[First published in *Foundations of Physics Letters* **10**, 153 – 181 (1997).
Typographical errors in the original have been corrected.]

TWISTS OF FATE: CAN WE MAKE TRAVERSABLE WORMHOLES IN SPACETIME?

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The scientific reasons for trying to make traversable wormholes are briefly reviewed. Methods for making wormholes employing a Machian transient mass fluctuation are examined. Several problems one might encounter are mentioned. They, however, may just be engineering difficulties. The use of "quantum inequalities" to constrain the existence of negative mass-energy required in wormhole formation is briefly examined. It is argued that quantum inequalities do not prohibit the formation of artificial concentrations of negative mass-energy.

Key Words: wormholes, exotic matter, Mach's principle, general relativity, time travel.

I. INTRODUCTION

"Tunnels Through Spacetime: Can We Build A Wormhole?" Such was the title of the cover story of the 23 March 1996 issue of *New Scientist*. In that story M. Chown reported on recent developments in wormhole physics, especially work that was stimulated by a NASA sponsored conference held at the Jet Propulsion Laboratory in Pasadena on 16 to 17 May 1994 [Cramer, *et al.*, 1995] and a proposal for the induction of wormholes based on strong magnetic fields [Maccone, 1995]. The tone of the article is serious throughout. Not so the proximate previous article on wormholes wherein I. Stewart [1994] related the efforts of Amanda Banda Gander, sales rep for Hawkthorne Wheelstein, Chartered Relativists, to sell Santa various exotic devices to facilitate his delivery schedule. This delightful piece culminates with the cumulative audience paradox -- gnomes piling up at the nativity -- and its resolution in terms of the Many Worlds interpretation of quantum mechanics.

It would appear that the status of wormhole research has changed a bit in the past few years. This is not to say, however, that skepticism has vanished. For example, Matloff [1996, esp. p. 13] has little time for wormhole shenanigans. Nonetheless, Matloff reports that there is talk that NASA may modestly fund a study of wormholes.[1] And S. Hawking, until recently a robust critic of time travel, at the outset of the revised edition of his best-selling book on the history of time [1996, p. 2] remarks: "What is the nature of time? Will it ever come to an end? Can we go back in time? Recent breakthroughs in physics, made possible in part by fantastic new technologies, suggest answers to some of these longstanding questions. Someday these answers may seem as obvious to us at the earth orbiting the sun -- or perhaps as ridiculous as a tower of tortoises [that supports the world in an outdated cosmology]. Only time (whatever that may be) will tell."

While the obvious lure of this area of physics is rapid transport via traversable wormholes in spacetime (TWISTs), especially traversable wormholes in time (TWITs), it speaks to fundamental issues of purely scientific interest too. For example, should it prove possible to punch a wormhole from one region of spacetime to another (or another universe perhaps), almost certainly a spacetime singularity will be at least fleetingly formed in the process. Since traversable wormholes are horizonless by construction and the singularity is a tear in spacetime, presumably the Planck-scale structure of reality would be revealed and could be studied. This is a matter of some interest for the ardently sought theory of quantum gravity -- the elusive theory of everything (TOE). Since there is no hope of ever being able to directly explore Planck-scale phenomena using, say, particle accelerators, making wormholes might prove the only way to probe this domain. So making a wormhole is a matter of scientific, as well as technical, commercial, and romantic interest.

2. EXOTICITY

Morris and Thorne [1988] inaugurated the modern era of wormhole physics.[2] Although they limited their investigations to static, spherically symmetric wormholes, they did a remarkably thorough job. In the plethora of papers stimulated by their work (all but the most recent of which can be found in the bibliography of Visser's [1995] first-rate text on wormhole physics) one seemingly irrefragable conclusion stands out: If we are ever to fabricate a wormhole by any conceivable means, the successful method will unavoidably require the use of "exotic" matter. Exotic matter is matter that violates one, or more of the various energy conditions (null, weak, dominant, strong, and "averaged" [along an appropriate worldline] versions of these) which posit the nonexistence, at least on average, of negative mass-energy.

We can distinguish two classes of exotic matter, the second being a subclass of the first: 1. plain old exotic matter (POEM) – matter which for some, but not all, observers with relative velocities ≤ c with respect to the matter see a negative mass-energy, and 2. really exotic matter (REM) – matter which is negative for observers with zero relative velocity (that is, matter with negative proper mass-energy density). Contemplating POEM may fire the imagination, but REM is the stuff that dreams are made of. The ideal type of TWISTs, from the engineering point of view, are those made with matter that is exotic in its proper frame. (See, in this connection, Visser [1995], chs. 13 - 15.) The prospect of even laying one's hands on some POEM, however, has seemed quite remote. Accumulating some REM usable for making a TWIST is widely deemed hopelessly beyond the pale. Indeed, inducing a wormhole where none existed before has appeared so formidable that the least implausible scenario for acquiring a TWIST has usually been taken to be the enlargement -- by unspecified means -- of a pre-existing wormhole present in the putative Planck-scale quantum spacetime foam. (This done, one might then manipulate the wormhole to one's purposes.) Since Planck-scale physics froze out at an infinitesimal fraction of a second after the onset of the big bang, it is far from obvious that such machinations could ever be successful.

Setting aside such concerns for the moment, we ask: How much REM do we need to make a TWIST with a diameter on the order of meters? The general spherical wormhole metric [Morris and Thorne, 1988] is:

$$ds^2 = -e^{2\Phi}c^2dt^2 + dr^2/(1-b/r) + r^2(d\theta^2 + \sin^2\theta d\phi^2). \qquad (2.1)$$

Φ is the "redshift" function and b the "shape" function of the wormhole.[3] The minimum traversibility conditions require that $e^{2\Phi}$ be everywhere finite (no horizons) and that b not involve excessive curvature. These constraints admit a wide variety of TWISTs made with POEM. With REM, though, we can make the "absurdly benign" wormhole discussed by Morris and Thorne [1988, esp. p. 410] where the exotic matter is restricted to a thin layer of thickness a_o around a throat of radius b_o. This wormhole has the desirable property that spacetime outside of the region of exoticity remains flat. The volume of the exotic matter is $4\pi^2 b_o^2 a_o$ and its density ρ is:

$$\rho = -[b_o c^2/4\pi G r^2 a_o][1 - (r - b_o)/a_o]. \qquad (2.2)$$

The mass M of the exotic matter then is:

$$M \approx -\pi b_o c^2/2G. \qquad (2.3)$$

To order of magnitude, this is just the negative of the amount of mass required to induce a normal Schwarzschild wormhole. The situation doesn't change much when one tries to make a Visser wormhole (with exotic struts configured aspherically). The REM mass turns out to be about a Jupiter mass. This is not a trivial amount of REM. As Visser [1995, p. 175] remarks, "The big open question, naturally, is whether a significant amount of exotic matter is in fact obtainable in the laboratory. The theoretical problems are daunting, and the technological problems seem completely beyond our reach." Perhaps.

3. AN INERTIAL REACTION EFFECT

Not long ago I pointed out that a peculiar little inertial reaction effect might make it possible to transiently induce a state of negative mass-energy, and that, in turn, might make it feasible to actually drive the formation of a TWIST [Woodward, 1995, hereafter MUSH (*i.e.*, Making the Universe Safe for Historians)]. While motivated by exploration of the technical feasibility of TWISTs and TWITs, in MUSH I dealt with a wide variety of related issues such as interpretations of quantum mechanics, Mach's principle, and alternatives to general relativity theory (GRT). Although these related matters are fascinating in their own rights, they are not central to the answer to the question: "Can we make a wormhole?" Here I focus on the answer to that question.

In MUSH, section 4, I have given a derivation of the inertial reaction effect in question. I now present a somewhat attenuated version of that derivation. We make two assumptions:

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.

2. Any acceptable physical theory must be locally Lorentz-invariant; that is, in sufficiently small regions of spacetime special relativity theory (SRT) must obtain.

We then 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 allows us to stipulate the inertial reaction force **F** on our test particle stimulated by the external accelerating force $\mathbf{F}_{ext}$ as:

$$\mathbf{F} = -\,\mathbf{F}_{ext} = -\,d\mathbf{P}/d\tau, \tag{3.1}$$

with,

$$\mathbf{P} = (\gamma m_o c,\ \mathbf{p}), \tag{3.2}$$

$$\gamma = (1 - v^2/c^2)^{-1/2}, \tag{3.3}$$

where bold capital letters denote four-vectors and bold lower-case 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. We specialize to the instantaneous frame of rest of the test particle. In this frame we can ignore the difference between coordinate and proper time, 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. (3.1) becomes:

$$\mathbf{F} = -\,d\mathbf{P}/d\tau = -\,(\partial m_o c/\partial t,\ \mathbf{f}), \tag{3.4}$$

with,

$$\mathbf{f} = d\mathbf{p}/d\tau. \tag{3.5}$$

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

$$\boldsymbol{F} = \mathbf{F}/m_o = -\,[(c/m_o)(\partial m_o/\partial t), \boldsymbol{f}]. \tag{3.6}$$

To recover a field equation of standard form we let the test particle have some small extension and a proper matter density ρ_o. Eq. (3.6) then is:

$$\boldsymbol{F} = -\,[(c/\rho_o)(\partial\rho_o/\partial t), \boldsymbol{f}]. \tag{3.7}$$

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

$$\boldsymbol{F} = -\,[(1/\rho_o c)(\partial E_o/\partial t), \boldsymbol{f}]. \tag{3.8}$$

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

$$(1/\rho_o c^2)(\partial^2 E_o/\partial t^2) + (1/\rho_o c^2)^2(\partial E_o/\partial t)^2 + \nabla\cdot\boldsymbol{f} = -\,4\pi Q_o. \tag{3.9}$$

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 Eq. (3.9) is:

$$\nabla^2\phi - (1/\rho_o c^2)(\partial^2 E_o/\partial t^2) - (1/\rho_o c^2)^2(\partial E_o/\partial t)^2 = 4\pi Q_o. \tag{3.10}$$

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:

$$E_o = \rho_o\phi. \tag{3.11}$$

This choice for E_o yields:

$$\nabla^2\phi - (1/c^2)(\partial^2\phi/\partial t^2) = 4\pi Q_o + (\phi/\rho_o c^2)(\partial^2\rho_o/\partial t^2) - (\phi/\rho_o c^2)^2(\partial\rho_o/\partial t)^2 - c^{-4}(\partial\phi/\partial t)^2. \tag{3.12}$$

If we ignore the terms of order c^{-4} and those involving derivatives of ρ_o, we have in Eq. (3.12) the usual wave equation for ϕ in terms of a source charge density Q_o. Since 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, $Q_o = G\rho_o$. Thus the field that produces inertial reaction forces is the gravitational field. Identifying $Q_o = G\rho_o$ makes it possible to get a rough estimate of the value of ϕ which is required to explore the effect of the terms involving time derivatives of ρ_o.

Considering the stationary case, where all terms involving time derivatives vanish, Eq. (3.12) reduces to Laplace's equation, 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. (3.12). 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 mass-energy density to fluctuate, the fluctuation itself, through both its first and second time derivatives, becomes a source of the gravitational field. And the Equivalence Principle tells us that these terms also contribute to the passive gravitational and inertial masses of the accelerating object. Experimental results that corroborate the existence of the transient effect derived here are summarized in the Appendix.

4. MAKING WORMHOLES

Deep analysis may be indicated in the views of some for those who study wormholes, but it is not required to see how the transient mass fluctuation discussed above might be used to induce one. To make a wormhole, the proper matter density of the stuff in the imminent throat must first go to zero and then become enormously negative. (This means that we cannot use the assumption that the transient mass density fluctuation is small compared to ρ_o that makes it possible to extract Eq. (A.2) from Eq. (A.1) in the Appendix.) The total matter density ρ that appears in Eq. (3.12) is:

$$\rho = \rho_o + (1/4\pi G)[(\phi/\rho_o c^2)(\partial^2\rho_o/\partial t^2) - (\phi/\rho_o c^2)^2(\partial\rho_o/\partial t)^2 - c^{-4}(\partial\phi/\partial t)^2]. \qquad (4.1)$$

Let us say that we seek to drive a state of exoticity electromagnetically in a capacitative [or inductive] component of an electrical circuit in the laboratory by applying an AC signal to it. To achieve exoticity we will have to drive a transient matter density fluctuation that is larger than the quiescent matter density of the stuff in which it is driven. In these circumstances the second term on the RHS of Eq. (4.1) will become negative and at least as large as the initial value of ρ_o. But ρ_o, as a result, will be getting smaller, tending to zero, as this process proceeds. Inspection of Eq. (4.1) reveals that an important behavior in this process is going to occur as ρ_o approaches zero, for the coefficients of the second and third terms on the RHS of Eq. (4.1) are singular at $\rho_o = 0$. These terms, which are driving the process, blow up as ρ_o goes to zero. We have a strongly nonlinear process on our hands.

To simplify matters a bit, we will drop the $(\partial\phi/\partial t)^2$ term in Eq. (4.1) from further consideration. We do so for the following reason: At each point in the circuit element ϕ will be changing because of the transient process going on in adjacent parts of the circuit element. But since the mass in which the exoticity is being induced is small, the rate of change of ϕ will be much smaller than that of the matter density *per se*. (Moreover, it has a coefficient of c^{-4}. And this term is negative anyway and thus could not suppress incipient exoticity.) Ignoring this term, we are left with:

$$\rho \approx \rho_o + (1/4\pi G)[(\phi/\rho_o c^2)(\partial^2\rho_o/\partial t^2) - (\phi/\rho_o c^2)^2(\partial\rho_o/\partial t)^2]. \quad (4.2)$$

Eq. (4.2) looks suspiciously like the differential equation describing a forced oscillator; and one might be tempted to treat it as such. Differences make this path inadvisable. For example, ρ is not the driving function in this situation.

To see what happens in the present circumstances we can solve Eq. (4.2) numerically. To do this we note that the driving source is contained in ρ_o since its fluctuation is what causes the transient terms to be non-zero. We write $\rho_o = E_o/c^2$ and then note that $E_o = E_q + E_d$, where E_q is the fixed quiescent proper energy density present in the absence of any transient effect, and E_d is the driving energy density supplied by the externally applied AC signal. Taking $E_d = E\sin(\omega t)$ we get:

$$(\partial^2\rho_o/\partial t^2) = -(E\omega^2/c^2)\sin(\omega t),$$

$$(\partial\rho_o/\partial t)^2 = (E\omega/c^2)^2\cos^2(\omega t). \quad (4.3)$$

Substituting into Eq. (4.2):

$$\rho \approx \rho_o - (k_1/\rho_o)\sin(\omega t) - (k_2/\rho_o^2)\cos^2(\omega t), \quad (4.4)$$

where,

$$k_1 = E\omega^2\phi/4\pi Gc^4,$$

$$k_2 = (E\omega\phi)^2/4\pi Gc^8. \quad (4.5)$$

We may now use Eq. (4.4) to examine the evolution of ρ in the circuit element being driven by the AC signal. We specify some initial values of ρ_o and t, choose E and ω sufficiently large so that $k_1 > \rho_o$, and calculate ρ for these values. Specifying some suitable time step size, we proceed a time step and repeat the calculation. However, instead of using the initial ρ_o, we use the computed value of ρ from the preceding step for the value of ρ_o. Iterating this procedure with a sufficiently small step size we can get a pretty good idea of the expected behavior for all times except those where $\rho \approx 0$. When the computed value of ρ gets close to zero in a given step, the coefficients of the trigonometric terms in Eq. (4.4) blow up and the next computed value of ρ is very large. Depending on the specific details of the assumed initial values and step size, the large value may turn out to be either positive or negative. Real, presumably continuous behavior should not have this property.

Unless, by happy coincidence, we choose initial data that cause the computed value of ρ to become exactly zero in some step of the procedure (so that the next step is exactly singular), the iterative procedure returns dubious results close to the singularity. And even if, fortuitously, we did choose initial data that gives this behavior, the post-singularity computations would be, at best, questionable. Negative infinity substituted in to Eq. (4.4) for ρ_o kills the time-dependent terms, and both ρ and ρ_o remain minus infinity for all subsequent steps; that is, forever. Appealing though this may be to the would-be wormhole wonk, it seems unlikely to be true. Were it true, we might reasonably expect reality to be riddled with random natural wormholes with an arbitrary range of sizes. While we all, at least occasionally, feel as though we have been through a time-warp, a quick check of clock time gives the lie to our sensations.

Although iterative solution of Eq. (4.4) breaks down at the singularity, qualitative inspection of Eq. (4.4) reveals the essential behavior of ρ. Very close to the singularity, unless $\cos^2(\omega t)$ is essentially exactly zero, the third term on the RHS of Eq. (4.4) dominates all others. It becomes extremely large [formally infinite] and negative. At any distance from the singularity, however, this term is essentially zero – many orders of magnitude smaller than the second term on the RHS. The second term, unless $\sin(\omega t)$ is exactly zero, also becomes infinitely large as ρ_o goes to zero. Unlike the third term, which is negative on both sides of the singularity, the second term reverses sign at the singularity because of sign reversal of ρ_o. So, if the $\sin(\omega t)$ term is negative as the singularity is approached, it becomes positive (and very large) on passing through the singularity – unless $\sin(\omega t)$ also reverses sign at the singularity.

If the behavior just described really occurs, the way to engineer a laboratory scale wormhole should now be evident. We simply choose all of our initial conditions so that $\sin(\omega t)$ reverses sign exactly as, or *immediately* after, ρ_o becomes zero. Sign reversal of $\sin(\omega t)$ means that $\sin(\omega t) = 0$, killing this term at the singularity if reversal is exactly coincident with it. No matter. The $\cos^2(\omega t)$ term peaks when $\sin(\omega t) = 0$, so we still have a formally infinite negative value for ρ at the singularity. Can we actually do this in the laboratory? Let us suppose, for example, we can engineer things so that the singularity occurs at $\sin(\omega t) = 0$, the trigonometric terms in Eq. (4.4) are both negative as the singularity is approached, and $k_1 = 100$. Taking the power frequency of the AC driving signal to be 1 megahertz, this choice of k_1 constrains the power density (E_ω) to be 1.2 kilowatts/cm^3.[4] k_2 is then constrained to the value 2.12 X 10^{-16}. Technically speaking, the power frequency and density assumed here are easily within present capabilities. So, if the volume of the material in which this process takes place remains finite as it proceeds, we will have an infinite negative mass induced in our circuit element at the singularity. Ha, ha! Laboratory scale wormholes! Well, maybe.

5. MUNDANE MATTERS

I expect that you don't really believe that the process just described would occur exactly as outlined if we actually did this experiment in a laboratory. Even if the effect on which the method is based really does exist. Several problems come quickly to mind. For example, in analogy with resonance behavior, it is easy to believe that some "damping" process will keep the state from becoming truly singular. How? Well, note that in all of the foregoing we have treated matter and fields as continuous. But in fact this isn't exactly so. Leptons and quarks are discrete. One might argue that they aren't little billiard balls; that their "matter" may be their self-energies, and that may be distributed in the fields they generate. But the fields themselves may be discrete. The point here is that it is by no means obvious precisely what is acquiring the large negative matter density and where exactly it is located. It may be that the discontinuities inherent in matter will somehow thwart at least the most extreme aspects of the process described above.

5.1 FORMATIVE DYNAMICS

Even if we admit, for the purposes of argument, that extreme, quasi-singular behavior might be attainable, other difficulties arise. Will such exotic matter form a wormhole? Because the effect involved is obtained in the neo-Newtonian approximation, the matter density source is a scalar and thus cannot be directly compared with the tensor source of a tensor field. But the negativity and enormous magnitude of ρ will lead to large gravitational repulsion of the exotic matter in the throat for itself – likely providing the gigantic pressures needed to stabilize a wormhole. This, however, is not an unmixed blessing. Rendering the inertial mass of the matter in the throat negative will cause direction of the action of all of the electromagnetic forces in the matter to be reversed. It is exceedingly unlikely that anything remotely resembling the normal structure of matter could be maintained in the active regions of the circuit elements as this process advanced. And it is easy to believe that such a device, given the rapidly developing, enormous internal repulsive forces, might well blow itself apart – perhaps with great violence – in the process. This, arguably, would merit the signifier "quintessential time-bomb". (For more on the counter-intuitive behavior of REM, see: Forward [1989] and Price [1993].)

5.2 POST FORMATION STABILITY

Is there any reason to believe, granting something approaching very nearly the singular behavior described above occurs, and assuming that the dynamics of the formative process do not include self-disruption, that a stable REM configuration is possible once a wormhole throat has been created? In other words, can it be that the quasi-perpetual post singularity enormous negative proper mass density might have some plausible physical basis? Curiously, the answer to this question seems to be yes. The reason why merits a little elaboration.

Recall that Morris and Thorne's absurdly benign wormhole solution entails:

$$b_o \approx -\,2GM/\pi c^2, \tag{5.1}$$

which is just Eq. (2.3) slightly rearranged. Note that the throat radius, up to factors of order of unity and the negative sign, is just the Schwarzschild horizon condition. (b_o here, of course, is not negative, because M is negative.) Recall too, as discussed at the end of section 3 [and also in Woodward, 1996a], that outside of the wormhole $\phi \approx GM/R \approx c^2$. That is, viewed by a distant observer, at points away from local concentrations of matter, the gravitational potential is roughly that for the horizon of a black hole generated by the mass of the Universe. So, in the wormhole throat, as viewed by a distant observer, the gravitational potential produced by the exotic matter will roughly (very likely exactly) cancel the gravitational potential produced by the rest of the matter in the Universe. What happens to the masses of things when the gravitational potential of local surrounding matter cancels that of distant matter?

To answer the just posed question we need to remember that in passing from Eq. (3.10) to Eq. (3.12) in section 3 we had to posit Eq. (3.11):

$$E_o = \rho_o\phi. \tag{5.2}$$

That is, the proper energy density of matter (and thus its mass) is just its total proper gravitational potential energy density. If ϕ due to the matter in the throat exactly cancels ϕ due to cosmic matter, then it would seem that the proper matter density of the stuff in the throat must vanish by Eq. (5.2). For distant observers this is certainly true. Outside of the throat spacetime is exactly flat for absurdly benign wormholes. So for observers in flat spacetime the wormhole appears to have zero mass (proper or otherwise) since it produces no spacetime curvature at their location.

But what about in the throat? There the matter density cannot be zero. It must be negative and enormous. How can that be? To answer this question we need to know what happens to the masses of the most elementary constituents of matter – elementary particles – when the total gravitational potential seen by them due to surrounding matter goes to zero. In MUSH, section 6, I called this the gravitationally decoupled state. To explore it we need a model of elementary particles that allows us to isolate the gravitational effect of surrounding matter on elementary particles. We need a general relativistic model of electrons (and quarks). The model that is well-suited to this task (also discussed in MUSH) is that developed by Arnowitt, Deser, and Misner (ADM) nearly forty years ago [1960a,b].

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:

$$m = m_o + (e^2/Rc^2) - (Gm^2/Rc^2), \tag{5.3}$$

where R is the radius of the cloud of dust.[5] The total mass is just the sum of the bare mass and the electrical and gravitational self-energies of the dust. When Eq. (5.3) is solved for m, we get:

$$m = -(Rc^2/2\mathrm{G}) \pm [(Rc^2/2G)^2 + 2(Rc^2/2G)m_o + (e^2/G)]^{1/2}. \tag{5.4}$$

As ADM remarked, when the dust collapses to a point, that is, R goes to zero, m goes to $\pm (e^2/G)^{1/2}$, which is finite, well defined, and depends only on the electrical charge of the dust.

We now posit that the dust that coalesces to form electrons (and quarks) may be presumed point-like. So it is reasonable to assume that the mass of a dispersed [non-interacting] dust particle dm_o is just $\pm\, d(e^2/G)^{1/2} = \pm \left| de/G^{1/2} \right|$. Integrating over the dispersed dust particles to get m_o, we get:

$$m_o = \pm (e^2/G)^{1/2}, \tag{5.5}$$

and when this expression for m_o is substituted into Eq. (5.4) we find for m:

$$m = -(Rc^2/2G) \pm [(Rc^2/2G) \pm (e^2/G)^{1/2}]. \tag{5.6}$$

Choosing both roots, and thus m_o, positive leads to the ADM mass. Its magnitude is comparable to the Planck mass, and thus of no interest here. To get a small, realistic mass we must allow m_o to be negative. If we do this, however, we must change the signs of the self-energy contributions to Eq. (5.3) in order not to violate the Equivalence Principle (EP), for when the inertial mass of the bare dust is negative, the electrical forces in the dust become attractive and gravitational forces are repulsive. This change made, the EP consistent solution is found to be:

$$m = (Rc^2/G) + [\pm (e^2/G)^{1/2}]. \qquad (5.7)$$

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 these model electrons are stable. Since gravity is repulsive and nonlinear 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 surrounding matter in the Universe, we proceed as follows. We first 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 since $\phi_u = c^2$, $mc^2 = m\phi_u$. 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:

$$m_o\phi_i = mc^2, \qquad (5.8)$$

and,

$$m_o = (c^2/\phi_i)m. \qquad (5.9)$$

We next note that ϕ_i consists of two parts: the background ϕ_u of surrounding matter, and the potential due to the dust bare mass ϕ_b. In normal circumstances ϕ_u is positive (and $\approx c^2$), but ϕ_b is negative because the dust bare mass is negative.

Now we can substitute the expression for m_o from Eq. (5.9) into $R = 2G|m_o|/c^2$, which is in turn substituted into Eq. (5.7) yielding:

$$m = (2mc^2/\phi_i) - (e^2/G)^{1/2}. \qquad (5.10)$$

A little algebraic manipulation produces:

$$\begin{aligned} m &= -(e^2/G)^{1/2}/[1 - (2c^2/\phi_i)] \\ &= -(e^2/G)^{1/2}/[1 - 2c^2/(\phi_u + \phi_b)]. \qquad (5.11) \end{aligned}$$

The observed mass of the electron (and other elementary particles) does depend on its gravitational coupling to the distant matter in the Universe. And we now see immediately what happens when ϕ_u, due to surrounding matter, goes to zero. Since the dust lies near its gravitational radius and has negative bare mass, $\phi_b \approx -c^2$. Eq. (5.11) becomes:

$$m \approx -(e^2/G)^{1/2}/3. \qquad (5.12)$$

This is a stupendously large exotic mass per elementary particle. So we need only start with a relatively modest amount of normal matter and zap it with the quasi-singular transient effect to expose the hideously large amount of REM required to produce an absurdly benign wormhole throat.

An obvious criticism is that the purely electrical, negative bare mass ADM model of elementary particles used here is not widely accepted.[6] True. So perhaps we shouldn't take this too seriously. It is worth noting, however, that the bare masses of elementary particles in the standard model are also negative – and infinite. Since the role of gravity is not encompassed by the standard model, and it is clearly essential when examining wormholes and gravitational decoupling, it is not possible to carry through an analysis parallel to that just presented. Nonetheless, given the infinite negative bare masses of the standard model, it seems at least plausible that gravitational decoupling will lead to the exposure of exceedingly large exotic masses.

5.3 DUMBELL TWISTs

What if the singular behavior of Eq. (4.4) is naturally suppressed, or we artificially suppress it by some unspecified means? Is it then impossible to make a wormhole? No, it may still be possible to make a wormhole. The technique that might work is a bit more complicated than simply zapping a circuit element in just the right way to drive singular behavior. But the basic idea is simple. So I shall just outline in rough, qualitative terms how one might proceed. The chief elements required for the method are sketched in Fig. 1 which, in keeping with the tradition of the now legendary spherical chicken,[7] exhibits only essentials.

A resonant inductive/capacitative (LC) circuit is depicted in Fig. 1. The AC power source (not shown) can be taken to be included with either the L or the C element, mounted midway between them, or remotely located. We posit that the driving signal is essentially the same as that adopted in section 4. Because we cannot make ρ_o, $\sin(\omega t)$, and $\cos(\omega t)$ all equal to zero at the same time to suppress singular behavior, we drop the k_2 term in Eq. (4.4). So, instead of Eq. (4.4) we have:

$$\rho \approx \rho_o - (k_1/\rho_o)\sin(\omega t). \qquad (5.13)$$

Since singular behavior is supposed suppressed, we must still assert that ρ_o and $\sin(\omega t)$ go to zero together. We also assume that, in the first cycle at least, they change sign together as well so that ρ becomes negative. A mass fluctuation will ensue. One might surmise that this fluctuation is periodically both positive and negative. On closer analysis, this turns out not to be right. As shown in Table 1, for a wide range of assumed initial densities at a milliradian of ωt beyond $\sin(\omega t) = 0$ a purely negative fluctuation ensues.[8] Moreover, this purely negative fluctuation is obtained for a considerable range of values of k_1, as we see in Table 2. With careful engineering, we should be able to make this happen in both the L and C components. But now, because ρ_o and $\sin(\omega t)$ go to zero together, the absolute value of $(k_1/\rho_o)\sin(\omega t)$ cannot become arbitrarily large. As the absolute value of this term becomes larger in any cycle, the instantaneous absolute value of ρ_o becomes larger too, driving down the instantaneous absolute value of (k_1/ρ_o) and quenching the transient effect. While Tables 1 and 2 show a gradual negative drift for the cycles as ωt increases, the rate of that drift decreases with increasing ωt. We might conclude that TWISTs cannot be made in this fashion.

We have not yet taken into account a couple of factors which may make it possible to weasel out of this apparent impasse. First we note that in relativistic gravity, the Newtonian gravitational potential propagates at light speed. So the changing instantaneous mass of each of the circuit elements is only detected at the other circuit element after a finite time has elapsed. We make use of this fact by adjusting the distance between the circuit elements mindful of the signal propagation delay. The trick is to adjust the distance between the L an C components so that just as one component – say C – is reaching its peak transient negative mass value, the delayed (that is, retarded) gravitational potential of the other component – L – seen by C is also just reaching its peak negative value at C. As far as *local* observers in proximity to the L and C components are concerned, this will appear to make no difference, for the *locally measured* value of the total gravitational potential, like the vacuum speed of light, is an invariant [Woodward, 1996a]. But distant observers will see something different since neither of these quantities are global invariants.

To see what will happen from the point-of-view of distant observers we employ the ADM solution, Eq. (5.11). Since this solution, as previously noted, is obtained for isotropic coordinates, we can use it unmodified for distant observers. We now remark that to get back the electron's mass (to within 10%) we must have:

$$\phi_u + \phi_b = 1, \tag{5.14}$$

yielding:

$$m \approx (e^2/G)^{1/2}/[2c^2/(\phi_u + \phi_b)]. \tag{5.15}$$

as long as $\phi_u + \phi_b << c^2$. As mentioned above, $\phi_b \approx -c^2$ because the dust bare mass is negative and concentrated at its gravitational radius. This does not change (for either local or distant observers). $\phi_u \approx c^2$ doesn't change for local observers either. But for distant observers ϕ_u does change because it, for them, is the sum of the potential due to cosmic matter, ϕ_c, and the potential due to the companion circuit element, ϕ_{ce}, that is, the potential produced by L at C in the case we are considering.

We next write:

$$\phi_u + \phi_b = \phi_c + \phi_{ce} + \phi_b. \tag{5.16}$$

This expression, if $\phi_{ce} = 0$, is just equal to one [as in Eq. (5.14)]. But if the mass of L seen at C is negative, then $\phi_{ce} < 0$ and the expression is less than one. To see the effect of L at C on m we take $\phi_c + \phi_b = 1$ in Eq. (5.16), substitute in to Eq. (5.15) and do a little rearranging to get:

$$m \approx [(e^2/G)^{1/2}/2c^2](\phi_{ce} + 1). \quad (5.17)$$

As ϕ_{ce} goes from zero to increasingly negative values, m first decreases to zero and then becomes increasingly negative too. This effect of the gravitational potential produced by L at C affects all of the elementary particles that make up C. It follows that distant observers see the mass of C made more negative by the action of L than it would be due to the transient effect in C *per se* alone. *Local observers in immediate proximity to either of the circuit elements, however, will be completely unaware of this effect.*

But this is only part of the story. As the periodic mass fluctuations in the L and C components proceed, the mass of L next becomes negative. The mass of L now is affected by the gravitational potential at L produced by C, which was affected by L in the previous cycle, and so on. *For distant observers* a bootstrap process appears to operate driving the mass of each of the components more and more negative as the device continues to cycle. If the amplitude of the effect driven in L and C is sufficiently large, some finite, reasonable number of cycles should be all that are required to attain the condition of Eq. (5.12) – assuming, of course, that the forming TWIST does not blow itself apart.

6. QUANTUM INEQUALITIES

Having just explored how real TWISTs might be made with extant technology (and a lot of clever engineering not yet done), we ask: Is there any principle or physical process that prohibits the formation of TWISTs? Hawking's "chronology protection conjecture", where the smooth deformation of spacetime to make a TWIST leads to the creation of a closed null geodesic (CNG) along which quantum vacuum fields recirculate and destroy the forming TWIST, is an example of the sort of idea sought here. The conditions posited in Hawking's argument can be sidestepped in several ways, so his argument is not an irrefutable proof that chronology is in fact protected. Others have explored alternative means to achieve this end.

Until roughly a couple of decades ago, it was thought that one could simply posit that the mass-energy density seen by all observers had to be ≥ 0. This is the weak energy condition (WEC):

$$T_{\mu\nu}v^\mu v^\nu \geq 0, \quad (6.1)$$

where $T_{\mu\nu}$ is the stress-energy tensor and v^μ the four-velocity of the observer relative to the event where $T_{\mu\nu}$ is being evaluated. The WEC is now well-known to be false. Quantum effects, the Casimir effect for example, violate Eq. (6.1). To preserve the idea that, at least on average, mass-energy is positive, the average WEC (AWEC) was invented. Here one averages Eq. (6.1) along some specified time-like geodesic:

$$\int_{-\infty}^{\infty} T_{\mu\nu}v^\mu v^\nu d\tau \geq 0, \quad (6.2)$$

where τ is the observer's proper time. The AWEC is sufficient for most theoretical purposes. But whether it is true is another matter. Indeed, claims that it is false have been advanced [Cramer, *et al.*, 1995].

In the matter of prohibiting traversable wormholes, even if true, the AWEC isn't really much help. Somewhere along the time-like geodesic one might encounter an enormous negative mass-energy density with significant duration. To satisfy the AWEC, all one need suppose is that somewhere – perhaps in the distant past or future – a compensating positive energy density lies on the geodesic. That is, a TWIT of finite duration is not obviously precluded by the AWEC *per se*. Ford and Roman [1995 and 1996] address this problem by the use of "quantum inequalities" (QIs) which put more stringent limits on exotic matter and seem to exclude traversable wormholes. If their arguments are right, then the method for making wormholes described above will be thwarted before a stable TWIST is formed.

6.1 ARGUMENT SUMMARY

Elaborating earlier work of Ford [1978 and 1991] on QIs, Ford and Roman [1995] calculate the integrated energy density for a massless, scalar field along a time-like geodesic according to quantum field theory (QFT) multiplied by a suitable (Lorentzian) "sampling function": $\tau_o/[\pi(\tau^2 + \tau_o^2)]$. This function, by itself, integrates to one along the geodesic, but is peaked at $\tau = 0$ with a characteristic width τ_o. As in Ford's earlier work, all calculations are done in flat spacetime. In QFT the energy density along the geodesic is the expectation value of the stress-energy tensor, so Ford and Roman calculate the quantity:

$$(\tau_o/\pi)\int_{-\infty}^{\infty}[\langle T_{\mu\nu}v^{\mu}v^{\nu}\rangle/(\tau^2 + \tau_o^2)]d\tau \geq -3/32\pi^2\tau_o^4, \tag{6.3}$$

finding the inequality here stated. (I replicate their use of "natural" units [c = h = 1].) When one lets the sampling interval $\tau_o \rightarrow \infty$, they note that the AWEC is recovered.

More important from the point of view of chronology protection, however, is the fact that the integrated energy density [Eq. (6.3)] can only become very large and negative for very short intervals. And when such an interval occurs, it must be followed by a comparable interval of positive energy density *shortly thereafter*. An explicit calculation illustrating this point is given by Ford [1991, esp. p. 3974] in the context of an integrated energy flux calculation that yields a similar result to Eq. (6.3). [Since an energy flux is just an energy density times a velocity, this similarity is expected.] Taking two delta function energy pulses of magnitude $|\Delta E|$, one negative and the other positive, Ford finds that:

$$|\Delta E| \leq 3/16\pi T, \tag{6.4}$$

where T is the time elapsed between the pulses. So it would seem – and this is Ford and Roman's argument in [1995] – that any time one tries to assemble a large concentration of negative mass-energy to make a TWIST (or build a "warp drive"), that exotic energy will almost immediately be nullified by a positive energy that must follow it in a time $1/|\Delta E|$. Try to make a TWIST and it will self-destruct – albeit by unspecified means.

In their more recent paper Ford and Roman [1996] did not discuss the detailed assumptions and calculations that lead to Eq. (6.3). They were preoccupied with showing that their QI [Eq. (6.3)], obtained in flat spacetime, is applicable as a reasonable approximation in curved spacetime. And instead of constructing their argument in terms of pulses of negative and positive mass-energy and their temporal separation, they develop length scales in terms of Morris and Thorne's redshift and shape functions (and their derivatives) to which Eq. (6.3) is applied in the context of various wormhole models. They then show that serious length scale discrepancies arise for almost all wormhole models. Their arguments leave the impression that QFT prohibits TWISTs (see for example, Matloff [1996], esp. p. 13).

6.2 QUANTUM FIELD THEORY AND CHRONOLOGY PROTECTION

I must own to an uneasy feeling about Ford and Roman's chronology protection argument. My concerns have nothing to do with trying to bootstrap a flat spacetime quantum calculation into curved spacetime. Neither do they arise from the fact that QFT has some pretty serious problems of its own (*e.g.*, the cosmological constant problem). They are much more pedestrian than these issues. One is a straight-forward issue of logic.

Eq. (6.3), the correctness of which is crucial to all of Ford and Roman's arguments, is motivated by, and justified in terms of, the validity of the second law of thermodynamics and the AWEC. But both the second law and AWEC, as universally valid propositions, are manifestly false if TWISTs of arbitrarily long duration can be made in fact. For example, low entropy material could be transported to the future to produce second law violations. One might counter that these propositions, within our experience at least, are observed to be true. The problem here, of course, is the "within our experience". Let us assume, for the sake of argument, that they are false, that TWISTs can and have been made. Should we expect to see evidence of the violations of these principles that might follow from the existence of TWISTs? Well, if TWISTs were common "natural" phenomena, the answer to this question is arguably yes. Since we do not see such widespread evidence, it is reasonable to infer that "natural" TWISTs are rare, if not prohibited. And the AWEC and second law, though they may not be absolutely, universally true, seem to be very good approximations to the truth for "natural" processes.

What if TWISTs can be made, but only "artificially" – that is, with a lot of careful engineering and a non-negligible investment of resources? Would we see evidence of them all over? Not unless the clever critters that created them wanted us to. For example, it seems unlikely, at best, that even inscrutable alien or evil future folk would make TWITs to prodigiously pollute their past with high entropy crud. After all, that crud would just evolve, gaining yet more entropy, into their present in the future making matters worse for them, not better. Our cosmic contemporaries and predecessors (if any) might be engaged in projects of the sort described by Sagan [1985, pp. 363-366]. But it is far from obvious that we would recognize them for what they are. So, while violations are manifestly possible, they need not necessarily either occur, or be recognizable.

A somewhat less romantic criticism of Ford and Roman's arguments is triggered by the way they use Eq. (6.3) in their [1995] paper. The large positive and negative spikes of mass energy separated by a very short time interval along a time-like geodesic in their argument sounds suspiciously like a fluctuational process. This suspicion is reinforced by relabeling T as Δt and abandoning the natural units of Eq. (6.4). Now we have:

$$|\Delta E|\,\Delta t \leq (3/16\pi)\text{h}, \tag{6.5}$$

which, up to factors of order of unity, is just the Heisenberg energy-time Uncertainty relationship (expressed as a limit on energy fluctuations). Ford and Roman [1995, p. 4278] are emphatic in remarking that, "It is important to note that *the energy-time uncertainty principle was not used to derive any of these* [2 and 4 dimensional] *QI restrictions*. They arise directly from quantum field theory." Why? Well, perhaps because if their QI [Eq. (6.3)] is taken to be an energy fluctuation constraint, then it cannot be used to exclude *artificial* concentrations of exotic matter. Note, again, that their argument does not include an explanation of *how* the production of a negative energy pulse forces the production of a compensating positive energy pulse that putatively follows it almost immediately. It merely shows that this must occur if the second law of thermodynamics is not to be violated.[9] As a constraint on a fluctuational process, such an assertion is quite plausible. As a constraint on artificial TWISTs, it is not, for the absolute, universal validity of the second law of thermodynamics is not established (or, for that matter, even establishable in principle).

It seems to me that careful *physical* consideration of the contents of Eq. (6.3) is warranted before we accept it on the terms it is proffered by Ford and Roman. Does it proceed directly from QFT without appeal to the uncertainty principle and fluctuational processes? Strict, formal QFT, in fact, only enters Eq. (6.3) through the computation of $\langle T_{\mu\nu}v^{\mu}v^{\nu}\rangle$. This is done by Ford and Roman in [1995] in a direct manner: $T_{\mu\nu}v^{\mu}v^{\nu}$ is expressed in terms of its corresponding field via an appropriate field equation; the field is quantized and expanded in creation and annihilation operators in the usual way. To complete the calculation of the RHS of Eq. (6.3), negative energy modes of the field are then selected out to get a lower energy density bound [Ford, 1991, p. 3974] and the indicated operations carried through. Fluctuational contributions to $\langle T_{\mu\nu}v^{\mu}v^{\nu}\rangle$ are explicitly ignored.

QFT is a local, microphysical theory. As such, it does not speak directly to macrophysical phenomena. While $\langle T_{\mu\nu}v^{\mu}v^{\nu}\rangle$ arises directly from QFT, the LHS of Eq. (6.3) is not an ineluctable consequence of that theory. In particular, the "sampling function" used by Ford and Roman is not a necessary consequence of QFT. What QFT does say is that when $\langle T_{\mu\nu}v^{\mu}v^{\nu}\rangle$ is calculated for the negative energy modes of the field, point by point in spacetime,[10] an invariant number for all points is obtained which is the lower bound of allowable proper field energy density. That number, however, is not, in general, given by the RHS of Eq. (6.3). For example, if τ_o in the sampling function is $\ll 1$, then at the spacetime point $\tau \approx 0$ the proper low energy density bound allowed by the integrand of Eq. (6.3) may be *many orders of magnitude* less than the proper low energy density bound $-\langle T_{\mu\nu}v^{\mu}v^{\nu}\rangle$ for negative energy modes – set by QFT. This means that the sampling function is not just selecting out some restricted region of spacetime for consideration; it is introducing physics that is independent of QFT by changing – perhaps quite radically – the proper low energy density bound for some points along the geodesic.

The well-known feature of quantum fluctuational processes is that they violate energy conservation constraints. The allowable violation is itself constrained by the energy-time uncertainty relation. Since the physical role of the sampling function in Eq. (6.3) is to *transiently*, radically alter the proper low energy density bound recovered with QFT, we see that it is in effect introducing a fluctuational process: If we consider sufficiently short times, the actual proper low energy density bound can be *far* lower than the invariant proper low energy density bound of QFT. But it must be followed almost immediately by a compensating positive energy fluctuation. None of this happens if we choose a sampling function that singles out some part of the geodesic without biasing $<T_{\mu\nu}v^{\mu}v^{\nu}>$ at the same time. For example, if we choose a function that is zero everywhere along the geodesic except in some restricted interval where it has the value one, we do not get Eq. (6.3). So, even though fluctuations were left out of the calculation of $<T_{\mu\nu}v^{\mu}v^{\nu}>$, they have been smuggled back into the result via the sampling function.

The upshot of all this is that Ford and Roman's QI relationship cannot be used in chronology protection arguments involving artificial concentrations of exotic matter. What Ford and Roman's arguments do show is that spontaneously formed TWISTs should not occur naturally since we observe the AWEC and second law of thermodynamics to have widespread, if perhaps not universal, validity. (The fact that they recover Eqs. (6.4) and (6.5) assures one that their unorthodox method of introducing fluctuations via the sampling function nonetheless leads to a defensible result.) It may be that QFT does prohibit TWISTs. But that is not yet demonstrated. Happily, these issues seem to be accessible via experiment.

8. CONCLUSION

How seriously should you take the methods of wormhole production sketched here? Well, there is no "new physics" in any of the foregoing other than possibly the proposition that inertial reaction forces are produced by a field interaction – that is, that Mach's principle obtains. The relativity of inertia (Mach's principle), however, is widely thought to be true. And experiments show that at least one of the transient source terms that appears in the field equation derived in section 3 exists in fact. There, I think, is the appropriate seriousness criterion: tangible, corroborable, physical evidence. And since such does not yet exist for REM *per se*, you may not want take all this too seriously. At least until convincing evidence for the production of REM is forthcoming.

It may be that TWISTs are physically prohibited.[11] Or it may be that some effect – catastrophic repulsive disruption mentioned above for example – renders the methods discussed here unworkable in practice. Nonetheless, I think it prudent to point out that, although it is unlikely that some nutty professor will be able to make a TWIST in his/her garage without flubbing the attempt, the means necessary to carry through an investigation of this business are relatively modest (orders of magnitude less than the cost of, say, a state-of-the-art particle accelerator). A real prospect exists, therefore, that someone may actually succeed in making a TWIST in the foreseeable future. Unless caution in such an undertaking is exercised – especially having an absolutely foolproof method for closing any TWIST made promptly – serious consequences might ensue. Given the nature of our Universe, the overwhelming probability is that the other mouth of a randomly generated TWIST would be formed in outer space. As a friend remarked when I mentioned this to him, this gives an entirely new meaning to Ross Perot's "sucking sound" remark about NAFTA.[12] Actions of breathtaking stupidity might be possible it would seem.

Can we make a wormhole? I must admit that my sense of reasonableness is offended by TWISTs – especially TWITs. Gut intuition (abetted by a little voice that keeps repeating J.B.S. Haldane's famous remark about reality[13]), however, tells me that with sufficiently clever engineering TWISTs may indeed be feasible. The essential physics of Star Trek may lie within our grasp.[14] So, perhaps in making a TWIT, eventually we will unveil the edge of spacetime (and in the process coax nature into revealing physical evidence of her big TOE).[15] Surely, could we do that, that could be called a TWIST of fate.

ACKNOWLEDGEMENT:

Discussions with colleagues, especially K. Wanser and M. Shapiro, have been helpful. The experiments described in the Appendix were supported in part by several CSU Fullerton Foundation grants.

APPENDIX

The transient source terms in Eq. (3.12) may be employable to produce TWISTs, as I show in sections 4 and 5. Since they have important practical and scientific consequences, we ask: Is any evidence available that shows these terms correspond to reality? The answer to this question is yes. I have done a series of experiments to see if effects that depend on their presence can be detected [Woodward, 1991 and 1996b]. I briefly recapitulate the methods and results of those experiments so that this paper is taken in cognizance of them.

We write the total matter density source ρ in Eq. (3.12):

$$\rho = \rho_o + (1/4\pi G)[(\phi/\rho_o c^2)(\partial^2\rho_o/\partial t^2) - (\phi/\rho_o c^2)^2(\partial\rho_o/\partial t)^2 - c^{-4}(\partial\phi/\partial t)^2]. \qquad \text{(A.1)}$$

It is the fact that the $(\partial^2\rho_o/\partial t^2)$ term can be either positive or negative and the $(\partial\rho_o/\partial t)^2$ term is always negative that is of interest for making wormholes. But for cheap laboratory scale experiments only one of the transient terms -- the largest in normal circumstances -- matters. As long as the transient density fluctuation is small compared to the static density, it is the $(\partial^2\rho_o/\partial t^2)$ term. Writing it separately:

$$\delta\rho_o(t) \approx (\phi/4\pi G\rho_o c^4)(\partial^2 E_o/\partial t^2), \qquad \text{(A.2)}$$

where $\rho_o = E_o/c^2$ has been used to express the proper mass density as a proper energy density. The total transient mass fluctuation δm_o induced in some volume V then is:

$$\delta m_0 = \int_V \delta\rho_0 dV \approx (\phi / 4\pi G\rho_0 c^4) \int_V (\partial E_0 / \partial t^2) dV . \qquad \text{(A.3)}$$

The experiments sketched below use a capacitor to which an alternating voltage is applied to produce the predicted transient mass fluctuation. In this case, since $\partial E_o/\partial t$ 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. (A.3) is $\partial P/\partial t$. Thus, for the capacitor,

$$\delta m_o(t) \approx (\phi/4\pi G\rho_o c^4)(\partial P/\partial t). \qquad \text{(A.4)}$$

The quantities measured permit the computation of ϕ/c^2 which is defined as β. As we saw in section 3, $\phi \approx c^2$, so we expect that $\beta \approx 1$. On a bit closer inspection [Woodward, 1996a], we find that in neo-Newtonian gravity $\beta = 1$, whereas in General Relativity Theory (GRT) $\beta = 4$. When a sinusoidal voltage of angular frequency ω is applied to the capacitors, we may write $P = P_o\sin(2\omega t)$ and Eq. (A.4) becomes:

$$\delta m_o(t) \approx (\beta\omega P_o/2\pi G\rho_o c^2)\cos(2\omega t). \qquad \text{(A.5)}$$

Substitution of realistic, laboratory scale values [*e.g.*, $P_o \approx 100$ Watts and $\omega \approx 2\pi$ X (100 to 10,000 Hz.)] yields mass transient amplitudes on the order of tenths to tens of milligrams. The coefficient of the cosine in Eq. (A.5) is the amplitude of the mass transient, δm_o, and β thus is:

$$\beta \approx 2\pi G\rho_o c^2\delta m_o/\omega P_o. \qquad \text{(A.6)}$$

The experimental apparatus I have used to make determinations of β under a variety of circumstances is shown in general, schematic form in Fig. 2. The capacitor (C) in which the mass fluctuation is induced [actually arrays of capacitors] is mounted on a pedestal (P) in a metal enclosure (E). The enclosure is mounted via a shaft on a stainless steel diaphragm (D), a spring that supports the enclosure and its contents. An exceedingly sensitive vertical position sensor (S) detects the location of the shaft. It enables one to measure the weight, and thus the mass, of the suspended apparatus. If a stiff diaphragm is used, the mechanical resonance frequency of the device turns out to be about 100 Hz. Tuning the power frequency (2ω) to this frequency enables one to directly detect the induced transient mass fluctuation. Although the effect is small, resonance amplification of the fluctuation makes it detectable.

From Eq. (A.5) it is evident that, for a given applied power, the magnitude of the induced mass fluctuation increases with increasing frequency. For higher operating frequencies [a kilohertz or more], however, a different approach must be employed because the diaphragm cannot be made sufficiently stiff to raise the frequency of mechanical resonance enough. This problem can be finessed by using a piezoelectric crystal as the pedestal in the enclosure. If a vertical oscillation is then separately driven in the pedestal at the power frequency and it is phase-locked to the mass fluctuation in the capacitor, then the stationary weight of the device can be altered [Woodward, 1996b]. For example, if the mass of the capacitor is lowered as the pedestal expands (and increased as the pedestal contracts), then the time averaged force on the diaphragm will be reduced compared to the phase reversed situation. Note that in these experiments it is a transient fluctuation in the passive gravitational mass (acted on by the Earth's gravitational field) that is detected while formally it is the active gravitational mass that fluctuates. Thus the applicability of the Equivalence Principle to this transient effect, as well as its existence, is tested.

Although this is a cheap, table-top type of experiment, great care must be taken in its execution. It is always easy to screw up even the simplest of experiments. One must be constantly on one's guard against subtle, ordinary effects that might masquerade as the effect sought. Protocols and procedures must be found that will suppress spurious signals. Nature does *always* act in concert with the hidden flaw. I will not belabor here my efforts in this direction. Suffice it to say, that when everything was running cleanly, for different capacitors at operating frequencies spanning the range 0.05 to 11 kHz, a β of order of unity was in every case recovered. (Technical details, error analysis, and the like for these experiments can be found laid out at length in Woodward 1991 and 1996b.) While it is always possible, I suppose, that I have loused up these experiments, I am quite sure that I have not done so. Allowing that the experiments are not seriously flawed, it would seem that at least the $(\partial^2\rho_o/\partial t^2)$ term in Eq. (A.1) is real.

NOTES

1. Matloff remarks that NASA is doing this in response to public pressure. Widespread, uncritical enthusiasm in the general public for wormholes is purportedly the source of the pressure. If you believe that, I have this bridge . . .

2. Those who think all of this wormhole stuff to be a lot of nonsense will doubtless feel that the signifier "postmodern" would be a better descriptor here.

3. In Morris and Thorne's analysis they are taken to be arbitrary functions of the radial coordinate r only, as they restrict their attention to stationary wormholes. Discussion of dynamic wormholes forces the relaxation of this constraint. (See, for example, Visser [1995], ch. 15.)

4. If the active part of the circuit element in which this effect is driven is less than several cm^3, then an off-the-shelf commercial power source – an inductive counter-top stove power supply – can be used to actually do such an experiment. (Those who were into high-tech iron pot cookery 20 or 30 years ago may remember these devices.)

5. The ADM solution is obtained in isotropic coordinates which, for distant observers, preserve the appearance of flatness despite the presence of strong curvature.

6. There is one fact that should at least give one pause here. It is that if $\phi_u + \phi_b = 1$ (as one might expect when the charged dust lies very near its gravitational radius), then $m \approx (e^2/G)^{1/2}/2c^2$ *in magnitude*. The numerical value of the RHS of this expression is the mass of the electron to within ten percent. Unlike when fooling around with *G, h,* and *c*, you do not get the Planck mass, which differs from the observed electron mass by a dimensionless factor of 10^{-22} that is without any explanation. (See, in this connection, the remarks of J. Ostriker in Lightman and Brawler [1990], p. 278. The Planck mass differs from the ADM mass by a factor of the square root of the fine structure constant.) That $(e^2/G)^{1/2}$ differs from m by a dimensionless factor of $2c^2$ I regard as quite

remarkable. That it can be accounted for with the ADM model suggests, I think, that the ADM model may capture a significant part of the essence of the structure of electrons. (Lest I stand accused of first degree numerology here, I point out that explaining a dimensionless factor of 10^{-22} difference in the Planck and electron masses is now replaced with the problem of accounting for $\phi_u + \phi_b = 1$ to within 10%.) So Eq. (5.12) may well give the gravitationally decoupled mass of elementary particles fairly closely.

7. An engineer and a physicist were asked to design an automatic chicken plucker . . .

8. Tables 1 and 2 were generated using the numerical integration protocol outlined above with a 0.001 rad. step size. Only the first cycle and cycles for successive orders of magnitude of ωt are shown. The evolution between the displayed cycle data is in all cases smooth. I should mention that the same behavior with inverted signs is obtained if one starts with a small positive ρ_o immediately after $\omega t = 0$.

9. This is Ford and Roman's explicit justification. As they remark [1995, p. 4278], "These inequalities are of the form required to prevent large scale violations of the second law of thermodynamics."

10. This calculation, in Ford and Roman [1995], is done ignoring cosmic evolutionary effects and, for convenience, with the observer assumed in the instantaneous frame of rest at each point along the geodesic.

11. The argument that were TWITs truly feasible, we would be inundated by temporal tourists – who are apparently absent – is not a good one. With "deinstitutionalization" of the mentally ill, fashionable in our "modern" times, temporal tourists in vast numbers could go completely undetected by an indigenous population unwilling to accept their existence – even if they declared themselves.

12. Actually, since the likelihood that the barometric pressure would be exactly equal at the two mouths of a generic TWIST is exceedingly small, either a sucking or blowing sound is a probable audible signature of a TWIST.

13. Namely, "Now my suspicion is that the universe is not only queerer than we suppose, but queerer than we can suppose."

14. As M. Kaku [1996] notes in his recent review of Lawrence M. Krauss' [1995] book on the subject, if you can make TWISTs, "transporter" technology is irrelevant. I should also mention that even should it prove impossible to assemble enough exotic matter with the hideously large densities required to make TWISTs, assembly of modest amounts of REM evidently is not prohibited. These can be used to null the inertia of objects, making rapid (but slightly sub-light speed) interstellar travel possible. Intrepid spacefarers traveling large distances, however, would have to abandon hope of seeing their immediate relatives again.

15. And for a lot less money than it would cost to make a particle accelerator with a circumference of 1,000 light years.

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FIGURE CAPTIONS:

Fig. 1. A schematic diagram of a dumbbell TWIST. The L and C components are inductive and capacitive elements of a resonant electrical circuit. Although drawn large here for clarity, the L and C elements should be small in comparison with their distance of separation. The resonance frequency and separation distance are chosen so that the retarded gravitational field of either circuit element just arrives at the other element so their fluctuating masses, as seen by each other, are synchronized.

Fig. 2. A schematic diagram of the generic components used in the experiments done to test for the existence of the effect predicted by the assumption of local Lorentz-invariance and the relativity of inertia (see section 3). An array of capacitors C is mounted on a pedestal P in a suitable enclosure E. This assembly is supported by a shaft attached to a stainless steel diaphragm D. The weight of the assembly (and thus its mass) is detected by a very sensitive position sensor S.

TABLE 1

Density as a Function of Initial Density and ωt

ωt (rad.)	*Initial Density* (gm/cm^3)				
	- 0.001	-0.01	-0.1	-1.0	-10
0.002	-200	-20	-2.1	-1.2	-10
3.142	-663.4	-632.9	-632.6	-632.6	-632.7
6.284	-200.4	-26.3	-17.6	-17.5	-20.0
59.69	-664.5	-634.8	-634.6	-634.6	-634.6
62.83	-204.2	-56.2	-53.0	-53.0	-53.8
625.2	-675.2	-650.3	-650.1	-650.1	-650.2
628.3	-236.5	-151.8	-150.9	-150.9	-151.1
6280	-748.6	-735.7	-735.7	-735.7	-735.7
6283	-400.5	-375.9	-375.8	-375.8	-375.8

TABLE 2

Density as a Function of k_1 and ωt

ωt (rad.)		k_1	
	25	50	100
3.142	-316.3	-447.3	-632.6
6.284	-8.8	-12.4	-17.6
59.61	-317.3	-448.7	-634.6
62.83	-26.5	-37.5	-53.0
625.2	-325.1	-459.7	-650.1
628.3	-75.4	-106.7	-150.9
6280	-367.8	-520.2	-735.7
6283	-187.9	-265.7	-375.8