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MAKING THE UNIVERSE SAFE FOR HISTORIANS: TIME TRAVEL AND THE LAWS OF PHYSICS

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The study of the hypothetical activities of arbitrarily advanced cultures, particularly in the area of space and time travel, as a means of investigating fundamental issues in physics is briefly discussed. Hawking's chronology protection conjecture as it applies to wormhole spacetimes is considered. The nature of time, especially regarding the viability of time travel, as it appears in several "interpretations" of quantum mechanics is investigated. A conjecture on the plausibility of theories of reality that admit relativistically invariant interactions and irreducibly stochastic processes id advanced. A transient inertial reaction effect that makes it technically feasible, fleetingly, to induce large concentrations of negative mass-energy is presented and discussed in the context of macroscopic wormhole formation. Other candidates for chronology protection are examined. It is pointed out that if the strong version of Mach's principle (the gravitational induction of mass) is correct, then wormhole formation employing negative mass-energy is impossible. But if the bare masses of elementary particles are large, finite and negative, as is suggested by a heuristic general relativistic model of elementary particles, then, using the transient effect, it is technically feasible to trigger a non-linear process that may lead to macroscopic wormhole formation. Such wormholes need not be destroyed by the Hawking protection mechanism.

Key words: time travel, negative mass, Mach's principle, relativity, quantum mechanics.

1. INTRODUCTION

In the physical sciences, until a decade or so ago at least, questions like: "*Do the laws of physics prevent arbitrarily advanced civilizations from constructing 'time machines' (machines for backwards time travel), and if so, by what physical mechanism are they* *prevented?*" offered as motivation for an investigation would not have been taken seriously. Kip Thorne, his students, and several colleagues changed that [Morris and Thorne, 1988; Thorne, 1993, 1994, and refs. Therein]. In tackling that question, they quickly discovered that an "arbitrarily advanced civilization" (AAC) would have to find some way to assemble or create "exotic matter" in order to construct macroscopic wormholes that might be used as time machines. [For an early review of how wormhole space-times might be used for rapid interstellar travel see Forward, 1989a.]

"Exotic matter", because of the high visibility of recent wormhole spacetime research, is now well-known to be a substance which has the property that, as viewed in some inertial frame of reference, it appears to have negative mass. That is, it violates the "weak energy condition" (WEC), a condition that must be posited as a separate constraint since neither special relativity theory (SRT) nor general relativity theory (GRT) prohibit the existence of negative mass-energy. While negative mass has been a subject of speculation for over a century [see Jammer, 1961, ch. 10], it did not have much impact until recently. The peculiar behavior of systems containing negative mass has been addressed by Price [1993], and Forward [1989b] has discussed how negative matter might be implemented in a spacecraft propulsion system. Recently, in this vein, Alcubierre [1994] has pointed out that in GRT, because the speed of light c is a local, not a global, invariant, superluminal transport speeds are possible without forming wormholes or creating closed timelike curves (CTCs). He calls his scheme "warp drive". As in the case of wormholes, however, very substantial concentrations of exotic matter are required for its realization.

The facet of wormhole spacetime research that has excited the greatest interest is the fact that if exotic matter can be obtained and macroscopic wormholes can be made, they can be used to make time machines. The two mouths of an arbitrarily short wormhole in hyperspace can have arbitrarily large spacelike or timelike separations in our normal spacetime. Most find the prospect that some AAC might really be able to make wormhole spacetime machines literally incredible. Even most of those willing to believe that intelligent alien life exists and that we may not be the cleverest critters in creation find time travel profoundly repugnant. If time travel is possible, then the past has a real objective existence, as does the future, and "free will" is irrelevant.

The distaste for real time travel is manifest in Hawking's [1992] "chronology protection conjecture": *The laws of physics do not allow the appearance of closed timelike curves*. No time machines. Hawking, after stating his conjecture, remarks that it, "makes the universe safe for historians." It also makes the universe "safe" for cosmologists. Hawking's conjecture, if true, really makes the universe safe for all those who act on the commonplace of practical political science that the halflife of the public memory is about three months: politicians, ideologues of all stripes [no doubt including some historians], genocidal maniacs, and the like. But is chronology actually protected?

2. CHRONOLOGY PROTECTION

Hawking makes the case for his conjecture in the most general possible terms for he seeks to prohibit not only time machines made with wormholes like those considered by Kim and Thorne [1991], but those too that employ cosmic strings discovered by Gott

[1991]. I will ignore the more general features of Hawking's argument and only briefly recapitulate its central points for the case of wormholes. I do so because if time machines are ever to be built, they almost certainly will be based on wormholes.

Hawking considers a region of spacetime which is a timelike tube intersected by two spacelike surfaces between which topology change [for our purposes, the formation of a wormhole with timelike separated mouths] has taken place. He then stipulates that the region be finite and not contain any singularities. Ho goes on to show that in such a region CTCs must form if the topology is changed, and that as the specetime distortion that produces the CTCs proceeds, at some point closed null geodesics (CNGs) [which are the generators of a Cauchy, or chronology, horizon] must form. When the CNGs form, the infinite recirculation of vacuum massless quantum fields along the CNGs cause an infinite energy buildup [divergence of the matter tensor] that destroys the imminent time machine. Chronology, accordingly, is protected.

Hawking's argument applies to the case considered by Kim and Thorne [1991] where one assumes that one has already acquired a wormhole with spacelike separated mouths that one wants to make into a time machine. The wormhole is transformed into a time machine, as shown schematically in Fig. 1, by taking one of the two mouths on a "twin paradox" excursion so that the proper times kept by the two mouths are separated. As the traveling mouth is being returned to the spatial location of the stationary mouth, it must cross the future light cone of the stationary mouth. At light cone traversal CNGs form, quantum fields recirculate, and the wormhole is destroyed before a chronology horizon can occur.

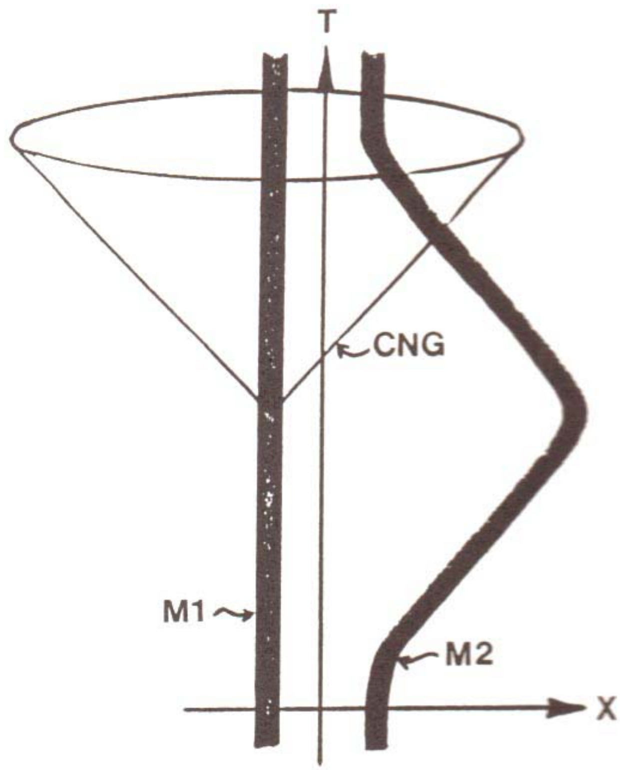

Fig. 1. Spacetime diagram schematically depicting the transformation of a wormhole with mouths M1 and M2 into a time machine by taking M2 on a "twins

paradox" excursion. The future lightcone of the stationary mouth M1 is shown for the instant at which a closed null geodesic (CNG) forms through the wormhole as M2 is returned to the spatial location of M1 to transform the wormhole into a time machine.

Kim and Thorne claimed that quantum gravity considerations – in particular the supposed beakdown at time at the Planck scale – would suppress the recirculation of massless fields. Hawking argues that their calculation, based on an observer at rest in the wormhole throat, is incorrect. And more recently, Visser [1994a, b] has argued that in the "short-throat, flat-space" approximation wormhole destruction occurs long before one reaches the Planck-scale of quantum gravity when a chronology horizon is imminent as the result of a wormhole mouth approaching the future light cone of the other mouth. (In this approximation spacetime is flat except in a highly localized wormhole throat of arbitrarily small radius and thickness. This is the "absurdly benign" wormhole of Morris and Thorne [1988] made with negative restmass.) Let us assume that Hawking and Visser are right. But even if they are right (and currently fashionable ideas about quantum gravity are basically correct), it does not necessarily follow that chronology is protected.

Thorne [1993], following a suggestion of Roman, notes that if two (or more) wormholes were used, instead of one, an AAC might be able to suppress the effect of recirculating fields on CNGs. (In the Roman spacetime two wormholes, each with synchronous mouths in their own rest frame, move with respect to each other at high speed.) Visser [1994b] argues that traversable wormholes cannot be made in this way, while Lyutikov [1994] leaves the question open. Ori [1993 and Ori and Soen, 1994] and LI-Xin, et al. [1993] have suggested other ways one might sidestep Hawking's conjecture. Another reasonable vein of inquiry is to ask if all of the assumptions attendant to Hawking's argument are defensible and necessary. In particular, his argument depends critically on two assumptions: (1) the absence of singularities in any acceptable topology changing process, and (2) the formation of CNGs (at a mouth lightcone traversal in the case of deformed static wormholes) in such processes. Neither of these assumptions need necessarily be valid.

Singularities one usually envisages are the type that inhabit the event horizons of black holes: points at which the scalar curvature and tidal forces diverge. Because our mathematics is not equal to the job of dealing with such eventualities, it is often assumed that it is not possible to talk meaningfully about regions containing singularities. However, Horowitz [1991] has pointed out that the occurrence of a singularity in topology change, signaled by degeneracy of the metric [i.e., $\det(g_{\mu\nu}) = 0$], need not be accompanied by curvature divergence. As he remarks, "The singularities can be . . . so mild that in some sense they are not there at all." Such benign singularities do not occur in gravitational collapse, but they *may* be produced when a wormhole is generated using exotic matter. Thus, while the exclusion of singularities may be mathematically defensible in our present circumstances, it may not be physically defensible.

If we admit the possibility of singularity formation during topology change we, despite our inability to deal with singularities mathematically, may in fact be able to make wormholes that do not lead to the formation of CNGs (and thus an unstable chronology horizon) in the process. Should we be able to induce the formation of a highly localized wormhole in such a way that neither mouth appeared near or approached the lightcone of the other of the other, recirculation of massless fields would be thwarted. This might be done in one of two ways. If we are limited to making spacelike wormholes, we could punch a wormhole directly through hyperspace from one region to another with a spacelike separation. After traversing the wormhole, we can close it (if we choose) and then repeat the process to a point in the future or the past of our starting point. (See Fig. 2A.) Or, if timelike wormholes can be induced, we can take the more straight-forward route of punching a wormhole directly from one spacetime point to another with a past or future timelike separation. (See Fig. 2B.)

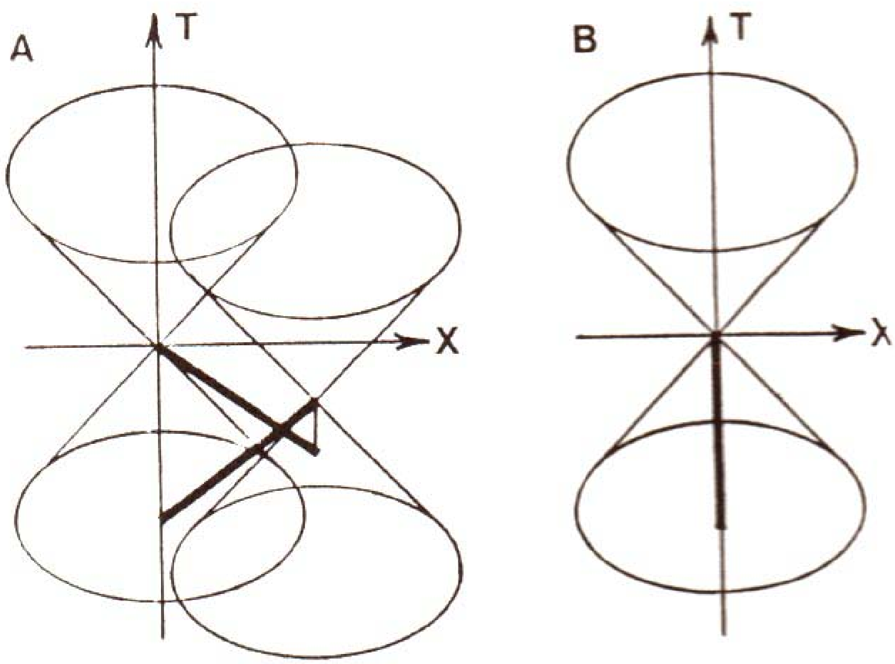

Fig. 2. Spacetime diagrams of the two types of induced wormholes discussed in the text that admit time travel without triggering the Hawking protection mechanism. The wormhole mouths, which are located at the ends of the bold lines in the diagrams, are induced so as to never lie on a shared lightcone. In A time travel is achieved by a two step process utilizing spacelike wormholes. In B a single timelike wormhole is employed to reach the same end. In both cases CTCs at least briefly form.

In both of the cases depicted in Fig. 2 CTCs are formed at least briefly and multiple circulation of massive particles through the wormhole(s) is possible [see Friedman, et al., 1990, esp. p. 1923 and Fig. 4]. As long as the curvature associated with the wormhole mouths remains essentially flat, however, while past and future chronology horizons form (roughly on the appropriate part of each mouth's light-cone), no CNGs from and the Hawking destruction mechanism accordingly is not enabled. If we were determined not to let a simple timelike wormhole form we could trap the future light-cone of the appropriate mouth (doing it with mirrors, but not too much smoke) and force the occurrence of the Hawking mechanism. But now we are talking about hypothetical AAC weapons systems, not the foundations of physics.

Since chronology is not protected by recirculating massless fields at the chronology horizons in the wormhole spacetimes of Fig. 2, it is reasonable to ask if any other field(s) might do the job. Recirculation along a CTC constrains the field(s) to be massive, and the exclusion principle eliminates fermionic fields as plausible candidates (unless the states of the field quanta are changed during transit along the CTC). Ideally, what we need is a massive, freely propagating, bosonic field that is present in the vacuum. Because the temporally separated wormhole mouths have an arbitrarily large separation at the instant when CTCs first form, the velocity of the field quanta , however, must be nearly zero and not be boosted appreciably on wormhole transit if they are to recirculate and destroy the wormhole(s).[1] Do such massive fields exist? Aside from the problem that 90-plus percent of the mass in the Universe seems to be "missing" or "hidden" in an as yet unidentified form, there is no evidence to suggest that such chronology enforcing fields exist. If we could get ahold of enough exotic matter to induce a wormhole, we could find out whether such fields are really present.[2] Even were we to find that such fields do exist, we could at least still build Alcubierre's "warp drive."

The whole business of wormholes, denizens of either the Planck regime and perhaps the worlds of AACs, both seemingly hopelessly inaccessible, may appear misguided. It is not. In fact, it may be possible with extant technology to produce sufficient exotic matter to explore wormhole formation. That, not future schlock, is the point of this paper. Below I suggest how this might be done without inventing any "new" physics (or violating any extant laws of physics). First, however, we briefly consider the role of time in fundamental physical theory. After all, if the past and future to not exist, all issues relating to time travel are moot. They are not "there" to travel to.

3. TIME IN CLASSICAL AND QUANTUM PHYSICS

The fundamental nature of time, especially given the time-reversal invariance of the dynamical laws of physics, has long had a powerful fascination for many interested in the foundations of physics. [See, for example, Gold, 1967, Davies, 1974, Whitrow, 1980, in the explicit context of time travel Nahin, 1993, and Halliwell, *et al.*, 1994 (esp. the contributions of Wheeler, Davies, Hawking and Halliwell).] In nonrelativistic classical physics the absolute time of Newton flows imperturbably on everywhere at the same rate. Concomitantly, the salient feature of all classical physics is that it is strictly deterministic: the future is an inexorable consequence of the past. Until this century determinism did not mean that the future and past have a real objective existence. The advent of SRT changed that.

Since absolute simultaneity does not exist in SRT and GRT, situations arise where an event has already occurred for one observer, but has not yet occurred for another observer. For the second observer, the future has already happened even though s/he does not know it. Generalization of this simple observation leads to the conclusion that the complete set of all future events has already occurred, and the past in some real sense still exists. This was the view that Einstein came to. As he remarked to his lifelong friend Besso's surviving relatives several weeks before his own death:

> And now he has preceded me briefly in bidding farewell to this strange world. This signifies nothing. For us believing physicists the distinction between past, present, and future is only an illusion, even if a stubborn one. [Hoffmann, 1972, pp. 257-258.]

(This remark has occasioned some interpretation. See Horwitz, *et al*. [1988], Zeh [1992], epilog, and Nahin [1993], pp. 69, 74, and 103-104.) Weyl [1949, p. 116], with comparable directness and elegance put it:

> Reality simply *is*, it does not *happen*. Only to the gaze of my consciousness, crawling upward along the life line of my body, does a section of this world come to life as a fleeting image in space which continuously changes in time. [Original emphasis.]

Thus we have a four-dimensional "block universe" in which common sense causality is an artifact of consciousness, not an inherent feature of an evolving, not yet actualized reality. Can time travel take place in this reality? Yes. Both the future and the past are there to travel to. And if it will happen, then it has already happened. So, should we succeed in building a wormhole time machine and discover a unique past and future (of which our machine and exploits are a part), we would be able to establish determinism in nature beyond a reasonable doubt.

3.1. Quantum Mechanics

Reality is quantum mechanical. How much this "helps" depends upon which "interpretation" of quantum mechanics one adheres to. The various "interpretations" all purport to merely supply explanatory material to elucidate the well-known formalism of quantum mechanics. In fact these "interpretations", while adhering to the formalism of quantum mechanics, are radically different constructs of physical reality.

The fundamental conceptual problems of quantum mechanics have been known since the inception of the theory: irreducible stochasticity [a dice-playing deity] and nonlocal interactions [violation of the principle of relativity]. They were encapsulated in the Einstein-Podolski-Rosen (EPR) "experiment" wherein measurement of a property of one of a pair of correlated particles leads to the other particle acquiring some property instantaneously. (That these effects cannot be employed by human beings for instantaneous telegraphy does not change the fact that a violation of SRT occurs.) Other fundamental problems are the relationship of the quantum and classical regimes and the nature and role of observers in the theory (*e.g.*, Schrödinger's cat and Wigner's friend).

When the nature of time is at issue, five "interpretations" of quantum mechanics stand out as especially important. They are the (1) Copenhagen, (2) histories/decoherence, (3) hidden variables, (4) transactional, and (5) many-worlds interpretations. All of these interpretations take the evolution equations of quantum mechanics (*e.g.*, the Schrödinger and Dirac equations) as time-reversal invariant, so state vector evolution is deterministic. In the Copenhagen interpretation, state vector reduction, precipitated by observation, is time-asymmetric and introduces irreducible stochasticity and nonlocal interactions (instantaneous collapse of the wavefunction throughout space). In light of the work of Bell [1988] and its experimental confirmation, there can be no doubt that the formalism of quantum mechanics is essentially correct and cannot be given a simple local realistic interpretation because of the long-range correlations observed.

The Copenhage and histories/decoherence interpretations [see Griffiths, 1993, Hartle, 1993, Onmès, 1992, DeWitt, 1994, and refs. therein] differ fundamentally from the other interpretations mentioned above in that they both posit the occurrence of irreducibly stochastic processes.[3] As a result, the future is not fully determined and therefore necessarily not yet actualized. So, aside from “twin paradox” excursions, time travel to the future is impossible if either of these interpretations is right. The indeterminacy of the future, by the way, is not an incidental feature of the histories/decoherence interpretation:

> It should be stressed that *actuality, whether in a quantum measurement or in plain classical situations, is the only point where theory and reality come into contact with each other* . . . . This is also the only point for which theory does not provide an explanation, nor a mechanism, nor a cause for what is observed.
>
> Perhaps the best way to see what it is all about is to consider what would happen if a theory were able to offer a detailed mechanism for actualization. This is, after all, what the advocates of hidden variables are asking for. It would mean that everything is deeply determined . . . nothing would distinguish reality from logos, the time-changing from the timeless. Time itself would be an illusion, just a convenient ordering index in the theory. [Omnès, 1992, pp. 379-380, original emphasis]

Omnès is right about the (nonstachastic) hidden variables interpretation of quantum mechanics. It, along with the transactional interpretation, is distinguished by either being exactly deterministic or acausal, both taken in the sense of the past and future having an objective existence. Exact determinism and acausality, as Omnès’ just quoted remark suggests, are really the same thing in disguise, although our consciousness leaves us with the illusion that they are not. Indeed, we normally regard deterministic theories as causal, not acausal. This is wrong. Causes and effects are sorted and labeled by our minds, but deterministic theories are time-reversal invariant and thus, while temporally ordered, quite insensitive to common sense notions of cause and effect.

Best known of the hidden variables interpretations of quantum mechanics, motivated by the desire to eliminate irreducible stochasticity, is the theory of Bohm [1957]. It is explicitly deterministic. In terms of the relationship between determinism and acausality just noted, it is not surprising that Bohm [1980] advanced ideas on an “implicate order” and advocated the “wholeness” of physical reality. This is just adumbration of the four-dimensional “block universe” of Einstein and Weyl with its objectively existent past and future. Bohm’s theory appears to have achieved adherents at least among philosophers of science in the past few years [Albert, 1994]. The problem with this theory, along with standard quantum mechanics, is that it is nonlocal. It violates at least the spirit, and arguably the letter, of SRT. Nonetheless, if it is right, time travel is in principle possible since the past and future are “there” somewhere to travel to.

3.2. The Transactional Interpretation

The transactional interpretation of quantum mechanics is quite remarkable. It is explicitly Lorentz-invariant and so consistent with SRT and, like the Copenhagen interpretation, does not invoke hidden variables. This is achieved by taking seriously the time-symmetry of the laws of physics, especially the fact that wave equations usually have advanced solutions that propagate backward in time, as well as the retarded solutions of everyday experience. It draws its inspiration from the Wheeler-Feynman [1945 and 1949] time-symmetric “absorber” theory of electrodynamics. Taking advanced waves seriously in quantum mechanics has long been championed by Costa de Beauregard [1953, 1971, 1983, 1992]. Others who have explored “absorber” field theory include Hogarth [1962], Hoyle and Narlikar [1974] and Davies [1974, esp. pp. 130-153 and 178-181]. As a general interpretation of quantum mechanics, this approach has been forcefully argued by Cramer [1986 and 1988 and refs. therein].

The Schrödinger equation, being first order in time and non-relativistic, admits only retarded solutions. But, as Cramer points out, when the Schrödinger equation is obtained as a non-relativistic limiting case from a relativistically invariant wave equation, one also gets its complex conjugate. The complex conjugate equation admits only advanced solutions and is normally dismissed as unphysical because its energy eigenvalues are negative. The Dirac equation, of course, has negative energy, advanced solutions. They are not rejected as unphysical. They are the antimatter solutions. (A positron is an electron propagating backward in time.) Analogously, Cramer argues that the advanced solutions to the complex conjugate of the Schrödinger equation should not be ignored. This yields a natural explanation of the Born probability interpretation of the wavefunction which is given by $p = \psi^*\psi$, not $p = \psi^2$.

In the transactional interpretation the state vector of an object, say an atom in an excited state, represented by the wavefunction ψ is taken to be an objectively real entity. The ψ wave propagates (at light speed) just like an electromagnetic wave, but it is “virtual” for it carries no energy or momentum. As the wave encounters potential absorbers of the photon the atom may emit, they are excited and in turn emit advanced waves ψ_i^* that propagate back to the source of the ψ wave, arriving at the instant the ψ was emitted with amplitude $\psi^* = \Sigma\psi_i^*$. The probability that any particular “transaction” (photon transfer) between the emitter and a particular absorber i will occur is given by $\psi_i^*\psi$ for that absorber (suitably normalized). Which transaction in fact occurs depends on this probability and the boundary conditions that characterized the disposition of the emitter and absorber.

Because the waves involved in this process are advanced and retarded, all of this is sorted out atemporally. Note, however, that (in this case) photon emission only occurs after the future absorption of the photon has been determined. Until the future absorption of the photon is irreversibly established, no emission can take place: open ended transactions are not possible because no advanced wave propagates from an indeterminate absorption event to establish the probability of the process. (Cramer

[1983] has argued that emission without subsequent absorption is possible if the advanced wave from the emitter is reflected off the initial cosmological singularity. In this case, the fact that the emitted photon will *never* be absorbed in the future is deterministically established, so, if this process occurs, it does not affect the arguments presented here.)

Cramer goes to considerable lengths to argue that the transactional and Copenhagen interpretations are equivalent, but that the transactional interpretation provides natural explanations for the situations that appear paradoxical in the Copenhagen interpretation. For example, in the case of EPR correlations the Copenhagen interpretation requires that one believe that instantaneous wavefunction collapse occurs. In the transactional interpretation the correlation is established at the instant of creation (emission, preparation) of the pair of correlated particles by the advanced waves that return from the future "measurements" of the particles. No superluminal signaling is involved. And the correlation determination is quite insensitive to delayed choice type experiments, for no matter when one makes one's choice, only one future is ultimately actualized, and it is the advanced waves from that actual future that determine the correlated properties. Advanced waves do not propagate from *potential* future dispositions of matter. This, it turns out, is an exceedingly important point.

The other well-known paradoxes of quantum mechanics have similarly simple explanations in the transactional interpretation. This led Cramer [1988] to remark: "However, let it be clearly understood that the transactional interpretation of quantum mechanics is applicable only to quantum mechanical formalisms that either have advanced solutions or that are special cases of reductions of more general formalisms that have advanced solutions. It is my view that valid Q[uantum] M[mechanical] formalisms that do not satisfy this criterion are a null set, but this proposition has not been proved." An argument that supports this conclusion can be constructed. First, however, a related issue must be discussed.

In large measure Cramer's arguments on behalf of the transactional interpretation of quantum mechanics are quite persuasive. In one instance, however, they are not. He argues that irreducible stochasticity, the central tenet of the Copenhagen interpretation, is a feature of the transactional interpretation too, because $\psi_i{}^*\psi$ remains a mere probability for the actualization of a particular transaction, so presumably the future does not determine the past. One might think this is true because the existence of $\psi_i{}^*\psi$ is a necessary, but not sufficient condition for a transaction to take place. The presumed irreducible stochasticity of the transactional interpretation is in fact illusory.

Irreducible stochasticity requires that future events not be fully determined. But, for example, some of the photons (or other transfer particles) emitted in the past will only be absorbed in the distant future, so that distant future and all intervening events must be determined. (We ignore transfer particles emitted that, deterministically, are never absorbed [Cramer, 1983].) If irreducible stocahsticity obtained, then the future could be changed between the emission and absorption of such photons (*e.g.*, as *appears* possible in delayed choice EPR type experiments). But that would preclude them being emitted in the first place because the advanced wave that enabled the emission process to proceed would no longer exist. This argument leads immediately to the conclusion that irreducible stochasticity makes the emission of radiation impossible in this relativistically invariant interpretation of quantum mechanics. Thus, the transactional interpretation of quantum mechanics cannot be consistent with irreducible stochasticity. So it would seem that quantum mechanics itself, since it admits the transactional interpretation without additional assumptions, must be a deterministic and acausal theory. Evidently, this is the case despite the fact that the Uncertainty Principle and the Copenhagen interpretation suggest the opposite for both interpretations cannot be right.

A general proposition about theories of reality can be inferred from the foregoing analysis of the transactional interpretation of quantum mechanics. Relativistically invariant formulations of quantum mechanics have advanced, as well as retarded, wave solutions. The effects of advanced wave solutions (ψ^* and antimatter) must be included in all consistent interpretations of quantum mechanics. Irreducible stochasticity is precluded since the advanced wave solutions that in part determine present [and past] events must arise from future events that cannot be changed by the action of intervening events. Thus, since both classical and quantum mechanical relativistically invariant theories are necessarily deterministic and acausal, I suggest the following conjecture: *if, in a theory of reality any interaction has the property of relativistic invariance, and no arbitrary, independent assumption of "causality" is made to suppress the advanced solutions of dynamical equations, then no process in that theory of reality, irrespective of whether it is relativistically invariant, can have the property of irreducible stochasticity.* The past and the future in such theories of reality have a unique, objective existence.

Demonstration of this conjecture is little more than an outline of the arguments that motivated it. Relativistically invariant theories of interactions are time reversal invariant and have advanced, as well as retarded, solutions. One may, and in some cases must, represent such interactions as depending on both the advanced and retarded solutions. The advanced solutions arise from the action of the retarded solutions on absorbers in the future. Any process operating in the reality with the property of irreducible stochasticity makes the future location (and possibly other properties) of the absorbers uncertain, making the emission of advanced waves impossible. Thus the relativistically invariant interaction cannot occur as posited. So no reality can have both relativistically invariant interactions and irreducibly stochastic processes.

It is now a straightforward matter to provide an argument for Cramer's observation on valid versions of quantum mechanics. In our reality at least one interaction, electrodynamics, is relativistically invariant. Thus, all irreducibly stochastic processes are prohibited. Therefore all complete theories of all interactions – quantum mechanics especially – must be time-reversal invariant and have advanced as well as retarded representations. The exclusion of irreducibly stochastic, relativistically invariant interactions, by the way, also has cosmological consequences. In this connection, see Davies [1974], pp. 143 – 153 and ch. 7, and Cramer [1983]. And in the matter of time machines, the past and the future are there to travel to in the transactional interpretation if we can make macroscopic wormholes.

3.3. Many Worlds

A caveat must be appended to the irreducible stochasticity conjecture: The universe and its evolution is unique. In other words, we do not allow a "many worlds" evolution of the universe to take place. The reason is simple. Irreducible stochasticity is irrelevant if many worlds evolution transpires since all possible futures for a particular event, through a "splitting" process, are actualized in some "world". This is a consequence of the fact that state vector reduction never takes place in Everett's [1957] many worlds interpretation (MWI) of quantum mechanics. In the MWI one considers only closed systems which include both the subsystem to be analyzed and the measuring apparatus to be used. There are no external classical observers as there are in the Copenhagen interpretation that induce state vector reduction (collapse of the wavefunction). So when a measuring apparatus makes a determination of the state of a subsystem, if the subsystem is in a mixed state all alternatives are realized in orthogonal worlds. Strictly deterministic (and thus acausal) evolution takes place in each of the realized worlds, so the issue of irreducibly stochastic processes occurring in any particular universe never arises. Since the worlds are orthogonal, observers in one world are completely unaware of the existence of the other worlds.

Deutsch [1991], a longtime supporter of the MWI, has taken the universe splitting version of the interpretation at face value and examined the chief time travel paradoxes therein. He shows that multiple universes enable one to easily resolve the various time travel paradoxes – especially the one where you go in to the past and kill your grandfather. Deutsch, however, is unable to stomach the intellectual free lunch paradox – for example, traveling to the future to discover how something is done and returning to the past to claim the invention. He thus proposes a "principle of evolution" that prohibits such exploits and their microscopic equivalents. In at least one universe the creation of knowledge must be done the old fashioned way: hard work. Inasmuch as hard work seems to be the only way to create new knowledge in our universe, it must be a highly improbable universe. [A popular account of these ideas is given by Deutsch and Lockwood, 1994.] It would appear that if the MWI is correct, time travel is indeed possible should we be able to make wormholes. Wormholes would connect different universes if this interpretation of quantum mechanics is right, a state of affairs that ought to be easily detectable.

In the MWI, as treated to this point, the "splitting" or "branching" process that transpires when events with several potential outcomes occur lead to the appearance of several *four-dimensional* "worlds," each of which then evolves independently of the others. Time marches on in each of these "parallel" universes as they are popularly known (which are in fact mutually perpendicular). In the past few years, however, with the realization that coordinate time of GRT is not directly observable and that experiential time is not a fundamental physical entity, Page (1994 and refs. therein) and independently Barbour (1994 and refs. therein) have reinterpreted the MWI in a novel way. The realization that time is in some sense not fundamental is not new (see for example the remarks of Einstein and Weyl quoted above). It is the underlying idea in Wheeler's concept of reality consisting of an infinite number of closed, spatial, three-dimensional universes that make up the points in his "superspace" (Wheeler, 1994) first advanced in the 1960s. Reality as we experience it, in this view, is nothing more than an ordered sequence of these universes selected by a trajectory in superspace.

Each spatial universe in superspace can be given a label that is identified as a "coordinate" time (that appears in the four-dimensional interval ds), but, as Page and Barbour point out, all observations we make are limited to three-dimensional hypersurfaces (one of Wheeler's superspace universes), so we can never directly compare events that occur at different "times." The best we can do is compare (or, more specifically, compute the conditional probabilities for) events with "records," "memories," or "time capsules" of other events that lie on different hypersurfaces. So the hypersurface coordinate time label never explicitly enters fundamental statements that we make about our observations. The reason for this seemingly peculiar state of affairs arises in GRT as a consequence of the coordinates of spacetime themselves being dynamical variables – and the consequent meaninglessness of the rate of change of coordinate time with respect to itself. (The rate of change of spatial coordinates, once a mapping from one spatial hypersurface to the next is established, is not physically meaningless – but observationally inaccessible.) This feature of GRT, of course, is already present in SRT and ultimately the principle of relativity – time is a relational concept, not an absolute, flowing physical entity.

The upshot of all of this for Page and Barbour is that the "worlds" of the MWI should be taken to be spatial hypersurfaces which are then sequentially ordered in a superspace. A coordinate time label can be attached to each hypersurface to indicate its location in the sequence, but the evolution of successive hypersurfaces from each other is neither possible nor meaningful for these is no "time" in which such a *process* can take place at the most fundamental level. And, accordingly, the MWI becomes a "many instants" interpretation, each spatial hypersurface "world" corresponding to an "instant". This result, as Barbour notes, has radical, profound consequences for quantum gravity and quantum cosmology (which is still strongly influenced by our experiential sense of the passage of time). They exceed the scope of this paper. For our purpose, we see that the principle of relativity has again pushed us in the direction of a "block universe" conception of reality, just as it did in the classical and transactional representations. If you find all of this, in the words of Newton (Tumulty, 1995, p. 23) "weird" (although perhaps "neat"), you are not alone. But the principle of relativity is not just a good idea . . . .

To sum up, the Copenhagen and histories/decoherence interpretations of quantum mechanics, because of their irreducible stochasticity, prohibit the creation of time machines and thus the formation of macroscopic wormholes that could be used as such. Nonlocal hidden variable interpretations and the transactional interpretation of Cramer are consistent with an objectively existing past and future and thus admit, at least in principle, the possibility of time travel. And the many worlds interpretation admits time travel, but not directly within the same universe since wormholes connect different universes. Which of these interpretations is right? I do not know. If you happen to be one of the elusive, allegedly nonexistent (according to Fermi, Hawking, and others) spatiotemporal tourists, you would know. If you are not a spatiotemporal tourist, would you believe a claim by someone who claimed to be one? There is a chance, however, that we can find out which, if any, of these interpretations corresponds to fact.

4. A TRANSIENT MASS FLUCTUATION

Despite the widespread belief that it is not technically possible to produce macroscopic concentrations of negative mass-energy, in fact, a curious inertial reaction effect can be employed to do just this, but only for very short intervals. I have discussed this effect at some length in other contexts [Woodward, 1992, 1993, 1994]. It follows from the consideration of a simple situation and a few general principles:

1. Inertial reaction forces in objects subjected to accelerations are produced by the interaction of the accelerated objects with a field – they are not the immediate consequence only of some inherent property of the object – and they are real, not fictitious.

2. Any acceptable physical theory must be locally Lorentz-invariant, that is, in sufficiently small regions of space-time special relativity theory must obtain.

3. The correct generalization of Newton's second law in special relativity theory is that universally accepted: the four-force acting on an object is equal to the derivative with respect to proper time of the four-momentum of the object.

The validity of SRT and the generalization of Newton's second law are so well-established that questioning them does not merit serious discussion. I assert the reality of inertial reaction forces, because centrifugal (inertial reaction) forces are widely thought to be fictitious [Assis, 1989, Zilbersztajn, 1994, Gribbin, 1994, but also 1992, p. 143].

To derive the effect of interest we ask: In the simplest of all possible circumstances – the acceleration of a test particle in a universe of otherwise constant matter density – what, in the simplest possible approximation, is the field equation for inertial forces implied by these propositions? SRT (proposition 3) allows us to stipulate the inertial reaction force **F** on our test particle stimulated by the external accelerating force $\mathbf{F}_{\mathrm{ext}}$ as:

$$\mathbf{F} = -\mathbf{F}_{ext} = -\frac{d\mathbf{P}}{d\tau}, \tag{4.1}$$

with,

$$\mathbf{P} = (\gamma m_0 c, \mathbf{p}), \tag{4.2}$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}, \tag{4.3}$$

where bold capital letters denote four-vectors and bold lowercase letters denote three-vectors, **P** and **p** are the four- and three-momenta of the test particle respectively, τ is the proper time of the test particle, v the instantaneous velocity of the test particle with respect to us, and c the speed of light. To keep life simple, we specialize to the instantaneous frame of rest of the test particle. This enables us to ignore the difference between coordinate and proper time, as they are the same in this frame, and γs since they are all equal to one. We will not recover a generally valid field equation in this way, but that is not our objective.

In the frame of instantaneous rest Eq. (4.1) becomes:

$$\mathbf{F} = -\frac{d\mathbf{P}}{d\tau} = -\left(\frac{\partial m_0 c}{\partial t}, \mathbf{f}\right), \tag{4.4}$$

with,

$$\mathbf{f} = \frac{d\mathbf{p}}{dt}. \tag{4.5}$$

Since we seek the equation for the field (*i.e.*, force per unit mass) that produces **F**, we normalize **F** by dividing by m_0. Defining $\boldsymbol{f} = \mathbf{f}/m_0$, we get

$$\boldsymbol{F} = \frac{\mathbf{F}}{m_0} = -\left(\frac{c}{m_0}\frac{\partial m_0}{\partial t}, \boldsymbol{f}\right). \tag{4.6}$$

To recover a field equation of standard form we let the test particle have some small extension and a proper matter density ρ_0. Equation (4.6) then reads

$$\boldsymbol{F} = -\left(\frac{c}{\rho_0}\frac{\partial \rho_0}{\partial t}, \boldsymbol{f}\right). \tag{4.7}$$

From SRT we know that $\rho_0 = E_0/c^2$, E_0 being the proper energy density, so we may write:

$$\boldsymbol{F} = -\left(\frac{1}{\rho_0 c}\frac{\partial E_0}{\partial t}, \boldsymbol{f}\right). \tag{4.8}$$

To get a field equation that corresponds to $\boldsymbol{F}$ in terms of its local source density we take the four-divergence of $\boldsymbol{F}$, getting

$$-\frac{1}{\rho_0 c^2}\frac{\partial^2 E_0}{\partial t^2} + \left(\frac{1}{\rho_0 c^2}\right)^2\left(\frac{\partial E_0}{\partial t}\right)^2 - \nabla.\boldsymbol{f} = 4\pi \mathrm{Q}_0. \tag{4.9}$$

At this point we might drop the second term on the LHS of Equation (4.9), since it is smaller by a factor of c^2 than the other terms. We preserve it for completeness. We write the source density as Q_o, leaving its physical identity unspecified for the moment. $\boldsymbol{f}$ is irrotational in the case of our translationally accelerated test particle, so we may write $\boldsymbol{f} = -\nabla\phi$, ϕ being a scalar field, and Equation (4.9) becomes

$$\nabla^2\phi - \frac{1}{\rho_0 c^2}\frac{\partial^2 E_0}{\partial t^2} + \left(\frac{1}{\rho_0 c^2}\right)^2\left(\frac{\partial E_0}{\partial t}\right)^2 = 4\pi \mathrm{Q}_0. \tag{4.10}$$

Now we must write E_o in such a way that we get a wave equation that is consistent with local Lorentz invariance. Given the coefficient of $\partial^2 E_o/\partial t^2$, only one choice is possible:

$$E_0 = \rho_0 \phi \, , \tag{4.11}$$

This choice for E_o yields

$$\nabla^2 \phi - \frac{1}{c^2}\frac{\partial^2 \phi}{\partial t^2} = 4\pi G \rho_0 + \frac{\phi}{\rho_0 c^2}\frac{\partial^2 \rho_0}{\partial t^2} - \left(\frac{\phi}{\rho_0 c^2}\right)^2 \left(\frac{\partial \rho_0}{\partial t}\right)^2 - \frac{1}{c^4}\left(\frac{\partial \phi}{\partial t}\right)^2 . \tag{4.12}$$

If we ignore the terms of order c^{-4} and those involving derivatives of ρ_o (assume, say, that they are negligibly small or that ρ_0 is a constant so they vanish), we have in Eq. (4.12) the usual wave equation for ϕ in terms of a source charge density Q_o. What are the charges Q_o? Well, ϕ is the potential of a field that acts on all matter in direct proportion to its mass and is insensitive to direct interaction with all other types of charge. It follows that the source of ϕ must be mass, that is, $Q_o = G\rho_o$. And the field that produces inertial reaction forces is the gravitational field. The gravitational induction of inertia we have recovered here is one of the various articulations of Mach's principle, to which we will return presently. Now, however, we note that identifying $Q_o = G\rho_o$ makes it possible to get a rough estimate of the value of ϕ which required to explore the effect of the terms involving time derivatives of ρ_o. And it is these terms that are of interest for the construction of wormholes.

Considering the stationary case, where all terms involving time derivatives vanish, Eq. (4.12) reduces to Laplace's equation [actually, the Poison equation as stationary sources are still present], and the solution for ϕ is just the sum of the contributions to the potential due to all of the matter in the causally connected part of the universe, that is, within the particle horizon. This turns out to be roughly GM/R, where M is the mass of the universe and $R \approx c$ times the age of the universe. Using reasonable values for M and R, GM/R is of the order of c^2. In the time-dependent case we must take account of the terms involving time derivatives on the RHS of Eq. (4.12). These terms act as transient restmass sources of the gravitational field. If, in the act of accelerating an object, the force that we apply causes the proper matter (energy) density to fluctuate, the fluctuation itself, through both its first and second time derivatives, becomes a source of the gravitational field.

If one takes ϕ to be due to local matter only, the transient terms in Eq. (4.12) are negligible. But ϕ in facts is $\approx c^2$ when all of the matter in the universe is considered. Moreover, ϕ cannot be scaled away by an arbitrary additive constant because, while a valid procedure in linear theories, gravity is nonlinear [Peters, 1981]. So these transient sources of the field, in general, cannot be ignored. Note too that these sources, through the $\left(\partial^2 \rho_o / \partial t^2\right)$ term, can be either positive or negative. If $\left|\left(\partial \rho_o / \partial t\right)^2\right| \approx \left|\left(\partial^2 \rho_o / \partial t^2\right)\right|$ and $\rho_o \leq 1$, because $\phi / c^2 \approx 1$, then the $\left(\partial \rho_o / \partial t\right)^2$ term will dominate the transient sources. It is always negative. If the fluctuation is quick, the transiently induced restmass can be made very large. Large enough – and negative – to make wormholes perhaps.

It is worth remarking that effects of the sort just derived have long been known [Dicke, 1964, p. 104, Robertson and Noonan, 1968, p. 157, Rindler, 1982, p. 104, Price, 1982]. To get a *rough* estimate of the size of the mass fluctuation that can be induced through this effect we separate out the transient part of the total local matter density and write it as

$$\delta\rho_o(t) \approx \left(\phi / 4\pi G\rho_o c^4\right)\left(\partial^2 E_o / \partial t^2\right), \tag{4.13}$$

where $\rho_o = E/c^2$ has been used. We have ignored the higher order terms in ($1/c^2$) in Eq. (4/12) which, as just noted, cannot always be done. The total transient mass fluctuation δm_o induced in a volume *V* then is

$$\delta m_o = \int_V \delta\rho_o dV \approx \left(\phi / 4\pi G\rho_o c^4\right)\int_V \left(\partial^2 E / \partial t^2\right) dV \; . \tag{4.14}$$

To get a sense of the practical scale of such mass fluctuations, consider a capacitor to which an alternating voltage is applied. In this case, since $\partial E / \partial t$ is the power density being stored in the capacitor at any instant, and the integral over the volume of the capacitor is just the instantaneous power *P* being delivered to the capacitor, the integral on the RHS of Eq. (4.14) is $\partial P / \partial t$. Thus,

$$\left(\delta m_o\right)_{cap} \approx \left(\phi / 4\pi G\rho_o c^4\right)\left(\partial P / \partial t\right). \tag{4.15}$$

If *P* is a megawatt applied at a 100 MHz frequency and we take $\rho_o \approx 1$, then the peak transient mass induced will be of the order of ± 10^7 gm. Taking $\rho_o \approx 1$, one should note, is *not* always a reasonable assumption if large concentrations of negative mass-energy are in fact being generated. Instantaneously ρ_0 may be << 1, in which case $\left(\phi / \rho_O c^2\right) >> 1$ consequently augmenting the magnitude of the effect. And if $\left(\phi / \rho_O c^2\right) >> 1$, then its square will be larger still, likely making the $\left(\partial\rho_o / \partial t\right)^2$ term in Eq. (4.12) non-ignorable.

10^7 gm of negative mass-energy, even if it only persists for several nanoseconds per cycle, is a quite respectable amount of exotic matter. It is enough to null the inertia of an object with a comparable mass, making it easy to accelerate the object to large velocities during the brief intervals of exoticity. It is not, by itself, enough exotic matter to induce a macroscopic wormhole however. Consider, for example, the "absurdly benign" wormhole discussed by Morris and Thorne [1998, exp. P. 410] where the exotic matter is restricted to a thin layer of thickness a_o around a throat of radius b_o. The volume of the exotic matter is $4\pi b_o^2 a_o$ and its density ρ is

$$\rho = -\left[b_o c^2 / 4\pi G r^2 a_o\right]\left[1 - \left(r - b_o\right)/ a_o\right] \; . \tag{4.16}$$

The mass of the exotic matter then is

$$M \propto -\pi b_o c^2 / 2G \; . \tag{4.17}$$

To order of magnitude this is just the negative of the amount of mass required to induce a normal Schwarzschild wormhole. So exotic matter makes it possible to avoid horizons and tidal stresses, but the absolute amount and density of matter required to form a wormhole is largely unaffected.

5. DISCUSSION

One may find the prospect of actually making, if only fleetingly, large amounts of negative mass-energy disturbing. Of course, one may always simply dismiss out-of-hand and ignore the effect isolated here. Or one may invoke some seemingly plausible principle – say, a principle of "asymptotic local linearity" for the sources of the gravitational field – to justify throwing out the terms involving time derivatives of ρ_o in Eq. (4.12). A somewhat more subtle approach to this problem is to change the equation of motion so that the undesired terms never appear in the first place [in this connection see Robertson and Noonan, 1968, p. 157]. That is, we reject proposition 3 above. The motivation for pursuing any of these paths, however, is plainly *ad hoc*.

Perhaps, because of the approximations invoked to obtain the effect, we have ignored some other effect that might cancel the effect found above, making it impossible to induce negative mass-energy in the fashion sketched here. We have, in fact, ignored another effect that does contribute to the transient mass fluctuation. In the foregoing analysis we considered only a small test particle occupying a small region of spacetime that could be assumed flat. Accordingly, the ordinary four-divergence could be used to obtain our special case, approximate field equation with its sources. But the result of this analysis cannot be extended to macroscopic extended objects in which large spacetime curvature is induced (wormholes ultimately) without taking account of the curvature.

In the presence of strong curvature, instead of the ordinary four-divergence, we must take the covariant four-divergence when calculating the local source density if it is to be applicable to real wormhole construction. The covariant four-divergence of a four-vector field yields a term that must be added to the ordinary four-divergence already calculated. That term is the scalar product

$$\left[1/\sqrt{-g}\,\right]\boldsymbol{F}\bullet\ \nabla\sqrt{-g}\ , \tag{5.1}$$

where $\boldsymbol{F}$ is the four-vector field and $\nabla\sqrt{-g}$ the four-gradient of the square root of $-g$, g being the determinant of the metric $g_{\mu\nu}$ [see, *e.g.*, Adler, Bazin and Schiffer, 1965, p, 73]. Will this term, in general, cancel the terms in time derivatives of ρ_o and φ that are transient sources of the field? No.

Consider, for example, the case of a spherical wormhole induced by applying a time-varying voltage to a spherical capacitor. The general spherical wormhole metric [Morris and Thorne, 1988] is

$$ds^2 = -e^{2\Phi}c^2dt^2 + dr^2/(1 - b/r) + r^2(d\Theta^2 + \sin^2\Theta d\phi^2). \tag{5.2}$$

Φ is the "redshift" function and b the "shape" function of the wormhole. In Morris and Thorne's analysis they are arbitrary functions of the radial coordinate r only, as they restrict their attention to stationary wormholes. Since strong time dependence is necessary to make the $\partial\rho_o/\partial t$ and $\partial^2\rho_o/\partial t^2$ terms in Eq. (4.12) large (and negative), we must take Φ and b, in general, to be functions of r and t.

If our objective were the design of an optimal, real wormhole a moderately elaborate analysis might be required. But we seek only to show that such wormholes can be designed, if desired. To avoid Hawking's protection mechanism, our constraint of concern is that the curvature of the wormhole throat is sufficiently confined so as to leave the light cones in immediate proximity to the mouths unaffected. That is, spacetime exterior to a restricted throat must be essentially flat. This is Morris and Throne's "absurdly benign" wormhole formed by an arbitrarily thin sphere of net negative mass-energy mentioned above. We make the simplifying assumption [made by Morris and Thorne to eliminate horizons and minimize tidal effects] that $\Phi(r, t) = 0$. The determinant of the metric then becomes

$$g = -\frac{r^4 \sin^2\Theta}{(1-b/r)} \tag{5.3}$$

and

$$\sqrt{-g} = \frac{r^2 \sin\Theta}{\sqrt{1-b/r}} \ . \tag{5.4}$$

By symmetry F_Θ and F_ϕ vanish, and so

$$\left[\frac{1}{\sqrt{-g}}\right]\mathbf{F}\bullet\nabla\sqrt{-g} = \left[\frac{1}{\sqrt{-g}}\right]\left\{F_t\left[\frac{1}{c}\frac{\partial\sqrt{-g}}{\partial t}\right]+F_r\left[\frac{\partial\sqrt{-g}}{\partial r}\right]\right\} \ . \tag{5.5}$$

Recalling that $F_t = \left(\frac{1}{c\rho_o}\right)\frac{\partial E_o}{\partial t}$, a little algebra yields

$$\delta\rho_o(t) = \frac{1}{4\pi G}\left\{\left(\frac{\phi}{\rho_o c^2}\right)\frac{\partial^2\rho_o}{\partial t^2} - \left(\frac{\phi}{\rho_o c^2}\right)^2\left(\frac{\partial\rho_o}{\partial t}\right)^2 - \frac{1}{c^4}\left(\frac{\partial\phi}{\partial t}\right)^2 - \frac{1}{2r(1-b/r)}\left[\left(\frac{1}{\rho_o c^2}\right)\frac{\partial E_o}{\partial t}\frac{\partial b}{\partial t}\right] + F_r\left\langle 4(1-b/r) - \left(\frac{\partial b}{\partial r} - b/r\right)\right\rangle\right\} \tag{5.6}$$

Now one might think that with careful choice of $b(r, t)$ one might be able to make $\delta\rho_o(t)$ vanish. A little reflection shows this not to be true. The physical role of the curvature terms is solely to correct the numerical value of the density to that for an invariant volume element. As such they cannot change the intrinsic source strength of the mass-energy present in the spacetime that produces the curvature. No amount of volumetric correction will change a negative mass-energy source into a positive one. Moreover, since the radial distribution of ρ_o and the time-dependence of the applied voltage can be chosen independently and arbitrarily, in general $\delta\rho_o(t)$ will not be zero for all t. In particular, if only briefly, it can be made negative and quite large.

In engineering a real device to produce this effect several issues would have to be taken into account; for example, each of the volume elements of the material in which the effect is induced would have to be Lorentz-boosted to the rest frame of the extended device. Since relativistic velocities are *not* required to produce the effect (which depends on the acceleration and its time-derivative in the material acted upon), this correction will normally be small. Similarly, the material in which the effect is produced should be chosen with care. It must be one in which high, rapidly changing internal energy densities can be induced without significant losses (which, of course, just heat things up). In this connection one may want to explore materials with non-linear responses to impressed forces. Such materials allow one to temporally displace the (inertial reaction) effect from the applied force that induces it. This is technically important for, while the weak energy condition (prohibition of negative mass) is violated transiently *in parts* of a complete system where this effect is induced, time-averaged over the complete system, the weak energy condition is not violated. Thus, without non-linear materials, notwithstanding the local induction of large transient mass fluctuations, spatially averaged over the complete system no net mass fluctuation is induced. These, however, are engineering issues. As such, they are not our concern here.

6. CHRONOLOGY PROTECTION MECHANISMS

We have seen that Hawking's chronology protection scheme depends on the denial of the possibility of singularity formation in topology change, and the formation of CNGs along which massless quantum fields destructively recirculate when on tries to transform an already existing wormhole into a time machine. This mechanism of chronology protection can be avoided if concentrations of negative mass-energy can be induced that drive wormhole generation admitting topology change with singularity formation. Wormholes so formed presumably can be induced so as to directly connect regions of spacetime anywhere and anywhen. So lightcone traversal by one of the wormhole mouths where CNGs form need not take place. Hawking's protection mechanism, thus is rendered ineffective (even though, in the multiple universe scenario, we would be screwing up somebody else's chronology). Since it seems that we may be able to induce sufficient exotic matter to explore wormhole formation, we ask: Are there any fundamental physical processes that preclude negative mass-energy induction of the type described above?

Two protection schemes present themselves as candidates that merit investigation. First, some limiting process analogous to velocities being limited to the speed of light in SRT precludes the formation of even transient negative masses. Second, the material in the throat of an absurdly benign wormhole, formed with net negative mass in the rest frame of the throat, is progressively gravitationally decoupled from the rest of the matter in the universe as its net mass becomes zero and then increasingly negative. It may be that as this decoupled state advances the throat material acquires a proper mass, otherwise suppressed by the gravitational interaction with distant matter, that either prevents or augments wormhole formation.

6.1 Maximal Acceleration

In the first scheme a limiting velocity is of no help for the effect derived above does not depend on the velocity of the matter in which it is induced. Indeed, the effect is easily generated with non-relativistic velocities. The effect does depend on the acceleration, and its rate of change, of the matter whose internal proper energy is changing . So what is needed is a natural upper limit to accelerations that is sufficiently low to prevent the transient formation of negative mass. There is an upper limit to the acceleration of extended objects determined by their length in the direction of the acceleration. Causality violation avoidance (an admittedly ironic condition to invoke in a paper on wormholes that admit CTCs) in SRT requires that a proper reference frame be limited to a length l inversely proportional to the proper three-acceleration a_o of the frame [Misner, Thorne, and Wheeler, 1973, esp. Chaps. 6 and 12]:

$$a_o = c^2 / l \,. \tag{6.1}$$

If the mass of an object is related to its size, then its mass determines the maximum proper acceleration that can be attained. Promising though this may seem, one cannot, however, it turns out, simply apply this to any old extended object [Fiorentini, *et al.*, 1992, and Woodward, 1993]. It only has fundamental significance when applied to elementary particles; and one cannot use their Compton wavelengths for l. l for electrons (and presumably quarks too) is known to be less than 10^{-16} cm. This value substituted into Eq. (6.1) above leads to a value of a_0 that is many orders of magnitude too large to be of any value in chronology protection.

6.2 Mach's Principle and the Origin of Inertia

To discuss the second protection candidate we need first to consider the nature and origin of mass. In particular, we must explore how the masses of local objects are related to the properties of the rest of the matter in the universe if we want to know their masses in the absence of external influences. This, inevitably, leads us into a discussion of Mach's principle, the Weyl Large Numbers conjecture [see, *e.g.*, Barbour,, 1990 and Barrow, 1981 and 1990], and related matters. I will try to limit this part of the exposition to only that which is essential to understanding how the various possible masses for gravitationally decoupled objects emerge. Keep in mind that our objective is not to discover, at this point, the truth about these highly speculative matters, It is to illuminate the range of possible outcomes to see how they impact chronology protection, and to show that we may be able to empirically establish the truth in these matters using the transient mass shift effect derived above.

Chiefly for historical reasons that are too well-known to repeat here, we distinguish three types of mass: inertial [the coefficient of the velocity in the momentum in Newton's second law], passive gravitational [the entity acted upon by gravitational forces], and active gravitational [the entity that produces gravitational forces]. The weak equivalence principle (WEP) is the assertion of the constant proportion between inertial and passive gravitational mass for all objects; and the strong equivalence principle (SEP) extends the constancy of the proportion to all three types of mass. (Depending upon how we choose to define gravitational charge, two of the three types of mass can be made equal; and if we choose units such that $G = 1$, all three types of mass can be made numerically equal.)

Newton took the mass of an object to be "the quantity of matter" it possessed – the product of its density and volume – an inherent property uninfluenced by external agents. Mach's criticism of Newton's definition of mass, together with his suggestion that the inertial behavior of objects must be related to the existence of other bodies in the universe, led to Einstein's articulation of "Mach's principle" – the assertion of the relativity of inertia and its gravitational origin. Debate about, and discussion of, this principle continues to this day. Progress, however, has been made. For our purposes that progress can be summed up in the statement that in our universe inertia is gravitationally induced if GRT is correct. That is, inertial reaction forces are in fact the gravitational forces exerted on accelerated objects by the rest of the matter in the universe. This is not true in all universes that are allowed by GRT, but Raine [1981a,b; also Raine and Heller, 1981], building on the work of Altshuler, Lynden-Bell, Sciama, Waylen, and Gilman, hwas shown that it is true for all non-empty Robertson-Walker (*i.e.*, isotropic) universes. Others, in more recent work, have extended Raine's work to articulate Mach's principle as an initial condition on the primeval fireball [Altshuler, 1985, Tod, 1994, Newman, 1993].

Given measurements of the cosmic background radiation, the astonishingly uniform nature of the distribution of matter in our Universe is beyond serious doubt. So, the origin of inertia is gravity. I should also mention that, at least as argued by Penrose [1987, 1989a,b, and 1993], the origin of time as we asymmetrically experience it is also to be found in the isotropy of the primeval fireball and the fact that in a system of gravitating objects entropy increases with increasing clumpiness. That experiential time [the second law of thermodynamics] and inertia should share their origin in gravity *and* the isotropy of the primeval fireball is indeed remarkable. It would be yet more remarkable if mass itself were gravitationally induced. Perhaps we are onto something big here. But there is a problem.

If the gravitational induction of inertia in GRT (for Robertson-Walker cosmologies) led to the conclusion that a single body in an otherwise empty universe would have no inertia, and thus no mass, life would be simple, at least from the point of view of Mach's principle. And we would then be able to infer that an object gravitationally decoupled from the rest of the matter in the Universe would likewise cease to have any appreciable inertial mass. GRT, unfortunately, does not give this result. Instead it yields the Schwarzschild solution with its well-defined, non-zero mass source. So, notwithstanding that inertial reaction forces are real gravitational forces in non-empty Robertson-Walker universes, in GRT mass continues to have something akin to the absolute character of Newton's "quantity of matter". And we may infer that while the inertial reaction forces gravitationally induced by the rest of the matter in the Universe vanish for a gravitationally decoupled object, its active gravitational mass does not concomitantly disappear. *So, if GRT is right, exotic matter of the order required to form a Schwarzschild horizon will have to be generated to form a wormhole.*

6.3 The "Salvation" of Historians and the Origin of Mass

The desire to have Mach's principle be a stronger statement than simply a boundary or initial condition on the global solutions of GRT has motivated the construction of at least several serious alternative theories. They share the feature of the induction of inertial mass be either gravity, or a coupled scalar field. Best known of these theories is the scalar-tensor theory of Brans and Dicke [Dicke, 1964], now widely believed to be inconsistent with observations. But for both microphysical and cosmological reasons scalar-tensor theories appear more attractive now. Accordingly, Berkin and Hellings [1994] have examined the consistence of multiple field scalar-tensor theories with the solar system scale evidence that led to the rejection of the Brans-Dicke theory.

Less well-known are the theories of Hoyle and Narlikar [1974] and Treder [Treder, *et al.*, 1980]. Effectively, they all posit that the inertial mass of an object $m_{\rm in}$ only acquires a non-zero value through the interaction of the object with the other material bodies in the universe

$$m_{in} = m^*\phi = m^* \sum_i m_i^* / r \ , \tag{6.2}$$

where ϕ, now, is a long-range scalar field, the sum extends over all bodies at distances r from m^* in the causally connected part of the universe, and starred m's are the charges of the interaction. Raine [1981b and Raine and Heller, 1981, ch. 11] has criticized Hoyle and Narlikar's theory, arguing that they have not really succeeded in getting away from a GRT type definition of mass. That is, Raine claims that m^* is really just $m_{\rm in}$ "in deep disguise."

Treder's theory is a generalization of GRT of the Einstein-Cartan type (with teleparallelism) explicitly constructed to encompass the strong form of Mach's principle (SMP: the gravitational induction of *mass*). It is a member of the class of "fourth order metric" theories of gravitation [see Schimming and Schmidt, 1990, for a review]. This theory makes the unusual prediction of "absorption" of gravity. This effect is a consequence of the field equations Treder adopts to implement the gravitational induction of mass. They have the form of Klein-Gordon equations which have the well-known stationary exponentially decremented solution. To see how this comes about in the context of our simplest approximation analysis above, consider Eq. (4.12):

$$\nabla^2\phi - \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} = 4\pi G\rho_0 + \frac{\phi}{\rho_0 c^2}\frac{\partial^2\rho_0}{\partial t^2} - \left(\frac{\phi}{\rho_0 c^2}\right)^2\left(\frac{\partial\rho_0}{\partial t}\right)^2 - \frac{1}{c^4}\left(\frac{\partial\phi}{\partial t}\right)^2, \tag{4.12}$$

and recall that in order to recover the wave equation we had to assume that $E_{\rm o}$ was $\rho_0\phi$, the proper gravitational energy density. Now we note that if *mass* is to be gravitationally induced instead of writing $4\pi G\rho_o$ we should use the fact that $\rho_o = E_o / c^2$ and $E_o = \rho_o\phi$

to write $4\pi G\rho_o = 4\pi G\rho_o \phi / c^2$. Ignoring the terms in the time-derivatives of ρ_o which are only important in extreme or contrived circumstances, we then have

$$\nabla^2 \phi - \frac{1}{c^2}\frac{\partial^2 \phi}{\partial t^2} \approx 4\pi G\rho_0 \phi / c^2 . \tag{6.3}$$

Our source charge $\rho_o \phi / c^2$ now goes to zero as ϕ goes to zero as the SMP demands. But this equation is just the Klein-Gordon equation for ϕ, and Treder's peculiar effect follows immediately from the exponential factor in the solution for ϕ. Since this effect putatively applies only to active gravitational mass, the SEP is violated in Treder's theory (and all theories that yield Eq. 6.3 without positing that the inertial and passive gravitational masses are similarly altered).

One might think that effects like that just mentioned should be sufficient cause to dismiss theories based on the SMP. Before doing so, however, one should note that the Klein-Gordon form of the gravitational/inertial field equations that follow from the SMP hold out the hope of accounting for the Higgs field(s) of the standard model of relativistic quantum field theory [Beckenstein, 1986]. I should also mention that superstring theory may not resolve the origin of mass problem. In the weak energy limit, one recovers GRT from superstring theory with zero cosmological constant, even if one starts with a scalar-tensor theory [Garay and Garcia-Bellido, 1993]. Raine's criticism of Hoyle and Narlikar's theory thus is applicable.

Either an effective or an explicit scalar component for gravity in our energy limit seems *essential* to explain the origin of mass and thus to satisfy the SMP. So Treder's and Hoyle and Narlikar's theories may yet prove to be steps in the right direction. Be all this as it may, from the point of view of chronology protection, if gravity conforms to the SMP, then as the throat material in our wormhole is gravitationally decoupled from the rest of the universe, its mass should decrease to zero. Since total mass << 0 in the throat is the necessary condition for wormhole formation using negative mass, the wormhole will *not* form. *So, if the SMP is right, wormhole formation is forbidden in principle as well as practice since no amount of matter can be assembled to produce a throat.* No time travel. Chronology protection!

6.4 Deep Throat – The Structure of "Elementary" Particles

So far we have treated the matter at the wormhole throat as a substance that either (1) acquires inertia (for observers far from the throat) via the gravitational interaction with distant matter (GRT), or (2) acquires mass (and thus inertia) as a consequence of that interaction (SMP). But we have not considered the possibility that there might be a more intimate relationship between the *local* properties of local objects and the global structure of the universe. It has long been suspected that such relationships may well exist. The evidence usually advanced to support claims of this sort rely on the "large numbers" conjectures first advanced by Weyl, then Eddington, Dirac, and others [Barrow, 1981 and 1990]. The large numbers are dimensionless ratios of either things like the classical electron radius and the radius of the universe, and the like, which usually turn out to be of the order 10^{40}, or the mass of the universe and the mass of a hadron [10^{80}, the putative number of hadrons in the universe]. The mass ratio, because hadrons are now known to be composite particles, is less compelling than it once was. Nonetheless, the numbers are still arresting.

Since gravity is the only known long-range interaction that couples local objects to the rest of the universe, if we were to believe that there was anything to the conjecture that these large dimensionless numbers signal a cosmic/microcosmic connection, then our theory of elementary particles would have to include gravity. Quantum mechanics and standard model relativistic quantum field theory ignore gravity. Talk of elementary particles and gravity leads to discussion of quantum gravity. It is sometimes argued that we must first understand quantum gravity before tackling the problem of elementary particles. Quantum gravity is usually taken to be a phenomenon of the Planck scale where, in the now fashionable view, time ceases to have meaning and spacetime degenerates into a foam made up of Euclidean (as opposed to Lortentzian) wormholes. From this foam come the "elementary" particles of our experience. How, precisely, this occurs is not yet worked out. (For an interesting critique of quantum gravity in the context of the large numbers hypothesis see von Borzeszkowski and Treder [1988 and 1994a, b].)

Other approaches to the structure of the charged leptons and quarks are possible. Einstein and Schrödinger long championed the view that if one could successfully unify the electromagnetic and gravitational fields, then quantum mechanics and elementary particle structure, including the weak and strong interactions, might emerge as a natural consequence of the hoped for unification [see Pais, 1982, pp. 460 – 469]. Never very fashionable, this approach to the problem of ultimate structure has been argued chiefly by Treder [1983, 1992, 1994] and Sachs [1992] for some time now. Ultimately, it may prove necessary to adopt this approach to account for the origin of mass. But for the purpose at hand, a heuristic classical model of the electron that includes nonlinear gravity will suffice.

Classical electron models with gravity accounted for include those of Einstein [1919], the wormhole models of Einstein and Rosen [1935] and Wheeler [1964], the charged dust model of Arnowitt, Deser, and Misner (ADM) [1960a, b, and 1962], the suggestion by Israel [1970] that the Kerr-Newman solution of the GRT field equations might describe electrons, and more recent work by, for example, Cooperstock [1991]. (See also Wesson [1992] for a recent review of the subject.) While none of these models can be regarded as successful, they are at least suggestive. Of particular interest for our purpose is the ADM electron model. As I have already shown [Woodward, 1993, 1994], it admits solutions of heuristic interest that allow one to account for the very small observed mass of the electron. And more to the point, the electron mass can be written so as to make the role of gravitational coupling to distant matter explicit.

As shown in the Appendix, for the purely electromagnetic ADM charged dust model that satisfies the WEP and yields a realistic [small] electron mass m one gets

$$m = -\frac{\sqrt{\frac{e^2}{G}}}{1 - \frac{2c^2}{\phi_u + \phi_b}}, \tag{6.4}$$

where e is the electronic charge, ϕ_u the gravitational potential due to all of the matter in the causally connected part of the universe at the electron, and ϕ_b is the gravitational potential due to the dust itself. Since a realistic m can only be recovered if one takes the bare mass of the charged dust to be negative [see the Appendix], ϕ_b is always negative. [This is not as crazy as it may sound. Note that electrically charged elementary particle bare masses are also negative (and infinite) in the quantum theoretic standard model as they must compensate for an infinite positive electromagnetic self-energy.] Because m is normally exceedingly small [$\approx 10^{-27}$ gm], the magnitude of ϕ_b must be almost exactly the same as that of ϕ_u which, from Mach's principle, we know to be $\approx c^2$. Thus, as ϕ_u is reduced in our imminent wormhole throat (initially because it is being suppressed by transiently induced negative mass-energy), the bare masses of the electrons [and other elementary particles] in the matter in the throat are partially revealed. This further suppresses ϕ_u in surrounding matter, which leads to more bare mass exposure, which ultimately becomes

$$m \approx -\frac{1}{3}\sqrt{\frac{e^2}{G}}\,. \tag{6.5}$$

This is an *enormous* negative mass per elementary particle – approximately the ADM mass and nearly the Placnck mass – and the total negative mass of all of the particles in the throat would be *stupendous*. It is enough to satisfy the wormhole formation criterion. In particular, using Morris and Thorne's "absurdly benign" wormhole mentioned at the end of section 4 and in section 5 above, taking the thickness a_o of the exotic matter that forms the wormhole to be a tenth of [the] throat radius b_o we find

$$b_o \approx \sqrt{\frac{5c^2}{4\pi G\rho_o}}\,. \tag{6.6}$$

Total bare mass exposure results from ϕ_u in Eq. (6.4) going from c^2 to zero while ϕ_b remains $\approx - c^2$, so if ρ_o in Eq. (6.6) is to be the pre-exposure density, it must be multiplied by c^2 and for this special case

$$b_o \approx \sqrt{\frac{5}{4\pi G\rho_o}}\,. \tag{6.7}$$

Substitution of realistic values for ρ_o ($\approx$ 1 to 10 gm/cm^3) yield throat radii of the order of 10 to 25 meters.

In consideration of power requirements, along with the throat dimensions, plainly this is not a spare-time/loose change/garage type project. Since [if the WEP is true] gravity is repulsive for negative masses, should a wormhole of this type be successfully attempted, it should be stable against collapse. Let me hasten to add, however, that massive engineering problems can be expected in trying to implement this method. (See also Price [1993] on the problems of manipulating negative mass.) But if successful feedback and control mechanisms can be made and this scenario is right, the stationary wormholes are technically feasible in the foreseeable future. One will, however, want to be very careful, for the exposed negative bare mass in the throat of a 10 meter diameter wormhole is about a hundredth of a solar mass (more than a thousand times the mass of the Earth). Nonetheless, if designed to be "absurdly benign", it will have no gravitational effect on exterior surrounding matter. The catastrophes that might occur in developing traversable wormholes make atmospheric ignition seem almost pallid by comparison. So outer space seems like a good place to fool around with such things, at least until the technique of making them has been mastered. Whether critters like us could survive the gravitationally decoupled environment of a negative mass wormhole throat is another matter. And hyperspace navigation is uncharted territory.

7. CONCLUSION

To sum up, if one allows singularity formation in the process of wormhole induction, and there is not physical reason to deny this possibility, then it may be possible in principle to make time machines that do not self-destruct employing exotic matter. If the Copenhagen or histories/decoherence interpretations of quantum mechanics are right, then time travel, at least to the future, is impossible because the future is in no sense actualized since it is not yet determined. If either the de Broglie-Bohm, transactional, or many worlds interpretations of quantum mechanics is correct, then time travel may be in principle possible because reality is deterministic and acausal and the past and the future, in some world at least, objectively exist. A transient inertial reaction effect can be used to induce substantial amounts of exotic matter. If no process acts to augment this mechanism of exotic matter induction, then, although wormhole formation is not forbidden in principle by GRT, it is likely not achievable in practice. If GRT is modified to conform to the strong version of Mach's principle (gravitational induction of mass), then wormhole formation is forbidden in principle. If the bare masses of elementary particles are negative, as required for the "realistic" purely electromagnetic ADM model, and the SMP is not right, then it may be possible to trigger wormhole formation with the transient inertial reaction effect.

Is the universe safe for historians? I certainly hope so. Surely it is better to be able to check to see if what you think about the past is right than not. And as a student of history, notwithstanding a nagging suspicion that time travel is bunk, I would be delighted if future-folk could meddle in the past to mitigate the untoward consequences of the acts of ideologues and genocidal maniacs (among others), even if it is only in someone else's universe. But these are sentimental speculations. The point of this paper is that it lies within our means to find out about these matters with the certainty that only tests in physical reality can supply.

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APPENDIX

To get equation for the ADM electron model that displays the effect of gravitational coupling to distant matter explicitly we proceed as follows. ADM showed that when the field equations of GRT are solved for a spherical cloud of electrically charged dust with charge *e* and bare [dispersed] mass m_o, one finds for the mass *m*

$$m = m_o + \frac{e^2}{Rc^2} - \frac{Gm^2}{Rc^2} \ , \tag{A1}$$

where *R* is the radius of the cloud of dust. This result is arguably obviously right as the total mass is just the sum of the bare mass and the electrical and gravitational self-energies of the dust. When Eq. (A1) is solved for *m*, we get

$$m = -\frac{Rc^2}{2G} \pm \sqrt{\left(\frac{Rc^2}{2G}\right)^2 + 2\left(\frac{Rc^2}{2G}\right)m_o + \frac{e^2}{G}} \ . \tag{A2}$$

As ADM remarked, when the dust collapses to a point, that is, *R* goes to zero, *m* becomes

$$m = \pm\sqrt{\frac{e^2}{G}} \ , \tag{A3}$$

which is finite, well-defined, and depends only on the electrical charge of the dust. All interaction energies save for the electrical and gravitational, which enter Eq. (A2) through m_o, are ultimately irrelevant.

Since the dust that coalesces to form electrons may be presumed pointlike, it is reasonable to assume that the mass of a dispersed [noninteracting] dust particle dm_o is just $\pm\, d(e^2/G)^{1/2} = \pm\, |de/G^{1/2}|$. Integrating over the dispersed dust particles to get m_o we get,

$$m_o = \pm\sqrt{\frac{e^2}{G}}\,. \tag{A4}$$

And when this expression for m_o is substituted into Eq. (A2), one finds for m

$$m = -\frac{Rc^2}{2G} \pm \left(\frac{Rc^2}{2G} \pm \sqrt{\frac{e^2}{G}}\right). \tag{A5}$$

Choosing both roots positive leads to the ADM mass

$$m = \pm\sqrt{\frac{e^2}{G}}\,. \tag{A6}$$

It differs from the Planck mass by less than two orders of magnitude, so it is of no interest for real electrons. Choosing the first root to be negative, however, gives

$$m = -\left[\pm\sqrt{\frac{e^2}{G}}\right] - \frac{Rc^2}{G}\,. \tag{A7}$$

If we pick *the negative root* in the square brackets – that is, if we take the bare mass of the dust to be negative – then we obtain a solution from which the real mass of the electron [positive and very small] can be recovered.

To get a realistic m from Eq. (A7) all we need to do is assume R to be about the gravitational radius of the bare dust. As the dust coalesces to a point as viewed in co-moving coordinates, it appears to freeze at this radius for external observers, making electrons quite stable. This solution, however, violates the WEP, for in taking m_o negative we have assumed the action and passive gravitational masses of the dust negative. But, by leaving Eq. (A1) unmodified we have implicitly assumed that the inertial mass of the dust remains positive. This may be called an "anti-gravity" solution, since particles with negative gravitational mass and positive inertial mass are repelled by normal positive masses. To get a solution that is consistent with the WEP we must change the signs of the self-energy contributions to Eq. (A1), for when the inertial mass of the bare dust is negative, the electrical forces in the dust become attractive and gravitational forces are repulsive. When this change is made, the WEP consistent counterpart of Eq. (A7) is found to be

$$m = \frac{Rc^2}{G} + \left[\pm\sqrt{\frac{e^2}{G}}\right]. \tag{A8}$$

As before, the bare mass of the dust must be taken as negative and R assumed to be about the gravitational radius of the bare dust to get a realistic value of m.

Note that in the WEP consistent case electron stability does not arise from the apparent freezing of the cloud of dust at its gravitational radius. Since gravity is repulsive and non-linear in these circumstances, when the dust collapses within its gravitational radius it is forced back out by gravity. Similarly, when the cloud of dust expands much beyond its gravitational radius, the attractive electrical force which, being linear, does not decrease as rapidly as the gravitational force, causes the cloud to recontract.

To calculate the explicit dependence of m on ϕ_u, the gravitational potential due to the rest of the matter in the universe, we proceed as follows. We note that we can write the energy of an electron in several ways. From the point of view of an exterior observer SRT gives $E_e = mc^2$, and by Mach's principle we know that $mc^2 = m\phi_u$. That is, the local rest energy of an electron is just its gravitational potential energy in the cosmic gravitational potential. But from the point of view of an observer outside the cloud of dust the *total* gravitational potential energy of the bare dust is the product of its bare mass m_o and the total gravitational potential within the dust s/he knows to be present in the dust, ϕ_i. By the conservation of energy these energies must all be equal, so

$$m_o\phi_i = mc^2, \tag{A9}$$

and

$$m_o = \frac{c^2}{\phi_i}m. \tag{A10}$$

We next note that ϕ_i consists of two parts: the background ϕ_u and the potential due to the dust bare mass ϕ_b. ϕ_u is positive, but ϕ_b is negative because the dust bare mass is negative.

Now we can substitute the expression for from Eq. (A10) into $R = 2G|m_o|/c^2$, which is in turn substituted into Eq. (A8), yielding

$$m = \frac{2mc^2}{\phi_i} - \sqrt{\frac{e^2}{G}}. \tag{A11}$$

A little algebraic manipulation produces

$$m = -\frac{\sqrt{\dfrac{e^2}{G}}}{\left[1 - \dfrac{2c^2}{\phi_i}\right]}$$

$$m = -\frac{\sqrt{\frac{e^2}{G}}}{\left[1 - \frac{2c^2}{\phi_u + \phi_b}\right]}. \tag{A12}$$

The observed mass of the electron [and other elementary particles presumably] does depend on its gravitational coupling to the distant matter in the universe if its bare mass is negative, even though this is not explicit in the ADM solution of the GRT field equations. As a matter of idle interest, I note that the "anti-gravity" ADM solution mentioned above also yields Eq. (A12), but plus signs replace the minus signs.

It is worth remarking that the minimum energy solution of Eq. (A12) is that where $\phi_u + \phi_b = 0$ and $m = 0$ exactly. The fact that the electron mass is not exactly zero means that we have left something out of our model: spin and the quantization of angular momentum. [Note, nonetheless, that the model is already implicitly quantized, for e is a quantized charge; and e^2/c is consequently a quantized action just like $\hbar$.] Presumably, the inclusion of quantized spin would yield a small nonzero value for m as a groundstate. And the excited states would give back Barut's [1979] phenomenological formula for the mass spectrum of the charged leptons. Exploration of this issue, however, exceeds the scope of this paper.

NOTES

1. Tanaka and Hiscock [1994] show that freely propagating, massive scalar fields produce behavior at the chronology horizons of Misner space equivalent to the massless case close to horizons with CNGs. (In Misner space one of the spatial coordinates is taken to be periodic, so in its complete analytic extension there are regions where the temporal coordinate is periodic.) Since CNGs form in the chronology horizons of Misner space, the divergent behavior Tanaka and Hiscock find is not applicable to the simple wormhole spacetimes of Fig. 2. They were designed to avoid just this problem.
2. The principle of least axion [*i.e.*, none] suggests that they are not. Real guts are required to take wimps seriously.
3. The notion of "irreducibly stochastic" processes plays a pivotal role in this discussion, so let me try to define it as precisely as I can. By irreducibly stochastic I mean inherently random and indeterministic. For a process with this property, not only is it impossible for us to predict with certainty its future evolution, its future evolution is not factually determined in reality until it actually happens. Indeterminacy is not a limitation on our ability to know facts, it is the fact.

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