Print - ISSN : 2319–9814
Online - ISSN : 2319–9822

Journal of
Space Exploration

WWW.MEHTAPRESS.COM

Full Paper

How long will it take to build starships?

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Received : November 08, 2013
Accepted : February 03, 2014
Published : May 25, 2014

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Abstract

The theme for Space Technology Applications International Forum II in 2013 was: when will it be possible to build craft capable of reaching the stars in reasonable lengths of time? "Reasonable" was understood to be significantly less than a human lifetime. That can only be done by implementing "exotic" technologies that are presently thought to be the stuff of science fiction. But there is at least one proposal may make such technologies practicable. It rests on "Mach's principle" as Einstein called it. This paper, which captures the contents of the keynote talk at that conference, recapitulates how we have reached our present pass, and tells of recent experimental developments in the "Mach effects" project. Though a small-scale, table top project, steady progress has been made. For example, switching transients that may have propulsive applications are reported here. Post conference comments on claims that the quantum vacuum can be exploited for propulsive purposes are included. It is shown that such speculations are without merit.

INTRODUCTION

Increasingly, in the past decade or two, it has come to be understood that creating the technology to get off Earth and out of the solar system to the stars is a necessary prerequisite to the long-term survival of our species. This realization informed the choice of the theme for STAIF II this year: How Long Will it Take to Build Starships? There are those, indeed many, who claim that the requisite technology has been understood and available for decades: nuclear rockets (NERVA), nuclear "pulse detonation" rockets (ORION), sails and beamed energy, and "generation ships" designed to support multiple generations of spacefarers because of the idiotically long transit times that these technologies entail. These schemes all have modern counterparts, now much discussed, but were already known and investigated in the 1960s and in some cases before.

The interstellar transport agenda was fundamentally changed in the late 1980s when Kip Thorne, at Carl Sagan's instigation, reverse engineered the general relativistic requirements for the construction of stable traversable wormholes[6], and eight years later, Miguel Alcubierre wrote down the "warp drive" metric[1]. Before that, those trying to figure out how to get around spacetime quickly had looked for anomalous couplings of gravity and electromagnetism, hoping that if found, they would enable inertia reduction, and so on. Some people still do this. But in the post-Thorne era, such activities can only be regarded as quaint at best. If you want to get to the stars, wormholes, and maybe warp drives, are the only realistic way. But traversable wormholes require gargantuan amounts of "exotic", that is, negative restmass, matter in compact structures – which hardly seems "realistic".

Many years ago, I blundered onto physics that, in principle, provided a way to realize the production of vast amounts of negative restmass "matter", enough to enable the creation of traversable wormholes[11,12]. That physics also enabled the creation of devices that would produce thrust without the ejection of normal material propellant. Since wormholes then were regarded as science fiction, notwithstanding Thorne's exposition of wormhole physics, work on "Mach effects" was focused on the less outlandish prediction of propellantless propulsion. Technologically speaking, work on this aspect of Mach effects is markedly less challenging than trying to induce wormholes. But since both techniques follow from Mach's principle, showing one to work guarantees that the other will too.

Experimental work on Mach effects has a tortuous history, summarily recounted in chapters 4 and 5 of *Making Starships and Stargates: the Science of Interstellar Transport and Absurdly Benign Wormholes*[12]. With the main focus of experimental work on propellantless propulsion, the fact that if Mach effects are real, wormholes lie in our future (and maybe our past) got lost in the noise of day to day activities. So, when an invitation to John Cramer's 75th birthday celebration arrived in the early summer of 2009, and my acceptance resulted in an invitation to give a talk, I decided to speak to the issue of the practicability of the construction of real traversable wormholes. The approach adopted was to cast the issue in the context of whether science fiction aficionados need be concerned that the central trope of their genre was imminently to be rendered real by scientists. These comments were contextualized by reference to the Venn diagram in Figure 1. While a few scientists bridge the worlds of science and science fiction (John being an example), the worlds of science and science fiction are quite separate. And those not either scientists or science fiction aficionados generally regard those who feign the practice of science on issues not sanctioned by mainstream scientists as crackpots. Those of us working on making wormhole tech a reality were not then sanctioned by mainstreamers. So I argued that science fiction aficionados had nothing to fear from scientists.

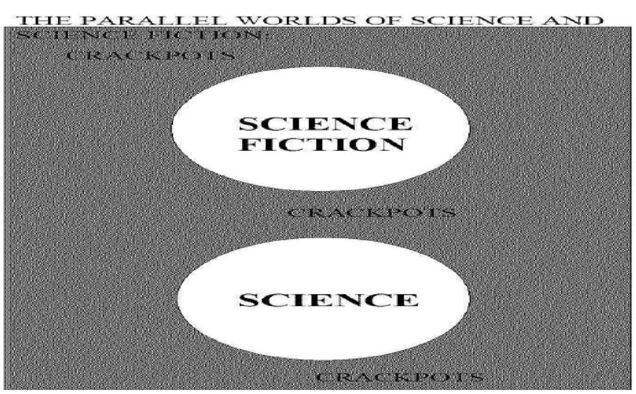

Figure 1 : A Venn diagram indicating the relationship between science and science fiction shown at John Cramer's 75th birthday celebration in September, 2009.

Times have changed. In the early summer of 2011, I responded to an automatically generated book proposal solicitation from Springer Verlag. The proposal I submitted was for *Making Starships and Stargates*, published last December. I made no attempt to disguise the intended content. To my amazement the proposal first passed initial editorial scrutiny, and then "stakeholder" review. The manuscript underwent only very light editing when it was submitted. A decade ago, all of this would have been simply unthinkable. Since STAIF II, further evidence of this shift has emerged. Not long ago, Dennis Overbye, writing in the New York Times about [desperate] efforts to avoid the black hole "firewall" paradox – by the use of wormholes to keep entangled particles, one of which has fallen through the event horizon of a black hole, and the other escaping, entangled – noted that wormholes were usually considered the preserve of science fiction writers and "interstellar pioneers". It appears that the Venn diagram may need another circle for the "pioneers", though whether it should overlap either of the existing circles is not clear at this point. At least we're not automatically relegated to the crackpot region in the diagram.

While these developments are interesting, the problem remains, what do we need to make wormholes and warp drives? And is there any even remotely realistic way to go about designing and building such things? The answer to the first question was provided by Thorne and his graduate students in the late '80s[6]. A Jupiter mass of negative rest mass matter – assembled in a thin walled structure on the order of meters in size – is what is required. With this amount of "exotic" matter, disposed in a structure of modest dimensions, you can make an "absurdly benign" wormhole. One that doesn't seriously disrupt the geometry of spacetime for thousands of kilometers around the vicinity of the wormhole. This utterly preposterous amount of exotic matter will also enable the constructions of warp drives. Those wanting to see exotic tech succeed, immediately set about trying to find ways to reduce the amount of exotic matter required. Wormholes and warp drives, it turns out, can be built with much, much less exotic matter than the Jupiter mass needed for "absurdly benign" devices. But not without screwing up spacetime for vast distances around the device. That makes such schemes unacceptable from the practical point of view. The sad fact of reality is that, though you can build negative mass drives with modest amounts of exotic matter, if you want an absurdly benign wormhole, or realistic warp drive, the Jupiter mass requirement cannot be evaded.

The answer to the second question depends on the answer to the question: where can we find vast amounts of exotic matter that can be formed into a wormhole support structure? Or already existing wormholes that can be "amplified" into wormholes of macroscopic dimensions? Over the years, a number of suggestions have been made. Thorne's early suggestion was to isolate a wormhole in the putative quantum spacetime foam that presumptively exists at the scale of the Planck length (10^{-33} cm.), and after having mastered the yet to be invented theory of quantum gravity, enlarge it to desired dimensions. Some of the smartest people who have lived in the past 60 or 70 years have tried to invent the quantum theory of gravity – and all have failed. Others have suggested trolling for exotic matter in the asteroid belt. Even were there lumps of exotic matter floating around in the asteroid belt, one would still be faced with the problems of finding enough of the stuff, and then figuring out how to compact it. To characterize these schemes as unpromising seems a bit of an understatement.

Another scheme, fashionable in some circles of pioneers, is "negative vacuum energy" which supposedly can be concentrated into very large amounts, if not the Jupiter masses actually required. This idea seems to have its origins in the discovery of the accelerating expansion of the universe, which leads to the notion of "dark energy", the presumed exotic substance, found in the vacuum, that is driving the accelerating expansion. Dark energy, whatever it may actually be, is not a candidate for this task. It has a known density: ~ 1.5 X 10^{-29} gm/cm.^{3}. To collect a gram of this stuff, the contents of roughly 10^{14} cubic kilometers of space would have to be scavenged. Good luck with that.

Is there any other source of negative vacuum energy that might be tapped? The pioneers who bandy around "negative vacuum energy" with abandon often talk about "Q" devices, and seem to think that by applying high frequency electric fields to ferroelectric materials, measurable amounts of negative vacuum energy can be created. "Q" presumably refers to the chiral symmetry breaking condensate of quantum chromodynamics, or, as Frank Wilczek refers to it, $Q\overline{Q}$, or quark-antiquark condensate. (Wilczek has a nice non-technical discussion of this in his book, *The Lightness of Being*, pp. 88 – 93.) $Q\overline{Q}$ "molecules" do have negative energy – because the attraction of the quark and antiquark for each other gives them greater negative potential (binding) energy than the sum of their individual positive rest energies. And these quark-antiquark molecules are real. That is, they are not transient "virtual" particles like the electron-positron pairs of quantum electrodynamics. So they don't flash into and out of existence. But when they form a condensate in the vacuum, they repel each other, creating positive energy, and when the total energy density reaches, you guessed it, ZERO, $Q\overline{Q}$ molecules stop being formed. What happens when you make this condensate wiggle? Well, if you wiggle it hard enough, you produce pions. Positive energy pions. Which makes sense as you are putting positive energy into the condensate. But there is no negative vacuum energy to be had this way.

Since the scenarios considered so far don't even rise to the level of the alchemists' dreams of making gold from base metals, or finding the elixir of eternal life, we may ask: Is there any other remotely plausible scheme that can get us the compact Jupiter mass of exotic matter we need – from stuff commonly available, using only power sources presently at hand? The answer to this question seems to be, yes. But to see how this might be done, we must first understand inertia and its origin.

MACH'S PRINCIPLE AND MACH EFFECTS

Nowadays, pretty much everybody thinks that they understand inertia – that property of things that causes them to resist external accelerating forces; that causes them, as Newton said, to produce equal and opposite forces, according to his third law, on the accelerating agents. The fact of the matter, though, is that almost no one really understands the nature and origin of inertial reaction forces. Einstein tried to incorporate it into his theory of gravity: general relativity theory (GRT). He called his articulation of the idea that inertia is a gravitational phenomenon Mach's principle, and asserted that it was one of the foundation principles of GRT. He is widely believed to have failed. In the early 1950s, Dennis Sciama[9], then a grad student of Paul Dirac, took another pass at explaining inertia – as a gravitational effect in a vector theory of gravity modeled on Maxwell's electrodynamics. Sciama pointed out that the "gravelectric" field, E_g, in contradistinction to Newtonian gravity, should be given by:

$$\mathbf{E}_g = -\nabla\phi - \frac{1}{c}\frac{\partial \mathbf{A}_g}{\partial t} \tag{1}$$

where ϕ and A_g are the scalar and vector potentials of the gravitational field respectively, and c is the vacuum speed of light. Newtonian gravity, of course, lacks the term in the vector potential. If we consider a test particle moving with velocity v in a universe of constant matter density ρ, A_g is just the integral of the matter current density ρv over all space. We can simplify this integration by noting that in the instantaneous frame of rest of the test particle, the rest of the universe appears to be moving rigidly in the opposite direction with velocity – v, so v can be removed from the integral, leaving the integral of the matter density, and that integrates to the scalar potential. That is:

$$\mathbf{A}_g = -\frac{1}{c}\int_V \frac{\rho \mathbf{v}}{\mathbf{r}}\mathbf{dV} = \frac{\mathbf{v}}{c}\int_V \frac{\rho}{\mathbf{r}}\mathbf{dV} = \frac{\phi}{c}\mathbf{v} \tag{2}$$

Substituting into Equation (1), we find:

$$\mathbf{E}_g = -\nabla\phi - \frac{\phi}{c^2}\frac{\partial \mathbf{v}}{\partial t} = -\nabla\phi - \frac{\phi}{c^2}\mathbf{a} \tag{3}$$

In these circumstances, the gradient of the potential vanishes. If $\phi = c^2$, then the gravitational force on the test particle is exactly the inertial reaction force that the object exerts on the accelerating agent. And Mach's principle – in the form of the assertion that inertial reaction forces are gravitational in origin – is true.

So what? Why care? Well, if inertial forces are gravitational, contrary to widespread belief, we can generate enormous gravitational forces locally, simply by applying large accelerating forces to normal objects. These forces can be decades of orders of magnitude larger than customary gravity forces: those due to the Earth or Sun for example.

And this is, in principle at least, what we must do if we are to manipulate gravity to make traversable absurdly benign wormholes. So, the question before us is: is Equation (3) also true in GRT? And is the condition $\phi = c^2$ universally true, as it must be if inertial reaction forces are to be gravitational in origin? The answer to the first question is simple. Yes. Einstein[4] had already recovered the vector potential dependence in Equation (1) here in his discussion of Mach's principle delivered in lectures at Princeton University in 1921. Others, including a physicist or two of non-negligible repute, have managed to screw this up. But Jose Pasqual-Sanchez (2000) straightened this out over a decade ago. The answer to the second question is also yes. Carl Brans[2], correcting Einstein's only really serious mistake, showed that the scalar Newtonian gravitational potential is a locally measured scalar invariant, as it must be if $\phi = c^2$ is universally true.

As far as the second question is concerned, $\phi = c^2$ is the GRT criterion for "critical cosmic matter density" [2 X 10^{-29} gm/cm^3], which in turn corresponds to cosmic scale spatial flatness. In the 1920s, when Einstein introduced Mach's principle, our galaxy was thought to be the extent of the universe, and general relativistic cosmology hadn't even been conceived, so this sort of criterion wasn't even on the table. In the 1950s, when Sciama first proposed that inertia be gravitational, more was known about the nature of the universe, and general relativistic cosmology had been invented, but cosmic scale spatial flatness, though sometimes assumed in cosmological discussions, was still a matter of speculation. The WMAP results, reported about a decade ago, changed that. At cosmic scale, space is flat as a matter of fact. So Mach's principle is true.? Yes, it is. Inertial reaction forces are caused by the gravitational action of chiefly the most distant stuff that gravitates in the universe.

Granting that Mach's principle is correct, we ask: What happens when you apply a large force to an object, thereby bringing into existence a large gravitational inertial reaction force? In particular, what happens to the object acted upon? We can write down the strength of the gravitational field that acts. It is just the inertial reaction force divided by the restmass of the object acted upon. This can be put in the customary language of densities by dividing the numerator and denominator of the resulting expression by the volume of the object. Then, to get the local source density of the field, we simply take the four-divergence of the field at the source. Judicious application of $E_o = \rho_o\phi$ and $\phi = c^2$, both consequences of Mach's principle, yields:

$$\nabla^2\phi - \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} = 4\pi G\rho_o + \frac{\phi}{\rho_o c^4}\frac{\partial^2 E_o}{\partial t^2} - \left(\frac{\phi}{\rho_o c^4}\right)^2\left(\frac{\partial E_o}{\partial t}\right)^2 - \frac{1}{c^4}\left(\frac{\partial\phi}{\partial t}\right)^2 \quad (4)$$

where the left hand side of the equation is the d'Alembertian of the scalar potential [the classical relativistically invariant wave equation for the potential] and E_o is the local proper energy density of the object acted upon. In addition to the usual static source term [$4\pi G\rho$] on the right hand side, we now have two transient terms that depend of the rate of change of the proper energy density. And a purely field term (treated as a source) $-\frac{1}{c^4}\left(\frac{\partial\varphi}{\partial t}\right)^2$ — that would louse up the d'Alembertian if put on the left hand side of Equation (4). Since ϕ is the total scalar gravitational potential, and that is a locally measured invariant equal to the square of the vacuum speed of light, this term can be assumed small and discarded. When the proper – that is, internal – energy of the object doesn't change, the other transient terms vanish. So any effects of this sort are *not* expected in rigid bodies.

The obvious question at this point is: Is there any reason, beyond that the physics is elementary and straight-forward, to believe that there is anything to Mach effects. Trying to build a wormhole generator is not the best strategy. But we can make "Mach effect thrusters" (METs) to check up on the underlying physics. In a MET, a mass fluctuation is driven by one voltage signal, and a second mechanical fluctuation at the frequency of the mass fluctuation is introduced to produce a steady acceleration in one direction. A variety of devices can be designed to do this, among the simplest are stacks of lead-zirconium-titanate (PZT) crystals. They can be attached to a tuned reaction mass, and a voltage signal applied at a resonant frequency of the device then produces the mechanical excursion and internal energy changes needed to produce mass fluctuations. Isolating the transient terms in Equation (4) and integrating over such a device, we find for the induced mass fluctuation:

$$\delta m_o \approx \frac{1}{4\pi G}\left[\frac{1}{\rho_o c^2}\frac{\partial P}{\partial t} - \left(\frac{1}{\rho_o c^2}\right)^2\frac{P^2}{V}\right] \quad (5)$$

where P is the power delivered to the device and V is the volume of the stack. The second term on the right hand side of Equation (5), because it is always negative, is referred to as the "wormhole" term. It is normally many orders of magnitude smaller than the first term. So, for our present purposes, we ignore it and write Equation (5) as:

$$\delta m_o \approx \frac{1}{4\pi G\rho_o c^2}\frac{\partial P}{\partial t} \approx \frac{1}{4\pi G\rho_o c^2} m_o a^2 \quad (6)$$

The mass fluctuation is written in Equation (6) both as a function of power, P, delivered to the device and acceleration, a, to remind us that this effect only occurs in extended objects undergoing accelerations. Much time and effort can be wasted if you forget the acceleration condition.

EXPERIMENTAL APPARATUS AND PROCEDURE

A number of METs have been built and tested over the years. They have all been of the same basic design. A recent example is shown in Figure 2. It consists of a stack of eight'19 mm diameter PZT disks 2 mm thick. They are made of Steiner-Martins SM-111 material (not, by the way, SM-112) which has the serendipitous property of unusually large electrostrictive response. The disks are polarized through their thickness, and glued together (with Epon 815 and Versamid 140 in a 1:1 mix, cured for two hours at 160 degrees F) with plus to plus and minus to minus facing. An accelerometer consisting of a pair of 0.3 mm thick disks is built into the stack one pair of 2 mm thick disks distant from the aluminum cap that with six 2-56 stainless steel socket head machine screws preloads the stack (torqued to 4.0 to 5.0 inch pounds). The brass reaction mass to which the PZT stack is clamped is 28.6 mm in diameter and 15.9 mm long. This length was chosen because it produces two distinct resonances in the 25 to 40 KHz range when the stack is excited with a single frequency voltage signal. And there is marked variation of the phase of the first (piezoelectric) and second (electrostrictive) mechanical harmonics (detected with the accelerometer) over the frequency range of interest. This is desirable because both harmonics must be present with the correct phase for an effect to be produced, and this enables operation with a single frequency tuned to a sweet spot.

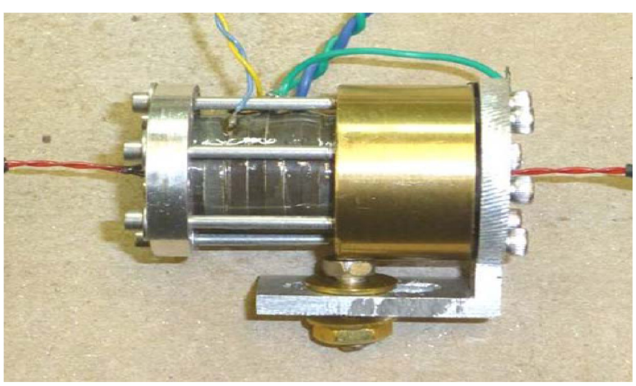

Figure 2 : A Mach effect thruster [MET] on its aluminum mounting bracket.

The assembled MET is attached to an aluminum mounting bracket with six 4-40 stainless steel socket head cap screws (torqued to 2.5 inch pounds). A thin rubber pad separates the reaction mass from the bracket to isolate the high frequency vibrations in the MET from the rest of the apparatus. The aluminum bracket is made from 1/8 inch thick aluminum "L" channel. The device is mounted in a small aluminum project box, lined with mu metal, that acts as a Faraday cage, as shown in Figure 3 where the device is partially assembled on the end of the thrust balance used to detect predicted thrusts. Note that the Faraday cage is mounted in a yoke attached to the thrust balance beam so that it can be rotated on the end of the beam to reverse the direction of the device.

Figure 3 : MET in a partially assembled Faraday cage on the end of a thrust balance beam.

The thrust balance, based on a design that originated with Andrew Ketsdever and colleagues at the University of Southern California, was designed and built by Thomas Mahood and tweaked by JFW. See Figure 4. It uses C-Flex E – 10 flexural bearings. One of its chief features is the use of power contacts coaxially aligned with the bearings made with galinstan (liquid metal) to minimize mechanical torques on the balance during operation. See Figure 5. The balance is located in a vacuum chamber, routinely pumped to several milliTorr, that sits on a vibration isolation table. See Figure 6. Position of the balance beam is detected with a Philtech optical position sensor. The Philtech electronics are supplemented with offset adjustment and amplification and filtering electronics that makes it possible to detect thrusts at the 100 nanoNewton level. (The supplementary electronics are a purchase option from Philtech not purchased by us when the sensor was acquired.)

The rest of the apparatus is straight-forward. A VCO signal generator produces a single frequency sine wave that is relay controlled en route to a Carvin DCM – 1000L power amplifier. The relay is computer controlled, as is the frequency of the signal generator. The output of the power amplifier is fed into a step-up/isolation transformer, through a voltage sense resistor and capacitor network, to the device in the Faraday cage on the end of the balance beam. Thermistors are embedded in the aluminum cap and brass reaction mass. Leads from the accelerometer in the stack and the thermistors are taken off the balance beam in a bundle of very fine stranded copper leads as close to the central column of the balance as

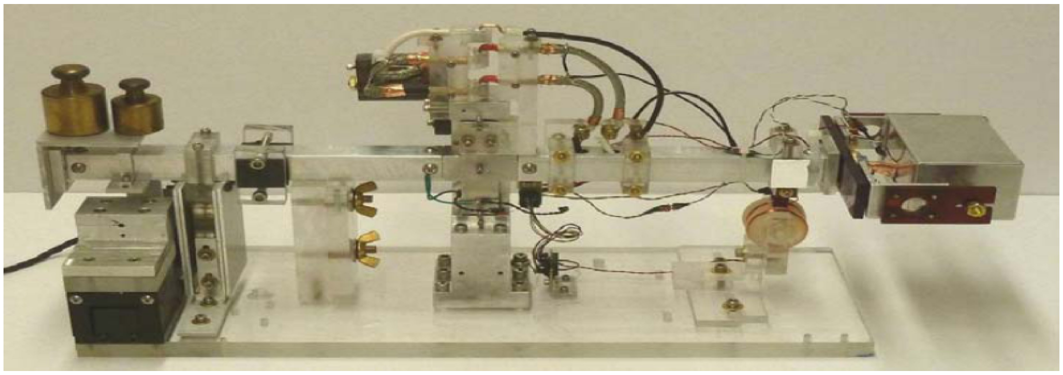

Figure 4 : The thrust balance used in experimental work at CSU Fullerton.

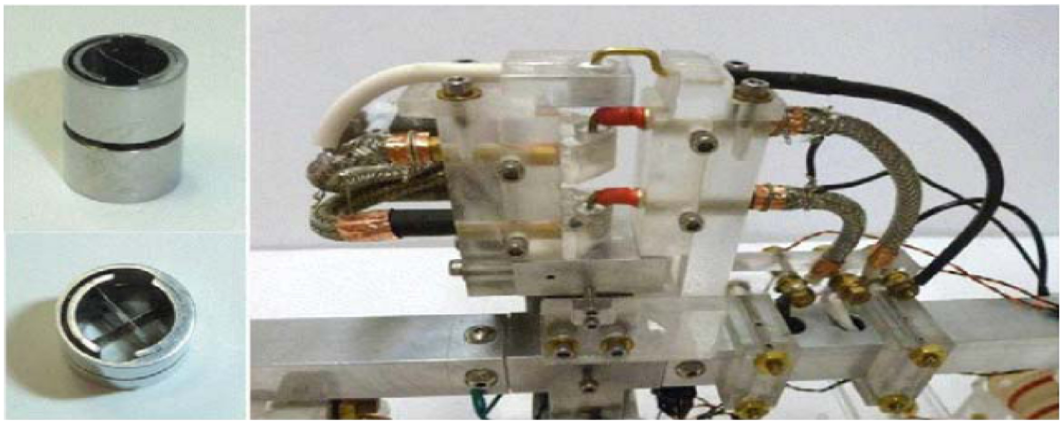

Figure 5 : Two views of a flexural bearing at the left. And a detailed view of the galinstan power contacts at the right.

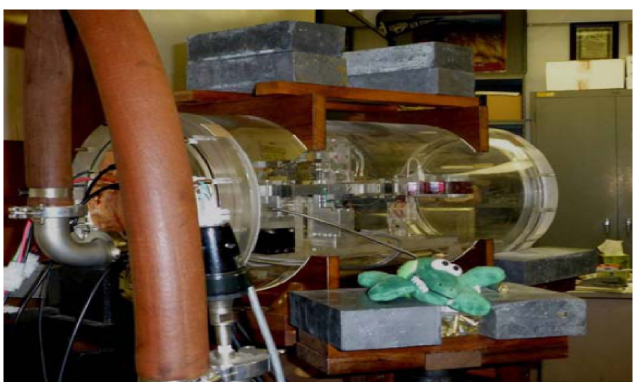

Figure 6 : The thrust balance in its vacuum chamber.

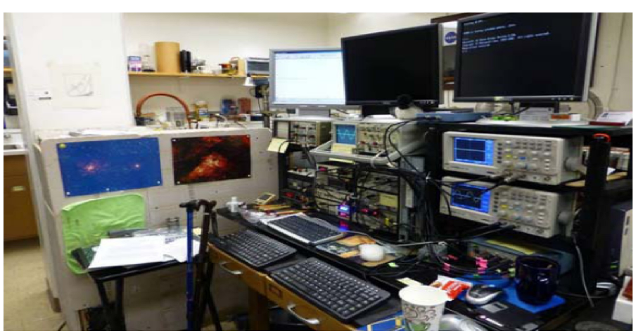

Figure 7 : Instrumentation and control.

possible. All signals were buffered and filtered for possible aliasing. Since the voltage and accelerometer signals were high frequency AC, they were rectified using circuits based on the self-referenced Analog Devices 630 synchronous demodulator chip. Data from the thrust sensor, voltage, accelerometer, and thermistor circuits were acquired at a rate of 100 Hz with a Canetics PCDMA analog to digital converter board. One of the digital to analog channels of this board was used to control the switching relay for the power circuit. The other D to A channel was used to generate a low voltage signal that controlled the frequency of the signal generator. All of the software for this experiment was written in Quick Basic 4.0. The instrumentation and display cluster is shown in Figure 7. The Canetics PCDMA A/D board and supporting Quick Basic software limit the acquisition of data taken at 100 Hz to five channels for 32 seconds. This limitation does not apply to less antique data acquisition systems. But the system works and is easy to reprogram, so it is still in use. For this reason, data runs were 32 seconds in length. After much fooling around, two protocols were settled upon for formal data runs. In the first protocol, the first 6 seconds of runs was quiescent data so that the unpowered background for each channel could be established. At 6 seconds the power relay switched on the power amplifier driven by the signal generator, which had been adjusted to a frequency where particular behavior of interest had been identified. From 6 to 9 seconds, operation at (roughly) constant frequency was maintained. At 9 seconds, a frequency sweep was initiated. The swept range of frequencies was programmable, 25 or 30 KHz being the ranges most commonly used. (The data of this sort displayed here was all done with a 30 KHz range.) The sweeps were centered on the frequency chosen for the initial 3 second constant frequency pulse. At the termination of the sweep at 17 seconds, a second 3 second, center frequency pulse was carried out. The remaining dozen seconds in the runs were again quiescent, unpowered data used to establish background behavior.

The second protocol used was to do constant frequency pulses of extended duration. This was done by setting the range of the sweep to 0.10 KHz – that is, a sweep range on the order of the fluctuation of the frequency due to random causes in the signal generator. For some runs of this type, the center frequency pulses before and after the 8 second sweeps were limited to 1 second, giving a pulse of 10 seconds duration. This was done to reduce heating of the device, thereby reducing the time between runs (typically 5 to 15 minutes). There is also a quirk of the power amplifier present in the data displayed here. The power amplifier was/is equipped with an internal filter circuit. Normally, that circuit should be switched with the power supply input. But, for unknown reasons, the switching of the filter circuit was delayed by about 2.5 seconds. So the first 2.5 seconds of powered operation are not exactly like the ensuing operation. And the filter circuit produces a low level signal for 2.5 seconds after the input from the signal generator is switched off by the relay.

Several important tests of the system must be executed to insure that any thrust signals seen are genuine evidence for the Mach effect sought. Among them, the most important are tests for the effects of vibration (so-called Dean drive effects) and thermal effects. These are both addressed at length in Chapter 5 of *Making Starships and Stargates* and elsewhere, and will not be further discussed in detail here. More important even than these tests is the "direction reversal" test. When looking for very small thrusts, a wide variety of spurious sources of signals may be present. For example, small torques may be generated in the liquid metal contacts that transfer power to the device on the beam. For the most part, if not exclusively, these spurious effects will be present independent of the direction in which the test device is oriented. So, if data is collected for runs with the device pointing, say, to the right on the end of the balance beam, and then data is collected for runs with it pointing to the left, and the averages for the right and left facing runs are subtracted, since the direction of the spurious effects doesn't change with the direction of the device, they will be cancelled by the subtraction procedure. In effect, they are being cancelled as "common mode" signals. The results displayed below are such "net" signals.

The thrust signals, as measured with this thrust balance, displayed below range from a microNewton or two, to ten microNewtons or so. The system in use is tuned so that thrust effects can be seen at the 3 to 5 sigma level in a single run (so that visitors can see the effect in real time). But in all but ideal circumstances, there is enough noise in any single run to make modest signal averaging sensible. Typically, a dozen or so runs are averaged together to suppress mostly seismic noise. In addition to the data acquisition system, several oscilloscopes are used. One is run in power spectrum mode to display the behavior of the test device across the frequency spectrum as the system is operated. Here, however, only the thrust, power (voltage squared) and accelerometer results are displayed for forward minus reversed averages.

RESULTS

Figure 8 displays the result of this experiment for the frequency sweeps mentioned in the previous section. The center frequency chosen, about 39.5 KHz, does *not* correspond to either of the pronounced resonances present in the sweep. The best Mach effect performance happens when the first and second harmonics are both present and *have the correct relative phase*. (Typical power and accelerometer waveforms of this sort can be found in Fearn, *et al.*[5]) This, in this case, did not correspond to either of the large resonances. (In the sweep, the center frequency is swept at 13.0 seconds. Inspection of Figure 8 shows that non-negligible power and mechanical responses are present at 13 seconds. But at levels that are only a fraction of the resonance responses.) While no detailed (and exhausting) treatment of the spurious effects examined at length in *Making Starships and Stargates* will be presented here, I note that the two chief candidates – Dean drive and thermal effects – are inconsistent with the thrust behavior during the sweep. This is more easily seen in Figure 9 where the powered interval and several seconds following in Figure 8 are plotted. A light vertical line in Figure 9 shows where the center frequency is swept, as can be ascertained by noting that the power and accelerometer responses in the post sweep 3 second center frequency pulse correspond to the levels where the line crosses these traces.

The first resonance to the right of this line is the peak power response in these runs. This is where heating, and changes in the rate of heating, are most pronounced. Yet this resonance is not accompanied by a strong accelerometer response (because the power is driving a radial resonance in the brass reaction mass). No large thrust response accompanies this resonance. So, simply putting power into the system is not enough to produce a thrust effect. Neither does a thrust response accompany the resonance to the right of the power resonance. This resonance is dominated by the accelerometer response, meaning that very large vibrations are produced. Vibration, by itself, evidently does not produce the thrust signals seen, especially in the 3 second center frequency pulses.

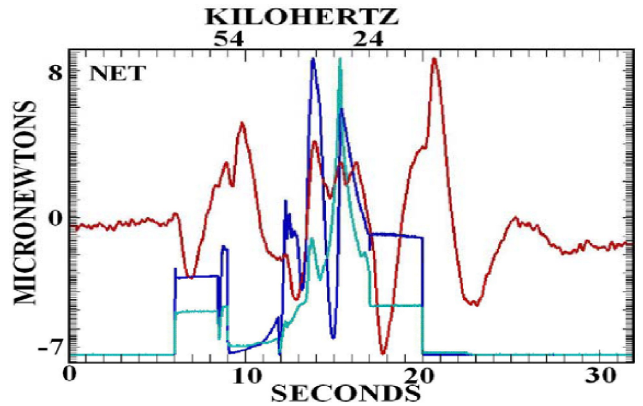

Figure 8 : A plot of several runs averaged together for sweeps of the sort discussed in the text. The thrust trace is red, power (voltage squared) dark blue, and accelero-meter response light blue.

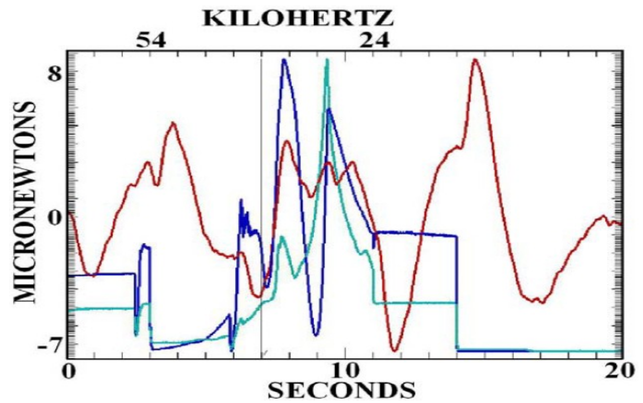

Figure 9 : A detailed display of the powered interval and immediately following in Figure 8.

Three seconds for the center frequency pulses that bracket the sweeps was chosen because the inertial lag introduced by the dynamics of the thrust balance make a shorter interval undesirable. A longer interval is likewise undesirable as it heats the device being tested more, leading to longer delays between runs to let the system cool. Careful inspection of the outgoing center frequency pulse thrust behavior suggests that something more complicated than simple switching of the thrust is going on. One of the distinguishing features of a real Mach effect is that the steady delivery of power in tuned circumstances should produce steady thrust, after any switching transients have been allowed to settle. Given the settling time of a few seconds for the thrust balance, three seconds is not enough to see this predicted behavior, especially as the thrust traces in Figures 8 and 9 clearly show transient variation. To test this prediction, runs were done at constant frequency and power with a duration of 10 seconds, more than enough time for the balance to settle.

The issue of steady thrust with constant power and frequency is sufficiently important to merit careful investigation. So, the program was changed to shorten the center frequency pulses to 1 second and the swept frequency range to 0.1 KHz (within the noise and drift of the frequency generator). This produces a 10 second pulse of nearly constant frequency (and power). The net (of forward minus reversed) average for this test is displayed in Figure 10. As thrust traces in the 3 second center frequency pulses in Figures 8 and 9 suggest, the initial response to the power being switched on is indeed a transient, for several seconds into the powered interval, the thrust settles to a value of a micronewton or two (recall, that as a difference, the thrusts shown in these "net" plots are twice the value present in the forward and reversed data) and persists until the power is switched off. So the prediction of steady thrust when the power and frequency are constant is confirmed. Perhaps more interesting even than the steady thrust are the pronounced thrust switching transients that are produced when the power is switched on and off. The obvious question is: Do these thrust transients have anything to do with Mach effects? The simple answer is yes. They are predicted. Recall that the mass fluctuation is given by Equation (6) above and is proportional to dP/dt. When the power is switched, dP/dt can become very large, especially in optimal circumstance for the production of Mach effects. Evidently, this is the case here. Inspection of the power rise and fall times using faster electronics than built into the data acquisition system shows that the rise time is a few milliseconds, and the fall time less than a millisecond – that is reflected in the thrust switching transients. To estimate the forces produced in these transients, we note that the thrust balance behaves as a horizontal ballistic pendulum, so the impulse (force times time) delivered by the transient is equal to the impulse recorded by the balance: a few micronewtons times a couple of seconds. Given a fall time of less than a millisecond, that means that the power off transient force is on the order of millinewtons.

Is there any way to discriminate a real Mach effect thrust transient from, say, a transient that arises from the electrical action of a voltage being switched on? Yes. Instead of applying a switched AC voltage to the device, we can

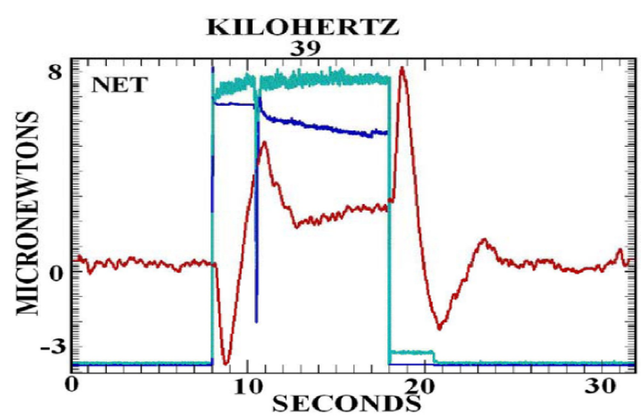

Figure 10 : Forward minus reversed for constant frequency (40 KHz), constant power (about 150 watts) operation. Note the steady thrust between 13 and 18 seconds, and the switching transients.

apply a switched DC voltage. When an AC voltage is switched, the power rises (falls) from zero (some finite value) to some finite value (zero), so dP/dt is positive (negative) throughout the transient. So the mass fluctuation is positive (negative) through the transient and the integrated impulse will be non-zero. When a DC voltage is switched, the power starts and ends at zero. So dP/dt is both positive and negative during the transient. And when the integrated impulse is computed, the mass fluctuation and associated thrust integrates to zero (or very near thereto). Pulsed DC voltages simply do not, as a matter of fact, produce the sort of thrust pulses that switched AC power does. (This is also discussed in Fearn, *et al.*[5])

One last issue remains to be dealt with: Are the observed effects consistent with prediction? Prediction, computed with the explicitly acceleration dependent formalism (see Woodward[12], chapter 5) turns out to be:

$$\mathbf{F} = \delta \mathbf{m}_o \ddot{\mathbf{x}} \approx \frac{\omega^6 \mathbf{m}_o \mathbf{K}_p \mathbf{K}_e \mathbf{x}_o^3 \mathbf{V}_o^4}{8\pi G \rho_o c^2}\left(1 + 2\cos 2\omega t + \cos 4\omega t\right) \quad (7)$$

Where K_e and K_p are the electrostrictive and piezoelectric constants of the stack respectively and x_o is the length of the stack. The time-averaged thrust is that for which the trigonometric terms on the right hand side of Equation (7) vanish. In earlier work the dimensions of these constants was incorrectly assumed to be fractional, whereas they are not. Together with the stack length, they define the oscillation amplitude, which must be on the order of 10 to 20 nm to return a thrust of the magnitude seen. Direct measurement of the oscillation amplitude shows that this condition is met. The observed thrust are, to order of magnitude, the same as those predicted.

SUMMING UP

We've covered a lot of ground. We've seen that notwithstanding the widespread belief that exotic propulsion is still the stuff of dreams and science fiction, there may be a way forward. It depends on the correctness of Mach's principle and so-called Mach effects. Regarding Mach's principle, perhaps its creator, Einstein, deserves the last word here (as quoted by Abraham Pais in his biography of Einstein):

> So strongly did Einstein believe at that time in the relativity of inertia that in 1918 he stated as being on an equal footing three principles on which a satisfactory theory of gravitation should rest:
>
> (1) The principle of relativity as expressed by general covariance
>
> (2) The principle of equivalence
>
> (3) Mach's principle (the first time this term entered the literature)... that the $g_{\mu\gamma}$ are completely determined by the mass of bodies, more generally by $T_{\mu\gamma}$.
>
> In 1922, Einstein noted that others were satisfied to proceed without this [third] criterion and added, "This contentedness will appear incomprehensible to a later generation however."

Einstein's prediction regarding Mach's principle has not yet been realized. But, like Einstein in 1922, I am convinced that it will be. Experiments inspired by Mach's principle suggest that inertia really is the gravitational phenomenon Einstein thought it to be.

But what about the theme of this conference? How long will it take to build starships? Well, if you've got a pretty good idea of how to solve a problem, and you are willing to commit significant resources to solve it, a decade is a long time. If you think it will take a century, you don't know what you're doing. How long do *you* think it will take?

A DIGRESSION ON THE QUANTUM VACUUM [POST CONFERENCE]

In the United States at least, advanced and exotic propulsion has been dominated by a loose group of physicists and aerospace engineers who are convinced that the zero point fluctuations (ZPFs) of quantum field theory are the solution to both our energy problems *and* all issues relating to advanced propulsion. At one point, many years ago, some of these folks even thought that they could explain inertia as an electromagnetic ZPF effect. That didn't work out so well. Nonetheless, a few of those enamored of ZPFs cling to the hope that they can convince others that the electromagnetic ZPF claim is correct. It isn't. As Planck once remarked when asked if his colleagues had cottoned to his quantum ideas on blackbody radiation, people don't change their minds. They die.

Most ZPFers seem to have moved on. This is a good sign. If you don't learn from your mistakes, paraphrasing de Santillana, you are condemned to repeat them. But while they have abandoned the electromagnetic ZPF explanation of inertia, they have not moved beyond the belief that the quantum vacuum is the answer to all problems, notwithstanding that most people regard the notion that you can get something from nothing as delusional. The 100 Year Starship project, set up by NASA and DARPA a few years ago, and Icarus Interstellar have become the showcase for the ZPFer position. At a recent conference arranged by Icarus Interstellar, the current positions of ZPFers were on display. Two claims are of particular interest. One is the claim that there is "negative vacuum energy" that can be increased by making, for example, high dielectric constant ferroelectric material in capacitors vibrate at high frequency. The second claim is that that it is possible to push off the quantum vacuum by simple electromagnetic processes – with so-called "Q" thrusters. Where do such claims come from? And are they reasonable?

Answering these questions if hindered by the fact that neither the claims nor the supporting details have been subjected to serious peer review and published in the professional physics literature. So one is reduced to piecing together the arguments from those informal sources that are available. Experience with the Mach effects project helps too, for both the Q-thruster and negative vacuum energy have their origins therein.

We first consider the business about negative vacuum energy. We've already seen that the only negative "vacuum" energy in standard physics is so-called "dark energy", and whatever it may be, its density is far too small to be a realistic source of exotic matter for practical devices. And there's another problem. Dark energy isn't a "substance" to which quantum field theory even necessarily applies. Its origin lies in the "cosmological constant" term in the field equations of GRT. So the obvious interpretation of dark energy is an inherent property of spacetime itself. Since spacetime *is* the gravitational field in GRT, dark energy is an inherently gravitational phenomenon. Were gravity merely a manifestation of some property of supposedly more fundamental quantum fields, I suppose that one might claim that dark energy is also a manifestation of those fields. But there is no evidence whatsoever that suggests gravity is any less fundamental than quantum fields. Indeed, those fields are unimaginable without spacetime as a real physical entity in which quantum fields exist. The fact that there is no quantum theory of gravity suggests that gravity and spacetime will not successfully be conceptualized as emergent from more fundamental quantum fields.

If dark energy has no role in practical devices employing negative vacuum energy, what might those who bandy this term about be talking about? Well, remember Equation (4)? That is:

$$\nabla^2\phi - \frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} = 4\pi G\rho_o + \frac{\phi}{\rho_o c^4}\frac{\partial^2 E_o}{\partial t^2} - \left(\frac{\phi}{\rho_o c^4}\right)^2\left(\frac{\partial E_o}{\partial t}\right)^2 - \frac{1}{c^4}\left(\frac{\partial\phi}{\partial t}\right)^2 \qquad (4)$$

and the last term on the right hand side that had to be treated as a source (to recover the d'Alembertian on the left hand side) and discarded as it is always small? This is what they are talking about. It is *not* a quantum effect. It *is* a gravitational effect (if it exists). Note that it is proportional to d-phi/dt you hear in discussions of negative vacuum energy and that, like the preceding term in Equation (4), it is always negative, regardless of the sign of the time-variation of the gravitational potential. The preceding term, however, holds out much more promise from the engineering point of view, for if the local rest energy density can be driven close to zero, that term dominates the sources. In any event, which ever term you choose to focus your attention on, none of this has anything to do with the quantum vacuum.

What about "Q-thrusters", or "quantum vacuum plasma thrusters" as they are called by their advocates? They consist of a toroidal capacitor (or capacitors arranged to approximate a torus, with the interior plates connected in parallel and the exterior plates connect in parallel) that is wound with magnet wire forming a coil around the torus. (These devices were first considered in the propulsion connection by Joseph Slepian in the 1940s.) If the coil and capacitor(s) are connected to separate power sources, the capacitor(s) can be charged up to some static voltage, and a steady current can be driven in the coil to create steady electric and magnetic fields in the dielectric of the capacitor(s). They will be mutually perpendicular. These "crossed" fields will act on any free electric charges present, accelerating them in a direction perpendicular to the plane of the crossed field (via the Lorentz force), creating a plasma drift condition. If you do the math, you'll find that electric charges of both signs are accelerated in the same direction, so, if free charges of whatever sign are present, their acceleration by the crossed fields will create a back reaction on the "Q-thruster", causing it to accelerate in the opposite direction. (As Slepian pointed out in the 1940s, doing this with AC signals won't work, for the time-averaged force on the hypothetical vacuum plasma is zero.)

It would seem that all we need to get Q-thrusters to work is an electrically charged quantum vacuum plasma. From the name, evidently those promoting this scheme think the $Q\overline{Q}$ condensate of QCD will do this. The condensate, of course, is electrical charge neutral. But that's because equal amounts of positive and negative charge are present, so the Lorentz force will act on the condensate notwithstanding that no net charge is present. And the condensate is real according to QCD, so we don't have to worry about dealing with, say, electron-positron pairs that are "virtual" and flit into and out of existence. Or do we? Is there a fly in the ointment that this scheme purports to be?

Rhetorical question. Of course there's a fly in the ointment. The energy density of the $Q\overline{Q}$ condensate is zero. That means that the inertia of the condensate is zero too. So, even if you can move it around with Lorentz forces, there is no back reaction on the device producing the crossed electric and magnetic fields as the condensate is inertialess. Have we found a fatal flaw in this scheme? The simple answer is: yes. But if you are determined to find a way to push off the vacuum, you have to find something with non-zero energy density therein to push off of. What about the electron-positron pairs? The problem with electron-positron pairs is that the known density of the vacuum — $\sim 2 \times 10^{-29}$ gm/cm^3 – is so small that there aren't anywhere remotely enough such pairs in the local vacuum to produce a detectable back reaction. Throwing a few tennis balls off of an aircraft carrier won't make it move detectably.

This is where the $Q\overline{Q}$ condensate comes in (and why advocates presumably call these things Q-thrusters). If you treat the condensate as a continuous substance and calculate its hydro-dynamical behavior, you will find that disturbances in the condensate propagate with infinite velocity. Why? Because the substance, with zero energy density, has no inertia. (Think proverbial massless springs of elementary mechanics.) From the point of view of pushing off the vacuum, this isn't a bad thing. It means that disturbances in the condensate can be communicated instantaneously throughout the universe. That means in turn that if you produce a disturbance in the condensate with your Q-thruster, that disturbance shows up instantly everywhere in the universe. Now, the known value of the mean matter density in the universe limits virtual electron-positron pairs to a pair every one to two hundred cubic centimeters or so, but if the disturbance in the condensate can effectively act on at least a large fraction of all of the pairs simultaneously and instantly, and if the back reaction is communicated back to the thruster instantaneously, then pushing off the vacuum becomes a plausible proposition.

Actually, if you admit that the $Q\overline{Q}$ condensate can act on normal matter, you can dispense with the electron-positron pairs of the quantum vacuum, for all that is really needed is a reaction mass for the field to act on. And all you need out there in the universe is enough matter with inertia to act on. It need not be the pairs of the electromagnetic quantum vacuum (which, according to theory, have much larger density than that of cosmic matter).

Is the Q-thruster scheme a plausible proposition? No. The instantaneous propagation of signals that convey real energy and momentum, even if only to and from virtual particles of the quantum vacuum, is a gross violation of the *principle* of relativity. Such processes are simply prohibited by relativity. Known since Galileo invented it in the early 17th century, the evidence for the correctness of the principle of relativity is simply overwhelming – quantum "entanglement" processes notwithstanding.

You may be wondering why Mach effects, which depend on Mach's principle, aren't discredited by the same sort of argument? After all, inertial reaction forces, due to the gravitational action of chiefly distant matter, are instantaneous. The trick that Sciama used to simplify an otherwise messy integration – taking the universe as moving "rigidly" past a test particle considered instantaneously at rest – makes it appear that inertial forces can be ascribed to a strictly local interaction between the gravity field of the universe and the test particle. (This is why Faraday invented the field concept in the first place.) But this view is deceptive. Inertial forces are acceleration dependent, but *not* velocity dependent, and thus involve propagating disturbances in the gravity field. Those disturbances propagate at the speed of light in vacuum, just like gravity waves. Instantaneity is accounted for by including advanced, as well as retarded, solutions of the field equations – as in Wheeler-Feynman "action-at-a-distance" electrodynamics. Can this "trick" be used to salvage the "quantum vacuum plasma thruster" scheme? No. The propagation velocity of disturbances in a zero energy density field like the $Q\overline{Q}$ condensate is infinite, so the action-at-a-distance scheme doesn't help. John Cramer, by the way, has shown that entanglement phenomena of quantum mechanics can also be explained in this way in his "transactional interpretation" thereof[3]. So appeal to the supposed instantaneous action of quantum phenomena cannot be claimed.

ACKNOWLEDGEMENT

Many people have contributed to the Mach effects project over the years, including in the past year or two, my colleagues Heidi Fearn and Keith Wanser. Since STAIF II concluded, an evaluation of the project was initiated at Aerospace Corp, and the members of the evaluation team (led by Greg Meholic) have made a number of helpful suggestions to advance the work. I am indebted to Takaaki Musha for prodding me into writing down an account of my comments at the conference.

REFERENCES

[1] M.Alcubierre; The Warp Drive: Hyperfast Travel within General Relativity, Class.Quant.Grav., **11**, L73-L77 **(1994)**.

[2] C.H.Brans; Mach's Principle and the Locally Measured Gravitational Constant in General Relativity, Phys.Rev., **125**, 388-396 **(1962)**.

[3] J.Cramer; The Transactional Interpretation of Quantum Mechanics, Rev.Mod.Phys., **58**, 647-697 **(1986)**.

[4] A.Einstein; The Meaning of Relativity, Princeton University Press, Princeton, **(1955)**.

[5] H.Fearn, *et al.*; Experimental Tests of the Mach Effect Thruster, IAC-13-C4.8.4, **(2013)**.

[6] M.Morris, K.Thorne; Wormholes in Spacetime and their use for Interstellar Travel: A Tool for Teaching General Relativity, Am.J.Phys., **56**, 395-412 **(1988)**.

[7] D.Overbye; Einstein and the Black Hole, The New York Times, D1, 12 August, **(2013)**.

[8] A.Pais; Subtle is the Lord: The Science and the Life of Albert Einstein, Oxford University Press, Oxford, **(1982)**.

[9] D.Sciama; On the Origin of Inertia, Mon.Not.Roy.Astron. Soc., **113**, 34-42 **(1953)**.

[10] F.Wilczek; The Lightness of Being: Mass, Ether, and the Unification of Forces, Basic Books, New York, **(2008)**.

[11] J.Woodward; Making the Universe Safe for Historians: Time Travel and the Laws of Physics, Found.Phys.Lett., **6**, 1-39 **(1995)**.

[12] J.Woodward; Making Starships and Stargates: the Science of Interstellar Transport and Absurdly Benign Wormholes, Springer-Verlag, New York, **(2012)**.