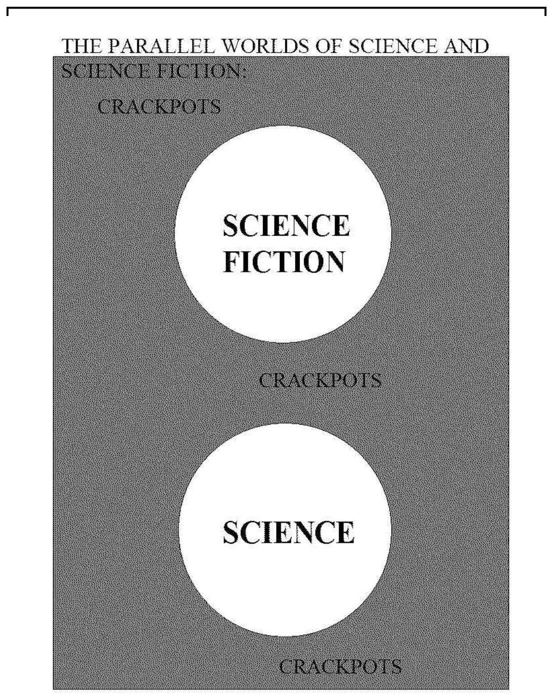
WHY SCIENCE FICTION HAS LITTLE TO FEAR FROM SCIENCE

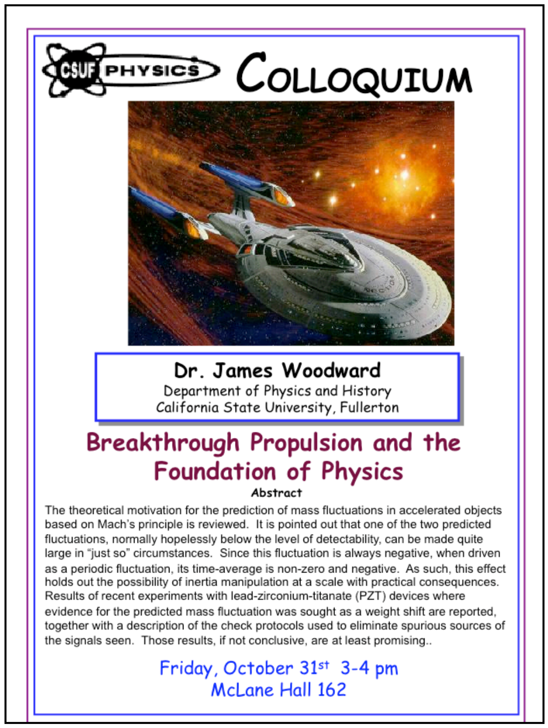
A talk by J.F. Woodward given at the symposium for John Cramer's 75^{th} birthday at the University of Washington on 10 September 2009. (His birthday is actually on 24 October.)



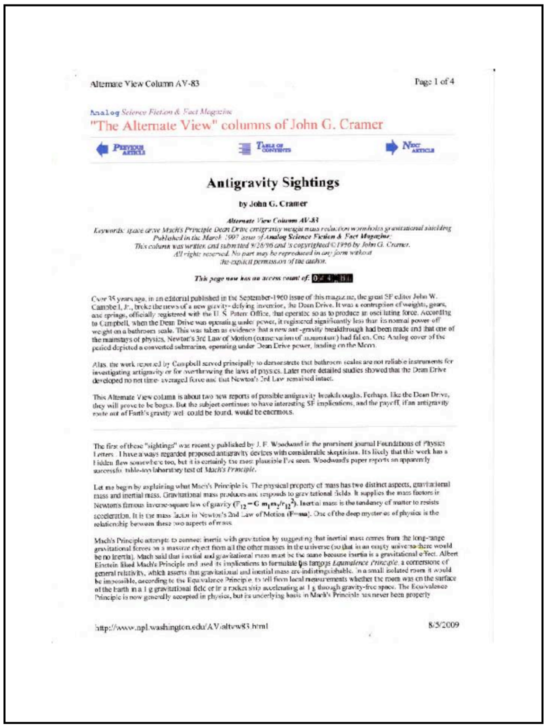
In a presentation following this one, Geoff Landis talks about the "parallel" worlds of science and science fiction. He is surely correct in identifying these "worlds" as ones populated by respectable practitioners and their acolytes. Generally speaking, to be a member of the scientific community requires particular expertise and acceptable behavior – more or less along the lines spelled out by Thomas Kuhn in his description of "normal" science in his *The Structure of Scientific Revolutions*. As a literary community, the "world" of science fiction is governed by a different set of tacit rules, and is not required to hew to the rules governing the creation of scientific knowledge. In particular, it is acceptable to speculate on plot devices involving "science" that does not yet exist, and perhaps, even likely may never exist – for example, time travel to the past.

In addition to these two "parallel worlds" there is a grey area in between and around them. For the most part, it is populated by crackpots. But it also is at least visited by those who consider themselves serious scientists who seek to try to realize as serious science things commonly regarded as science fiction (at best). They do this at serious risk to their credibility and reputations as competent scientists, for usually work on subjects that fall in the grey area is not regarded by those in the community of professional scientists as legitimate subjects for investigation. In an earlier talk, John Clauser related this sort of reaction to his early investigations of the foundations of quantum mechanics.

This talk will be about a grey area investigation that suggests that as long as the "standard model" of relativistic quantum field theory prevails, the likelihood that "absurdly benign" wormholes will be made is essentially zero. Accordingly, taking rapid spacetime transport to be the centerpiece of science fiction, those in the world of science fiction have nothing to fear from scientists removing their central trope into the world of science.



I was invited, in the spring of 2002, to give a talk for the physics colloquium in the fall of that year at Cal State Fresno on the work that I was engaged in. As the agreed upon date approached, I contacted the colloquium coordinator for logistical information. He allow as how he thought I had flaked out on the commitment, but would reinstate my talk in the series. I sent him some description of what I was doing, and shortly thereafter, he sent the announcement shown here, along with directions on campus and so forth. Immediately on glancing at the announcement, it was clear to me that I was to give the science fiction talk for the series. The talk went off as planned – and no one objected when I identified it as the science fiction talk for the semester.



Alternate View Column AV-83 Page 1 of 4

Analog Science Fiction & Fact Magazine

"The Alternate View" columns of John G. Cramer

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Antigravity Sightings

by John G. Cramer

Alternate View Column AV-83

Keywords: space drive Mach's Principle Dean Drive antigravity weight mass reduction wormholes gravitational shielding

*Published in the March 1997 issue of **Analog Science Fiction & Fact Magazine**;*

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Over 35 years ago, in an editorial published in the September-1960 issue of this magazine, the great SF editor John W. Campbell, Jr., broke the news of a new gravity-defying invention, the Dean Drive. It was a contraption of weights, gears, and springs, officially registered with the U. S. Patent Office, that operated so as to produce an oscillating force. According to Campbell, when the Dean Drive was operating under power, it registered significantly less than its normal power-off weight on a bathroom scale. This was taken as evidence that a new anti-gravity breakthrough had been made and that one of the mainstays of physics, Newton's 3rd Law of Motion (conservation of momentum) had fallen. One Analog cover of the period depicted a converted submarine, operating under Dean Drive power, landing on the Moon.

Alas, the work reported by Campbell served principally to demonstrate that bathroom scales are not reliable instruments for investigating antigravity or for overthrowing the laws of physics. Later more detailed studies showed that the Dean Drive developed no net time-averaged force and that Newton's 3rd Law remained intact.

This Alternate View column is about two new reports of possible antigravity breakthroughs. Perhaps, like the Dean Drive, they will prove to be bogus. But the subject continues to have interesting SF implications, and the payoff, if an antigravity route out of Earth's gravity well could be found, would be enormous.

The first of these "sightings" was recently published by J. F. Woodward in the prominent journal Foundations of Physics Letters. I have always regarded proposed antigravity devices with considerable skepticism. It's likely that this work has a hidden flaw somewhere too, but it is certainly the most plausible I've seen. Woodward's paper reports an apparently successful table-top laboratory test of *Mach's Principle*.

Let me begin by explaining what Mach's Principle is. The physical property of mass has two distinct aspects, gravitational mass and inertial mass. Gravitational mass produces and responds to gravitational fields. It supplies the mass factors in Newton's famous inverse-square law of gravity ($F_{12}=G\ m_1m_2/r_{12}^2$). Inertial mass is the tendency of matter to resists acceleration. It is the mass factor in Newton's 2nd Law of Motion ($F=ma$). One of the deep mysteries of physics is the relationship between these two aspects of mass.

Mach's Principle attempts to connect inertia with gravitation by suggesting that inertial mass comes from the long-range gravitational forces on a massive object from all the other masses in the universe (so that in an empty universe there would be no inertia). Mach said that inertial and gravitational mass must be the same because inertia is a gravitational effect. Albert Einstein liked Mach's Principle and used its implications to formulate his famous *Equivalence Principle*, a cornerstone of general relativity, which asserts that gravitational and inertial mass are indistinguishable. In a small isolated room it would be impossible, according to the Equivalence Principle, to tell from local measurements whether the room was on the surface of the Earth in a 1 g gravitational field or in a rocket ship accelerating at 1 g through gravity-free space. The Equivalence Principle is now generally accepted in physics, but its underlying basis in Mach's Principle has never been properly

http://www.npl.washington.edu/AV/altvw83.html 8/5/2009

In the ’90s at least, the chief reason that anyone was aware of the work that I was engaged in was that John Cramer had written an “Alternate View” column in *Analog: Science Fiction and Science Fact* about it in 1996. So, such notoriety as I have enjoyed for some years now is largely due to his having taken note of my work, and thinking it worthy of writing about in his regular column. My work having come to his attention, however, was not by chance. A couple of years earlier, I had published a paper in Foundations of Physics Letters that came to his attention.

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

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Received September 21 1994; revised December 2, 1994

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*

That paper was titled Making the Universe Safe for Historians: Time Travel and the Laws of Physics" [a take-off on a joke by Stephen Hawking in his "chronology protection conjecture" paper of several years earlier claiming that time travel to the past was impossible]. A happy, unintended consequence of this title choice is that it has the acronym "MUSH".

The then Editor of FoPL [Alwyn van der Merwe, whom I know] had a policy of soliciting the names of a half-dozen potential referees from prospective authors, from whom he might select one or two. One might be tempted to supply the names of friends, or others one might hope to be sympathetic to one's article I suppose, but I was chiefly interested in getting the leading people in the world to read the paper I had written. John was one of the people on my potential referees list. You can probably guess two or three of the others. You would probably not guess Hans-Jurgen Treder, who was on the list. I asked the Editor to send the paper to all of the referees I had suggested, as well as anyone else he might think appropriate. He told me that he did so.

> Ignoring each other is something that physicists do all the time. Generally, to read someone else's paper is the exception, not the rule. There are far too many papers, even in a small field, to read all of them, and most physicists don't much like to read. They prefer to do their own research. Bondi, to give one example among many, told me he was notorious for not reading papers; he preferred to talk to people about their work. Infeld tells us that Einstein would never look something up in the literature, preferring always to work it out for himself:

The reason why I pursued the strategy mentioned in conjunction with the previous slide is captured nicely by Dan Kennefick in the opening to his chapter on "the skeptics" in his recent (excellent) book on the history of gravitational wave physics: *Traveling at the Speed of Thought* (Princeton, 2007, p. 180). I wanted what I had to say read – carefully and completely – by a certain group of folks. . . . and to get their honest reactions. I was not disappointed. And my friends were spared the burden of refereeing my paper for the journal.

WHAT IS THE CENTERPIECE OF SCIENCE FICTION?

- ARTIFICIAL INTELLIGENCE?
- BEAMED ENERGY WEAPONS?
- FORCE FIELDS?
- ALIEN ENCOUNTERS?
- GREY GOO?
- RAPID SPACETIME TRANSPORT.

There are many plot themes that are used in science fiction. Most of them – like those in the above list – are not so central to the genre that they cannot be ignored. It is, however, inconceivable that the genre could exist in its present form without the assumption of "rapid spacetime transport". And were rapid spacetime transport ever to be actually realized, the genre of science fiction would be radically transformed. So the question is: Is there even the remotest chance that rapid spacetime transport will ever actually be achieved?

Clips from War of the Worlds and Forebiden Planet were intended here, but not shown because of technical difficulties [Luddite operator].

For reasons of supporting evidence – and nostalgia – I intended to show clips of a couple of "classic" science fiction films from the '50s. In particular, two clips from the George Pal production of War of the Worlds. The first clip started right after the padre intoned "beings from another world" and concluded right after the professor from Pacific Tech made some vapid comments on magnetic levitation. The second started a few minutes later (with the heroine holding her ears to shut out the din of battle), as the Martians, protected by dome shaped force fields, opened up with their directed energy beam weapons and blasted the holy living b'jesus out of everything in sight. (It ended 40 seconds later, right after the vaporizing of a tank.) The clip from Forbidden Planet was from the beginning of the film where a narrator in voice-over a disk shaped craft plotzing along in deep space recounts the discovery of "hyperdrive" a couple of hundred years hence.

- A Chesley Bonestell picture of a rocket [a V-2 with wings] on the Moon goes here.

A Chesley Bonestell picture of a [wheeling toroidal] space station goes here.

DO WE KNOW HOW TO DO RAPID SPACETIME TRANSPORT?

- YES.

- CARL SAGAN AND KIP THORNE.

The story of how Carl Sagan wanted a scientifically credible plot device to get the protagonists in his novel Contact to the center of the galaxy and back in no time at all is well-known. He appealed to Kip Thorne, who told him black holes weren't viable. But traversable wormholes were. . . .

A picture of Kip Thorne in the early ‘90s goes here.

Kip Thorne (Feynman professor of theoretical physics at Cal Tech).

Wormholes in spacetime and their use for interstellar travel: A tool for teaching general relativity

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(Received 16 March 1987; accepted for publication 17 July 1987)

Rapid interstellar travel by means of spacetime wormholes is described in a way that is useful for teaching elementary general relativity. The description touches base with Carl Sagan's novel *Contact*, which, unlike most science fiction novels, treats such travel in a manner that accords with the best 1986 knowledge of the laws of physics. Many objections are given against the use of black holes or Schwarzschild wormholes for rapid interstellar travel. A new class of solutions of the Einstein field equations is presented, which describe wormholes that, in principle, could be traversed by human beings. It is essential in these solutions that the wormhole possess a throat at which there is no horizon; and this property, together with the Einstein field equations, places an extreme constraint on the material that generates the wormhole's spacetime curvature: In the wormhole's throat that material must possess a radial tension τ_0 with the enormous magnitude $\tau_0 \sim$ (pressure at the center of the most massive of neutron stars) $\times (20\ \text{km})^2/$(circumference of throat)^2. Moreover, this tension must exceed the material's density of mass-energy, $\rho_0 c^2$. No known material has this $\tau_0 > \rho_0 c^2$ property, and such material would violate all the "energy conditions" that underlie some deeply cherished theorems in general relativity. However, it is not possible today to rule out firmly the existence of such material; and quantum field theory gives tantalizing hints that such material might, in fact, be possible.

The abstract of the paper that started the modern era in investigations of rapid spacetime transport published in the May 1988 issue of the *American Journal of Physics* (vol. 56, pp. 395 – 412). Wormholes, if optimally engineered, would solve the rapid spacetime transport problem, making, as in the title of a recent book by John Gribbin, "hyperspace: our final frontier". Thorne and his then grad student Michael Morris presented this work as a pedagogical device for teaching general relativity. They fooled no one.

- A picture of an enterprise class starship under construction in the Tenneco ship yards goes here.

A victorian style picture of a starship inducing a wormhole (from S. Hawking's books) goes here.

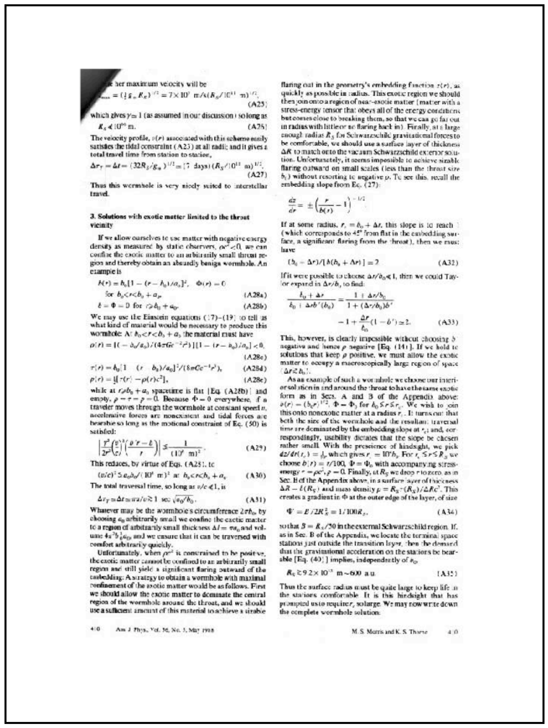
Artist's romantic rendition of a hypothetical starship in the act of inducing a wormhole. From Hawking's *The Universe in a Nutshell* (2002).

- A picture (of recent vintage) of an hypothetical starship with an embedding diagram of an Alcubierre warp bubble below goes here.

ANY OLD TYPE OF WORMHOLE?

ABSURDLY BENIGN WORMHOLES

As Morris and Thorne elaborated, many types and shapes of traversable wormholes are possible. If a wormhole is to be generated locally, however, without screwing up spacetime for everything around it, it has to be of a special type: absurdly benign. These wormholes, as Morris and Thorne pointed out in an appendix to their paper (keep in mind Dan Kennefick's remarks), have the special property that the spacetime in their vicinity, save for the throat itself, is sensibly flat. The problem is that they require large amounts of negative *restmass* for their construction.



…her maximum velocity will be

$$v_{max} = (\tfrac{1}{2} g_\oplus R_S)^{1/2} = 7\times 10^7 \text{ m/s} (R_S/10^{11} \text{ m})^{1/2}, \quad (A25)$$

which gives $\gamma \simeq 1$ (as assumed in our discussion) so long as

$$R_S \ll 10^{14} \text{ m}. \quad (A26)$$

The velocity profile, $v(r)$ associated with this scheme easily satisfies the tidal constraint (A23) at all radii; and it gives a total travel time from station to station,

$$\Delta\tau_T \approx \Delta t \approx (32R_S/g_\oplus)^{1/2} \approx (7 \text{ days})(R_S/10^{11} \text{ m})^{1/2}. \quad (A27)$$

Thus this wormhole is very nicely suited to interstellar travel.

3. Solutions with exotic matter limited to the throat vicinity

If we allow ourselves to use matter with negative energy density as measured by static observers, $\rho c^2 < 0$, we can confine the exotic matter to an arbitrarily small throat region and thereby obtain an absurdly benign wormhole. An example is

$$b(r) = b_0[1-(r-b_0)/a_0]^2, \quad \Phi(r) = 0 \quad \text{for } b_0 < r < b_0 + a_0, \quad (A28a)$$

$$b = \Phi = 0 \text{ for } r \geq b_0 + a_0. \quad (A28b)$$

We may use the Einstein equations (17)–(19) to tell us what kind of material would be necessary to produce this wormhole. At $b_0 < r < b_0 + a_0$ the material must have

$$\rho(r) = [(-b_0/a_0)/(4\pi G c^{-2} r^2)][1-(r-b_0)/a_0] < 0, \quad (A28c)$$

$$\tau(r) = b_0[1-(r-b_0)/a_0]^2/(8\pi G c^{-4} r^3), \quad (A28d)$$

$$p(r) = \tfrac{1}{2}[\tau(r) - \rho(r)c^2], \quad (A28e)$$

while at $r \geq b_0 + a_0$ spacetime is flat [Eq. (A28b)] and empty, $\rho = \tau = p = 0$. Because $\Phi = 0$ everywhere, if a traveler moves through the wormhole at constant speed v, accelerative forces are nonexistent and tidal forces are bearable so long as the motional constraint of Eq. (50) is satisfied:

$$\left|\frac{\gamma^2}{2r^2}\left(\frac{v}{c}\right)^2\left(\frac{b'r-b}{r}\right)\right| \lesssim \frac{1}{(10^8 \text{ m})^2}. \quad (A29)$$

This reduces, by virtue of Eqs. (A28), to

$$(v/c)^2 \lesssim a_0 b_0/(10^8 \text{ m})^2 \text{ at } b_0 < r < b_0 + a_0. \quad (A30)$$

The total traversal time, so long as $v/c \ll 1$, is

$$\Delta\tau_T \simeq \Delta t \simeq \pi a/v \gtrsim 1 \text{ sec } \sqrt{a_0/b_0}. \quad (A31)$$

Whatever may be the wormhole's circumference $2\pi b_0$, by choosing a_0 arbitrarily small we confine the exotic matter to a region of arbitrarily small thickness $\Delta l = \pi a_0$ and volume $4\pi^2 b_0^2 a_0$, and we ensure that it can be traversed with comfort arbitrarily quickly.

Unfortunately, when ρc^2 is constrained to be positive, the exotic matter cannot be confined to an arbitrarily small region and still yield a significant flaring outward of the embedding. A strategy to obtain a wormhole with maximal confinement of the exotic matter would be as follows. First we should allow the exotic matter to dominate the central region of the wormhole around the throat, and we should use a sufficient amount of this material to achieve a sizable flaring out in the geometry's embedding function $z(r)$, as quickly as possible in radius. This exotic region we should then join onto a region of near-exotic matter [matter with a stress-energy tensor that obeys all of the energy conditions but comes close to breaking them, so that we can go far out in radius with little or no flaring back in]. Finally, at a large enough radius R_S for Schwarzschild gravitational forces to be comfortable, we should use a surface layer of thickness ΔR to match onto the vacuum Schwarzschild exterior solution. Unfortunately, it seems impossible to achieve sizable flaring outward on small scales (less than the throat size b_0) without resorting to negative ρ. To see this, recall the embedding slope from Eq. (27):

$$\frac{dz}{dr} = \pm\left(\frac{r}{b(r)} - 1\right)^{-1/2}.$$

If at some radius, $r_c = b_0 + \Delta r$, this slope is to reach 1 (which corresponds to 45° from flat in the embedding surface, a significant flaring from the throat), then we must have

$$(b_0 + \Delta r)/[b(b_0 + \Delta r)] = 2. \quad (A32)$$

If it were possible to choose $\Delta r/b_0 \ll 1$, then we could Taylor expand in $\Delta r/b_0$ to find:

$$\frac{b_0 + \Delta r}{b_0 + \Delta r b'(b_0)} = \frac{1 + \Delta r/b_0}{1 + (\Delta r/b_0)b'} \simeq 1 + \frac{\Delta r}{b_0}(1 - b') \simeq 2. \quad (A33)$$

This, however, is clearly impossible without choosing b' negative and hence ρ negative [Eq. (14)]. If we hold to solutions that keep ρ positive, we must allow the exotic matter to occupy a macroscopically large region of space ($\Delta r \gtrsim b_0$).

As an example of such a wormhole we choose our interior solution in and around the throat to have the same exotic form as in Secs. A and B of the Appendix above: $b(r) = (b_0 r)^{1/2}$, $\Phi = \Phi_0$ for $b_0 \leq r \leq r_c$. We wish to join this onto nonexotic matter at a radius r_c. It turns out that both the size of the wormhole and the resultant traversal time are dominated by the embedding slope at r_c; and, correspondingly, usability dictates that the slope be chosen rather small. With the prescience of hindsight, we pick $dz/dr(r_c) = \frac{1}{10}$, which gives $r_c = 10^4 b_0$. For $r_c \leq r \leq R_S$ we choose $b(r) = r/100$, $\Phi = \Phi_0$ with accompanying stress-energy $\tau = \rho c^2$, $p = 0$. Finally, at R_S we drop τ to zero, as in Sec. B of the Appendix above, in a surface layer of thickness $\Delta R = l(R_S)$ and mass density $\mu = R_S \tau(R_S)/\Delta R c^2$. This creates a gradient in Φ at the outer edge of the layer, of size

$$\Phi' = B/2R_S^2 = 1/100 R_S, \quad (A34)$$

so that $B = R_S/50$ in the external Schwarzschild region. If, as in Sec. B of the Appendix, we locate the terminal space stations just outside the transition layer, then the demand that the gravitational acceleration on the stations be bearable [Eq. (40)] implies, independently of b_0,

$$R_S \gtrsim 9.2 \times 10^{13} \text{ m} \sim 600 \text{ a.u.} \quad (A35)$$

Thus the surface radius must be quite large to keep life in the stations comfortable. It is this hindsight that has prompted us to require r_c so large. We may now write down the complete wormhole solution.

410 Am. J. Phys., Vol. 56, No. 5, May 1988

M. S. Morris and K. S. Thorne 410

The relevant page in the Appendix.

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The relevant language on the relevant page.

- A picture of an absurdly benign short throat wormhole (from a Scientific American article on time travel of several years ago) goes here.

WORMHOLES ENABLE TIME TRAVEL

- TIME TRAVEL IS SILLY
- WERE IT TRUE, THE PAST AND FUTURE WOULD ACTUALLY BE “OUT THERE”
- IN 1992, HAWKING PROPOSED HIS “CHRONOLOGY PROTECTION CONJECTURE”

A picture of Stephen Hawking from the mid '90s goes here.

Hawking.


THE SUNDAY TIMES

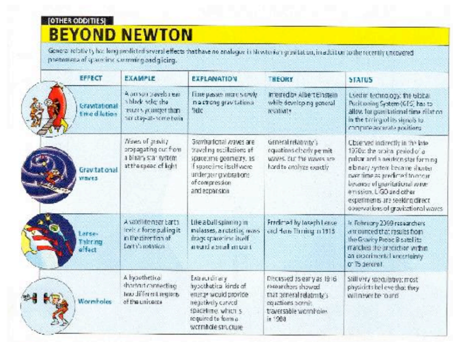
FRAMED!

How Diana fell for another dark handsome man

JEKYLL and HYDE

Hawking: we'll be able to travel back in time

Hawking changed his mind about time travel in 1995. He intimated his changed opinion to several grad students who promptly reported this development to the press. He did not become an enthusiast, indeed, he remained a skeptic. But he abandoned his "chronology protection conjecture" and still refuses to take bets on the possibility of time travel to the past. [This was faxed to me by the Editor of FoPL shortly after it was published.]



[OTHER ODDITIES]

BEYOND NEWTON

General relativity has long predicted several effects that have no analogue in Newtonian gravitation, in addition to the recently uncovered phenomena of spacetime swimming and gliding.

EFFECT	EXAMPLE	EXPLANATION	THEORY	STATUS
Gravitational time dilation	A person travels near a black hole; she returns younger than her stay-at-home twin	Time passes more slowly in a strong gravitational field	Inferred by Albert Einstein while developing general relativity	Used in technology: the Global Positioning System (GPS) has to allow for gravitational time dilation in the timing of its signals to compute accurate positions
Gravitational waves	Waves of gravity propagating out from a binary star system at the speed of light	Gravitational waves are traveling oscillations of spacetime geometry, as if spacetime itself were undergoing vibrations of compression and expansion	General relativity's equations clearly permit waves, but the waves are hard to analyze exactly	Observed indirectly in the late 1970s: the orbital period of a pulsar and a neutron star forming a binary system became shorter over time as predicted to occur because of gravitational wave emission. LIGO and other experiments are seeking direct observations of gravitational waves
Lense-Thirring effect	A satellite near Earth feels a force pulling it in the direction of Earth's rotation	Like a ball spinning in molasses, a rotating mass drags spacetime itself around a small amount	Predicted by Joseph Lense and Hans Thirring in 1918	In February 2009 researchers announced that results from the Gravity Probe B satellite matched the prediction within an experimental uncertainty of 15 percent
Wormholes	A hypothetical shortcut connecting two different regions of the universe	Extraordinary hypothetical kinds of energy would provide negatively curved spacetime, which is required to form a wormhole structure	Discussed as early as 1916; researchers showed that general relativity's equations permit traversable wormholes in 1988	Still very speculative; most physicists believe that they will never be found

This chart accompanied a piece in a recent (2009) Scientific American on "swimming" through spacetime – made possible by the curvature of spacetime according to general relativity in the vicinity of local concentrations of mass. Note the lower right hand corner where wormholes are dismissed as impractical.

WHAT IS NEEDED TO MAKE AN ABSURDLY BENIGN WORMHOLE?

- A JUPITER MASS OF MATTER WITH NEGATIVE RESTMASS.
- RIGHT.

It is a straight-forward matter to compute the amount of “exotic” matter needed to stabilize an absurdly benign wormhole of traversable dimensions. It is a Jupiter mass. If that mass forms a thin shell in the throat of the wormhole, note that the density of the exotic matter has to be very much greater – decades of orders of magnitude greater – than the densities typical of normal matter. This fact is often glossed by aficionados in their discussions of wormholes.

WHERE DO YOU GET
A JUPITER MASS OF
EXOTIC MATTER?

- BY "AMPLIFYING" A PLANCK-SCALE WORMHOLE?
- BY SCAVENGING IT OUT THERE IN (DEEP?) SPACE?
- BY FIGURING OUT HOW TO TRANSFORM NORMAL MATTER INTO EXOTIC MATTER?

Nowadays there is quite a bit of rank speculation in the public media about making wormholes and time machines. When the issue of creating the wormholes is addressed, the usual comments typically include speculations on microscopic wormholes that purportedly flit into and out of existence at the level of the conjectured "quantum spacetime foam" – a feature of spacetime supposed to exist at the scale of the Planck length, 10^-33 cm. The alleged process involved is "amplification" of a Planck-scale wormhole. Quite apart from whether such wormholes even exist in the first place, no one has even the slightest clue of how you would "amplify" such a thing. Science fiction has nothing to fear if this is how wormholes are to be made.

Some have suggested that exotic matter might be a naturally occurring substance, and when we master space travel, we may happen upon it in our travels. Perhaps, for example, in the asteroid belt. The problem is that the exotic matter is supposed to solve the space travel challenges that must be solved, it would seem, before we can tool around looking for exotic matter. . . . I should add that if exotic matter comes in planetary or larger objects, John and several colleagues in the mid-'90s suggested a way to look for it. Such objects should deflect background starlight with a distinctive signature.

This last suggestion, transforming normal matter into exotic matter, seems to be the only scheme that holds out any promise at all. . . .

USING ONLY "LOW" ENERGY ELECTROMAGNETIC FIELDS

The caveat to any scheme that purports to generate exotic matter for rapid spacetime transport is that however it is done, it has to be done with "low" energy electromagnetic fields. Why? Because that's all we have available with which to accomplish the task. So, not only must the density of the Jupiter mass of exotic matter be literally astronomical, it must be induced with piddling fields.

IN THE STANDARD MODEL, THE BARE MASSES OF ELEMENTARY PARTICLES ARE NEGATIVE AND INFINITE

•HOW DO YOU "UNDRESS" ELEMENTARY PARTICLES?

•IS THERE A "NON-STANDARD" MODEL THAT MIGHT HELP?

In the matter of transforming normal into exotic matter, it is worth noting that in the standard model of relativistic quantum field theory [actually, QED for electrons] the bare masses of elementary particles are negative and infinite. As Peter Milonni pointed out to me many years ago, they must be to counter the infinite positive energy of the cloud of virtual particles expected to "dress" bare particles. So, in principle, normal matter has resident in its bare particles an infinite amount of exotic matter.

The question is, if the exotic bare matter is really there, is there any way to "undress" matter to expose its exotic core? This presumably would involve finding a way to shut off the production of the virtual particles that dress the bare matter. At present, this seems an impossible task. So the generation of traversable wormholes seems impossible as long as the standard model of RQFT prevails.

YES, BUT IT REQUIRES UNDER-STANDING OF THE ORIGIN OF MASS.

THAT'S THE "HIGGS" MECHANISM, ISN'T IT?

NO, IT'S "MACH'S PRINCIPLE" (AS EINSTEIN CALLED IT).

It has been fashionable for some time now to assert that the Higgs process is the "origin of mass". As Frank Wilczek has pointed out in a recent book (*The Lightness of Being,* Basic Books, 2008), this is wrong. The Higgs process transforms zero restmass particles that propagate at the speed of light into fermions with finite restmass that propagate at speeds less than that of light. But, in the case of nucleons, the quarks (fermions) make up less than 5% of their mass, the remainder arising from the energies of the gluons (that propagate at light speed) that hold the quarks together. So, almost all of the masses of nucleons has nothing to do with the Higgs mechanism. They arise from the energies of the gluons via $m = E/c^2$ (which, as Wilczek notes, is the way Einstein first wrote down his famous equation). So, the question of the "origin of mass" is really the question: Why do elementary particles have energy?

The usual answer to this question is to say simply that they do. That is, energy is a primordial property of elementary particles or, perhaps, due to a local interaction, say, with the vacuum. But this view ignores the fact that local phenomena are coupled to the distant matter in the Universe. Ignoring local concentrations of matter, local inertial frames of reference do not rotate with respect to distant matter for example. This has been known at least since the late 19th century when Ernst Mach pointed it out. Some believe that this cannot be just an accident. Because there are equal amounts of positive and negative electrically charged matter in the Universe, electromagnetic coupling turns out to be unimportant. But that isn't true for gravity. So, if there is anything to the coupling to distant matter as the origin of mass, it must be that mass is due to the gravitational potential energy things possess, or, $E = m\Phi$, and if $\Phi = c^2$ clearly this will work. For $m = E/\Phi$ and $E = mc^2$, so we arive at m = m. But is $\Phi = c^2$?

MACH'S PRINCIPLE:

- THE INERTIAL PROPERTIES AND BEHAVIOR OF ALL OF THE STUFF IN THE UNIVERSE IS CAUSED BY THE GRAVITATIONAL ACTION OF ALL OF THE MATTER TO WHICH IT IS GRAVITATIONALLY COUPLED.

Although it is not widely appreciated, Mach's principle is in fact true in general relativity. This can be shown using the PPN formalism as developed by Nordtvedt (and others) and considering linear accelerational frame dragging. See the slides 43 and those there following. And, up to a geometrical factor of order unity, Φ is indeed $= c^2$, as required if gravitational potential energy is to be the origin of mass.

To change the properties of local matter, if this is true, we need only gravitationally decouple it from the bulk of the distant mass in the Universe.

Recent Developments in Quantum Gravity

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INTRODUCTION

I would like to divide this report into three parts. In the first, I would like to explain, in general terms, what the basic questions of quantum gravity are; in the second, I would like to point out the main difficulties that we face; and, in the third, I would like to discuss some recent results. The last part is a summary of the present status of a program that was first developed during a six-month workshop on quantum gravity, held at the Institute of Theoretical Physics at Santa Barbara in 1986. Since then, about two dozen individuals have made substantial contributions to this program. Unfortunately, because my space is somewhat limited, I will be able to discuss only a few of these contributions and I apologize in advance for the omissions. Also, because this is a "general interest" report rather than a technical presentation, discussion will be somewhat qualitative. I hope the experts will excuse me for repeating some of the well-known points and for glossing over references to the older material.

The central messages are the following:

(i) Nonperturbative quantum gravity (say, quantum general relativity) is feasible and may well be a viable theory.
(ii) It is very likely that the microstructure of space-time is radically different from the one suggested by perturbation theory. In particular, the space-time metric may not be a good variable to discuss this microstructure.
(iii) Because, a priori, there is no space-time in quantum gravity, quantum mechanical notions such as the Schrödinger equation and the resulting unitary evolution, which are normally regarded as fundamental, are now derived concepts that emerge when "time" is appropriately identified from among the basic mathematical variables used in the theory.

BASIC QUESTIONS OF QUANTUM GRAVITY

In broad terms, the aim of quantum gravity is to unify the principles underlying general relativity and quantum mechanics. General relativity has been successful in explaining the large-scale structure of the universe, whereas quantum mechanics seems indispensible in the microscopic domain. Quantum gravity would be a theory applicable in both domains; general relativity and quantum mechanics, as we know it, are to emerge as limiting cases of this deeper theory.

Because general relativity is not only a theory of gravity, but also of space-time structure, the task of constructing a quantum theory of gravity leads us to a number of

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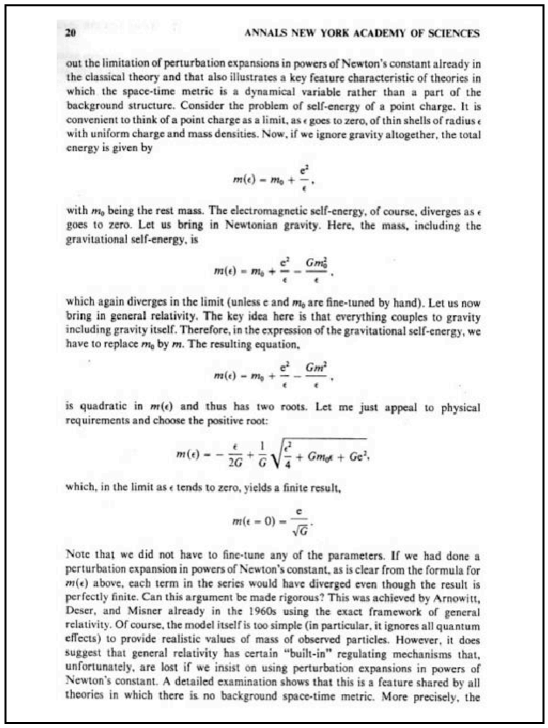
To see how gravitational coupling to distant matter – and its manipulation – affects the masses of elementary particles we need a model of elementary particles that includes gravity. This the standard model of RQFT does not have. But, as Abhay Ashtekar noted in an article on his ideas about quantum gravity some years ago, the electron model of Arnowitt, Deser, and Misner [ADM] does include non-linear gravity – indeed it is an exact solution of Einstein's field equations – and it doesn't require the procedures of renormalization to suppress divergences.



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out the limitation of perturbation expansions in powers of Newton's constant already in the classical theory and that also illustrates a key feature characteristic of theories in which the space-time metric is a dynamical variable rather than a part of the background structure. Consider the problem of self-energy of a point charge. It is convenient to think of a point charge as a limit, as ϵ goes to zero, of thin shells of radius ϵ with uniform charge and mass densities. Now, if we ignore gravity altogether, the total energy is given by

$$m(\epsilon) = m_0 + \frac{e^2}{\epsilon},$$

with m_0 being the rest mass. The electromagnetic self-energy, of course, diverges as ϵ goes to zero. Let us bring in Newtonian gravity. Here, the mass, including the gravitational self-energy, is

$$m(\epsilon) = m_0 + \frac{e^2}{\epsilon} - \frac{Gm_0^2}{\epsilon},$$

which again diverges in the limit (unless e and m_0 are fine-tuned by hand). Let us now bring in general relativity. The key idea here is that everything couples to gravity including gravity itself. Therefore, in the expression of the gravitational self-energy, we have to replace m_0 by m. The resulting equation,

$$m(\epsilon) = m_0 + \frac{e^2}{\epsilon} - \frac{Gm^2}{\epsilon},$$

is quadratic in $m(\epsilon)$ and thus has two roots. Let me just appeal to physical requirements and choose the positive root:

$$m(\epsilon) = -\frac{\epsilon}{2G} + \frac{1}{G}\sqrt{\frac{\epsilon^2}{4} + Gm_0\epsilon + Ge^2},$$

which, in the limit as ϵ tends to zero, yields a finite result,

$$m(\epsilon = 0) = \frac{e}{\sqrt{G}}.$$

Note that we did not have to fine-tune any of the parameters. If we had done a perturbation expansion in powers of Newton's constant, as is clear from the formula for $m(\epsilon)$ above, each term in the series would have diverged even though the result is perfectly finite. Can this argument be made rigorous? This was achieved by Arnowitt, Deser, and Misner already in the 1960s using the exact framework of general relativity. Of course, the model itself is too simple (in particular, it ignores all quantum effects) to provide realistic values of mass of observed particles. However, it does suggest that general relativity has certain "built-in" regulating mechanisms that, unfortunately, are lost if we insist on using perturbation expansions in powers of Newton's constant. A detailed examination shows that this is a feature shared by all theories in which there is no background space-time metric. More precisely, the

The page where Ashtekar discusses the ADM electron model. The "new Hamiltonian variables" approach he advocated has not produced the divergence free theory of quantum gravity that he hoped for yet. Nonetheless, the ADM model can be used to investigate the issues of interest here.

ASHTEKAR CHOSE THE POSITIVE ROOT BY IMPLICIT APPEAL TO THE POSITIVE ENERGY THEOREM

- BUT THE POSITIVE ENERGY THEOREM IS FALSE
- AND QUANTUM MECHANICS REQUIRES THAT THE BARE MASS OF PARTICLES BE NEGATIVE
- WHAT HAPPENS WHEN WE TAKE THESE THINGS INTO ACCOUNT?

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_0, 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

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

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_0, 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

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

The issue of inducing a Jupiter mass of exotic matter from a small quantity of normal matter using the ADM model for electrons was considered in an appendix to MUSH. That appendix and a small part of MUSH are reproduced here. Quite apart from the question of making traversable wormholes, Mach's principle makes it possible to understand why the ADM elementary particle mass differs from the measured electron mass by a factor of c^2 (to better than 10%). c, as pointed out by a participant at the symposium, has dimensions of velocity, so the fact that the ADM and electron masses differ by a factor of c^2 can only be regarded as a fluke accident unless a way can be found to account for the dimensions in question. Note that this issue is addressed in the appendix reproduced here.

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

$$m = -\left[\pm\sqrt{\frac{e^2}{G}}\right] - \frac{Rc^2}{G}. \qquad \text{(A7)}$$

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

$$m - \frac{Rc^2}{G} + \left[\pm\sqrt{\frac{e^2}{G}}\right]. \qquad \text{(A8)}$$

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_0 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

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

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

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

Note that the electron mass is recovered from Equation (A12) when the potentials in the denominator of the factor involving the speed of light in the denominator are essentially the same (because the dust has collapsed to its gravitational radius), making the expression for the difference of the potentials of order unity. When this is true, c^2 dominates the denominator and the electron mass is recovered – and since the potentials in the denominator cancel the dimension of the factor of c^2, no fudging of dimensions is required.

As an aside I note that in RQFT infinities are subtracted to yield small finite results. Here two factors of roughly c^2 are subtracted to yield a small finite result that causes Equation (A12) to return the electron mass. So differences of very large quantities are still required to account for very small quantities.

quantized charge; and e^2/c is consequently a quantized action just like η.] 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.

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_0 of the exotic matter that forms the wormhole to be a tenth of [the] throat radius b_0 we find

$$b_c \approx \sqrt{\frac{5c^2}{4\pi G\rho_c}}. \tag{6.6}$$

Total bare mass exposure results from ϕ_e in Eq. (6.4) going from c^2 to zero while ϕ_s 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

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

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.

The notes for this slide are printed on **two** slides. This is the first.

The ADM model of elementary particles leads to a Jupiter mass of negative restmass matter, provided a way can be found to screen that matter from the gravitational action of the chiefly distant matter in the Universe. One might reasonably ask, if that can be done, what will be the physical conditions in the wormhole throat encountered by a traveler? This turns out to be related to a different set of questions – since the masses things are equal to their gravitational potential energies divided by c^2 according to Mach's principle, shouldn't the masses of things change as the Universe expands? And shouldn't the masses of things depend on the presence of other nearby masses? These questions are fundamental and important.

The answers to these questions turn upon the fact that the speed of light is NOT, in general, a constant (as widely believed). It is a *locally measured invariant*, and that is NOT the same thing as a constant. All observers making local measurements of a locally measured invariant get the same number. But non-local observers may get different numbers. [One of the few places I have found that addresses this distinction in print is in Taylor and Wheeler's *Spacetime Physics*, Freeman, 1992, pp. 208 - 209.] In special relativity the speed of light can be treated as a constant, for it is unaffected by the presence (or absence) of other fields, and all inertial observers measure the same value everywhere and everywhen. But in general relativity, for example, the allegedly constant speed of light measured by a local observer at the horizon of a black hole gets 3 X 10^10 cm/s. A distant observer, however, gets zero for *c*. The speed of light depends on whether a gravitational field is present – and it depends on where the observer is located relative to the location of the measurement. This is a straight-forward, well-known consequence of general relativity theory.

Another well-known feature of general relativity theory is that the "Einstein Equivalence Principle" [EEP] must be valid. The best-known consequence of the EEP, other than the assertion of the equivalence of gravity fields and accelerations, is that it prohibits the localization of energy of the static (or stationary) gravitational field. [There is a small community of Einstein critics who are convinced that this is wrong. In the 1920s Levi-Civita was among their numbers. They are determined to believe that there is an objective Newtonian-like gravity field that possesses energy that can be localized.] Einstein rejected Levi-Civita's claim, realizing that its acceptance would destroy the relativistic invariance of his theory. Actually, accepting the claim would destroy more than that. It would destroy all of relativistic mechanics, and indeed, Newton's laws of motion. Why?

Well, the non-localizability of stationary gravitational field energy asserted by the EEP amounts to the claim that the total gravitational field potential at any point is a *locally measured invariant*, just like the speed of light. Why is this important? Because when account is taken of the fact that inertial reaction forces are gravitational in origin [see the demonstration at slide 43 ff], and the potential must, up to a factor of order unity, be equal to c^2 for this to be true, this ensures that inertial reaction forces will always obey Newton's third law. If the potential can have locally observed values different from c^2, then inertial reaction forces may be more or less than applied forces – and Newtonian mechanics is false.

Notes continue on next slide…

Total bare mass exposure results from ϕ_+ in Eq. (6.4) going from c^2 to zero while ϕ_- 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

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The notes for this slide are printed on **two** slides. This is the second.

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Now, if the total gravitational potential is a locally measured invariant (as the EEP requires), then a person in a wormhole throat will see the matter supporting the throat – that looks like a Jupiter mass of exotic matter to those outside the throat – as being completely normal and the environment in the throat as being completely benign. I point out that denial of the EEP and Mach's principle would lead to radically different situations, so if you want rapid spacetime transport, you'd better keep your fingers crossed that Einstein was right about the EEP – and that Mach's principle is correct. I also note that this is why the specification of observer as well as location of measurement is treated so carefully in the appendix to MUSH.

I should also note that the foregoing is only obvious in retrospect. Even world-class physicists sometimes screw this up. The best example of this is Einstein himself. In 1921, shortly before he learned of Mach's denial of godparenthood of relativity theory, in his Stafford Little Lectures given at Princeton [published as *The Meaning of Relativity*, 5th ed., Princeton, 1955], argued that general relativity encompassed Mach's principle to some extent. Starting on page 99, he outlines those things that he takes Mach's principle to imply. One of them is the proposition that the presence of nearby objects should change the mass of some object under consideration. Moreover, if nearby objects are accelerating in some direction, they should exert a force in that direction on the body under consideration. That is, Einstein then thought that gravitational potential energy should contribute to the masses of bodies. And accelerating nearby matter should either produce a force on a body, or, equivalently, should induce local frame dragging. Einstein went on to show that in a vector approximation to general relativity, both of these things seemed to take place.

In a sense, Einstein was right about these things. The masses of things do depend on their gravitational potential energy; and linear accelerational frame dragging is predicted by general relativity [see Nordtvedt's comments, at slide 43 ff]. But since he failed to take account of the locally measured invariant character of the total gravitational potential required by the EEP, he was wrong about the "piling up" of nearby masses affecting the masses of other objects. This mistake was not fixed until 1962 when Carl Brans pointed it out and corrected it. As for Einstein, he abandoned Mach's principle shortly after delivering his lectures in Princeton. Mach's last writings, including a blunt rejection of relativity theory, were published then, a number of years posthumously (Mach died in 1916). Einstein's regard for Mach, not surprisingly, dropped precipitously when he learned what Mach really thought of relativity.

A cartoon showing two spiders at the bottom of a playground slide across which they have spun a web goes here. One spider says to the other, “if we pull this off, we’ll eat like kings.”

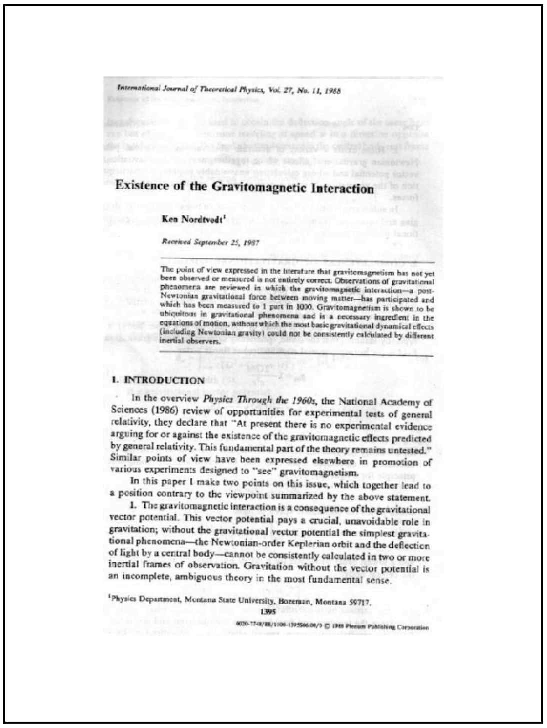
Tom Mahood, now a former grad student, brought this cartoon into the lab, where it is still posted, when he began to figure out what was involved in the rapid spacetime transport business.

SINCE THE STANDARD MODEL, NOT THE ADM MODEL, WILL DICTATE OUR VIEW OF ELEMENTARY PARTICLES FOR THE FORESEEABLE FUTURE, SCIENCE FICTION HAS LITTLE TO FEAR FROM SCIENCE

The standard model of RQFT has massive experimental confirmation. It seems unlikely to be successfully challenged by any other model for the foreseeable future. So Jupiter masses of exotic matter made from normal matter doubtless won't be seen any time soon. And the centerpiece of science fiction is safe from the depredations of science, notwithstanding that the absurdly benign wormhole metric has been known for more than 20 years.

THE END

That inertial reaction forces are produced by gravity in general relativity can be shown using the "PPN" formalism as developed by Ken Nordtvedt in a 1988 paper, parts of which follow.



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Existence of the Gravitomagnetic Interaction

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The point of view expressed in the literature that gravitomagnetism has not yet been observed or measured is not entirely correct. Observations of gravitational phenomena are reviewed in which the gravitomagnetic interaction—a post-Newtonian gravitational force between moving matter—has participated and which has been measured to 1 part in 1000. Gravitomagnetism is shown to be ubiquitous in gravitational phenomena and is a necessary ingredient in the equations of motion, without which the most basic gravitational dynamical effects (including Newtonian gravity) could not be consistently calculated by different inertial observers.

1. INTRODUCTION

In the overview *Physics Through the 1960s*, the National Academy of Sciences (1986) review of opportunities for experimental tests of general relativity, they declare that "At present there is no experimental evidence arguing for or against the existence of the gravitomagnetic effects predicted by general relativity. This fundamental part of the theory remains untested." Similar points of view have been expressed elsewhere in promotion of various experiments designed to "see" gravitomagnetism.

In this paper I make two points on this issue, which together lead to a position contrary to the viewpoint summarized by the above statement.

1. The gravitomagnetic interaction is a consequence of the gravitational vector potential. This vector potential pays a crucial, unavoidable role in gravitation; without the gravitational vector potential the simplest gravitational phenomena—the Newtonian-order Keplerian orbit and the deflection of light by a central body—cannot be consistently calculated in two or more inertial frames of observation. Gravitation without the vector potential is an incomplete, ambiguous theory in the most fundamental sense.

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Nordtvedt's motivation is clearly stated at the outset. "Gravitomagnetic" effects must be considered in situations a simple as orbit calculations unless one's frame of reference is specially chosen so they can be ignored.

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5. DRAGGING OF INERTIAL FRAMES AND MACH'S IDEAS

What seems to have especially caught the interest of physicists in searching for the spin–spin interaction in gravity is that this would seem to be a manifestation of ideas of Mach, who a century ago believed that inertia was caused, in some sense, by the universe's matter distribution. Lense and Thirring later showed that, indeed, in general relativity rotating matter would drag the inertial frame around at a slow rate which fell off with distance from the rotating matter,

$$\mathbf{\Omega} = \frac{G}{c^2}\left(\frac{\mathbf{J} - 3\mathbf{J}\cdot\hat{\mathbf{r}}\hat{\mathbf{r}}}{r^3}\right) \quad (16)$$

$\mathbf{J}$ is the angular momentum of the spinning body and $\mathbf{r}$ is the distance to the point of space in question, $\mathbf{\Omega}(\mathbf{r})$ is the rotation rate and rotation axis for the inertial space at that point of space which is induced by the spinning source. Equation (16) follows from (12) with choice of PPN coefficients appropriate to general relativity, and the identification

$$\mathbf{\Omega} = -\frac{c}{2}\nabla\times\mathbf{h}$$

Looking at the general case, one can ask what is the complete effect of the gravitational vector potential in dragging inertial frames? This question can be addressed by calculating the contribution of $\mathbf{h}$ in establishing the geodesic coordinate frames (inertial frames). The general formula

$$[x^\gamma - x^\gamma_{(0)}]' = [x^\gamma - x^\gamma_{(0)}] + \tfrac{1}{2}\Gamma^\gamma_{\alpha\beta}[x^\alpha - x^\alpha_{(0)}][x^\beta - x^\beta_{(0)}] \quad (17)$$

in which $\Gamma^\gamma_{\alpha\beta}$ are the Christoffel symbols produced from first derivatives of the gravitational metric field, gives the transformation from original space-time coordinates x^γ to inertial (geodesic) coordinates $x^{\gamma'}$ in the vicinity of any chosen space-time point $x^\gamma(0)$. Examining solely the vector potential (g_{0i}) contribution to (17) yields

$$[\mathbf{r} - \mathbf{r}_{(0)}]' = [\mathbf{r} - \mathbf{r}_{(0)}] - c\left[\frac{1}{2}\frac{\partial\mathbf{h}}{\partial t}(t - t_0)^2 + \left(\frac{\nabla\times\mathbf{h}}{2}\right)\times(\mathbf{r} - \mathbf{r}_{(0)})(t - t_0)\right] \quad (18)$$

The gravitational vector potential produces in this general case a "dragging" of inertial space at each locality with both an acceleration of the inertial frame at rate

$$\mathbf{a}(\mathbf{r}, t) = -c\,\partial\mathbf{h}/\partial t \quad (19a)$$

and a rotation of the inertial frame at angular rate and axis

$$\mathbf{\Omega}(\mathbf{r}, t) = -\tfrac{1}{2}c\nabla\times\mathbf{h} \quad (19b)$$

Toward the end of his paper, Nordtvedt considered the Machian implications of gravitomagnetism. Gravitomagnetism, of course, has an underlying gravitomagnetic vector potential analogous to the familiar vector potential of electrodynamics. And this can contribute in unexpected ways. For example, the electric field is not simply the gradient of the scalar potential. It also depends on the time-derivative of the vector potential. Indeed, Dennis Sciama had used a simple vector theory of gravity (an approximation to general relativity) to show that this term in the gravitoelectric field accounts for inertial reaction forces. In this page and the next, Nordtvedt shows in the PPN formalism that the vector potential produces linear accelerational frame dragging. The potential involved occurs at the bottom of this page.

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If we return to the problem of light deflection by a body moving at speed w and employ the vector potential given by (7), we find that (19a) gives no contribution to the light ray deflection; however, (19b) produces a rotational dragging of inertial frames at a rate

$$\Omega(r, t) = (1+\gamma)\frac{GMDw}{c^2}\frac{1}{|\mathbf{r}-\mathbf{w}t|^3}$$

and in a counterclockwise sense. The time integral of this rotation rate over the entire trajectory of the light ray produces the total deflection or rotation angle

$$\delta\theta = -\frac{2w}{c}\theta_0$$

which is what is needed to obtain agreement with (5) as discussed in Section 2.

The periastron precession of the binary pulsar orbit discussed previously received contributions of inertial frame dragging from both (19a) and (19b). The situation can be viewed this way: part of the motion of the two bodies in the binary pulsar results from the "Coriolis" acceleration that each body experiences because the motion of the other body is producing rotational dragging of the inertial frame at the locality of each body in question.

Finally, the accelerated celestial body mentioned previously drags the inertial frames through (19a), with the resulting acceleration of inertial space being

$$\delta\mathbf{a}(\mathbf{r}, t) = -\left(2+2\gamma+\frac{\alpha_1}{2}\right)\frac{U(\mathbf{r}, t)}{c^2}\mathbf{a}$$

in which $U(\mathbf{r})$ is the Newtonian potential function of that body's mass distribution and $\mathbf{a}$ is the body's acceleration.

6. CONCLUSION

The gravitomagnetic interaction—the post-Newtonian gravitational interaction between moving masses—has been observed and measured in a number of different phenomena. The strength of this interaction is now known to an accuracy of 1 part in 1000. The gravitomagnetic interaction is also required in order to have a complete and consistent theory of gravity at all: even static source gravitational effects when viewed in another inertial frame require the gravitomagnetic interaction in order for basic consistency of a theory's equations of motion. Just as in electromagnetic theory, there is no absolute separation of "electric" and "magnetic" effects; such a division is inertial frame dependent.

The last equation on this page gives the linear accelerational frame dragging. When general relativistic values for all of the PPN parameters are put in, the term in parentheses turns out to have the value 4. And the rate at which frames are dragged by the accelerating body is just 4 times the Newtonian gravitational potential divided by c^2. Evidently, when the potential is roughly equal to c^2, frames are dragged rigidly by the accelerating body. And an object inside the accelerating body behaving inertially does NOT detect the acceleration of the surrounding body. If we seek to keep the interior object at rest with respect to the spacetime through which the larger body is accelerating, we will have to provide an "external" force to do so. And the force of gravity will produce the inertial reaction force we take to be present as long as the gravitational potential due to the larger body is roughly equal to c^2. This is exactly what Sciama found 35 years earlier.