INERTIA: MACH'S PRINCIPLE OR QUANTUM VACUUM?

Bernhard Haisch[1], Alfonso Rueda[2] and York Dobyns[3]

[1]Solar & Astrophysics Laboratory, Lockheed Martin, L9-41, B252, 3251 Hanover St., Palo Alto, CA 94304
haisch@starspot.com

[2]Dept. of Electrical Engineering, California State University, Long Beach, CA 90840
arueda@csulb.edu

[3]C-131 Engineering Quad, Princeton University, Princeton, NJ 08544-5263
arueda@csulb.edu

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

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

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

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

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

where **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

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

The four-divergence of a four-vector is

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

and since

$$\mathbf{f} = -\nabla\phi \rightarrow \nabla \cdot \mathbf{f} = -\nabla^2\phi \qquad (e)$$

we find

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

For the stationary case we know that

$$-\nabla^2\phi = -4\pi G\rho . \qquad (g)$$

Retaining only the first remaining term we arrive at

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

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

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