as formalized in general relativity or in the energy density of the cosmological vacuum as measured by the cosmological constant. This is a peculiar situation, and arguably unique in modern physics.

In Section 2 there was given an account of recent work on the electromagnetic zpf. In Section 3 there was presented an 11-point summary of outstanding problems, and in Section 4 there was given a 6-item list of recommendations for future research. These suggestions should lead to a resolution of the difficulties which exist in the amalgamation of quantum mechanics and classical field theory.

The conclusion to be drawn from this report is that research into the zpf is justified because it is of fundamental academic importance and of potential importance to technology.

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