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 **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 ≈10 MeV, and the hadron mass of ≈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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REFERENCES

(1) R. J. Adler, B. Casey and O. C. Jacob, *Am. J. Phys.* **63**, 720 (1995).
(2) R. Loudon, *The Quantum Theory of Light,* Clarendon Press, Oxford, (1982).
(3) P. Ramond, *Field Theory — A Modern Primer.* Beryaunka, Menlo Park CA USA, pp. 55 ff. (1981).
(4) A. D. Sakharov, *Dokl. Acad. Nauk SSSR* **177**, 70 (1968); translated in Sov. Phys. Dokl **12**, 1040 (1968).
(5) Ya. B. Zel'dovich, *Usp. Fiz. Nauk.* **95**, 209 (1968); translated in Sov. Phys. Usp. **11** (3), 381 (1968).
(6) S. L. Adler, *Rev. Mod. Phys.* **54**, 729 (1982).
(7) H. E. Puthoff, *Phys. Rev. A* **39**, 2333 (1989).
(8) J. F. Woodward and T. Mahood, *Found. Physics*, in press. (1999).
(9) B. Haisch, A. Rueda and H.E. Puthoff, *Phys. Rev. A* **49**, 678 (1994).

(10) A. Rueda and B. Haisch, *Physics Letters A* **240**, 115 (1998); A. Rueda and B. Haisch, *Found. Physics* **28**, 1057 (1998).
(11) Strictly speaking this is true only for translational motions of spinless point particles. Since nothing in this discussion of inertial reactions depends either on physically extended bodies or on the presence or absence of tidal forces, this caveat is irrelevant to the remainder of the analysis. We likewise ignore the general relativistic spin-orbit interaction, since in any gravitational field there exist trajectories for which it vanishes.
(12) A. Einstein, *Ann. der Phys.* **49**, p. 769 (1916) as quoted in H. C. Ohanian and R. Ruffini *Gravitation and Spacetime.* Second Edition. W. W. Norton & Company, New York, London, p. 53 (1994).
(13) D. W. Sciama, *Mon. Not. Roy. Astron. Soc.* **113**, 34 (1953).
(14) U. S. Patent No. 5,280,864, "Method for Transiently Altering the Mass of Objects to Facilitate Their Transport or Chage Their Stationary Apparent Weights," Inventor: James F. Woodward.
(15) James F. Woodward, 1997. "Mach's Principle and Impulse Engines: Toward a Viable Physics of Star Trek?" Presentation to NASA Breakthrough Propulsion Physics Workshop, Cleveland, Ohio, August 12-14, 1997, Proc. NASA Breakthrough Propulsion Physics Workshop, NASA/CP-1999-208694, p. xx (1999).
(16) W. Rindler, *Physics Letters A* **187**, 236 (1994).
(17) K. Nordtvedt, *Int. J. Theor. Phys.* **27**, 1395 (1988).
(18) S. Haroche and J. M. Raimond, *Scientific American* **268**, No. 4, 54 (1993).
(19) W. McCrea, *Q. J. Royal Astro. Soc.*, **27**, 137 (1986).
(20) J. T. Cushing and E. McMullin (eds.), *Philosophical Consequences of Quantum Theory.* University of Notre Dame Press, Notre Dame, Indiana (1989).
(21) J.R. Letaw, *Phys. Rev. D* **23**, 1709 (1981); P.G. Grove and A.C. Ottewill, *Class. Quantum Grav.* **2**, 373 (1985).
(22) D.C. Cole and A. Rueda, 1999 (in preparation) and D.C. Cole, 1999 (in preparation).