INERTIA AND GRAVITATION IN THE ZERO-POINT FIELD MODEL

Final Report

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The results of this four-year research program are documented in the following published and as yet unpublished papers.

Inertia: Mach's Principle or Quantum Vacuum?, B. Haisch, A. Rueda and Y. Dobyns.
copy attached - intended for Physics Today

On the Relation Between Inertial Mass and Quantum Vacua, B. Haisch and A. Rueda.
copy attached - intended for Annalen der Physik

The Case for Inertia as a Vacuum Effect: A Reply to Woodward and Mahood, Y. Dobyns, A. Rueda and B. Haisch, Foundations of Physics, in press (2000).
(http://xxx.lanl.gov/abs/gr-qc/0002069)
copy attached - to appear in Foundations of Physics

Toward an Interstellar Mission: Zeroing in on the Zero-Point-Field Inertia Resonance, B. Haisch and A. Rueda, Space Technology and Applications International Forum (STAIF-2000), Conference on Enabling Technology and Required Developments for Interstellar Missions, Amer. Inst. Phys. Conf. Publ. 504, p. 1047 (2000).
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INERTIA: MACH'S PRINCIPLE OR QUANTUM VACUUM?

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Abstract. Two competing theories are tackling the foundational question of whether inertia may have an extrinsic origin. One based on Mach's principle makes the startling prediction that transient mass fluctuations may be created to yield propellant-free propulsion. One based on quantum vacuum fluctuations may revise the conventional understanding of why moving particles have wavelike properties.

Background

Perhaps the most basic equation of physics is $\mathbf{f} = m\mathbf{a}$, Newton's equation of motion, in which m is the inertial mass of any object. Hereafter we specifically designate inertial mass as m_i to differentiate it from other aspects of mass, such as gravitational mass, m_g, and the rest mass of special relativity based on the energy content of an object in its rest frame, $m_0 = E/c^2$. It is usually assumed that m_i is an intrinsic property of matter. In that case any deeper understanding of the nature of inertial mass must be sought in the standard model of particle physics and experiments attempting to elucidate the interconnections among the fundamental forces and the many apparently fundamental properties of matter, such as charge, spin, parity, etc. But there is the possibility that m_i is extrinsic to matter, arising from interactions between the innermost fundamental entities, such as leptons and quarks, constituting matter and some inherently external field. Such an idea was proposed by Mach in the 19th century: he proposed that a given object acquires its inertial mass via interaction with all other matter in the Universe. This concept was dubbed "Mach's principle" by Einstein, but for decades it remained more a matter of philosophy than science. Indeed, there was the nagging problem that general relativity (GR) appeared to be inconsistent with Mach's principle since solutions of the field equations of GR allowed for both an empty Universe in which a test particle could still possess mass, and a rotating Universe which would make no sense from the Machian perspective since the matter in the Universe must define the rotational frame of reference.

A significant development was the publication in 1953 by Sciama [1] of a simplified but nonetheless quantitative link between a hypothesized gravitational vector potential and inertia. A scalar potential for the Universe may be defined as

$$\Phi = \int_V \frac{G\rho}{r} dV \tag{1}$$

where as usual ρ is the local density corresponding to a source point inside the volume, dV, and r is the distance of the point of observation, or test point, from the source point. The integration extends over the Universe presumably out to the limit of causal connection which would be the cosmological event horizon. If one moves "relative to the smoothed out universe" (as Sciama wrote prior to the discovery of the cosmic microwave background and its role as a reference frame) with velocity $\mathbf{v}$, then one may define a gravitational vector potential $\mathbf{A} = \Phi\mathbf{v}/c$. The gravitational force on a small object (the smallness becomes important later on) having (passive) gravitational mass m_g would then be

$$\mathbf{f}_g = -m_g \nabla\Phi - m_g \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t} \ . \tag{2}$$

In any region of the Universe in which the scalar potential is constant, we find that

$$\mathbf{f}_g = -m_g \frac{\Phi}{c^2}\frac{\partial \mathbf{v}}{\partial t} \tag{3}$$

which now becomes relevant for an object undergoing acceleration.

What has been accomplished with this? This equation tells us that a reaction force proportional to and opposed to acceleration would arise as a result of what might be termed an inductive interaction between an object and the gravitational vector potential. To maintain the acceleration, one thus would have to apply a compensating motive force, $\mathbf{f} = -\mathbf{f}_g$, and therefore we arrive at

$$\mathbf{f} = m_g \frac{\Phi}{c^2} \mathbf{a} \ . \tag{4}$$

If $\Phi = c^2$ then this looks identical to Newton's equation of motion with m_g standing in for m_i. In other words, inertial mass in this view becomes a manifestation of the (passive) gravitational mass, and the property of inertia itself as a resistance to acceleration is merely a reaction force generated by the vector gravitational potential of the entire Universe: inertia would be a gravitational induction effect.

As intriguing as this is, there are several problems. First of all, we have simply substituted one mass for another. If inertial mass is really (passive) gravitational mass reacting to acceleration via a gravitational induction effect, then what is gravitational mass? We do not dwell on this though, because it would still be a major advance in our understanding to know that inertia is really an induction effect of gravitation, not something separate. A more serious problem is the requirement that $\Phi = c^2$. If this is not satisfied exactly the principle of equivalence is lost. Equally serious is the problem of causality. For a Universe of uniform density on average, Φ is dominated by the most distant matter (as is evident in eqn. (1) by letting $dV = 4\pi r^2 dr$). The shell of matter at distances of billions of parsecs thus dominates in producing the inertia-induction effect. But how can all of that cosmic matter in the most remote galaxies react collectively and instantaneously to any local acceleration, such as lifting a paperclip or pushing a pencil?

One might think that geometrodynamics could solve the causality problem, but it does not. According to GR, the gravitational potential at any given point in space is really a spacetime curvature. The most distant matter has already left its (retarded) local signature in the spacetime geometry of any point. This is true, but what this accomplishes is simply to specify the geodesic path for a freely moving object. Curved spacetime is no more capable of generating a force in and of itself than is flat spacetime. If an object is forced to move along some other path, i.e. to accelerate, geometrodynamics itself cannot be the source of a force. One is merely back to the square-one argument that one has to overcome the inertia of an object to make it deviate from the local geodesic; but that of course takes us full circle: one has to assume inertia to explain inertia in the context of geometrodynamics. Whether one accelerates an object in curved spacetime or in flat spacetime amounts to the same thing. viz. forced deviation from the local geodesic path. But this tells us immediately that the spacetime curvature itself does not generate forces anymore than does ordinary space. The point is that geometrodynamcs does not offer any way out of the problem of instantaneous gravitational induction of a reaction force over billions of light years that appears locally as inertia in the Machian view.

Gravitomagnetism and Transient Mass Terms

A report by the National Academy of Sciences in 1986 [2] declared that "At present there is no experimental evidence arguing for or against the existence of the gravitomagnetic effects predicted by general relativity." This report led to the publication in 1988 by Nordvedt [3] of arguments in favor of the existence of gravitomagnetism which appear to be irrefutable unless one discards both special and general relativity. One case involves the classical GR effect of light deflection by the Sun. How would the light deflection measurement be modified for an observer moving radially away from the Sun at a sufficiently large distance. This is easily calculated by a Lorentz transformation from a stationary to a moving frame with respect to the Sun. According to relativity, one can just as well assume, though, that the moving observer is stationary and the Sun is moving away: the calculated deflection had better be the same. Nordvedt show that it is not... unless one assumes the existence of a gravitational vector potential. The effects of a gravitational potential make the two calculations agree.

But Nordvedt did more than show that gravitomagnetic effects are real: he also showed that they can be surprisingly large. If one regards the entire Universe as being in motion relative to a test particle, one can couch Mach's principle in terms of his linear-order relativistic gravitational development. Curiously though, the requirement for the Nordvedt formulation to yield the $m_i = m_g$ identity aspect of Mach's principle is $4\Phi = c^2$. Compare this to Eq. (4) where $\Phi = c^2$ is required to make the connection between gravitation and inertia. Given the inherent uncertainty in how to properly judge the gravitational potential of the entire Universe, a factor of four should perhaps not be worrisome.

In the discussion above, m_g was assumed to represent the gravitational mass of a *small* object. This is an important limitation: an ordinary object of matter will possess gravitational self-energy. Would the identity of m_i with m_g still hold if in addition to the summation of masses of atoms or molecules in an object one adds the mass equivalent of the interaction energy? If it is *assumed* that $m_i = m_g$ when m_g includes the self-energy term, then there results an acceleration-dependent correction to the inertial reaction of a body, or to m_i in this Machian perspective. This is called the Nordvedt effect. A nice discusion of it has been given in the book by Ohanian and Ruffini and an article by Will. [4] It appears to be a necessary correction to properly account for the highly precise observations of the orbit of the moon, for example.

The Nordvedt effect and Machian inertia are very similar effects but on different scales. In Machian inertia, acceleration of an object with respect to the gravitational potential of the entire Universe generates a reaction force which we interpret as inertia and we thus attribute inertial mass m_i to an object on this basis. In the Nordvedt effect, acceleration of an object with respect to the potential of its own self-interaction generates a much smaller but not necessarily negligible reaction force which we may interpret as a mass shift, δm_i. For the case of the earth, the Nordvedt effect results in a mass shift $\delta m_i = 3.5 \times 10^{-9} m_i$ which must be taken into account for the most precise celestial dynamics. The self-energy potential of the Earth and its acceleration are essentially unchanging in magnitude, so that δm_i is a constant. But if rapid changes in the self-energy potentials of objects could be induced, significant changes in δm_i might result.

The Nordvedt effect was the inspiration for a series of papers by Woodward, beginning in 1990 [5], which have resulted in further development of the gravitomagnetic version of Mach's principle leading even to a patent (No. 5,280,864) for a "Method for Transiently Altering the Mass of Objects to Facilitate their Transport or Change their Stationary Apparent Weights." One application of this would allow a science-fiction sort of propellantless propulsion which Woodward has indeed likened to a Star Trek-like impulse engine.

In Box 1 we follow Woodward's arguments leading to prediction of possible transient changes in the proper mass density of any object attributable to the Nordvedt effect resulting in the relation:

$$\delta\rho = \left(\frac{1}{4\pi G\rho c^2}\right)\frac{\partial^2 E}{\partial t^2} \ . \tag{5}$$

Woodward claims that rapid changes in energy, in this case electrical energy, on the order of 10^{10} to 10^{12} erg cm^{-3} s^{-1} can be induced by charging and discharging capacitors. This would result in milligram-level fluctuations in δm_i, where δm_i is the integral of $\delta\rho$ over the device.

While minute changes in $\delta m_i/m_i$ would be of considerable theoretical significance, it would take values near unity to be of any practical use as a means to effectively modify weight of an object. However the real potential would lie in the ability to phase the ejection and retraction of an object with changes in δm_i. This would result in creation of a net unidirectional force: throw out an object when it is heavy, retract it when it is light, and one has a seemingly miraculous means of propulsion without the use of expendible propellant. This would indeed constitute a violation of momentum conservation at the level of the device. It is difficult to say whether this does or does not violate momentum conservation at the Machian level of the entire Universe since there is no definable reference of motion for the Universe itself.

The Quantum Vacuum Approach

While the Machian approach to inertia depends on an instantaneous reaction from the most distant matter in the Universe, the alternative is a theory which involves *local* interaction between the quarks and leptons in matter and the electromagnetic component of the quantum vacuum, i.e. the zero-point fluctuations. Quantum field theory predicts an enormous electromagnetic zero-point energy density for these fluctuations which can be understood from the Heisenberg uncertainty relation. The uncertainty relation states that the ground state of a harmonic oscillator has a non-zero minimum energy of $\hbar\omega/2$ because an oscillator cannot simultaneously be exactly at the bottom of its potential well and have exactly zero momentum. The same logic applies to the electromagnetic field, which is quantized "by the association of a quantum mechanical harmonic oscillator with each mode **k** of the radiation field." [6] Summing up the energy over the modes for all frequencies, directions, and polarization states, one arrives at a zero-point energy density for the electromagnetic fluctuations of

$$W = \int_0^{\omega_{max}} \rho_{zp}(\omega)d\omega = \int_0^{\omega_{max}} \frac{\hbar\omega^3}{2\pi^2 c^3}d\omega \tag{6}$$

where ω_{max} is a postulated cutoff in frequency.

There is an obvious problem: Beyond what frequency do the zero-point fluctuations cease and why? One plausible cut-off is the Planck frequency which originates from the following considerations. The minimum quantum size of an object is roughly a sphere whose Compton radius is $\hbar/mc$. The Schwarzschild radius for the same object is Gm/c^2. Any object so dense that the two radii become the same would put the two conflicting requirements of quantum physics and GR in direct opposition: a further compression should lead to collapse to a mini-black hole, yet the uncertainty relation should forbid any further collapse. This density corresponds to a Planck mass (2.2×10^{-5} g) in a sphere whose radius is the Planck length (1.6×10^{-33} cm). The Planck length is thus usually interpreted as the smallest allowable physical interval of space. The Planck time is the time it would take light to traverse one Planck length; the Planck frequency is the inverse of that, $\omega_P = (4\pi^2 c^5/G\hbar)^{1/2} = 1.2 \times 10^{44}$ rad s^{-1}.

Assuming that $\omega_{max} = \omega_P$ results in a zero-point energy density of $\sim 10^{116}$ ergs cm^{-3}. Adler, Casey and Jacob [7] have dubbed this the *vacuum catastrophe* to parallel the *ultraviolet catastrophe* that Planck and other physicists faced in 1900: the problem being that if one naively assumes that the energy density of the electromagnetic fluctuations gravitates, the Universe should be microscopic in size, yet the arguments leading to the existence of zero-point fluctuations are quite fundamental and so these fluctuations cannot just be dismissed out of hand. The enormity of this energy density is certainly worrisome, yet the useful concept of the Dirac sea, for example, suffers the a similar problem.

As summarized some years ago by Sir William McCrea [8] there are numerous phenomena which point to the reality of zero-point fluctuations. One is spontaneous emission: it can almost (there is a nagging factor of two) be attributed to stimulation by the zero-point fluctuations. This would neatly account for the inhibition of spontaneous emission in suitable cavities. Writing on cavity quantum electrodynamics involving suppression of spontaneous emission Haroche and Raimond [9] raise a paradox:

> These experiments indicate a counterintuitive phenomenon that might be called "no-photon interference." In short, the cavity prevents an atom from emitting a photon because that photon would have interfered destructively with itself had it ever existed. But this begs a philosophical question: How can the photon "know," even before being emitted, whether the cavity is the right or wrong size?

There is no such paradox if the inhibition of spontaneous emission reflects merely a reduction by the cavity of the zero-point fluctuations which are actually doing the stimulating which only appears to be spontaneous.

The effect most often attributed to the zero-point fluctuations is the Casimir force which has recently been well measured [10]. One physical interpretation of the Casimir force is that it is a radiation pressure from the zero-point fluctuations [11]; however the Casimir force, and other effects such as the Lamb Shift and van der Waals forces, can equally be attributed to either radiation-reaction fields (due to the quantum motions of particles) or to the vacuum zero-point fluctuations; and most characteristically to combinations of both, in several possible proportions, according to the various possible equivalent orderings of the creation and annihilation quantum operators. [12]

The ontological status of the electromagnetic zero-point fluctuations thus remains an outstanding problem.[a] However the discipline of stochastic electrodynamics (SED) has demonstrated the usefulness of treating the

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[a] Another major objection to a real ZPF has to do with its presumed gravitational effect. According to general relativity theory, the energy density of the ZPF would generate an enormous spacetime curvature,

zero-point fluctuations as if they constituted real electromagnetic fields with average energy $\hbar\omega/2$ in each mode and using the techniques of classical electrodynamics to solve quantum problems. [13] The random electromagnetic fluctuations provide a physical mechanism for the spread in particle position, momentum, energy etc. that quantum wave functions normally represent. It is possible, for example, to derive the blackbody spectrum without the assumption of quantization using SED. [14] Using SED a local origin for inertia can be attributed, at least in the sense of its electromagnetic aspect, to the interactions between the quarks and leptons in matter and the electromagnetic zero-point fluctuations. This is interesting as it indicates that a more advanced theory should produce an inertia reaction force coming from the vacua of its quantized fields. A corollary of this SED analysis also results in an electromagnetic basis for interpreting the de Broglie wavelength of a moving object.

An Electromagnetic Basis for Mass and the Wave Nature of Matter

In 1994 a first attempt was made, using SED, to find a connection between inertia and the zero-point fluctuations. [15] This was successful in that it demonstrated that the magnetic component of the zero-point fluctuations acting on a classical Planck oscillator would generate a reaction force proportional to the acceleration of the oscillator. (The acceleration of the oscillator was in the direction perpendicular to the oscillation.) In this representation then, inertia is actually the electromagnetic Lorentz force provided by the zero point fluctuations. There were several limitations to this approach: (1) the analysis was dependent on a very specific interaction between the zero-point fluctuations and the fundamental particles constituting matter, namely that of a classical Planck oscillator; (2) the requisite mathematical development was sufficiently complex so as to make it difficult to assess the validity; and (3) the interaction was assumed to take place at a presumed very high frequency (ω_P) cutoff of the zero-point fluctuations.

Thanks to a NASA research contract a completely new approach was carried through which proved to be analytically simpler and yet at the same time yielded the proper relativistic equation of motion, $\mathcal{F} = d\mathcal{P}/d\tau$, from electrodynamics as applied to the zero-point fluctuations.[16] The analysis hinged on finding the Poynting vector of the zero-point fluctuations in an accelerating frame of reference. Due to the perfect randomicity of the fluctuations, no net energy flux accompanies the huge energy density of eqn. (6). That is why, in principle at least, it is possible to conceive of this vast sea of zero-point energy filling the universe without apparent electromagnetic consequences: it is perfectly uniform and isotropic, inside and outside all matter. All other electromagnetic radiation that we see and measure is over and above this apparently vast electromagnetic ground state.

Once again using SED, but this time concentrating solely on the electromagnetic fields of the zero-point fluctuations it was possible to show that the Poynting vector becomes non-zero when viewed from an accelerating frame, and that in the subrelativistic regime the strength of the Poynting vector increases linearly with the acceleration. A non-zero Poynting vector implies a non-zero momentum flux, the two being related by simply a factor of c. If we assume that the quarks and electrons in atoms of matter scatter this radiation in the same way that ordinary electromagnetic radiation would be scattered, then a net reaction force on

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akin to a huge cosmological constant. This is, of course, true in the standard interpretation of mass-energy. However one has to be careful to maintain self-consistency when comparing theoretical models: the ZPF-inertia concept implies, via the principle of equivalence, that gravitation must also have a connection to the ZPF (along lines conjectured by Sakharov in 1968). If that is the case, then the ZPF cannot gravitate, because gravitation would involve the interaction of the ZPF with fundamental particles, not with itself. The energy density of the ZPF could then no longer be naively equated to a source of gravitation. Such an electromagnetically-based theory of gravitation has only undergone a preliminary development, but it does appear that the general relativistic curvature of spacetime can be mimicked by a vacuum having variable dielectric properties in the presence of matter. This raises the question of whether spacetime is actually physically non-Euclidean or whether our measurements of curvature merely reflect light propagation through a polarizable medium (the vacuum itself). Since the assumed curvature of spacetime is measured (by definition) via light propagation, there may be no way to distinguish one from the other: curved spacetime vs. light propagation with a dielectrically-modified speed-of-light. (We note that Einstein himself spent many years looking for an electromagnetic basis for gravitation, albeit unsuccessfully.)

matter results from the scattering of the momentum flux of the zero-point fluctuations. This reaction force is proportional to acceleration, and indeed owing to the fact that the transformation of the electromagnetic zero-point fluctuations from a stationary to an accelerating frame can be carried through exactly, the resulting equation of motion proves to have the relativistically correct form: $\mathcal{F} = d\mathcal{P}/d\tau$.

The resulting expression for the electromagnetic parameter that behaves like inertial mass is

$$m_i = \frac{V_0}{c^2} \int \eta(\omega)\rho_{zp}(\omega)d\omega \ , \tag{7}$$

where $\eta(\omega)$ is a frequency-dependent fraction ranging from zero to, perhaps, unity. This "mass", m_i, is actually a manifestation of an electromagnetic reaction force. It is assumed that momentum is carried by the electromagnetic fields of the zero-point fluctuations, and that this momentum is transferred to massless scattering centers throughout any object (the quarks and electrons in atoms of matter) resulting in a reaction force that is identical to what would ordinarily be called the inertia of the object. The physical interpretation of eqn. (7) is that some fraction $\eta(\omega)$ of the energy of the zero-point fluctuations at frequency ω instantaneously contained in the volume, V_0, of an object is scattered, i.e. is the part of the total ZPF energy that actually interacts with the object.

It was speculated that the scattering parameter, $\eta(\omega)$, would be found to be a resonance at some frequency, rather than be associated with the cutoff frequency of the zero-point fluctuations as in the 1994 approach. A very interesting corollary follows from this assumption. It was proposed by de Broglie that an elementary particle is associated with a localized wave whose frequency is the Compton frequency, yielding the Einstein-de Broglie equation:

$$\hbar\omega_C = m_0 c^2. \tag{8}$$

As summarized by Hunter [17]: "... what we regard as the (inertial) mass of the particle is, according to de Broglie's proposal, simply the vibrational energy (divided by c^2) of a localized oscillating field (most likely the electromagnetic field). From this standpoint inertial mass is not an elementary property of a particle, but rather a property derived from the localized oscillation of the (electromagnetic) field. De Broglie described this equivalence between mass and the energy of oscillational motion... as *'une grande loi de la Nature'* (a great law of nature)." The rest mass m_0 is simply m_i in its rest frame. What de Broglie was proposing is that the left-hand side of eqn. (8) corresponds to physical reality; the right-hand side is in a sense bookkeeping, defining the useful but not truly ontological concept of rest mass.

This perspective is consistent with the proposition that inertial mass, m_i, is also not a fundamental entity, but rather a coupling parameter between particles and the zero-point fluctuations, i.e. the vacuum fields if we contemplate prospective generalizations of our approach. De Broglie assumed that his wave at the Compton frequency originates in the particle itself. An alternative interpretation is that a particle "is tuned to a wave originating in the high-frequency modes of the zero-point background field."[12][18] The de Broglie oscillation would thus be due to a resonant interaction with the zero-point fluctuations, presumably the same resonance that is responsible for creating inertial mass as in eqn. (7). In other words, the zero-point fluctuations would be driving this ω_C oscillation of a fundamental particle, such as the electron. These particle oscillations were named *zitterbewegung* by Schrödinger.

We therefore suggest that an elementary charge driven to oscillate at the Compton frequency by the zero-point fluctuations may be the physical basis of the $\eta(\omega)$ scattering parameter in eqn. (7). For the case of the electron, this would imply that $\eta(\omega)$ is a sharply-peaked resonance at the frequency, expressed in terms of energy, $\hbar\omega = 512$ keV. The inertial mass of the electron would physically be the reaction force due to scattering of the zero-point fluctuations at that resonance.

This leads to a surprising corollary. It can be shown that as viewed from a laboratory frame, the standing wave at the Compton frequency in the electron's own rest frame transforms into a traveling wave having the de Broglie wavelength, $\lambda_B = h/p$, for a moving electron, as first measured by Davisson and Germer in 1927. The wave nature of the moving electron appears to be basically due to Doppler shifts associated with its Einstein-de Broglie resonance frequency. This has been shown in detail in the monograph of de la

Peña and Cetto [12] (see also Kracklauer [18]). The approach described above thus suggests very intriguing connections between electrodynamics, inertia and the quantum wave nature of matter.

Mach's Principle or Quantum Vacuum?

The Machian approach to inertia as developed by Woodward has led to a remarkable prediction, viz. that transient changes in mass may be achieved via the inflow and outflow of electrical energy to a device. Such transient mass changes could even result in the generation of a net unidirectional force which could serve for propulsion. The NASA Breakthrough Propulsion Physics program has selected an investigation by John Cramer of the University of Washington to attempt to experimentally verify this prediction. It is not yet known whether the quantum vacuum approach to inertia will make the same or an analogous prediction. Since the quantum vacuum approach finds mass to be, in part at least, an electromagnetic phenomenon it would not be surprising to find some way to electromagnetically vary inertial mass.

The Machian approach states that inertial mass is the very same thing as gravitational mass, the latter being the interaction of matter with the scalar gravitational potential, the former with an additional vector gravitational potential. Nordvedt has shown why such a vector potential must exist. The Machian approach simplifies things by reducing the types of mass — by having inertial mass and gravitational mass be the same thing — but it does not offer any new explanation of mass itself. Moreover there is the problem that for deviations from geodesic motion there is no explanation for why a reaction force arises which must be overcome by a motive force to bring about the acceleration. Geometrodynamics can only specify which path a free particle will take; it cannot generate forces to oppose motion on a non-geodesic path. To some extent one could argue that the Machian approach must therefore really assume inertial mass as the fundamental entity, and that gravitational mass must be a form of inertial mass, rather than vice versa. The bottom line is that it may be an accomplishment to link inertia and gravitational mass via a gravitational vector potential, the concept of mass as an intrinsic feature of matter of one sort (gravitational) or the other (inertial) still lies at the root of Machian inertia.

The major weakness of the Machian approach is that it would appear to call for an instantaneous and collective reaction of cosmically remote matter to any local acceleration. The quantum vacuum approach, by contrast, is based on local interaction, but one can argue that it too has its own major weakness: that one must accept the existence of a zero-point ground state of electromagnetic fluctuations of enormous energy density in the first place. However if one does this, one can arrive at a purely local explanation of inertia which does do away with the concept of inertial mass itself, interpreting it as simply a background vacuum fields force. If one also assumes that the interactions between the quarks and electrons in matter takes place at a resonance frequency identified with the Compton frequency, then one can also provide a new physical interpretation for the wave nature of matter as described by the de Broglie wavelength of a moving object. One has therefore arguably suggested the path for a true reduction in fundamental concepts from the quantum vacuum approach.

The issue of binding energies and fundamental particle masses is an area where the quantum vacuum approach to inertia may have an opportunity to make predictions that a Machian approach might not. If the scattering of zero-point radiation takes place at specific resonances, then there may be the opportunity to discover why, for example, a muon appears to be just a heavy electron via arguments based on resonance frequencies. A muon might just be an electron excited to a higher resonance. Similarly, the resonance of an ensemble of bound quarks would not be expected to be simply a linear function of the number of quarks. The 12 quarks bound together in a He nucleus would not be expected to have the same resonance as the sum of the four triplets of quarks in two protons and two neutrons. Changes in resonance thus afford a potential explanation for binding energies. Moreover in the quantum vacuum approach to inertia there is no need to postulate that one thing, mass, can be converted into something else, energy (and vice versa) via the $E = mc^2$ relationship. All forms of mass really trace back to the energy of the zero-point fluctuations and their association with *zitterbewegung* of and scattering by fundamental particles.

A massive neutrino poses no known problem for the Machian perspective, but the quantum vacuum approach in its restricted electromagnetic zero-point field formulation could not explain the mass of a truly charge-free particle. However it is important to bear in mind that the mass determination of the neutrino is not a direct measurement of inertial mass: it is an indirect inference based on a measurement of muon to electron neutrino populations resulting from cosmic rays. The existence of mass is then *inferred* from application of the current standard model. Since the quantum vacuum approach offers a completely new interpretation of mass itself, this indirect inference based on the current standard model may prove to be inappropriate.

It is also important to bear in mind that no particle is truly charge-free. The purely electromagnetic derivation of inertia from ZPF [14][15], as a necessary simplifying measure, glosses over the existence of other fields which must have their own zero-point oscillations, and with which particles must interact. It is known that electromagnetism is merely one aspect of a more general electroweak interaction. Neutrinos, while electrically neutral, have a nonzero coupling to the "weak" aspects of the electroweak force and so must interact with their quantum vacuum oscillations. A fully rigorous theory of ZPF-based inertia must deal with the quantum vacua, not only of electromagnetism, but of the full electroweak force and of quantum chromodynamics as well. The current, purely electromagnetic theory is known to be incomplete, and we should not be surprised that it omits such features as possible neutrino masses.

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Box 1: Derivation of the Woodward Effect

The four-momentum of an object is

$$\mathbf{P} = \left(\frac{E}{c}, p_1, p_2, p_3\right) . \tag{a}$$

In the frame of reference of the object $\tau = t$, and thus we have for the four-force per unit density

$$\mathbf{F} = \frac{1}{\rho}\frac{d\mathbf{P}}{d\tau} = \left(\frac{1}{c\rho}\frac{\partial E}{\partial t}, \mathbf{f}\right) \tag{b}$$

where $\mathbf{f}$ is the ordinary three-force (per unit density). In the Machian view, the gravitational induction force constitutes inertia, and so the divergence of the force is the negative of the gravitational source term. The induction effect is automatically included via the first term in the four-divergence. Anticipating a mass shift we write

$$\nabla \cdot \mathbf{F} = -4\pi G(\rho + \delta\rho) . \tag{c}$$

The four-divergence of a four-vector is

$$\partial^\alpha A_\alpha = \partial_\alpha A^\alpha = \frac{\partial A^0}{\partial x^0} + \nabla \cdot \mathbf{A} \tag{d}$$

and since

$$\mathbf{f} = -\nabla\phi \rightarrow \nabla \cdot \mathbf{f} = -\nabla^2\phi \tag{e}$$

we find

$$-\nabla^2\phi + \left(\frac{1}{\rho_0 c^2}\right)\frac{\partial^2 E}{\partial t^2} - \left(\frac{1}{\rho_0 c^2}\right)^2\left(\frac{\partial E}{\partial t}\right)^2 = -4\pi G(\rho + \delta\rho) . \tag{f}$$

For the stationary case we know that

$$-\nabla^2\phi = -4\pi G\rho . \tag{g}$$

Retaining only the first remaining term we arrive at

$$\delta\rho = \left(\frac{1}{4\pi G\rho c^2}\right)\frac{\partial^2 E}{\partial t^2} \tag{h}$$

Note that Woodward writes this as

$$\delta\rho = \left(\frac{\phi}{4\pi G\rho c^4}\right)\frac{\partial^2 E}{\partial t^2}$$

but since $\phi \sim c^2$ this is the same.

Box 2: The Zero-Point Field in Quantum Physics

The Hamiltonian of a one-dimensional harmonic oscillator of unit mass may be written

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

where $\hat{p}$ is the momentum operator and $\hat{q}$ the position operator. From these the destruction (or lowering) and creation (or raising) operators are formed:

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

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

The application of these operators to states of a quantum oscillator results in lowering or raising of the state:

$$\hat{a}|n\rangle = n^{1/2}|n-1\rangle, \tag{3a}$$

$$\hat{a}^\dagger|n\rangle = (n+1)^{1/2}|n+1\rangle. \tag{3b}$$

Since the lowering operator produces zero when acting upon the ground state,

$$\hat{a}|0\rangle = 0, \tag{4}$$

the ground state energy of the quantum oscillator, $|0\rangle$, must be greater than zero,

$$\hat{H}|0\rangle = E_0|0\rangle = \frac{1}{2}\hbar\omega|0\rangle, \tag{5}$$

and thus for excited states

$$E_n = \left(n + \frac{1}{2}\right)\hbar\omega. \tag{6}$$

The electromagnetic field is quantized by associating a quantum mechanical harmonic oscillator with each $\mathbf{k}$-mode. Plane electromagnetic waves propagating in a direction $\mathbf{k}$ may be written in terms of a vector potential $\mathbf{A_k}$ as (ignoring polarization for simplicity)

$$\mathbf{E_k} = i\omega_\mathbf{k}\{\mathbf{A_k}\exp(-i\omega_\mathbf{k}t + i\mathbf{k}\cdot\mathbf{r}) - \mathbf{A_k^*}\exp(i\omega_\mathbf{k}t - i\mathbf{k}\cdot\mathbf{r})\}, \tag{7a}$$

$$\mathbf{B_k} = i\mathbf{k}\times\{\mathbf{A_k}\exp(-i\omega_\mathbf{k}t + i\mathbf{k}\cdot\mathbf{r}) - \mathbf{A_k^*}\exp(i\omega_\mathbf{k}t - i\mathbf{k}\cdot\mathbf{r})\}. \tag{7b}$$

Using generalized mode coordinates analogous to momentum ($P_\mathbf{k}$) and position ($Q_\mathbf{k}$) in the manner of (2ab) above one can write $\mathbf{A_k}$ and $\mathbf{A_k^*}$ as

$$\mathbf{A_k} = (4\epsilon_0 V\omega_\mathbf{k}^2)^{-\frac{1}{2}}(\omega_\mathbf{k}Q_\mathbf{k} + iP_\mathbf{k})\varepsilon_\mathbf{k}, \tag{8a}$$

$$\mathbf{A_k^*} = (4\epsilon_0 V\omega_\mathbf{k}^2)^{-\frac{1}{2}}(\omega_\mathbf{k}Q_\mathbf{k} - iP_\mathbf{k})\varepsilon_\mathbf{k}. \tag{8b}$$

In terms of these variables, the single-mode energy is

$$< E_\mathbf{k} >= \frac{1}{2}(P_\mathbf{k}^2 + \omega_\mathbf{k}^2 Q_\mathbf{k}^2). \tag{9}$$

Equation (8) is analogous to (2), as is Equation (9) with (1). Just as mechanical quantization is done by replacing $\mathbf{x}$ and $\mathbf{p}$ by quantum operators $\hat{\mathbf{x}}$ and $\hat{\mathbf{p}}$, so is the quantization of the electromagnetic field accomplished by replacing $\mathbf{A}$ with the quantum operator $\hat{\mathbf{A}}$, which in turn converts $\mathbf{E}$ into the operator $\hat{\mathbf{E}}$, and $\mathbf{B}$ into $\hat{\mathbf{B}}$. In this way, the electromagnetic field is quantized by associating each $\mathbf{k}$-mode (frequency, direction and polarization) with a quantum-mechanical harmonic oscillator. The ground-state of the quantized field has the energy

$$< E_{\mathbf{k},0} >= \frac{1}{2}(P_{\mathbf{k},0}^2 + \omega_\mathbf{k}^2 Q_{\mathbf{k},0})^2 = \frac{1}{2}\hbar\omega_\mathbf{k}. \tag{10}$$

On the relation between inertial mass and quantum vacua

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1 Introduction

In his 1905 paper "On the Electrodynamics of Moving Bodies" Einstein eliminated the notions of a mechanical ether and of an absolute frame of rest [1]. A consequence of his resulting principle of relativity was the abandonment of the concepts of absolute space and of absolute time. The new mechanics of relativity replaced that of Newton through an epistemological change in foundation: relativity is founded upon physically measureable quantities rather than abstract concepts such as absolute space and absolute time. It is the observation of light signals that defines the lengths of rulers and durations of time intervals. A similar emphasis on measureable quantitites is the basis of the standard interpretation of quantum mechanics. We propose that such an *epistemology of observables* is also appropriate for the interpretation of the concept of mass. [a]

The existence of matter is self-evident and fundamental: we are made of matter. Mass however — like absolute space and time — is an abstraction. Though it is usually regarded as an innate property of matter, mass is not in fact directly observable. The mass we habitually attribute to matter manifests in two ways: as a force and as energy. In classical mechanics, one applies a force, $\mathbf{f}$, to an object and measures its resultant acceleration, $\mathbf{a}$. The force and the acceleration are the observables. We relate these two observables by assuming the existence of an innate property of matter known as inertial mass and thus we write $\mathbf{f} = m\mathbf{a}$. The existence of an innate inertial mass, m, is an inference and an abstraction. Using the methodology of stochastic electrodynamics [3] it has been shown that it *may* be possible to view Newton's equation of motion, $\mathbf{f} = m\mathbf{a}$, as well as its relativistic generalization, $\mathcal{F} = d\mathcal{P}/d\tau$, as a consequence of the electromagnetic zero-point field (ZPF) or more generally of the quantum vacuum fields [4] [5]. Of course the situation is more complex in that quantum vacua other than the electromagnetic ZPF must presumably also be involved.

The resistance to acceleration attributed to the existence of inertial mass in matter appears to be logically and quantitatively attributable instead to a resistance on accelerated matter due to the zero-point vacuum fields. In other words, inertia would appear to be a kind of reaction force that springs into existence out of the quantum vacuum whenever acceleration of an object takes place, for reasons given below. The m in $\mathbf{f} = m\mathbf{a}$ thus would become a coupling parameter that quantifies a more fundamental relationship between the elementary charged particles (quarks and electrons) in matter and the surrounding vacuum. This is not inconsistent with the ordinary concepts of momentum and kinetic energy which are calculated using the same m. Momentum and kinetic energy of a moving object can take on any value depending on the relative motion of the observer. It is only changes in momentum or kinetic energy that manifest as real measureable effects when a collision or a mechanical interaction takes place. Momentum, kinetic energy and mass itself are useful bookkeeping tools that become manifest only upon acceleration.

Our attempts to link inertia to the actions of the quantum vacuum have been limited to the electromagnetic zero-point field. We have not considered the zero-point fields of the weak or strong interactions.

[a] A lucid discussion concerning the epistemology of observables is found in Phillip Frank's "Einstein, Mach and Logical Positivism" [2]. The influence on the early work of Einstein (up to approximately 1920) by Mach and his Logical Positivistic viewpoint is widely known. The emphasis on observables as the essence of scientific verification was widely promoted by the thinkers of the Vienna Circle and by Auguste Compte.

In the electromagnetic case, this comes about through the Poynting vector of the ZPF: in an accelerating reference frame it becomes non-zero and proves to be proportional to acceleration. [b] A non-zero Poynting vector implies a non-zero radiative momentum flux transiting any accelerating object. If one assumes that the quarks and electrons in such an object scatter this radiation, stochastic electrodynamics shows that there will result a reaction force on that accelerating object having the form $\mathbf{f}_r = -\sigma\mathbf{a}$, where the σ parameter quantifies the strength of the scattering process. In order to maintain the state of acceleration, a motive force $\mathbf{f}$ must continuously be applied to balance this reaction force $\mathbf{f}_r$. Applying Newton's third law to the region of contact between the agent and the object, $\mathbf{f} = -\mathbf{f}_r$, we thus immediately arrive at $\mathbf{f} = \sigma\mathbf{a}$, which is identical to Newton's equation of motion. However now a parameter originating in the zero-point field scattering, σ, accomplishes the very thing that inertial mass, m, is assumed to do: resist acceleration. One can conceptually replace inertial mass, m, by a ZPF-based parameter representing a scattering process, σ. We discuss this relationship in § 4.

This is not merely a trivial substitution of nomenclature: *Taking this approach one may be able to eliminate a postulate of physics.* Newton's second law, $\mathbf{f} = m\mathbf{a}$, may cease to be fundamental as it can be derived from the vacuum fields plus the third law. Newton's third law of action and reaction would be axiomatic; Newton's second law would not. For practical purposes one can retain the concept of inertial mass, m, while realizing that it is not physically fundamental. One might regard mass in the same way one makes use of a classical thermodynamic parameter, such as heat capacity, for example. The measurable heat capacity of a given substance is a useful concept, but we know that it really represents an ensemble of atomic processes at a more fundamental level. So it appears to be with inertial mass as well: it represents a more fundamental vacuum process involving interactions like that between the ZPF and the particle and anti-particle pairs in the Dirac sea. Inertial mass would be due to interactions between the ZPF and the quarks and electrons constituting the matter of an accelerating object. [c]

In conventional QCD the proton and neutron masses are explained as being primarily the energies associated with quark motions and gluon fields. That sort of reasoning is considered sufficient explanation of nucleon masses, but the quantum vacuum-inertia hypothesis addresses the possibility that there is a deeper level to the nature of mass *by asking where inertia itself comes from.* We are proposing that there is a physical basis underlying the reaction force that characterizes inertia. If this is true, that would certainly be a deeper explanation than simply saying that there is so much energy (mass) in the quark motions and gluon fields and by definition that such energy (mass) simply resists acceleration. Where does the specific reaction force that opposes acceleration come from? Why does mass resist acceleration? Even more puzzling, why does the energy equivalent of mass resist acceleration? One possibility is that this will never be solved and forever remain a mystery. Another possibility is that this *can* be explained and that the present approach offers a truly new insight.

Inertial mass is only one of several manifestations of the concept of mass. If a ZPF-scattering process can account, at least in part, for inertial mass is there an analogous basis for the $E = mc^2$ relation? This equation is universally regarded as a statement that one kind of thing (energy) can be transformed into a totally different kind of thing (mass), and vice versa. Following an epistemology of observables, we propose that this is not the case, and that just as the physical reality of inertial mass is force, the physical reality of rest mass is energy. In preliminary attempta to develop the Sakharov [8] conjecture of a vacuum-fluctuation model for gravity, Hestenes and Kruger [9] proposed that the $E = mc^2$ relationship reflected the internal energy associated with *Zitterbewegung* of fundamental particles (see also Puthoff [10] for a similar suggestion). *Zitterbewgung*, so named by Schrödinger [11], can be understood as the oscillatory motion associated with the center of charge operator in the electron with respect to the center of mass operator. It can be interpreted as a motion of the center of charge around the averaged center of mass point. It is attributed in stochastic electrodynamics to the fluctuations induced by the ZPF. In the Dirac theory of the electron the eigenvalues of the *Zitterbewegung* velocity are $\pm c$ (see [12]), and the amplitude of these oscillations are on the order of

[b] In this respect, the fact that here we deal with a vector field that has a Poynting vector and not with a scalar field may be critical. For simple scalar fields such a resistance opposing accleration is not present. This has been reviewed and studied by, e.g., Jaekel and Raynaud [6]. Here however [5] we are dealing with a vector field with a well defined Poynting vector and associated momentum density

[c] J. P. Vigier [7] has proposed that there is a contribution to inertia due to the interaction of the accelerated particle with the surrounding virtual particles of the Dirac vacuum.

the Compton wavelength. In the view proposed by Puthoff, the rest mass of a particle is actually the field energy associated with point charge particle oscillations driven by the ZPF. If that is the case, there is no problematic conversion of mass into energy or enigmatic creation of mass from energy, but rather simply a concentration or liberation of ZPF-associated energy. Here too mass may become a useful but no longer fundamental concept.

This approach appears to allow yet another reduction in physical postulates. Just as the laws of electrodynamics applied to the ZPF appear to explain and support a former postulate of physics ($\mathbf{f} = m\mathbf{a}$) via a new interpretation of inertial mass, a postulate of quantum mechanics can be derived via a new interpretation of rest mass as the energy of ZPF-driven *Zitterbewegung*: The de Broglie relation for the wavelength of a moving particle, $\lambda = h/p$, may be derived from straightforward application of relativity theory. This is discussed in § 5.

There is one final mass concept: gravitational mass. Einstein's principle of equivalence dictates that inertial and gravitational mass must be the same. Therefore if inertial mass is a placeholder for vacuum field forces that arise in accelerating reference frames, then there must be an analogous connection between gravitation and vacuum fields. The attempt of Puthoff a decade ago to develop the Sakharov conjecture along the lines of a stochastic electrodynamics approach seemed promising, but now we know that it needs considerable further development.[13] We limit our discussion on gravitation to some comments on this and on the associated problem of the cosmological constant in § 6.

To summarize the view that emerges, all energy and momentum that we normally associate with matter appears to actually reflect some part of the energy and momentum of the underlying vacuum. The classical kinetic energy, $T = mv^2/2$, or momentum, $\vec{p} = m\vec{v}$, that we ascribe to an object depend entirely on the relative motion of the object and the observer. Both T and $\vec{p}$ are necessarily calculated quantities; a real observation only arises when object and observer are made to closely interact, e.g. when brought together into the same frame, which is to say when a collision occurs. But to achieve that requires a change in velocity, and it is precisely upon deceleration that the vacuum generates a reaction force that is called the inertial reaction force which Newton took to be an irreducible property of the so-called inertial mass, m. Again, we may retain the concept of inertial mass as a convenient bookkeeping tool for kinetic energy, momentum and other calculations, but the actual observable measurement of forces can be traced back to the vacuum reaction force on the most elementary components of matter (e.g., in the electromagnetic case, quarks and electrons) that accompanies acceleration.

2 Historical remarks on the zero-point field of Stochastic Electrodynamics

The clearest introduction to the classical electromagnetic ZPF concept of Stochastic Electrodynamics (SED) was the review paper of Boyer in 1975 [14] that discussed the foundational aspects of SED theory. In the Lorentz-Maxwell classical electrodynamics or Lorentz theory of the electron, one automatically assigns a zero value everywhere for the homogeneous solutions for the potential equations. In other words, it is taken for granted that the classical electron is not immersed in an incoming free background field: all electromagnetic radiation at any point in the Universe is due solely to discrete sources or to the remnant radiation from the Big Bang. Boyer argued that this is not the only possible assumption: it is also legitimate to assume a completely random but on average homogeneous and isotropic electromagnetic radiation field provided that it is Poincaré and Lorentz invariant. It was shown by Marshall [15] and later independently by Boyer that the only spectrum of a random field with these characteristics is a ν^3 distributed spectral energy density. This is exactly the form of the spectrum studed by Planck in 1911 [16] and is the spectrum of the ZPF that emerges from QED. We now consider the motivation for considering such a non-intuitive, non-zero universal electromagnetic radiation field unrelated to the 2.7 K cosmic microwave remnant radiation of the Big Bang.

SED is precisely classical physics with the sole addendum of a uniform, isotropic, totally random radiation field (the ZPF) having a ν^3 spectral energy density and a field strength whose value is related to Planck's constant, h. In this view, h is not a unit of quantization nor quantum of action, but rather a scaling parameter for the energy density of the ZPF. The rationale of SED has been primarily to explore a classical foundation for quantum fluctuations, which in this view, may be interpreted as the result of random electromagnetic perturbations; for that reason h as a measure of quantum uncertainty translates into a measure of ZPF energy density in SED since electromagnetic fluctuations are assumed to generate uncertainty as embodied in the Heisenberg relation in the conventional quantum view. So far, the main outcome of SED has been that some aspects of quantum mechanics would appear to be explicable in terms of classical electrodynamics if one accepts as an *Ansatz* the existence of a real electromagnetic ZPF.

Planck [17] derived a closed mathematical expression that fit the measurement of the spectral distribution of thermal radiation by hypothesizing a quantization of the emission of the radiation process. This yielded the well-known blackbody function,

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

written here as an energy density and factored so as to show the two components of density of modes (i.e. number of degrees of freedom per unit volume) times the thermal energy per mode in the frequency interval $d\nu$. As discussed in detail in Kuhn [18], Planck himself remained skeptical of the physical significance and importance of his theoretical discovery an apparently new constant of nature, h, for over a decade.

In 1913 Einstein and Stern [19] studied the interaction of matter with radiation using classical physics and a model of simple dipole oscillators to represent charged particles. They found that if, for some reason, such a dipole oscillator had a zero-point energy, i.e. an irreducible energy even at $T = 0$, of $h\nu$, the Planck formula for the radiation spectrum would result *without the need to postulate quantization as an a priori assumption.*

The existence of such a ZPF had already been envisaged by Planck around 1910 when he formulated his so-called second theory: namely an attempt to derive the blackbody spectral formula with a weaker quantization assumption. Nernst [20] proposed that the Universe might actually contain enormous amounts of such ZPF radiation and became the main proponent of this concept. Both Planck and Nernst used the correct $h\nu/2$ form for the average energy of the zero-point electromagnetic fluctuations instead of the $h\nu$ value assumed by Einstein and Stern; the $h\nu$ assumption is correct for the sum of interacting harmonic oscillator plus the energy of the electromagnetic field mode. The electromagnetic blackbody spectrum including ZPF would then be:

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

This appears to result in a ν^3 ultraviolet catastrophe in the second term. In the context of SED, however, that divergence is not fatal. 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 and isotropy. This approach of Einstein and Stern to understanding the blackbody spectrum was not developed further thereafter, and was essentially forgotten for the next fifty years until its rediscovery by Marshall [15]. In recent times, several modern derivations of the blackbody function using classical physics with a real ZPF but without quantization (i.e. SED) have been presented mainly by Boyer (see Boyer [21] and references therein; also de la Penã and Cetto [3] for a thorough review and references to other authors). In other words, if one grants the existence of a real ZPF, the correct blackbody formula for the thermal emission of matter seems to naturally follow from classical physics without quantization.

Another curiousity of the SED approach is that it could have provided a different method of attack to the problem of the stability of the ground-state of hydrogen. Rutherford's discovery of the atomic nucleus in 1911 together with Thomson's previous discovery of the electron in 1897 led to the analogy between atomic structure and planetary orbits about the Sun. In this naive analogy however, electrons, being charged, would radiate away their orbital energy and quickly collapse into the nucleus. Bohr [22] resolved the problem of radiative collapse of the hydrogen atom. He recognized that Planck's constant, h, could be combined with Rydberg's empirical relationship among the spectral lines of hydrogen to solve the problem of atomic stability by postulating that only discrete transitions are allowed between states whose angular momenta are multiples of $\hbar$, where $\hbar = h/2\pi$. The ground state of the hydrogen atom would then have angular momentum $mva_0 = \hbar$, or equivalently $m\omega_0 a_0^2 = \hbar$, and would be forbidden to decay below this "orbit" by Bohr's fiat. A more complex picture quickly developed from this that substituted wave functions for orbiting point particles, and in that view the orbital angular momentum of the ground state is actually $l = 0$: the wavefunction is spherically symmetric and has a radial probability distribution whose most probable value is a_0 (the expectation value being $\frac{3}{2}a_0$).

As with the classical derivation of the blackbody function made possible by the assumption of a real ZPF, modern SED analysis of the Bohr hydrogen atom has yielded a suggestive insight. A simple argument assuming strictly circular orbits by Boyer [14] and Puthoff [23] indicated that while a classically circularly-orbiting electron would indeed radiate away energy, if one takes into account the ZPF as a source of energy to be absorbed, then it is at the Bohr orbit, a_0, that a condition of balance would take place in absorbed and emitted power such that $< P^{abs} >_{circ} = < P^{rad} >_{circ}$. In other words, a classically orbiting and radiating electron would pick up as much energy as it loses, and thus be energetcially stabilized. In the analysis a strong assumption was introduced, namely that the electron moves around the nucleus along strictly circular orbits. This stabilization was found to be somewhat at odds with the more realistic analysis of Claverie and coworkers [24] who studied the problem in detail. A prediction of this much more detailed stochastic but still subrelativistic analysis was that the atom would, unfortunately, undergo self-ionization.

The detailed SED analysis of Claverie and coworkers was not restricted to global quantities and contemplated the general case of orbits not restricted to be circular, but where the much more realistic stochastic motion was allowed to happen. It used the more sophisticated Fokker-Planck approach (see [24] and references therein) and it involved other dynamic quantities such as momentum and not just average energies. But, being subrelativistic, these models assumed the electron to be a purely pointlike particle with no structure and therefore neglected *Zitterbewegung* and spin, ingredients that surely are relevant and probably essential for the stability conjecture of the hydrogen atom. This was discussed in detail by Rueda [25]; see also Haisch, Rueda and Puthoff [26] and de la Peña and Cetto [3] for a general discussion and references. The ultrarelativistic point-electron motions should be an essential ingredient not only in the constitution of the particle itself but also in the stability of its states in the hydrogen atom. This is why an SED theory at subrelativistic speeds and without possibilities to apprehend the particle structure features is unlikely to succeed in solving problems such as that of the stability of the hydrogen atom. The fact that $\hbar$ independently appears in the ZPF spectrum and in the spin of the electron clearly points towards their common origin. The proper SED study of this will require not only the difficulties of the ultrarelativistic speeds of the electron point charge but also should give rise to stochastic non-linear differential equations with colored noise that are beyond present-day techniques. [25]

3 The zero-point field in accelerating reference frames

The ZPF spectral energy density

$$\rho_{ZP}(\nu) = \frac{4\pi h\nu^3}{c^3} \tag{3}$$

would indeed be analogous to a spatially uniform constant offset that cancels out when considering net energy fluxes. However an important discovery was made in the mid-1970s that showed that the ZPF acquires special characteristics when viewed from an accelerating frame. In connection with radiation from evaporating black holes as proposed in 1974 by Hawking [27],Davies [28] and Unruh [29], working independently, determined that a Planck-like component of the ZPF will arise in a uniformly-accelerated coordinate system, namely one having a constant proper acceleration $\mathbf{a}$ (where $a = |\mathbf{a}|$) with what amounts to an effective "temperature"

$$T_a = \frac{\hbar a}{2\pi ck}. \tag{4}$$

This "temperature" does not originate in emission from particles undergoing thermal motions. [d] As discussed by Davies, Dray and Manogue [30]:

> One of the most curious properties to be discussed in recent years is the prediction that an observer who accelerates in the conventional quantum vacuum of Minkowski space will perceive a bath of radiation, while an inertial observer of course perceives nothing. In the case of linear

[d] One suspects of course that there is a deep connection between the fact that the ZPF spectrum that arises in this fashion due to acceleration and the ordinary blackbody spectrum have identical form.

acceleration, for which there exists an extensive literature, the response of a model particle detector mimics the effect of its being immersed in a bath of thermal radiation (the so-called Unruh effect).

This "heat bath" is a quantum phenomenon. The "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 QED [28][29] and in the SED formalism [31]. For the classical SED case it is found that the spectrum is quasi-Planckian in T_a. Thus for the case of zero true external thermal radiation ($T = 0$) but including this acceleration effect (T_a), eqn. (3) becomes [31] [e]

$$\rho(\nu, T_a) = \frac{8\pi\nu^2}{c^3}\left[1 + \left(\frac{a}{2\pi c\nu}\right)^2\right]\left[\frac{h\nu}{2} + \frac{h\nu}{e^{h\nu/kT_a} - 1}\right], \qquad (5)$$

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 negligibly 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 (vector) 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 eqn. (12) of HRP mirror the two leading terms in eqn. (5).

An analysis was carried through by HRP and this resulted in the apparent derivation of at least part of Newton's equation of motion, $\mathbf{f} = m\mathbf{a}$, from Maxwell's equations 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) treated as a classical Planck oscillator and the ZPF, i.e. it was found that the stochastically-averaged expression $< \mathbf{v}_{osc} \times \mathbf{B}^{ZP} >$ was exactly 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. 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 due to Einstein and Hopf [33]. Owing to its linear dependence on acceleration we interpreted this resulting force as a contribution to Newton's inertia reaction force on the particle.

The HRP analysis can be summarized as follows. The simplest possible model of a particle (which, following 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, $\mathbf{v_{osc}}$, assumed for simplicity to be in a plane. The oscillator is then given a constant proper acceleration, $\mathbf{a}$, by an independent, external agent. This acceleration is 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 the spectral energy density given in eqn. (5). 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 $\mathbf{B}^{ZP}$ acting upon the Planck oscillator is calculated. This is found to be proportional to acceleration. The constant of proportionality is interpreted as the inertial mass, m_i, of the Planck oscillator and thus at least as a contribution to the total mass of the particle. This inertial mass, m_i, is a function of the Abraham-Lorentz radiation damping constant, Γ, of the oscillator and of the interaction frequency with the ZPF,

[e] However, further analysis by Boyer [32] showed that although the spectrum of the fields in an accelerated frame is correctly given by eqn. (5), a dipole oscillator attached to the frame will have an additional radiation reaction term that exactly compensates for the additional factor $\left[1 + (a/2\pi c\nu)^2\right]$ in eqn. (5). As a result the detector will still detect only a Planckian spectrum insofar as the *scalar* detector-ZPF interaction is concerned.

$$m_i = \frac{\Gamma h \nu_0^2}{c^2}, \tag{6}$$

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 (but see § 5) we can make no absolute prediction of mass values in this simple model. Nevertheless, if correct and considering only the electromagnetic interaction, the HRP concept substitutes for Mach's principle a very specific electromagnetic effect acting between the ZPF and the charge inherent in matter. Inertia appears as an acceleration-dependent electromagnetic (Lorentz) force. Newtonian mechanics would then be derivable in principle from the ZPF via Maxwell's equations and in the more general case from the other vacuum fields also. 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. A similar observation, we conjecture, should hold for the other vacuum fields. So we conclude that inertia appears as a radiation pressure exerted by the fields in the vacuum opposing the acceleration of material elementary particles.

4 The relativistic formulation of inertia from the ZPF Poynting Vector

The 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 [5], which is independent of any particle model, relying solely on the standard Lorentz-transformation properties of the electromagnetic fields.

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 mechanical 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 & Haisch [5] demonstrated that from the point of view of the pushing agent there exists a net flux (Poynting vector) of ZPF radiation transiting the accelerating object in a direction opposite to the acceleration. The scattering opacity of the object to the transiting flux creates the back reaction force called inertia.

The new approach is less complex and model-dependent than the HRP analysis in that it assumes simply that the elementary particles in any material object interact with the ZPF in some way that is analogous to ordinary scattering of radiation. It is well known that treating the ZPF-particle interaction as dipole scattering is a successful representation in that the dipole-scattered field exactly reproduces the original unscattered field radiation pattern in unaccelerated reference frames.[14] It is thus likely that dipole scattering is an appropriate way — at least to first order — to describe the ZPF-particle interaction, but in fact for the more general RH analysis one simply needs to assume that there is some dimensionless efficiency factor, $\eta(\omega)$, that describes whatever the process is (be it dipole scattering or not). We suspect that $\eta(\omega)$ contains one or more resonances — and in the following section discuss why this resonance likely involves the Compton frequency — but again this is not a necessary assumption.

The new approach relies on making standard transformations of the $\mathbf{E}^{zp}$ and $\mathbf{B}^{zp}$ from a stationary to an accelerated coordinate system.[34] In a stationary or uniformly-moving frame the $\mathbf{E}^{zp}$ and $\mathbf{B}^{zp}$ constitute an isotropic radiation pattern. In an accelerated frame the radiation pattern acquires asymmetries. There is thus a non-zero Poynting vector in any accelerated frame carrying a non-zero net flux of electromagnetic momentum. The scattering of this momentum flux generates a reaction force, $\mathbf{f}_r$. Moreover since any physical object will undergo a Lorentz contraction in the direction of motion the reaction force, $\mathbf{f}_r$, can be shown to depend on γ_τ, the Lorentz factor (which is a function of proper time, τ, since the object is accelerating).[5] Rueda and Haisch find [5] that

$$m_i = \frac{V_0}{c^2} \int \eta(\omega)\rho_{ZP}(\omega)\, d\omega, \tag{7}$$

where ρ_{ZP} is the well known spectral energy density of the ZPF:

$$\rho_{ZP}(\omega) = \frac{\hbar\omega^3}{2\pi^2 c^3}. \tag{8}$$

The momentum of the object is of the form

$$\mathbf{p} = m_i \gamma_\tau \mathbf{v}_\tau. \tag{9}$$

Thus, one can also obtain the relativistic equation of motion [5]

$$\mathcal{F} = \frac{d\mathcal{P}}{d\tau} = \frac{d}{d\tau}(\gamma_\tau m_i c,\ \mathbf{p}\ ). \tag{10}$$

The origin of inertia, in this picture, becomes remarkably intuitive. Any material object resists acceleration because the acceleration produces a perceived flux of radiation in the opposite direction that scatters within the object and thereby pushes against the accelerating agent. Inertia in the present model appears as a kind of acceleration-dependent electromagnetic vacuum-fields drag force acting upon elementary charged particles.

5 Inertial mass and the de Broglie relation for a moving particle: $\lambda = h/p$

De Broglie proposed that an elementary particle is associated with a localized wave whose frequency is the Compton frequency, yielding the Einstein-de Broglie equation:

$$\hbar\omega_C = m_0 c^2. \tag{11}$$

As summarized by Hunter [35]: "...what we regard as the (inertial) mass of the particle is, according to de Broglie's proposal, simply the vibrational energy (divided by c^2) of a localized oscillating field (most likely the electromagnetic field). From this standpoint inertial mass is not an elementary property of a particle, but rather a property derived from the localized oscillation of the (electromagnetic) field. De Broglie described this equivalence between mass and the energy of oscillational motion...as *'une grande loi de la Nature'* (a great law of nature)." The rest mass m_0 is simply m_i in its rest frame. What de Broglie was proposing is that the left-hand side of eqn. (11) corresponds to physical reality; the right-hand side is in a sense bookkeeping, defining the concept of rest mass.

This perspective is consistent with the proposition that inertial mass, m_i, is also not a fundamental entity, but rather a coupling parameter between electromagnetically interacting particles and the ZPF as discussed above. De Broglie assumed that his wave at the Compton frequency originates in the particle itself. An alternative interpretation is that a particle "is tuned to a wave originating in the high-frequency modes of the zero-point background field."[36] The de Broglie oscillation would thus be due to a resonant interaction with the ZPF, presumably the same resonance that is responsible for creating a contribution to inertial mass as in eqn. (7). In other words, the ZPF would be driving this ω_C oscillation.

We therefore suggest that an elementary charge driven to oscillate at the Compton frequency, ω_C, by the ZPF may be the physical basis of the $\eta(\omega)$ scattering parameter in eqn. (7). For the case of the electron, this would imply that $\eta(\omega)$ is a sharply-peaked resonance at the frequency, expressed in terms of energy, $\hbar\omega_C = 512$ keV. The inertial mass of the electron would physically be the reaction force due to resonance scattering of the ZPF at that frequency.

This leads to a surprising corollary. It can be shown that as viewed from a laboratory frame, the standing wave at the Compton frequency in the electron frame transforms into a traveling wave having the de Broglie wavelength, $\lambda_B = h/p$, for a moving electron. The wave nature of the moving electron appears to be basically due to Doppler shifts associated with its Einstein-de Broglie resonance frequency. This has been shown in detail in [36].

Assume an electron is moving with velocity v in the $+x$-direction. For simplicity consider only the components of the ZPF in the $\pm x$ directions. The ZPF-wave responsible for driving the resonant oscillation impinging on the electron from the front will be the ZPF-wave seen in the laboratory frame to have frequency $\omega_- = \gamma\omega_C(1-v/c)$, i.e. it is the wave below the Compton frequency in the laboratory that for the electron is Doppler shifted up to the ω_C resonance. Similarly the ZPF-wave responsible for driving the electron resonant oscillation impinging on the electron from the rear will have a laboratory frequency $\omega_+ = \gamma\omega_C(1+v/c)$ which is Doppler shifted down to ω_C for the electron. The same transformations apply to the wave numbers, k_+ and k_-. The Lorentz invariance of the ZPF spectrum ensures that regardless of the electron's (unaccelerated) motion the up- and down-shifting of the laboratory-frame ZPF will always yield a standing wave in the electron's frame.

It has been proposed [36] that in the laboratory frame the superposition of these two waves results in an apparent traveling wave whose wavelength is

$$\lambda = \frac{c\lambda_C}{\gamma v} , \tag{12}$$

which is simply the de Broglie wavelength, $\lambda_B = h/p$, for a particle of momentum $p = m_0\gamma v$. This is evident from looking at the summation of two oppositely moving wave trains of equal amplitude, ϕ_+ and ϕ_-, in the particle and laboratory frames. In the rest frame of the particle the two wave trains combine to yield a single standing wave.

In the laboratory frame we have for the sum,

$$\phi = \phi_+ + \phi_- = \cos(\omega_+ t - k_+ x + \theta_+) + \cos(\omega_- t - k_- x + \theta_-) \tag{13}$$

where

$$\omega_\pm = \omega_z \pm \omega_B \tag{14a}$$
$$k_\pm = k_z \pm k_B \tag{14b}$$

and

$$\omega_z = \gamma\omega_C \ , \quad \omega_B = \gamma\beta\omega_C \tag{15a}$$
$$k_z = \gamma k_C \ , \quad k_B = \gamma\beta k_C \ . \tag{15b}$$

The respective random phases associated with each one of these independent ZPF wavetrains are $\theta_{+,-}$. After some algebra one obtains that the oppositely moving wavetrains appear in the form

$$\phi = 2\cos(\omega_z t - k_B x + \theta_1)\cos(\omega_B t - k_z x + \theta_2) \tag{16}$$

where $\theta_{1,2}$ are again two independent random phases $\theta_{1,2} = \frac{1}{2}(\theta_+ \pm \theta_-)$. Observe that for fixed x, the rapidly oscillating "carrier" of frequency ω_z is modulated by the slowly varying envelope function in frequency ω_B. And *vice versa* observe that at a given t the "carrier" in space appears to have a relatively large wave number k_z which is modulated by the envelope of much smaller wave number k_B. Hence both timewise at a fixed point in space and spacewise at a given time, there appears a carrier that is modulated by a much broader wave of dimension corresponding to the de Broglie time $t_B = 2\pi/\omega_B$, or equivalently, the de Broglie wavelength $\lambda_B = 2\pi/k_B$.

This result may be generalized to include ZPF radiation from all other directions, as may be found in the monograph of de la Peña and Cetto [3]. They conclude by stating: "The foregoing discussion assigns a physical meaning to de Broglie's wave: it is the *modulation* of the wave formed by the Lorentz-transformed, Doppler-shifted superposition of the whole set of random stationary electromagnetic waves of frequency ω_C with which the electron interacts selectively."

Another way of looking at the spatial modulation is in terms of the wave function. Since

$$\frac{\omega_C \gamma v}{c^2} = \frac{m_0 \gamma v}{\hbar} = \frac{p}{\hbar} \tag{17}$$

this spatial modulation is exactly the $e^{ipx/\hbar}$ wave function of a freely moving particle satisfying the Schrödinger equation. The same argument has been made by Hunter [35]. In such a view the quantum wave function of a moving free particle becomes a "beat frequency" produced by the relative motion of the observer with respect to the particle and its oscillating charge.

It thus appears that a simple model of a particle as a ZPF-driven oscillating charge with a resonance at its Compton frequency may simultaneously offer insight into the nature of inertial mass, i.e. into rest inertial mass and its relativistic extension, the Einstein-de Broglie formula and into its associated wave function involving the de Broglie wavelength of a moving particle. If the de Broglie oscillation is indeed driven by the ZPF, then it is a form of Schrödinger's *Zitterbewegung*. Moreover there is a substantial literature attempting to associate spin with *Zitterbewegung* tracing back to the work of Schrödinger [11]; see for example Huang [12] and Barut and Zanghi [37]. In the context of ascribing the *Zitterbewegung* to the fluctuations produced by the ZPF, it has been proposed that spin may be traced back to the (circular) polarization of the electromagnetic field, i.e. particle spin may derive from the spin of photons in the electromagnetic quantum vacuum [5]. It is well known, in ordinary quantum theory, that the introduction of $\hbar$ into the ZPF energy density spectrum $\rho_{ZP}(\omega)$ of eqn. (2) is made via the harmonic-oscillators-quantization of the electromagnetic modes and that this introduction of $\hbar$ is totally independent from the simultaneous introduction of $\hbar$ into the particle spin. The idea expounded herein points however towards a connection between the $\hbar$ in $\rho_{ZP}(\omega)$ and the $\hbar$ in the spin of the electron. In spite of a suggestive preliminary proposal, an exact detailed model of this connection remains to be developed [25]. Finally, although we amply acknowledge that other vacuum fields besides the electromagnetic do contribute to inertia, no attempt has been made within the context of the present work to explore that extension.

6 Comments on Gravitation

If inertial mass, m_i, originates in ZPF-charge interactions, then, by the principle of equivalence so must gravitational mass, m_g. In this view, gravitation would be a force originating in ZPF-charge interactions analogous to the ZPF-inertia concept. Sakharov [8], presumably inspired by previous work of Zeldovich [38], 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 the other fields.

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: (1) general relativity and quantum physics are at present irreconcilable, therefore something substantive is either wrong or missing in our understanding of one or both; (2) 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 [8] ideas would predict gravitational waves, but the coordinate ambiguities of GR should not appear in a ZPF-referenced theory of gravitation.)

General relativity (GR) attributes gravitation to spacetime curvature. Modern attempts to reconcile quantum physics with GR take a different approach, treating gravity as an exchange of gravitons in flat spacetime (analagous to the treatment of electromagnetism as exchange of virtual photons). A non-geometric (i.e. flat spacetime) approach to gravity is legitimate in quantum gravity. Similarly another non-geometric approach would be to assume that the dielectric properties of space itself may change in the presence of matter: this can be called the polarizable vacuum (PV) approach to gravity. Propagation of light in the presence of matter would deviate from straight lines due to variable refraction of space itself, and other GR effects such as the slowing down of light (the coordinate velocity as judged by a distant observer) in a gravitational potential would also occur. But of course it is the propagation of light from which we infer that spacetime is curved in the first place. This raises the interesting possibility that GR may be successful and yet not because spacetime is really curved: rather because the point-to-point changes in the dielectric (refractive) properties of space in the presence of matter create the illusion of geometrical curvature. A PV type of model does not directly relate gravitation to the ZPF (or to the more general quantum vacuum) but it does appear to provide a theoretical framework conducive to developing the conjecture of Sakharov that it is changes in the ZPF that create gravitational forces.

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 [39]) as well as within SED (see Surdin [40]). The first step in developing Sakharov's conjecture in any detail within the classical context of nonrelativistic SED was the work of Puthoff [10]. In this approach 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 Schrödinger. 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_g should be reduced by a factor of two, yielding $m_i = m_g$ 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 to which Puthoff has responded [41], but, since problems remain [42], 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 SED approach to gravity proposed by Puthoff, if correct, 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, Λ, 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 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 [43].)

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 [8] 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.

7 Concluding comments on the Higgs Field as originator of mass

In the Standard Model of particle physics it is postulated that there exists a scalar field pervasive throughout the Universe and whose main function is to assign mass to the elementary particles. This is the so-called Higgs field or Higgs boson and it originated from a proposal by the British physicist Peter Higgs who introduced that kind of field as an idea for assigning masses in the Landau-Ginzburg theory of superconductivity. Recent predictions of the mass that the Higgs boson itself may have indicate a rather large mass (more than 60 GeV) and this may be one of the reasons why, up to the present, the Higgs boson has not been observed. There are alternative thories that give mass to elementary particles without the need to postulate a Higgs field, as, e.g., dynamical symmetry breaking where the Higgs boson is not elementary but composite. But the fact that the Higgs boson has not been detected is by no means an indication that it does not exist. Recall the 26 years which passed between the proposal by Pauli in 1930 of the existence of the neutrino and its first detection when the Reines experiment was performed.

It should be clearly stated that the existence (or non-existence) of the hypothetical Higgs boson does not affect our proposal for the origin of inertia. In the Standard Model attempt to obtain, in John Wheeler's quote, "mass without mass," the issue of inertia itself does not appear. As Wilsczek [44] states concerning protons and neutrons: "Most of the mass of ordinary matter, for sure, is the pure energy of moving quarks and gluons. The remainder, a quantitatively small but qualitatively crucial remainder — it includes the mass of electrons — is all ascribed to the confounding influence of a pervasive medium, the Higgs field condensate." An explanation of proton and neutron masses in terms of the energies of quark motions and gluon fields falls short of offering any insight on inertia itself. One is no closer to an understanding of how this energy somehow acquires the property of resistance to acceleration known as inertia. Put another way, a quantitative equivalence between energy and mass does not address the origin of inertial reaction forces.

Many physicists apparently believe that our conjecture of inertia originating in the vacuum fields is at odds with the Higgs hypothesis for the origin of mass. This happens because of the pervasive, one might even say invisible, assumption that inertia can only be intrinsic to mass and thus if the Higgs mechanism creates mass one automatically has an explanation for inertia. If inertia is intrinsic to mass as postulated by Newton, then it (inertia) cannot simultaneously have an extrinsic basis deriving from either the Higgs field or from our proposed mechanism whereby real reaction forces are generated by the quantum vacua. However if one accepts that there is indeed an extrinsic origin for the inertia reaction force, be it the gravity field of the surrounding matter of the Universe (Mach's Principle) or be it the electromagnetic quantum vacuum (or more generally the quantum vacua) that we propose, then the question of how mass originates — possibly by a Higgs mechanism — is a separate issue from the property of inertia. This is a point that is often not properly understood. The modern Standard Model explanation of mass is satisfied if it can balance the calculated energies with the measured masses (as in the proton) but merely equating energy and mass does not explain inertia. Returning to our *epistemology of observables*, it is the inertia reaction force associated with acceleration that is measureable and fundamental, not mass itself. We are proposing a specific mechanism for generation of the inertia reaction force resulting from distortions of the quantum vacua as perceived by accelerating elementary particles.

We do not enter into the problems associated with attempts to explain inertia via Mach's Principle, since we have discussed this at length in a recent paper in collaboration with Y. Dobyns [45]: a detailed discussion on intrinsic vs. extrinsic inertia and on the inability of the geometrodynamics of general relativity to generate inertia reaction forces my be found therein. It had already been shown by Rindler [46] that Mach's Principle is inconsistent with general relativity, and Dobyns et al. further elaborate on a crucial point in general relativity that is not widely understood: Geometrodynamics merely defines the geodesic that a freely moving object will follow. But if an object is constrained to follow some different path, geometrodynamics has no mechanism for creating a reaction force. Geometrodynamics leaves it to inertia to generate such a force upon deviation from a geodesic path, but this becomes an obvious tautology if an explanation of inertia is sought in geometrodynamics.

We acknowledge that Newton's proposal that inertia is intrinsic to mass is more economical (Occam's razor) but it is also oversimplistic as one may always continue asking for a deeper reason for the operation of physical processes or for more fundamental bases for physical laws. The question of why the mass associated with either matter or energy should possess a resistance to acceleration is a valid one that would need to be addressed even if the Higgs boson were to be found.

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APPENDIX: A SHORT REVIEW ON QUANTIZATION OF THE RADIATION FIELD (SECOND QUANTIZATION)

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

$$\hat{H} = \frac{1}{2}(\hat{p}^2 + \omega^2\hat{q}^2), \tag{A1}$$

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

$$\hat{a} = (2\hbar\omega)^{-1/2}(\omega\hat{q} + i\hat{p}), \tag{A2a}$$

$$\hat{a}^\dagger = (2\hbar\omega)^{-1/2}(\omega\hat{q} - i\hat{p}). \tag{A2b}$$

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

$$\hat{a}|n\rangle = n^{1/2}|n-1\rangle, \tag{A3a}$$

$$\hat{a}^\dagger|n\rangle = (n+1)^{1/2}|n+1\rangle, \tag{A3b}$$

$$\hat{H} = \hbar\omega\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right). \tag{A3c}$$

It can then be seen that since the lowering operator produces zero when acting upon the ground state

$$\hat{a}|0\rangle = 0 \tag{A4}$$

this implies that the ground state energy of the quantum oscillator, $|0\rangle$, is greater than zero, and indeed has the energy $\frac{1}{2}\hbar\omega$, i.e.

$$\hat{H}|0\rangle = E_0|0\rangle = \frac{1}{2}\hbar\omega|0\rangle, \tag{A5}$$

and thus for excited states

$$E_n = \left(n + \frac{1}{2}\right)\hbar\omega. \tag{A6}$$

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

$$\mathbf{E_k} = i\omega_\mathbf{k}\{\mathbf{A_k}\exp(-i\omega_\mathbf{k}t + i\mathbf{k}\cdot\mathbf{r}) - \mathbf{A}^*_\mathbf{k}\exp(i\omega_\mathbf{k}t - i\mathbf{k}\cdot\mathbf{r})\}, \tag{A7a}$$

$$\mathbf{B_k} = i\mathbf{k}\times\{\mathbf{A_k}\exp(-i\omega_\mathbf{k}t + i\mathbf{k}\cdot\mathbf{r}) - \mathbf{A}^*_\mathbf{k}\exp(i\omega_\mathbf{k}t - i\mathbf{k}\cdot\mathbf{r})\}, \tag{A7b}$$

(where we have, for simplicity, not explicitly expressed the polarization). Using generalized mode coordinates analogous to momentum ($P_\mathbf{k}$) and position ($Q_\mathbf{k}$) in the manner of (A2ab) above one can write $\mathbf{A_k}$ and $\mathbf{A}^*_\mathbf{k}$ as

$$\mathbf{A_k} = (4\epsilon_0 V\omega_\mathbf{k}^2)^{-\frac{1}{2}}(\omega_\mathbf{k}Q_\mathbf{k} + iP_\mathbf{k})\varepsilon_\mathbf{k}, \tag{A8a}$$

$$\mathbf{A}^*_\mathbf{k} = (4\epsilon_0 V\omega_\mathbf{k}^2)^{-\frac{1}{2}}(\omega_\mathbf{k}Q_\mathbf{k} - iP_\mathbf{k})\varepsilon_\mathbf{k}. \tag{A8b}$$

In terms of these variables, the single-mode phase-averaged energy is

$$< E_{\mathbf{k}} >= \frac{1}{2}(P_{\mathbf{k}}^2 + \omega_{\mathbf{k}}^2 Q_{\mathbf{k}}^2). \quad (A9)$$

Note the parallels between Eqs. (A8) and (A2) and Eqs. (A9) and (A1). Just as mechanical quantization is done by replacing position, $\mathbf{x}$, and momentum, $\mathbf{p}$, by quantum operators $\hat{\mathbf{x}}$ and $\hat{\mathbf{p}}$, so is the quantization of the electromagnetic field accomplished by replacing $\mathbf{A}$ with the quantum operator $\hat{\mathbf{A}}$, which in turn converts $\mathbf{E}$ into the operator $\hat{\mathbf{E}}$ and $\mathbf{B}$ into $\hat{\mathbf{B}}$. In this way, the electromagnetic field is quantized by associating each $\mathbf{k}$-mode with a quantum-mechanical harmonic oscillator. This is why it results that the ground-state of the quantized field has the same energy as a corresponding mechanical harmonic oscillator

$$< E_{\mathbf{k},0} >= \frac{1}{2}(P_{\mathbf{k},0}^2 + \omega_{\mathbf{k}}^2 Q_{\mathbf{k},0})^2 = \frac{1}{2}\hbar\omega_{\mathbf{k}}, \quad (A10)$$

and why the corresponding excited states mimic also the excited state energy expressions of the mechanical harmonic oscillator.

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THE CASE FOR INERTIA AS A VACUUM EFFECT: A REPLY TO WOODWARD AND MAHOOD

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ABSTRACT: The possibility of an extrinsic origin for inertial reaction forces has recently seen increased attention in the physical literature. Among theories of extrinsic inertia, the two considered by the current work are (1) the hypothesis that inertia is a result of gravitational interactions, and (2) the hypothesis that inertial reaction forces arise from the interaction of material particles with local fluctuations of the quantum vacuum. A recent article supporting the former and criticizing the latter is shown to contain substantial errors.

1. INTRODUCTION

Since the publication of Newton's *Principia* the default assumption of most physicists has been that inertia is intrinsic to mass. Theories of an extrinsic origin for inertia, however, have seen perennial if minor interest. Since the task of physics is to explore causative relationships among natural phenomena, it is appropriate for physicists to devote some work to asking how and why the property of mass arises to produce the phenomenon of inertia, rather than always and only treating it as a definitional property. Recent work, on the other hand, provides a more urgent reason to look into theories of extrinsic inertia: some of them suggest a resolution to one of the more intractable difficulties of current physical theory.

There appears to be a fundamental conflict between quantum theory and gravitational theory. Adler, Casey, and Jacob[(1)] have dubbed this the "vacuum catastrophe" to parallel the "ultraviolet catastrophe" associated with blackbody radiation 100 years ago. Quantum field theory predicts a very large vacuum zero-point energy density, which according to general relativity theory (GRT) should have a huge gravitational effect. The discrepancy between theory and observation may be 120 orders of magnitude. As Adler *et al.* point out: "One must conclude that there is a deep-seated inconsistency between the basic tenets of quantum field theory and gravity."

The problem is so fundamental that elementary quantum mechanics suffices to demonstrate its origin. The intensity of any physical field. such as the electromagnetic field, is associated with an energy density; therefore the average field intensity over some small volume is associated with a total energy. The Heisenberg uncertainty relation (in the $\Delta E \Delta t$ form) requires that this total energy be uncertain, in inverse proportion to the length of time over which it obtains. This uncertainty requires fluctuations in the field intensity, from one such small volume to another. and from one increment of time to the next; fluctuations which must entail fluctuations in the fields themselves, which must be seen to be more intense as the spatial and temporal resolution increases.

In the more formal and rigorous approach of quantum field theory, the quantization of the electromagnetic field is done "by the association of a quantum-mechanical harmonic oscillator with each mode ... of the

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radiation field."[2] Application of the Heisenberg uncertainty relation to a harmonic oscillator immediately requires that its ground state have a non-zero energy of $\hbar\omega/2$, because a particle cannot simultaneously be exactly at the bottom of its potential well and have exactly zero momentum. The harmonic oscillators of the EM field are formally identical to those derived for a particle in a suitable potential well; thus there is the same $\hbar\omega/2$ zero-point energy expression for each mode of the field as is the case for a mechanical oscillator. Summing up the energy over the modes for all frequencies, directions, and polarization states, one arrives at a zero-point energy density for the electromagnetic field of

$$W = \int_0^{\omega_c} \rho(\omega)d\omega = \int_0^{\omega_c} \frac{\hbar\omega^3}{2\pi^2 c^3}d\omega, \tag{1}$$

where ω_c is a postulated cutoff in frequency. In conventional GRT, this zero-point energy density must be a source of gravity. This conflicts with astrophysical observations such as the size, age, and Hubble expansion of the Universe by as much as a factor of 10^{120}. Moreover, in addition to the electromagnetic zero-point energy there is also zero-point energy associated with gluons and the W and Z vector bosons. From naïve mode counting it would seem that the gluons should contribute eight times as much zero-point energy as do the electromagnetic zero-point photons, since there are eight types of gluons. While this estimate could doubtless be refined with a more sophisticated examination of the gluon model, it nevertheless seems clear that the vacuum energy density of gluons must be at least comparable to, and could quite easily be an order of magnitude or so larger than, the vacuum energy density of photons. The massive vector bosons must likewise provide a contribution of roughly similar scale. The fields associated with other forces thus exacerbate a problem that is already difficult when only electromagnetism is considered.

There is no accepted quantum theory of gravity, but "we might expect on the basis of studies of weak gravitational waves in general relativity that the field would also have a ground state energy $\hbar\omega/2$ for each mode and the two polarization states of the waves."[1] This too would only compound the problem.

One possible solution to the dilemma lies in the Dirac vacuum. According to theory, the fermion field of virtual quarks, leptons, and their antiparticles, should have negative energy. If there were precise pairing of fermions and bosons, as for example results from supersymmetry, there could be a compensating negative zero-point energy. Unfortunately, while supersymmetry is often used as a starting point in modern theoretical investigations, it has neither been proven necessary nor demonstrated empirically; indeed, the ongoing failure to observe superpartners for any known particles is a longstanding albeit minor embarrassment for the theory (see e.g. Ramond 1981[3]).

Another approach is more phenomenological in content. It comes from GRT, though its quantum-field-theoretic interpretation is usually connected to the Dirac vacuum approach. This technique uses the "cosmological constant" of the Einstein equation to absorb or cancel the effects of an arbitrary energy density. This will be discussed in more detail in a later section; for now it is sufficient to note that both of these approaches require cancellation of opposed densities to an utterly fantastic degree of precision.

One might try taking the position that the zero-point energy must be merely a mathematical artifact of theory. It is sometimes argued, for example, that the zero-point energy is merely equivalent to an arbitrary additive potential energy constant. Indeed, the potential energy at the surface of the earth can take on any arbitrary value, but the falling of an object clearly demonstrates the reality of a potential energy field, the gradient of which is equal to a force. No one would argue that there is no such thing as potential energy simply because it has no well-defined absolute value. Similarly, gradients of the zero-point energy manifest as measurable Casimir forces, which indicates the reality of this sea of energy as well. Unlike the potential energy, however, the zero-point energy is not a floating value with no intrinsically defined reference level. On the contrary, the summation of modes tells us precisely how much energy each mode must contribute to this field, and that energy density must be present unless something else in nature conspires to cancel it.

Further arguments for the physical reality of zero-point fluctuations will also be addressed in later sections. For the current introductory purposes we may simply observe that Adler *et al.* [1] summarize the situation thus:

> Quantum field theory predicts without ambiguity that the vacuum has an energy density many orders of magnitude greater than nuclear density. Measurement of the Casimir force between conducting plates and related forces verify that the shift in this energy is real, but considerations of gravity in the solar system and in cosmology imply stringent upper limits on the magnitude, which

are in extreme conflict with the theoretical estimate, by some hundred orders of magnitude! Unless one considers an ad hoc constant cancellation term an adequate explanation then there appears to be a serious conflict between our concepts of the quantum vacuum and gravity; that is, there is a vacuum catastrophe.

None of the resolutions to this "vacuum catastrophe" suggested above is entirely satisfactory, but some speculative developments suggest one more potential alternative. We may consider the possibility that the electromagnetic and other zero-point fields really do exist as fundamental theoretical considerations mandate, but that their zero-point energies do not gravitate because it is the actions of these fields on matter that generate gravitational forces (which are mathematically represented by the curving of spacetime). The zero-point energies do not gravitate because the zero-point fields do not, indeed cannot, act upon themselves. The basis of such a zero-point gravitation theory was conjectured by Sakharov[(4)] and Zel'dovich[(5)] and has undergone a preliminary development by several authors (see e.g. Adler[(6)]). More recently, and in consonance with our approach, this situation appeared in a clearer manner in the attempt of Puthoff.[(7)]

We point to the potential importance and possible direction of a zero-point gravitation theory, but do not attempt to develop this ourselves. The principle of equivalence, however, dictates that if gravitation is an effect traceable to the action of zero-point fields on matter, then so must the inertia of matter be traceable to zero-point fields. This approach Woodward and Mahood[(8)] vehemently find to be objectionable, treating it as if it were a dangerous new heresy. In their paper they summarize some connections between gravity and inertia, but fail to see that this simply establishes relationships that must exist between the two regardless of whether gravity and inertia are due to zero-point fields or not. Their arguments about inertia leave the paradox between quantum theory and gravitation theory as unresolved as ever.

As alluded to above, the recent work of Haisch, Rueda, and Puthoff[(9)], and more recent development by Rueda and Haisch[(10)], derives inertial reaction forces from interactions with the zero-point fluctuations of the quantum vacuum. The contrary theory of Woodward and Mahood[(8)] builds on earlier work in gravity and GRT to suggest that inertia is an extrinsic result of interactions with the gravitational field arising from the overall mass distribution of the cosmos.

The current analysis consists largely of a rebuttal to this last reference, and a response to its criticisms. Due to the frequency of reference, we shall use WM to refer to Woodward and Mahood[(8)], HRP to refer to Haisch, Rueda, and Puthoff[(9)], and RH to refer to Rueda and Haisch.[(10)]

2. CRITIQUE OF GRAVITATIONAL INERTIA

2.1 General problems with a gravitational theory of inertia

One of the most striking features of the General Theory of Relativity is that it essentially banishes the concept of a gravitational force. Gravity, according to GR, is a distortion of the metric of spacetime. An object seen by a distant observer to be accelerating in a gravitational field is, in fact, pursuing a geodesic path appropriate to the spacetime geometry in its immediate vicinity: no accelerometer mounted on such an object will detect an acceleration.

The Principle of Equivalence, adopted by Einstein as a starting point in the construction of GR, asserts that the state of free-fall one would encounter in deep space, far from all gravitational sources, is in fact the same state one encounters while falling freely in a strong gravitational field.[(11)] As a corollary of this equivalence, an acceleration relative to the local free-fall geodesic has the same effects, whatever the local geometry. Near Earth's surface, for example, geodesic paths accelerate toward Earth's center. To hold an object at rest relative to Earth's surface, therefore, requires that it be "accelerated" relative to this geodesic by the application of force; and, by Einstein's original formulation of equivalence, the effects of this acceleration are indistinguishable from those encountered in an accelerating reference frame in remote space (see, e.g. Einstein[(12)]).

In other words, the Principle of Equivalence asserts that gravitational "forces" as conventionally measured are inertial reaction forces – pseudo-forces, as these are sometimes called. We thus see that any attempt to identify gravity as the source of inertia, within the context of GRT, suffers from an essential circularity. At the level of ordinary discourse, this is almost trivially obvious. We consider an extrinsic theory of inertia which claims that inertial reaction forces are gravitational forces. But the equivalence principle requires that gravitational forces are inertial reaction forces, so applying equivalence to the theoretical claim we see it reduce to the uninformative declaration that inertial reaction forces are inertial reaction forces.

To demonstrate that this is not simply linguistic play, let us consider the situation with a bit more rigor. The various extrinsic-inertia models discussed by WM all have the common feature that they mandate the appearance of a gravitational field in an accelerated frame of reference. This is, in fact, quite uncontroversial and in no way depends on the acceptance of Mach's principle. Traditional, non-Machian approaches to GRT note that an accelerating reference frame will see a space-time metric corresponding to a gravitational field pervading all space. This is quite unsurprising since the accelerating observer sees the entire Universe accelerating relative to itself, and how better to explain this than by a cosmic gravitational field? The Machian element comes in only when one requires that the source of this cosmic field should be the overall mass distribution of the cosmos, rather than an intrinsic property of spacetime.

Regardless of the source of the cosmic gravitational field, an object held at rest in it — that is to say, any massive object sharing the motion of the accelerating reference frame — will, of course, exert weight on whatever agency is holding it at rest. In the reference frame of the cosmos, on the other hand, the accelerating body is exerting the expected inertial reaction force on whatever agency is causing it to accelerate. Have we explained inertia via the cosmic gravitational field?

Unfortunately, the standard geometrical approach to GRT says otherwise. In the presence of a gravitational field, an unconstrained body must fall freely along a geodesic path. To alter its motion from this spontaneous condition, one must apply a force to it, creating an acceleration which will be noted by, for example, any accelerometer rigidly mounted on the body. Common experience requires that this will produce an inertial reaction force as the body's inertia resists this acceleration. At this point we can identify three alternative explanations for the inertial reaction:

1. The inertia is intrinsic to the mass of the body. While this is consistent with observation it simply postulates inertia without explaining it.
2. The inertia is extrinsic to the mass, being the result of the interaction of the mass with some non-gravitational field. The ZPF-inertia theory of HRP falls into this class.
3. The inertia is extrinsic to the mass and results from the interaction of the mass with the apparent gravitational field. This gravitational explanation of inertia is the one WM are claiming.

To see how peculiar a theory of the third class above actually is, let us ask why the inertial reaction force appears at all in this theory. WM apparently believe that the presence of a gravitational field in the accelerating frame is a sufficient explanation: the reaction force is the body's weight in this field. But why do bodies have weight in a gravitational field? In the standard formalism of geometrodynamics, gravity is not a force but a consequence of the local shape of spacetime. "Weight" is actually the inertial reaction force that results from accelerating an object away from its natural geodesic path. But we are, here, trying to *explain* inertial reaction forces. To say that an inertial reaction force is the weight resulting from gravity in the accelerated frame explains nothing in geometrodynamics, because weight is already assumed to be an inertial reaction force and one is therefore positing inertial reactions to explain inertial reactions. Therefore, this "explanation" of the origin of inertial reaction forces is circular *if* one is operating in the standard geometrical interpretation of GRT.

It is, of course, possible to abandon this interpretation and presume that gravity actually does exert forces directly on objects, as in the original Newtonian theory. This, unfortunately, introduces a different circularity. The fact that a gravitational field appears in an accelerating frame is, as noted above, true in any formulation of GRT, Machian or not, and remains true whether inertia is intrinsic or extrinsic. The gravitational-inertia theory wishes to assert that this gravitational field is the cause of the inertial reaction force. But this is the same as the assumption that gravitational fields exert forces; we cannot claim to have explained inertia in this formalism when we incorporate our desired conclusion into the initial assumptions.

This would appear to be a very general problem with efforts to find a gravitational origin for inertia in the standard, geometrodynamic interpretation of GRT. There are, of course, ways around this. An argument by Sciama[13], for example, finds a reaction force arising from a "gravito-magnetic" reaction with a presumed gravitational vector potential. It is, however, well worth noting that Sciama's argument is based on analogizing gravitation to electromagnetism, in the weak-field limit of GR. In this weak-field limit one typically does not work explicitly with the geometrical consequences of metric distortion, but rather represents interactions in terms of potentials and forces. The circularity noted above disappears, but with it the conceptual parsimony of GR. Indeed, as WM themselves assert (their section 3.2), Sciama's argument was originally conceived as a refutation of GRT.

General relativity, in reducing gravity to a consequence of geometry, offers a very hostile background to a gravitational theory of extrinsic inertia. GR shows how mass distorts spacetime, and allows one to calculate the trajectories unconstrained bodies will follow in the resulting distorted spacetime. It does not explain why a body, constrained by non-gravitational forces to travel on some trajectory that is not a geodesic, exerts an inertial reaction force proportional to its mass.

This is, of course, a trivial non-mystery if one naïvely presumes inertia to be intrinsic to mass. The attempt, however, to construct a gravitational theory of extrinsic inertia within geometrodynamics seems doomed to circularity.

2.2 Specific problems with WM argument

In fairness to WM they do seem aware, to a certain extent, of the circularity problem. At the end of their section 3.4 they devote a paragraph to an attempt to address it. Unfortunately, they dilute and weaken their argument by attempting to portray the circularity argument as a defense of ZPF-inertia theory, which it is not. Indeed, it would seem that the WM response to the the circularity argument consists mainly of the complaint that ZPF theories do not successfully explain inertia either, which even if it were the case is irrelevant to the failure of gravitationally based theories to do so. One should bear in mind that the default explanation of inertia, currently highly favored by Ockham's Razor as the least hypothesis, is that inertia is intrinsic to mass. Various important elements of physical theory, such as the conservation of momentum, which flow quite naturally from a theory of intrinsic inertia, require complicated supporting arguments or may even be violated in a theory of extrinsic inertia. (It is worth noting that one of the authors of WM has in fact published articles — and obtained a U. S. Patent[14] — demonstrating ways in which a theory of extrinsic gravitational inertia allows local violations of momentum conservation.[15] While one might hope, and indeed the same papers claim, that momentum is still conserved globally, this is actually a meaningless assertion in the Machian perspective of this theory.)

In their section 3.2 WM make the peculiar claim that "GRT dictates that inertia is gravitationally induced irrespective of whether cosmic matter density is critical or not." This claim is odd, because it seems to be supported only by the assertion that in Robertson-Walker cosmologies the local metric is determined solely by the distribution of material sources within the current horizon. While this claim is true, it does not address the relationship between critical density and gravitational inertia. All of the arguments employed by WM require a specific value for the total gravitational potential ϕ in order for inertial reaction forces to behave properly. This depends on the cosmic mass density ρ in a Robertson-Walker cosmology. While WM's demonstration that sources outside the horizon may safely be ignored is valid and useful, it falls badly short of explaining why the actual density of sources *inside* the horizon can also be ignored in declaring that physics is Machian and inertia results from gravity.

In section 3.3 WM provide a general discussion of the relation between Mach's principle and GRT. In the current context this is notable mostly for its complete omission of results suggesting that GRT is not only not a Machian theory, but in fact incompatible with Mach's principle. For example, the Lense-Thirring precession is often touted as an example of the "Machian" dragging of inertial frames by a rotating mass, but recent work by Rindler[16] demonstrates that the equatorial Lense-Thirring effect is inconsistent with a Machian formulation. Granted, the Lense-Thirring rotation is such a minute effect that it has not been empirically tested, but it is an unambiguous prediction of GRT: to have an anti-Machian effect emerge from GRT impedes the joint claim of WM that GRT is the correct theory of gravity and that the Universe is Machian.

WM go on in section 3.4 to discuss an argument by Nordtvedt[17] concerning frame dragging in translational acceleration. They present as their eq. 3.7 the relation:

$$\delta \mathbf{a} = (4\phi/c^2)\mathbf{a}, \tag{2}$$

which relates the induced (frame-dragging) acceleration $\delta\mathbf{a}$ to the acceleration $\mathbf{a}$ of the accelerated mass and the gravitational potential ϕ induced by that same mass. They point out that if $4\phi = c^2$, then $\delta\mathbf{a} = \mathbf{a}$ and all inertial frames are dragged rigidly along with the inducing body. If one regards the universe at large as Nordtvedt's inducing body, and presumes that it has the appropriate value of ϕ throughout, then any hypothetical acceleration of the universe would necessarily drag along all inertial frames; an alternative way of expressing this is to say that the bulk mass distribution of the cosmos defines which frames are inertial. So far this would appear to be an excellent demonstration of Mach's principle.

As a possible quibble we note that for $\phi > c^2/4$ the "frame dragging" acceleration is *greater* than the acceleration of the inducing body, a bizarre result that seems very difficult to attribute to frame dragging. In fact, as WM acknowledge, Nordtvedt's derivation is of linear order in the mass, and is therefore of questionable validity for the large values of ϕ they wish to apply. But this ranks only as a quibble, because the problem of inertia has not been addressed at all. Even if one, implausibly, stipulates the validity of eq. 2 over all ϕ, one has merely identified which states of motion are inertial reference frames: no explanation has been offered for the appearance of inertial reaction forces in non-inertial frames. We are once again facing the circularity problem of the previous section, with no progress toward an explanation. As noted above, WM have not successfully addressed this problem anywhere in their discussion of gravitational inertia.

The next difficulty in WM is perhaps best introduced by quoting their own argument, noting that ϕ is their symbol for total gravitational potential as in eq. 2 above.

> Since the locally measured value of ϕ must be an invariant to preserve the principle of relativity, one might think that the gradient of the gravitational potential must vanish everywhere. Accordingly, it would seem that no local gravitational fields should exist. But the gradient of a locally measured invariant need not vanish if it is not a *global* invariant. The total gravitational potential is not a global invariant. As a result, the "coordinate" value of the gravitational potential in some frame of reference may vary from point to point, notwithstanding that the numerical value measured at each point is the same everywhere. And the gradient of the potential in these coordinates may be non-vanishing. As a familiar example of this sort of behavior we point to the vacuum speed of light — a locally measured invariant — in the presence of a gravitational field. As is well known, the speed of light in intense gravitational fields measured by *non-local* observers (that is, the "coordinate" speed of light) is often markedly different from the locally measured value. And for these non-local observers, the speed of light in general will have a non-vanishing gradient in their coordinates. (WM, section 4.2, excerpt from final paragraph.)

Clever as this argument and analogy may seem, it introduces a new paradox worse than the one they seek to evade. The speed of light in vacuum is deeply embedded in relativistic kinematics. If a given coordinate system measures an altered value of c in some remote regions, it will also note distortions in lengths and time intervals in those regions such that it will expect an observer in that region to find the standard local value for c. The potential ϕ, on the other hand, is a dynamic variable, not a kinematic one. Where c appears in such fundamental and inescapable relations as the velocity-addition rule, ϕ is merely a potential; its value dictates how specific objects will move, not the nature of motion itself.

Let us posit the WM scheme of a locally invariant ϕ that is nevertheless observed to vary and have a gradient in certain reference frames. The quantity ϕ is, by definition, a gravitational potential: $m_g\phi$ is the gravitational potential energy of an object with gravitational mass m_g. The value of ϕ used in computing this quantity is, of course, the local value at the current position of the object. If ϕ is a local invariant, no object can change its gravitational potential energy by moving from one location to another. A distant observer, seeing an object move from a region with potential ϕ_0 to a region at a different ϕ_1, would expect to see its kinetic energy change by the quantity $m_g(\phi_0 - \phi_1)$. A comoving observer, in contrast, observing that the gravitational potential energy is $m_g\phi$ at both locations, does not expect any change in the relative velocity of the object with respect to the rest of the cosmos. These conflicting expectations cannot be reconciled.

As if the above problems were not enough, this new perspective on ϕ shows that the Nordtvedt frame-dragging effect of eq. 2 above is, rather than a support of the WM inertia theory, absolutely fatal to it. If ϕ is a locally measured invariant due to the action of the entire cosmos, no local concentration of matter can affect ϕ, which leads to the startling conclusion that *no body smaller than the Universe as a whole can produce any frame dragging effects whatsoever!* WM require this locally invariant character for ϕ in order to avoid having inertia behave unacceptably (that is, in a manner contrary to long-established observation) in the vicinity of gravitating masses. Yet the price of this local invariance is the disappearance of all local frame-dragging effects. And, again as WM themselves point out, Nordtvedt's frame-dragging effect is necessary for such quotidian phenomena as planetary orbits to display the proper invariance under arbitrary choices of coordinates.

In their section 4.3 WM refer to a "stronger version" of Mach's Principle, in which "...*mass itself* arises from the gravitational action of the distant matter in the universe on local objects — mass is just the total gravitational potential energy a body possesses." Unfortunately this does not work, at least not in the all-encompassing sense that WM seem to have in mind. In order to establish the gravitational potential energy of a body, one must have at least one kind of mass, the gravitational mass m_g, as a preexisting quantity, so that $m_g\phi$ gives the total gravitational potential energy. This version of Mach's principle would allow one to derive the energetic content of mass and explain why $E/c^2 \equiv m_g$, but does not quite explain mass itself *ex nihilo* as WM appear to be claiming.

While certain other parts of WM's explication of gravitational inertia are flawed, these closely involve their criticisms of ZPF theories, and so discussion of them is better deferred to the next section.

3. CRITICISMS OF ZPF: ERRORS AND CORRECTIONS

WM raise numerous criticisms, both of the notion of quantum zero-point fluctuations and of the specific HRP theory of extrinsic inertia based on interactions with ZPF. Most of these are severely flawed. Before dealing with the WM criticisms in detail, it is worth noting that the strongest criticism is not one that they raise explicitly, though it is implied by certain of their other arguments. The exact identity between the inertial mass which resists accelerations, the gravitational mass which acts as a source term in the Einstein field equation, and the energetic-content mass E/c^2 follows quite naturally in simplistic intrinsic-inertia theories. It needs careful attention, though, in any theory of extrinsic inertia, and the ZPF-inertia theory put forward in HRP is not yet able to account for this identity. Since the ZPF-inertia theory is still in its early stages of development, this should not be considered either surprising, or a refutation of the theory.

The various points raised in WM actually address two distinct issues, the physical reality of ZPF and the theory that ZPF interactions are the cause of inertial reaction forces. Obviously the former issue is logically prior to the latter; it is also empirically of greater consequence, since the existence of ZPF-driven effects such as the Casimir force and the Lamb shift have been confirmed experimentally. Some alternative explanation for them must be found if we wish to keep our theories in consonance with reality. We will therefore address the existence of the ZPF first.

3.1 Elementary theoretical justification

The Introduction above, in explaining the ≈ 120 order-of-magnitude discrepancy that motivates the search for a ZPF-inertia theory, already provided several strong arguments for considering the ZPF physically real. One further argument worthy of consideration, however, emerges from experiments in cavity quantum electrodynamics involving suppression of spontaneous emission. As Haroche and Ramond explain[18]:

> These experiments indicate a counterintuitive phenomenon that might be called "no-photon interference." In short, the cavity prevents an atom from emitting a photon because that photon would have interfered destructively with itself had it ever existed. But this begs a philosophical question: How can the photon "know," even before being emitted, whether the cavity is the right or wrong size?

The answer is that spontaneous emission can be interpreted as stimulated emission by the ZPF, and that, as in the Casimir force experiments, ZPF modes can be suppressed, resulting in no vacuum-stimulated emission, and hence no "spontaneous" emission.[19]

3.2 The cosmological constant problem

WM object that "...if the ZPF really did exist, the gravitational effect of the energy resident in it would curl up the universe into a minute ball" (section 2.2, WM). This, of course, is precisely the vacuum catastrophe problem discussed in detail in the Introduction. When various solutions to that quandary were being discussed, it was pointed out that several of them require an implausibly precise cancellation between the ZPF energy density and other physical factors. However, one of those theoretical devices — the cosmological constant — suffers a fine-tuning problem, whether or not it is invoked to avoid the vacuum catastrophe. The general form of the Einstein field equation,

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu}, \tag{3}$$

includes an arbitrary "cosmological" constant Λ. This term can absorb any contribution from a uniform density such as the vacuum energy. As noted in the Introduction, actually matching the ZPF energy density would be a feat of remarkable precision. The fine-tuning problem persists even if one assumes that something else averts the vacuum catastrophe, because observational astronomy increasingly favors a cosmology with a small nonzero value of Λ. Unfortunately, field-theoretic considerations suggest that "natural" values of Λ should be either exactly zero, or else correspond to an energy density (positive or negative) on the rough order of one Planck mass per Planck volume. We are thus confronted with a fine-tuning problem for Λ whether or not we wish to use it to resolve the ZPF energy density problem.

3.3 Local fluctuations versus nonlocal interactions

WM point out that "... *any local fluctuational explanation can be reinterpreted as a non-local, retarded/advanced interaction with distant matter.*" (Section 4.4, emphasis in the original.) This may very well be true, but it can scarcely be taken as support for their thesis. Insofar as there is a consensus in the physics community on the issue of nonlocality, it would seem to be that nonlocality is to be avoided at almost any cost. WM refer to the well-established "nonlocal" interactions of quantum mechanics (earlier in their section 4.4 than the above quote) in an attempt to justify their preference for a nonlocal explanation of ZPF-driven effects. Unfortunately, what quantum mechanics refutes is not locality but the conjunction of locality with some aspects of objective realism. (The minimal part of realism that must be rejected has been labeled "contrafactual definiteness," the notion that it is meaningful to discuss the potential outcomes of experiments that might have been performed but in fact were not.) By observation, most physicists confronted with the failure of local realism prefer to abandon some aspect of realism rather than some part of locality.[20]

Other justifications WM present for preferring a theory that mixes retarded and advanced waves are the utility of Feynman-Wheeler absorber theory and the recent proposal of Cramer's "transactional interpretation" of quantum mechanics. Remarkable though the Feynman-Wheeler theory is, we should not lose sight of the fact that it is one of several formalisms that all account successfully for the non-observation of advanced waves. The "transactional interpretation," on the other hand, is *by construction* devoid of empirical content: all philosophical interpretations of quantum mechanics of necessity agree with all empirical predictions of QM and therefore permit no empirical preference for one over another. One's choice of QM interpretation is therefore a matter for philosophical aesthetics rather than scientific judgement.

Contrary to the claims of WM, standard relativity theory in no way demands the "radical timelessness" they advocate. At least, it does not do so as long as nonlocal interactions are kept from contaminating the theory. In a conventional relativistic world without nonlocality, time proceeds in a well-ordered fashion along every timelike worldline. The inability of observers in different states of motion to agree on the relative ordering of remote, spacelike-separated events is irrelevant; this ambiguity can never lead to causal confusion or lead to "future" events affecting the "past." Essentially, this is because the conventional interpretation of relativity replaces the traditional view of past, present and future with a four-part division of reality. From any given event, the "future" encompasses everything in the future light cone, the "past" the entire contents of the past light cone. "Now," which a Newtonian physicist could conceptualize as a shared instant of simultaneity encompassing all space, has shrunk to the single space-time point of the event under consideration. And the rest of the universe is in a region commonly dubbed "elsewhere," a constellation of space-time events that can neither affect nor be affected by the event under consideration in any way. So long as all interactions are local, the potentially inconsistent time-ordering of events "elsewhere" can never lead to the slightest confusion between events in the past and events in the future, nor allow the latter to affect the former.

This of course breaks down if one admits of nonlocal interactions. By means of a nonlocal connection an event in the future light-cone can send a signal to an event "elsewhere," and cause a returning nonlocal signal to arrive at an event in the past. This should make it clear that it is not relativity, but relativity plus nonlocality, which demands the radical timelessness and its "very strange consequences" advocated by WM.

Having addressed WM's primary arguments against the physical reality of ZPF in general, we now turn to their arguments against the HRP theory of ZPF as the origin of inertia.

3.4 A Sketch of HRP's and RH's Claims

In the discussion by this name in their section 2.1, WM, in order to criticize the arguments of HRP and RH, present a simplified argument that in their terminology is intended to uncover "the crux of the whole business." A simplified argument which still contained the essential physical ingredients of the calculation would be a useful pedagogical as well as conceptual excercise. It must, however, remain physically accurate. Unfortunately this is not the case with the presentation of WM, which, despite their claim of "accurate formalism", is both misleading and erroneous.

Before discussing this presentation in detail, however, it seems desirable to clarify the motivations two of the current authors (AR and BH) had for producing the HRP and RH papers. The HRP paper involved a detailed calculation of the behavior of a Planck oscillator pushed by an external agent to move under uniform proper acceleration (so-called hyperbolic motion). In spite of some simplifying assumptions and a few fairly reasonable approximations, the mathematical development of the HRP article came out to be quite complex. The inertia effect was clearly obtained but assessment of the calculations and of the argument was challenging. It was not clear whether there was something in the vacuum, as viewed from an observer comoving with an accelerated frame, that could produce the effect predicted in HRP. Calculations in QED and QFT for a detector accelerated in a *scalar* vacuum field did not seem to find any anisotropy in the scalar field even though the well-known Unruh-Davies thermal background was predicted to occur.[21] It was necessary to check if the *vector* nature of the electromagnetic ZPF (as opposed to a scalar field) would produce the expected anisotropy in the vacuum background from the viewpoint of such a uniformly accelerated observer.

This problem was attacked and a confirmatory result emerged from the calculations. After approaching the problem in four different ways, as detailed in RH, it was in all four ways clearly found that an anisotropy appeared in the ZPF Poynting vector and hence that an anisotropy appeared in the flux of momentum density. More than that, the anisotropy in the Poynting vector was of the precise form to produce a radiation pressure opposite to the acceleration and proportional to it in the subrelativistic case, and also extended properly to the standard relativistic form of the inertial reaction 4-force at large speeds.

In their section 2.1 WM attempted to do two things, both of which were commendable in principle. First, they tried to present a simplified pedagogical view that would clearly illustrate the physics of the situation analyzed in the calculations presented in HRP and RH. Second, they attempted to relate the analysis of RH to that of HRP so that the physics of the inherent connection could easily be seen. We must report, however, that they were unfortunately unsuccessful in both of these endeavors. The main point of this part of their presentation in this respect was to replace eqs. (26) to (28) of HRP by the very simple proportionality relationship between the electric field $\mathbf{E}_{zp}$ and the velocity $\mathbf{v}$ of vibration of the subparticle component in the instantaneous inertial frame of reference at particle proper time τ, in the form of WM eq. 2.1:

$$e\mathbf{E}_{zp} = k\mathbf{v}. \tag{3}$$

This enormous simplification had the following consequences:

(i) All $\mathbf{E}$-field frequency components and all components in all directions seemed to contribute with the same weight to the instantaneous velocity of the subparticle, contrary to the facts.

(ii) All those contributions appeared to come exactly in phase, contrary to the facts.

(iii) As a consequence of (i) and (ii) we get the physically very surprising feature that the electric field force was proportional to the velocity. (This might be called Aristotelian physics.) But we know this cannot happen unless energy is not conserved, or more precisely, unless energy goes to degrees of freedom that have not been accounted for in detail, as happens with a thermal reservoir. In reality the Planck oscillators interact with the ZPF in a dissipationless manner, so the dissipative force in the WM analysis is both inaccurate and misleading.

After such a disastrous start in the first equation, it is tempting to simply discard the entirety of WM's subsequent argument. In particular, since WM eq. 2.3 depends on the inaccurate 2.1, it is itself invalid, and all conclusions drawn from it are suspect. However, there are additional and independent errors in the WM analysis which merit separate comment.

To reprise briefly the development of the HRP/RH argument given above: The inertialike reaction force appearing at the end of the HRP derivation implies the necessary existence of an anisotropy in the accelerated ZPF. However, earlier work in vacuum scalar fields found no such anisotropy. RH therefore investigated the existence of such anisotropy in vector fields, and found a net Poynting vector in accelerated vector ZPF by four separate lines of argument.

However, in RH no details on the particle were used since the analysis concentraed on the fields. The Poynting vector appears in the accelerated ZPF regardless of any entity that may interact with it. That interaction was introduced only at the end, in the form of a normalizing function $\eta(\omega)$ that quantified the momentum density passed to the accelerated object at every frequency. In contrast, the original HRP analysis modeled this interaction in great detail. In this case the Einstein-Hopf model was used, which implied only a first-order iterative solution and hence some degree of approximation. The considerable difference in methods between RH and HRP is the reason for the difference in appearance of the inertial mass expressions in RH and HRP. It seems likely that to derive the RH form from the expressions of HRP one would have had to pursue an iterative solution to many orders, going far beyond the Einstein-Hopf approximation.

The discussion presented by WM contrasts with the detailed analysis done in RH and HRP. For a serious discussion of the technical aspects of HRP (and to a lesser extent RH) we prospectively refer the interested reader to works presently in progress by Cole and Rueda, and by Cole.[22]

3.5 The problem of representing the accelerating body

Aside from the general flaws of WM section 2.1 noted above, we note that their simplified model includes the assumption that the "oscillator" interacting with the ZPF is in fact an elementary point charge. This is problematic. A point charge in classical theory has infinite self-energy, leading to some question of whether it is legitimate to deal with such objects except as an approximation good for long wavelengths and modest accelerations. This, unfortunately, is the exact opposite of the regime crucial to the ZPF-inertia theory. The empirical verification of quarks (or leptons) as pointlike extends only to length scales orders of magnitude longer than the wavelengths important to either the HRP or RH derivations. The representation of the particle/radiation interaction, in the one case by a generalized damping coefficent Γ, in the other by an unspecified interaction function $\eta(\omega)$, seems appropriately cautious at our current level of ignorance.

3.6 The bare mass problem

In the discussion subsequent to their eq. 2.8 WM discuss the apparent circularity of using $\Gamma = 2e^2/3m_0c^3$, with a contribution from a "bare" mass m_0 with presumed inertial effects, in the HRP derivation that purports to identify the source of inertial mass. This is a valid criticism, which suggests that a reworking of the formalism is desirable. In fact the later work of RH presents such a reworking, with no reference to unobservable "bare" masses.

3.7 Quark and hadron masses

The extended discussion WM conduct in their section 2.2 on this issue implies the general mass-equivalence problem which, as noted above, is a valid concern and an unmet challenge for the ZPF-inertia theory. However, the specific points made by WM are, as they themselves point out, largely answered by HRP; and their rebuttal of this answer appears to misunderstand it. As is clearly indicated in the text WM choose to quote, the authors explicitly propose a revised formalism in which the interaction is assumed to be dominated by a resonance frequency ω_0, determined by the particle dynamics, rather than the ZPF cutoff frequency ω_c. WM respond to this proposed model by asserting:

> Well, ω_c isn't a "resonance" frequency. It is the upper limit in the integration over the frequency spectrum of the ZPF, and if that limit is not imposed, the result of that integration, and the

inertial mass of the particle, is infinite irrespective of any resonances that may be present at finite frequencies. Remember, the spectral energy density of the ZPF goes as ω^3, so invoking a "low" frequency resonance will not suppress the cutoff unless the cutoff is assumed to lie quite close to the resonance frequency.

But this counterargument is clearly without merit. Any resonant phenomenon with a frequency response that falls off sharply enough for $\omega > \omega_0$ will have a converging and therefore finite integral in the reaction-force calculation. And the criterion for "sharply enough" is much less stringent than WM seem to imagine.

HRP present, in their eq. (3), the spectral energy density of the ZPF in an accelerated frame. We reproduce this equation (aside from a common factor $d\omega$ on both sides) here:

$$\rho(\omega) = \left[\frac{\omega^2}{\pi^2 c^3}\right]\left[1 + \left(\frac{a}{\omega c}\right)^2\right]\left(\frac{\hbar\omega}{2} + \frac{\hbar\omega}{e^{2\pi c\omega/a} - 1}\right). \tag{4}$$

We can see that there are four terms when this expression is multiplied out. One has ω^3 spectral dependence and is in fact the unaltered $\hbar\omega^3/2\pi^2c^3$ ZPF spectrum itself. This means that an accelerated reference frame contains the same ZPF as in an inertial frame, plus three new components. Of these three, one is the thermal bath identified with the Davies-Unruh effect, one is not thermal but is, like thermal radiation, suppressed as $e^{-\omega}$ for large ω, and the third and last has a spectral dependence of ω. It is this last term, varying as ω, not ω^3, which HRP propose as the source of the reaction force in their discussion consequent to this formula.

If we assume then that the radiation term responsible for the reaction force has a frequency dependence of ω, it follows naturally that any resonance centered on a frequency ω_0 will have a finite total reaction force integral, even in the limit $\omega_c \to \infty$, so long as its frequency response falls off faster than ω^{-2} for $\omega \gg \omega_0$. Even if we retain the assumption that the inertial reaction force derives from the full ZPF spectrum with its ω^3 energy density, a resonance falling off faster than ω^{-4} will remain finite regardless of cutoff.

This point incidentally answers the objection WM raise to the notion of changes in resonance being responsible for the inertial mass of a proton. They object that, since the scale of a proton is 20 orders of magnitude larger than the Planck length, resonances due to the proton's structure are 20 orders of magnitude lower in frequency than the cutoff ω_c. But we have just seen that the cutoff frequncy is irrelevant. The difference between the electron mass of .511 MeV, the quark mass of $\approx$10 MeV, and the hadron mass of $\approx$940 MEV can, at least in principle be accomodated by particle-specific resonances. These would almost certainly be different for a bound triplet of particles than some linear summation of individual resonances for three unbound particles.

If the electron has a resonant frequency ω_e, we must presume that a "free" quark has a resonant frequency $\omega_q \approx 20\omega_e$ to account for their mass difference. The term "free" is used loosely, since of course color confinement demands that there really is no such thing as a free quark. What is commonly reported as quark mass is inferred from high-energy collisions between various sorts of projectiles and components within hadrons; the phenomenon of "asymptotic freedom" in quantum chromodynamics means that in such high-energy interactions the quark is little constrained by the color force and behaves almost as a free particle. On the other hand, in the low-energy state of an unexcited proton or neutron, the quarks are presumably distributed as widely as is consistent with color confinement — if they were more closely clustered than necessary, the resulting momentum uncertainty would equate to excess internal energy which would swiftly be emitted as gamma rays or possibly other particles. In the normal conditions within a proton or neutron, then, we would expect quarks to be strongly bound by the color force; and thus, there is plausible justification in principle for their resonance at a frequency $\omega_p \approx 30\omega_q$.

Moreover, a less strained justification is available. The HRP derivation deals only with EM vacuum fluctuations, as does the RH analysis. WM, in castigating an implied model of gluons as vast clouds of charged dust (to produce EM-ZPF reaction effects), overlook the fact that gluons, too, have a vacuum fluctuation spectrum. This fact was pointed out in the introductory discussion of the vacuum catastrophe problem; it does not disappear merely because we are examining a different consequence of ZPF effects. Electrons, being colorless, do not interact at all with gluon fluctuations. We must expect, however, that colored quarks do so quite strongly. If the ZPF-inertia theory gives the correct explanation of inertial reactions, therefore, all color-bearing particles must experience intense inertial reaction effects from a field orders of magnitude stronger than electromagnetism.

We may note in passing that this disposes of another WM criticism, that elementary particles do not show inertial masses proportional to the squared particle charge e^2. Since both e^2 and ω_0 are factors in the inertial mass, and a general theory for ω_0 values is not yet available, we cannot expect $m_i \propto e^2$ to hold between different particles at even a heuristic level. Nor does the e^2 argument pay the slightest attention to the interaction of particles with fields other than the electromagnetic.

4. DISCUSSION AND CONCLUSIONS

In reviewing the arguments of Woodward and Mahood (1999), the following conclusions can clearly be seen:

1. Within the standard geometrical interpretation of general relativity, any attempt to identify gravity as the source of inertial reaction forces can succeed only by postulating the thesis it purports to prove. Such arguments can therefore be dismissed as circular.
2. While one can construct a gravitational theory for inertial reaction forces, as in the case of Sciama's 1953 theory, such theories are necessarily theories of explicit forces coupled to a source m_g, and therefore are quite distinct from the geometrical theory we know as general relativity.
3. The particular gravitational-inertia theory propounded by WM suffers a consistency problem in the handling of ϕ as a quantity that (a) acts as a potential, (b) has a gradient, and (c) is a locally measured invariant. These three properties prove to be mutually incompatible.
4. The advocacy of WM for the philosophy of "radical timelessness" is, contrary to their own assertion, not a consequence of relativity but a consequence of their acceptance of nonlocal interactions in a relativistic framework.
5. The arguments of WM against the existence of quantum zero-point fluctuations are deeply flawed, being based in one case on a misunderstanding of the cosmological constant problem and in the second case on a willingness to adopt nonlocal interactions in a way which most working physicists would find unacceptable.
6. The arguments of WM against the HRP theory of extrinsic inertia arising from interactions with the ZPF make it clear that WM have misunderstood almost every important point of the argument. Their arguments are in most cases invalid, in some cases useful criticisms pointing to ways in which the theory needs to be strengthened and improved. In no case whatever do they constitute actual refutations.

Finally, we should note that among the possible theories of inertia the most plausible current contender, albeit also the least informative, remains the simplest: That inertia is inherent in mass. No theory of extrinsic inertia yet proposed has been able successfully to reproduce all of the observed phenomena which are trivial consequences of this simple premise. The alternative theories of extrinsic inertia require considerable further development before they can practically replace the standard interpretation of inertial reaction forces which has been thoroughly successful since the days of Newton.

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13. ABSTRACT *(Maximum 200 words)*

This is a study in the area of theoretical physics exploring the possible connection and its implications between the electromagnetic zero-point field of the quantum vacuum and the inertia of matter as proposed by Haisch, Rueda and Puthoff (Phys. Rev. A, 49, 678, 1994) and Rueda and Haisch (Physics Letters A, 240, 115, 1998; Foundations of Physics, 28, 1057, 1998).

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