



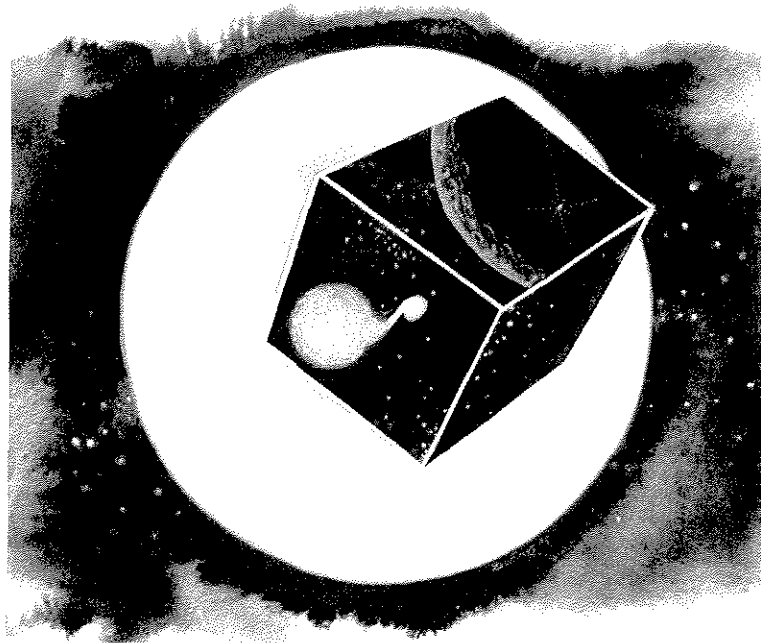
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**Report on the NASA/JPL Workshop on
Advanced Quantum/Relativity Theory
Propulsion**

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ABSTRACT

In May 1994, NASA and JPL sponsored a workshop on advanced quantum/relativity theory propulsion concepts to establish and use new frames of reference for thinking about the faster-than-light (FTL) question. Using the horizon mission methodology, the participants reviewed wormholes; a hypothetical physics where the speed of light (c) is a lower bound; and the physics of additional space dimensions. While the participants did not identify any obvious method to achieve FTL travel they did identify enough open issues in physics that FTL travel could not be ruled out. Moreover, several experiments were identified that could elucidate some possible FTL-related phenomena.

1. INTRODUCTION

Contained within the paradigm of the human race as a species genetically predisposed toward exploration is the view that eventually our species will expand beyond the Solar System. In order to realize interstellar civilizations in which the vast distances between star systems must be spanned in times much less than the lifetimes of the crew and the people remaining on the planets, there must be a revolution in transportation technology. However, the general opinion within the physics community has been that the special theory of relativity precludes such short transit times because they would involve faster-than-light (FTL) travel.¹

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In an effort to address the FTL question the Office of Advanced Concepts and Technology (OACT) of NASA Headquarters and the Jet Propulsion Laboratory (JPL) sponsored a workshop on advanced quantum/relativity theory propulsion at JPL on 16-17 May 1994. Appendix 1 lists the attendees at the workshop.

The first premise of the workshop was that theoretical perspectives exist in advanced quantum and relativity theory that could conceivably permit FTL travel or information transfer. A second premise was that investigation of these perspectives from other frames of reference could possibly provide fresh insights.

The purpose of the workshop was to establish and use new frames of reference for thinking about the FTL problem. The objectives of the workshop were to

- identify theoretically permitted "scientific windows" that could permit FTL travel or information transfer;
- identify manifestations of the underlying physics;
- identify avenues of scientific and technological research to explore and validate the possibilities;
- define (where possible) enabling technology concepts for FTL travel; and
- introduce the horizon mission methodology as a tool for thinking in other frames of reference.

The critical reader should be aware that even though the special theory of relativity seems to present insurmountable obstacles to FTL travel or communication (infinite energies, time travel paradoxes, etc.) there are at least thirteen "things"

that move faster than light^{2,3,4}

- Scissor-blade intersection
- Searchlight beam image
- Eclipse shadow
- Perfectly rigid rod
- Galloping waves
- Quasar expansion
- Plasma phase velocity
- Marquee light
- Comet tail
- Riptide
- Oscilloscope trace
- Expansion of spacetime
- "Practical speed" of a nearly-as-fast-as-light spaceship

More recently there have been a series of experiments showing either that light quanta can tunnel through barriers or that microwaves can travel through the "forbidden regions" of a wave guide at speeds greater than the speed of light, although it is not certain that this technique allows signals (in Einstein's sense of transmitting useful information) to be sent.^{5,6} Even Einstein wrote that ". . . our result shows that, according to the general theory of relativity, the law of the constancy of the velocity of light *in vacuo*, which constitutes one of the two fundamental assumptions in the special theory of relativity and to which we have already frequently referred, cannot claim any unlimited validity. A curvature of rays of light can only take place when the velocity of propagation of light varies with position".⁷

1.1 Horizon Mission Methodology

Recognizing that solving a problem in advanced missions or technology by extrapolating from the conventional technology can create obstacles to breakthrough solutions, John L. Anderson of NASA Headquarters developed the horizon mission methodology (HMM). As Anderson has written, "The Horizon Mission Methodology is a highly structured process for both creating and thinking within a new frame of reference. It is not a process of forecasting, scenario-generation or brainstorming. It first poses a truly challenging, relevant space future that is beyond our reach. The process then places people mentally in that 'fixed' future, which is treated as an accomplished fact. Next it stimulates the imagination to generate breakthrough-based alternatives for accomplishing that future and to reconstruct pathways that could have led to it. This process requires significant mental discipline to 'stay in character,' but it is

highly productive".⁸

As shown in Figure 1, the HMM is based on creating a future frame of reference for evaluating a topic. In the case of the advanced quantum/relativity theory propulsion workshop the invited participants were asked to imagine that they were in the future where FTL travel or information transfer had been achieved and then to "look backward" to see how it was accomplished. In essence, are there theoretically permitted reinterpretations of physics or "scientific windows" that could permit FTL travel?

These scientific windows could be expressed in terms of new axioms or principles such as

- Cosmic (spacetime) tunnels exist and can be used.
- There exists an "entire physics" in which the speed of light (*c*) is a *lower* bound.
- Other, perhaps "higher" dimensions exist that can interact with the spacetime that we know.

For each of these scientific windows background information was provided by specialists in the field and then the participants discussed the particular scientific window using the horizon mission methodology to "look backward" to see how that particular scientific window could have led to FTL travel or communication.

The following sections discuss these three scientific windows as they were covered in the workshop. For each scientific window, the participants were asked to consider the following questions:

- What properties does it have?
- What is the evidence for/manifestation of?
- What are the alternative physics interpretations?
- What are the implications and manifestations of these alternative interpretations?
- What avenues and approaches can be taken for validation?
- What are the potential technological concepts?

1.2 FTL Horizon Missions

Robert H. Frisbee, who was the JPL host and organizer of the workshop, followed the HMM discussion with an overview of the three principal scientific windows. He noted that any interstellar mission, whether conventional or FTL, will require

major investments by human society. For example, an interstellar fusion rocket will require on the order of 37 TW of power while a laser lightsail will require 1500 TW. In contrast, an Apollo Saturn V at liftoff produced 0.04 TW. (Current power production by human technology on Earth is about 1 TW or an annual energy production of about 10^4 TWh.)

For wormholes and warp drives, Frisbee noted that the traditional science fiction assumption is for on-board "warp" engines but that the newer approach is to use wormholes (either artificial or natural). Two recent science fiction novels have been based on the wormhole theory developed by Michael Morris and Kip S. Thorne.^{9,10} R. L. Forward had earlier reviewed various concepts of space warps.¹¹

For physics where "c" is a lower bound, Frisbee included tachyons, imaginary mass neutrinos, advanced solutions to the Maxwell and/or Schrodinger equations, and quantum connectedness. One of us (GLB) has used this approach with tunnels to higher dimensions in a science fictional view of FTL.¹²

For additional space dimensions, Frisbee noted the possible relevance of twistor theory, extra dimensions (e.g., string theory) and quantized spacetime.

Additional written material on possible FTL physical phenomena was provided to the participants in advance of the workshop. This material has since been published for a more general readership.¹³ Summaries of the workshop have been separately published to a wider audience by Cramer and Forward.¹³⁻¹⁵

2. WORMHOLE PHYSICS

The participants began by reviewing wormhole theory, wormhole engineering and then considering wormholes within the context of FTL HMM.

2.1 Traversable Wormholes and Timeholes

Michael S. Morris provided an overview of wormhole theory. He began by showing that black holes are not traversable. He showed there can be enormous tidal forces even at the horizon of a black hole so that unless the black hole is very large ($>10^5$ solar masses) a human being could

not even survive the trip to the horizon. Even variations on the classic static black hole present problems. A Schwarzschild (spherically symmetric) wormhole would pinch off into infinite tidal forces before anything could get through. The horizon of a black hole is a one-way membrane, i.e., once inside nothing can get back out. For Kerr (rotating) black holes and Reissner-Nordstrom (charged) tunnels, Morris observed that while they are mathematically exact they are unrealistic with ring-shaped singularities and that the interim tunnels are unstable.

Morris listed the following desired properties for traversable wormholes (see also Ref. 16 and 17):

- Wormholes are spherically symmetric, static (time independent) spacetimes;
- Wormholes are tunnels that connect asymptotically flat regions;
- They everywhere satisfy the Einstein field equations;
- They must have no horizons;
- Tidal forces must be everywhere bearably small;
- Travel time must be convenient;
- The tunnels must be perturbatively stable;
- The assembly must be feasible; and
- Any construction material must be possible to get.

Morris noted that the first four properties contain the key features ("basic wormhole criteria") while the fifth and sixth properties are conveniences for human comfort ("usability criteria"). (The first property permits finding simple solutions to Einstein's equations.) The seventh and eighth properties are dynamical questions which are not easily addressed. Figure 2 is a sketch of a traversable wormhole tunnel without horizons connecting Earth with the Sirius star system.

Morris outlined the wormhole solutions to the Einstein field equations that might allow humans to traverse the wormhole. To overcome the horizon problem with black holes the wormhole must not have a horizon in its throat. Coupling this constraint with the Einstein field equations leads to a form of "exotic matter" to generate the wormhole's curvature. This material must have a

radial tension approaching the pressure at the center of a massive neutron star:

$$\text{Tension} \sim 10^{42} \text{ dynes/cm}^2 [10 \text{ meters}/b_0]^2$$

where b_0 is the throat radius.

Morris observed that for humans to be able to survive a trip through the wormhole, even in a suitable spaceship, this exotic material must not couple strongly to ordinary matter.

Another serious problem is that the tension of this exotic material must exceed the material's density of mass-energy which violates the weak energy condition (the condition in which it is forbidden to have observers seeing a negative mass density).¹⁶⁻¹⁸ While Morris commented that the violation of the weak energy condition was deeply troublesome it is not possible to rule out such exotic material by any present-day knowledge of physics. He listed other examples of violations of the weak energy condition in (1) quantum field theory in curved spacetime; (2) the Unruh vacuum near the horizon of a black hole; (3) the squeezed state of the vacuum; and (4) the Casimir effect.

An additional potentially serious problem with wormholes is that while one static wormhole tunnel in the universe seems to cause no difficulty with causality violations, two wormholes can cause violations of causality.

2.2 Wormhole Engineering

Matt Visser summarized our knowledge of wormholes and then discussed how wormholes might be constructed. References 19-27 describe some of Visser's work on wormholes. Visser noted that one approach to constructing a wormhole is to surgically modify Minkowski space, i.e., "cutting similar holes in two regions of space-time and then sewing the edges together".

Referring to Figure 3, Visser suggested taking two copies of Minkowski space (with time suppressed) and excising two identical compact regions Ω_1 and Ω_2 . Next one identifies the two boundaries $\partial\Omega_1 = \partial\Omega_2$. Visser observed that the surface $\partial\Omega \times (\text{time})$ is now a timelike hypersurface, that is, it is the throat of a wormhole. He pointed out that this spacetime is geodesically complete and that it has two asymptotically flat regions. By inspection he said the Riemann tensor is identically zero *except* at the throat ($\partial\Omega$) where we would expect the

Riemann tensor to have the appearance of a delta function.

To minimize the use of exotic matter Visser considered a case in which the wormhole throat has one face that is flat. On such a flat face the radius of curvature would be infinite. A traveler intercepting the flat face would feel no forces (tidal or otherwise) and would encounter no exotic matter. The traveler would simply be shunted into the other universe. In effect, while exotic stress energy may be necessary for wormhole construction, it may be hidden from the traveler.

Visser reviewed the concept of exotic matter, noting as Morris had that there is negative energy density ("exotic matter") at the throat of the wormhole. He pointed out that exotic matter is not the same as antimatter. For example, where a positive energy focuses light, negative energy defocuses light and violates the weak energy condition.

As another example of minimizing the use of exotic matter Visser considered the possibility of the throat of a wormhole being a cube with rounded edges and rounded corners as illustrated in Figure 4. This gives six flat faces with infinite curvature, twelve edges that are quarter cylinders and eight corners which are octants. In a cubical wormhole all the stress energy would be concentrated in the twelve struts which from Einstein's equations would have a mass per unit length (μ) of -1.52×10^{43} J/m

Visser estimated that a 1-m cube would require a field with a total negative mass equal in magnitude to that of Jupiter.

The struts would have to be built out of negative tension classical strings which certainly poses a challenge to current technology! However, as Cramer has observed, "The Visser Cube of wormhole mouths is reminiscent of the familiar SF notion of a star gate".¹⁴

2.3 HMM Discussion of the Physics of Wormholes

The workshop participants discussed the physics of wormholes in the context of looking backward from the future. It was generally agreed that the desirable properties of wormholes should include those elucidated above by Morris and Thorne. The participants noted that creating wormholes out of the quantum foam of the vacuum would require

mass-energies on the order of Jupiter applied to length scales on the order of the Planck-Wheeler length

$$L_{P-W} = (Gh/2\pi c^3)^{1/2} = 1.6 \times 10^{-33} \text{ cm}$$

where $G = 6.673 \times 10^{-8}$ dyne-cm²/g² is Newton's gravitation constant; $h/2\pi = 1.055 \times 10^{-27}$ erg-sec is Planck's quantum mechanical constant divided by 2π , and $c = 2.998 \times 10^{10}$ cm/sec is the speed of light.

Even the Visser cubes would require negative mass strings with linear mass densities of the order of 28 Earth-masses per meter. While these physical requirements may be possible for a sufficiently advanced civilization they appear to be well beyond current extrapolations of human capabilities.

The group considered the issue of moving one wormhole mouth relative to its companion which has the effect of creating a time machine similar to the "twin paradox" that occurs in special relativity (where one twin travels at a high speed relative to the other twin and so ages less). While there appears to be no physical reason to prohibit time travel or even the causality violations associated with FTL wormhole travel and signals, they are certainly not observed in nature.

As an aside, it is worth noting that Hawking believes that nature abhors time machines and he has gone so far as to propose a chronology protection conjecture "which says that *the laws of physics do not allow time machines*" [emphasis in original].¹⁷ As Thorne has explained it: "Whenever one tries to make a time machine, and no matter what kind of device one uses in one's attempt (a wormhole, a spinning cylinder, a 'cosmic string', or whatever), just before one's device becomes a time machine, a beam of vacuum fluctuations will circulate through the device and destroy it" [emphasis in original].¹⁷

Earlier, Herbert had written that "To plug these leaks and clearly establish all notions of superluminal transport as heretical, physicists added an extra assumption to Einsteinian relativity, an assumption we call the causal ordering postulate, or COP . . . A curious aspect of COP is that it does not require that a cause always precede its effect. COP actually permits backward causality, in which an event in the future influences what happens in the past. However if

such backward-causal events actually occur in nature, COP requires that they appear backward-causal in all reference frames . . . COP is not part of relativity but is an extra assumption concerning the presumed nature of causal relations in space-time".²

It is also worth noting that this is not the first time that the issue of causality has arisen. Henry Margenau, in discussing the philosophical legacy of the quantum theory has stated that "*causality is a methodological, nonempirical regulative maxim which belongs to the metaphysical domain*" [emphasis in original].²⁸ Margenau went on to point out that ". . . if we insist on the older definition of states even with respect to subatomic systems, it turns out that there is no law known to science by which such states are propagated in time. Hence, those who feel that an electron, for example, is still a particle and as such must be described by the good old Newtonian concept of state (position and velocity) are forced to admit that causality has failed".²⁸ As a consequence, Margenau specifically called attention to the philosophical consequence that our classical concept of causality had to be abandoned in quantum theory in favor of a new relation termed *stochastic* or *statistical causality*.²⁸ In this way physicists were allowed to get on with the application of quantum theory which has been shown to be one of the most successful theories in physics. By analogy, one is entitled to wonder if a new definition of causality is in order for FTL-related phenomena.

Kip S. Thorne and his colleagues have investigated closed timelike curves (CTCs) (e.g., time machines) finding "that CTC's may not be as nasty as people have assumed" because "they do not affect Gauss's theorem and thus do not affect the derivation of global conservation laws from differential ones. The standard conservation laws remain valid globally, and in asymptotically flat, wormhole spacetimes they retain a natural, quasilocal interpretation".²⁹ Thorne has observed that "It may turn out that on macroscopic lengthscales chronology is *not* always protected, and even if chronology *is* protected macroscopically, quantum gravity may well give finite probability amplitudes for microscopic spacetime histories with CTCs".³⁰ Whether or not CTCs exist, such theoretical explorations into the frontiers of quantum and relativity theory will clearly add to our understanding of the universe.

Two of the workshop participants had earlier considered causality as one of several boundary conditions on assumed FTL travel.³¹

Having considered the construction of wormholes, the group then considered the possible occurrence of natural wormholes, perhaps even wormholes left over from the big bang creation of the universe. If one of a pair of wormhole mouths accretes "normal" positive mass then the other mouth will in effect have a negative mass. If wormholes exist they could signal their presence through the appearance and disappearance of mass or through the repulsive gravity field of the negative energy density exotic matter. Related to such primordial wormholes there has been theoretical speculation that cosmic strings may have been created in the big bang; could then cosmic strings of negative mass have been created that might hold open the mouth of a wormhole?

Several workshop participants suggested an astronomical search for such negative mass wormholes. It is known that dark body objects termed massive compact halo objects (MACHOs) will cause a lensing effect if they pass between Earth and a distant star. In effect the starlight is bent causing an increase of the perceived brightness of the star.³²⁻³⁵

A negative mass object would cause a different brightness versus time profile. The gravitational field of the negative mass would force the starlight into a paraboloid shape such that an observer on Earth would first see an increase in brightness followed by a sharp cutoff followed by another peak that gradually tapers off. The cutoff results from the shadow zone or demagnification zone within the paraboloid. These workshop participants subsequently published a paper in *Physical Review* with this abstract.³⁶

"Once quantum mechanical effects are included, the hypotheses underlying the positive mass theorem of classical general relativity fail. As an example of the peculiarities attendant upon this observation, a wormhole mouth embedded in a region of high mass density might accrete mass, giving the other mouth a net *negative* mass of unusual gravitational properties. The lensing of such a gravitationally negative anomalous compact halo object (GNACHO) will enhance background stars with a time profile that is observable and qualitatively different from that recently observed for massive compact halo

objects (MACHO's) of positive mass. While the analysis is discussed in terms of wormholes, the observational test proposed is more generally a search for compact negative mass objects of any origin. We recommend that MACHO search data be analyzed for GNACHO's."

As a result of this work, the astronomers searching for evidence of MACHOs will also examine their data for the specific double-peaked light intensity profile that is predicted to be caused by the gravitational lensing of a negative mass. One double peak has been found by the Optical Gravitational Lensing Experiment (OGLE) group and confirmed by the MACHO team but the shape, which was different from that predicted for GNACHOs, suggested gravitational lensing that was caused by a binary system.³⁷

Morris, in his presentation, and Cramer noted that the vacuum is squeezed near a black hole and therefore has negative energy density (and mass). This effect does not integrate out to a significant negative mass near a stellar-mass black hole because only wavelengths greater than about 5 km are affected. Near Planck-mass quantum black holes ($\sim 10^{-35}$ m), all wavelengths greater than the Planck-Wheeler length ($\sim 10^{-35}$ m) would be squeezed. Cramer talked about the possibility of using this negative energy to stabilize a Morris-Thorne wormhole. The participants wondered if there is any way to experimentally verify the existence of negative energy in a region of squeezed vacuum. One question raised was whether the integral of the negative energy in the volume of squeezed vacuum around a quantum black hole might equal the Planck mass which might explain why the high mass-energy density of the vacuum fluctuation "quantum foam" is not observed.

Following the workshop, a letter by Miguel Alcubierre of the University of Wales in Cardiff proposed a mechanism for expanding and contracting spacetime near a spaceship to achieve FTL travel.^{38,39} His abstract states:³⁸

"It is shown how, within the framework of general relativity, and without the introduction of wormholes, it is possible to modify a spacetime in a way that allows a spaceship to travel with an arbitrarily large speed. By a purely local expansion of spacetime behind the spaceship and an opposite contraction in front of it, motion faster than light as seen by observers outside the disturbed region is possible. The resulting

distortion is reminiscent of the 'warp drive' of science fiction. However, just as happens with wormholes, exotic matter will be needed in order to generate a distortion of spacetime like the one described here."

This, in effect, reaffirms the view of the workshop participants that a search should be made for the effects of negative matter ("exotic matter") in astronomical lensing data

3. PHYSICS WHERE THE VELOCITY OF LIGHT IS A LOWER BOUND

R. H. Frisbee set the stage for this portion of the workshop which was concerned with a hypothetical physics in which the velocity of light (c) would be the lower bound. As noted earlier this area includes tachyons (hypothetical FTL particles), imaginary mass neutrinos, advanced solutions to the Maxwell and/or Schrodinger equations, and quantum connectedness.

3.1 General Overview of Physics Where the Velocity of Light is a Lower Bound

J. G. Cramer summarized the theory of tachyons which are hypothetical FTL particles first postulated by O. M. Bilaniuk, V. K. Deshpande, and E. C. G. Sudarshan.⁴⁰⁻⁴² From the special theory of relativity we know that the following relationship holds between the mass m of a particle and its rest mass m_0

$$m = \frac{m_0}{(1 - \beta^2)^{1/2}}$$

where $\beta = v/c$ and m_0 is the mass measured in the proper ("rest") frame of the particle. This well-known relationship clearly illustrates the problem in pushing any object to and beyond the speed of light. Similarly, a time interval Δt between two events measured in a frame moving with velocity $\pm v$ relative to a frame in which the corresponding time interval $\Delta t'$ is proper (i.e., the two events occur at one place) is given by

$$\Delta t = \frac{\Delta t'}{(1 - \beta^2)^{1/2}}$$

The total energy (E) for a finite mass particle is given by the sum of the kinetic energy of the particle and its rest-frame energy (E_0):

$$E = mc^2 = \frac{m_0 c^2}{(1 - \beta^2)^{1/2}}$$

or in terms of the square of the energy which is often what is measured

$$E^2 = p^2 c^2 + m_0^2 c^4$$

where p is the momentum of the particle. For a tachyon which, by definition, has a velocity $v > c$, the following properties apply in order to have measurable (real) numbers for the energy and momentum

- m_0 is imaginary ($m_0 = i |m_0|$, where $i = \sqrt{-1}$)
- $E^2 = p^2 c^2 - m_0^2 c^4$
- $\beta > 1$ ($v > c$ always); note that $\beta = p c/E$
- $p = E \beta/c$ as usual and it cannot go to zero
- When $|p| = |m_0 c|$ (the minimum value)

$$\beta \rightarrow \infty$$

$$E \rightarrow 0$$

- The lowest values of the mass-energy is zero (not $i |m_0| c^2$), and there $\beta = \infty$

From the foregoing, Cramer listed the following properties for "bradyons" ("normal", sublight matter) and tachyons:

| <u>Property</u> | <u>Bradyons</u> | <u>Tachyons</u> |
|-------------------------------|--|-----------------|
| Minimum speed | 0 | c |
| Maximum speed | c | ∞ |
| Minimum mass-energy | $m_0^2 c^2$ | 0 |
| Minimum momentum | 0 | $ m_0 c $ |
| Mass-energy momentum relation | $E^2 = p^2 c^2 + m_0^2 c^4; p^2 = (E/c)^2 + m_0 ^2 c^4$ | |

Cramer called attention to the fact that (at the time of the workshop) some of the published values of the electron neutrino mass-squared (m_ν^2) were negative such that the mass of the electron neutrino might be about $12i$ eV (1.8×10^{-36} kg = 2×10^{-6} electron mass) meaning that the electron neutrino could be a tachyon. Forward summarized the measurements on the muon

neutrino mass reporting that the latest (at the time of the workshop) implied a mass of about $0.4 \text{ eV}/c^2$ ($7 \times 10^{-31} \text{ kg} = 0.8 \text{ electron mass}$).

It was noted that a small number of neutrinos had been detected in various detectors just before the visual observation of Supernova (SN) 1987A. The participants wondered if there was any correlation between the arrival time and the energy of the neutrinos. (A faster, lower-energy tachyon would arrive sooner than a nearer "c", higher-energy tachyon.)

Cramer and Forward suggested (and the attendees heartily agreed) that there was a need to measure accurately the mass of the electron neutrino. (Since the workshop, there have been reports, but no peer-reviewed published scientific evidence, that the masses of both the muon and electron neutrinos lie somewhere between 0.5 eV and 5 eV.⁴³ However, the last published scientific paper known to the authors showed imaginary mass. Since the neutrino was originally thought to be massless and to travel at the speed of light such measurements, if confirmed, would require a fundamental rethinking of neutrinos. Neutrinos with mass might also account for some of the missing mass of the universe.)

Cramer noted the following

- Unlike normal matter and light (photons), in theory, tachyons can escape from a black hole because they travel faster than the speed of light. Theoretically a tachyon moves in the opposite manner to normal matter--as energy is removed the tachyon speeds up until at zero energy a tachyon would move at infinite speed. Thus, as the gravity field of a black hole removes energy from a tachyon the tachyon would speed up to infinite speeds. According to theory, information (negative entropy) is trapped in a black hole. "Hawking radiation" would remove mass-energy from a black hole but not information. However, a "stripped" tachyon could remove information at infinite speed. (For the interested reader, Jayant V. Narlikar, among others, has studied the interaction of tachyons with gravity.⁴⁴)

- If neutrinos have a mass of 12 eV then it should in principle be possible to construct a nuclear reaction (for example, one in which the products are an electron neutrino and an electron anti-neutrino) in which tachyons are emitted with zero energy (hence infinite speed) but with momentum of $12 \text{ eV}/c$. The tachyons would

provide a finite recoil momentum at no energy cost which would make them ideal "rocket fuel".

Cramer listed several problems that need to be addressed:

- Are neutrinos tachyons?
- Are there any nuclear reactions that would produce such a tachyon drive?
- How would one go about solving the engineering problems?

3.2 The Casimir Effect

Cramer called the workshop's attention to the Casimir effect in which closely spaced, grounded capacitor plates allow only the electromagnetic modes that "fit into the gap" (only photons with wavelengths less than twice the separation distance of the plates are allowed). Consequently the free energy of the vacuum between the plates is lowered and the plates experience a compressive force pushing them together.

According to quantum electrodynamic (QED) theory, photons can change into a variety of short-lived or "virtual" particles (such as virtual electron and virtual positron pairs) as they travel. Based on some theoretical work done by K. Scharnhorst some of the virtual particle modes may be eliminated for a photon traveling between the plates which should have the effect of increasing the speed of light. For photons traveling perpendicularly between plates separated by $1 \mu\text{m}$, the speed of light is increased by about one part in 10^{36} over its value in the vacuum.⁴⁵⁻⁴⁷

3.3 The Formalism of Quantum Mechanics

In view of the relevance of quantum mechanics to questions of causality (which arise in studying FTL phenomena) and its possible allowance of FTL, Cramer provided an overview of the formalism of quantum mechanics. As John Archibald Wheeler has observed: "The quantum is the 'crack' in the armor that covers the secret of existence. And I think we have to find out what lies under that armor to get to the bottom of things. That's the biggest mystery".⁴⁸

One of the puzzling aspects to quantum mechanics was elucidated by Albert Einstein, Boris Podolsky, and Nathan Rosen in 1935, the so-called "EPR" thought experiment in which the three physicists considered the interaction of two

correlated particles. Applying quantum mechanical rules to the EPR thought experiment one sees that any measurement of particle 1 immediately influences the state of particle 2 no matter how far apart they may be. If the distance separating the particles is space-like (non-local) then the influence that tells particle 2 what state to be in when a measurement is made on particle 1 must be traveling at FTL velocities. Attempts to explain this by sub-quantum effects (such as "hidden variables") were excluded by the work of John S. Bell. Cramer cited two works which experimentally showed that quantum mechanics (and not some hidden variable theory) correctly predicts the correlation of two particles.^{49,50} Thus, quantum mechanics has buried within it the idea of instantaneous, i.e., FTL, communication between particles no matter how far apart they are.

Cramer showed that from a quantum mechanical perspective the EPR non-locality could not be used for FTL communication. However, he called attention to some work by Steven Weinberg showing the possibility of small, non-linear effects in quantum mechanics which, if present, would allow an FTL signal to leak through based on theoretical work by Joseph Polchinski.

The workshop participants noted that both quantum mechanics (via the Schrodinger equation) and classical electrodynamics (via Maxwell's equations) allow two solutions: waves traveling forward in time ("retarded wave" solution) and waves traveling backward in time ("advanced wave" solution). As Cramer has written, "The advanced-wave solutions of the electromagnetic wave equation are usually ignored as unphysical because they seem to have no counterpart in nature".⁵¹ If, however, advanced waves could be found they could conceivably provide a way to send messages to the past. To overcome the apparent paradoxes in the standard Copenhagen interpretation of quantum mechanics, Cramer has developed a "transactional interpretation" of quantum mechanics in which a quantum event is described by the exchange of advanced and retarded waves.^{51, 52} It is possible that some combination of retarded and advanced (if they exist) waves could be used for FTL communication.

At this point it is worth observing that if the many worlds interpretation of quantum mechanics first proposed by Hugh Everett III is valid, then quantum mechanics offers a way out of the time

travel paradoxes inherent in FTL travel. According to this interpretation the universe is constantly branching (in other words, all of the possible outcomes of a quantum mechanical calculation are real) so that the past a traveler could theoretically return to would be in one of these parallel universes and not in the universe he/she left. Hence, there would be no way for the travel to cause or create paradoxes.⁵³

3.4 HMM Discussion of Physics Where "c" is a Lower Bound

The workshop participants discussed tachyon theory, the Casimir effect and quantum theory. It was noted that while there had been some possible evidence for tachyons in measurements of cosmic ray showers in the 1970s there appeared to be no confirmatory support for the existence of tachyons. (The interested reader is referred to references 54 to 57 for reports on some of the early searches for tachyons. Michael N. Kreisler concluded in 1973 that ". . . the limits on the existence of tachyons have been pushed quite low. This author, at least, would be very surprised if they were found".⁵⁶)

Related to the Casimir effect, one idea suggested during the workshop was surrounding a moving spaceship with a "bubble" of highly energy-depleted vacuum where the speed of light would be greater so the spaceship could travel at FTL velocities. Cramer has written that "This speculation produced the following thought experiment. Suppose that one produces an energy-depleted region of space using the Casimir Effect and then somehow makes the parallel conducting plates disappear. What happens to the 'bare' volume of energy-depleted space left behind? Does it return to normal space? If so, where does the energy come from to make up for the energy that is missing? Does the volume of energy-depleted space persist as a 'bubble'? If so what shapes does it assume? Does it expand or contract?"¹⁵

The workshop participants discussed the possibility of determining if an FTL signal could be transmitting through modulating a beam of neutrinos. To take advantage of the possible low mass (~12 eV) of the neutrino, it was suggested that the target nuclei (such as doubly charged helium-3) be accelerated into the neutrinos. Detection of such neutrinos is not currently feasible.

Other observations and comments from the participants included the following:

- If neutrinos have a non-zero rest mass (of any kind), then a gravitational lens will affect them differently from how the lens affects photons. (It was noted that photons have zero rest mass to 10^{-20} eV from a reported measurement of the magnetic dipole field structure of Jupiter.)
- Neutrino oscillations (which is a postulated phenomenon that has been proposed as an explanation of why we don't observe all the neutrinos predicted to be released from the nuclear reactions in the Sun) require a non-zero rest mass. What do neutrino oscillations mean if the square of the neutrino mass is negative? If the tau neutrino has a positive or zero rest mass, could a neutrino oscillate from a tachyonic electron neutrino to a bradyonic or luxonic tau neutrino (in effect "tunneling" through or to the speed-of-light barrier)?
- Are monoenergetic neutrinos produced in K-capture processes? Would this make them easier to detect? Could such neutrinos be directed by orienting the atom?
- Is a $+i$ tachyon different from a $-i$ tachyon or are they just antiparticles of each other?
- What properties would a non-neutrino tachyon have that would be experimentally observable?
- Will a charged tachyon (if it exists) emit Cerenkov radiation in a vacuum? (Here there is a difference of opinion depending on the model one uses. The model that explains Cerenkov radiation as coming from the re-radiation reaction of the atoms in the transparent material surrounding the particle path would not predict such radiation from a charged tachyon. The model that explains Cerenkov radiation as being caused by "kinks" in the electrostatic field emitted by the charge on the tachyon would predict such radiation.)
- Is the Higgs boson a tachyon?
- Could a neutrino-antineutrino "Cooper pair" be a bosonic tachyon?

The workshop participants agreed that the following experiments would provide extremely useful information regarding physics where "c" is a lower bound:

- Good, confirmatory, unambiguous measurements of the mass of the three flavors of neutrinos (electron, muon, and tau neutrinos) should be undertaken to clarify whether or not the neutrino is a tachyon. Are there any other neutrino rest mass experiments possible other than using molecular tritium and pion decay? (One idea to overcome questions about the experimental effects of molecular tritium which is usually used in measuring the mass of the electron neutrino would be to put tritium or K-capture atoms in a Penning or other trap, cool them to millidegrees Kelvin, and then measure the energy of all particles and photons emitted.)
- Good measurements of the velocity of light perpendicular to the Casimir plates should be made to determine if the speed of light is increased as predicted. (This may be measurable if the effect can be turned into a frequency measurement.) Because the mass of a particle is related to the energy and speed of light through Einstein's equation $m = E/c^2$, changes in "c" should lead to changes in "m"; therefore, Casimir-type experiments could also focus on measuring the mass of particles between the plates. Would the rest mass of a particle between Casimir plates be less than the rest mass in a vacuum? Since the velocity of light between Casimir plates is anisotropic (greater than "c" normal to the plates but equal to "c" parallel to the plates) does this mean that the rest mass is also anisotropic? Can this be measured?
- Experiments run at very high energies (to reach the smallest scales and times) could possibly determine if there are any Weinberg-type nonlinearities in quantum mechanics that could be exploited for FTL communication.
- Using a laser to focus enough energy in "empty" space might cause negative-energy virtual pairs to become positive-energy pairs thereby proving the existence of virtual particles.
- Good, time-phased studies of cosmic ray showers should be undertaken to determine if tachyons are present. R. L. Forward suggested a space-based experiment in which the cosmic rays and their secondary particles would impact incident and secondary targets respectively of known compositions on board a specially designed satellite as illustrated in Figure 5. Detectors located a known distance from the targets (such as on a long tether that would provide gravity gradient stabilization to maintain

pointing toward the zenith) would sense any particles arriving ahead of the main shower, thereby providing a more unambiguous measurement uncomplicated by the Earth's atmosphere for the presence of FTL particles. Careful design work would be needed to provide an optimal ratio of the target thickness to target area that could both (1) be placed in space economically and (2) provide enough events per day to make the experiment worth doing.

- The detection of a nearby black hole that was a source of neutrinos would show that neutrinos must be tachyons since only FTL particles can escape from a black hole. (Could tachyon emission be the reason why we have not observed the postulated explosions of primordial black holes?)
- Some equations of state for neutron stars predict that the speed of sound in neutron star matter will be greater than the speed of light. Measurements of the frequency of the acoustical modes of a neutron star (similar to measurements that have been made of the Sun's acoustical modes) could possibly detect such an effect. *

4. PHYSICS OF ADDITIONAL SPACE DIMENSIONS

The workshop participants next considered the possibility of additional space dimensions. Traditionally, science fiction has explained FTL by invoking higher dimensions as a way to get around the speed limit of light in normal four-dimensional spacetime.

4.1 General Overview of Physics of Additional Space Dimensions

R. L. Forward provided a general overview of space-time structures, including superstring theories, Penrose twistor space, vacuum fluctuations, charge-parity-time (CPT) "space" asymmetries, point particles, and spin space. The following paragraphs summarize the discussion of these topics.

4.1.1 Superstring Theories

Regarding superstring theories, Forward observed that there are ten-dimensional (10-D) and twenty-six dimensional (26-D) versions in which particles are mathematically treated to be like the vibrations of strings. The strings have dimensions on the order of the Planck length ($\sim 10^{-35}$ m). In

effect the unseen additional dimensions are "rolled up" into this Planck-length radius. This approach avoids the infinities that occur with point particles. While the group noted that some string theories predict the existence of tachyon-like particles there was no obvious way identified to use strings for FTL travel and communication. Forward has observed that "One could 'unroll' a rolled-up dimension, use it to travel in a tachyonic mode, then roll it up. If dimensions in general can be rolled up then it might be possible to roll up one of our three space dimensions, rapidly move to a new point in the rolled up dimension, then unroll it".¹³

Forward noted that some cosmic string theories predict the temporary production of a time machine when two of these hypothetical galaxy-sized cosmic strings left over from the Big Bang pass each other fast enough.

4.1.2 Penrose Twistor Space

Forward described twistor space which is a concept that has been mathematically developed by Roger Penrose. Twistor space is an eight-dimensional complex space developed by Penrose as a non-local theory of spacetime. Twistor space represents an effort by Penrose "to probe a region deeper than the fields and particles of quantum mechanics" by using "abstract geometrical objects which operate in a higher-dimensional complex space that underlies space-time. . ."⁵⁸ (Penrose has categorized twistor theory as "tentative" which is the second lowest in his scheme for the fourfold classification of theories.⁵⁸) Forward explained that in twistor space both space and time are naturally quantized and combinations of twistors form the known particles. In twistor theory, twistor space generates the observable four-dimensional spacetime and 8-D distortions cause 4-D forces. If the 8-D twistor space is warped enough then the 4-D known space would "disappear", in effect providing a means for FTL travel. However, Forward has commented that "This is not really FTL travel, since the disappearance of space will probably happen at light speed, but it achieves the same result".¹³

4.1.3 Vacuum Fluctuations

Forward categorized vacuum fluctuations into electromagnetic fluctuations, virtual particle fluctuations and quantum fluctuations (see discussion in Section 2).

Forward explained that electromagnetic fluctuations have been experimentally confirmed through studies of surface energy and tension; Van der Waals force; and the Casimir force between conducting plates (see Section 3). Forward noted that electromagnetic fluctuations could be a possible alternative "source field" theory and that there is a remote possibility that they could be a source of energy but he saw no obvious FTL application.

Regarding virtual particles, Forward commented that they have been experimentally "confirmed" by the measured shift in the energy of the electron in the hydrogen atom (sometimes referred to as the "Lamb shift" or "Lamb-Rutherford" shift). Another outcome of the presence of virtual particles is contained in Stephen Hawking's calculations about the evaporation of black holes. Forward observed that virtual particles also represented an alternative "source field" theory which appears to work if charged particles are nearby but the theory fails for virtual pair production by laser. While virtual particles may be a possible source of energy Forward saw no obvious FTL application.

Quantum fluctuations, which have been discussed in Section 2, occur at the size of the Planck length ($\sim 10^{-35}$ m) and Planck density ($\sim 10^{93}$ g/cm³). Theoretical models include Wheeler's spacetime "foam" and Hawking's "baby universes". At present there is no good theory of quantum fluctuations and it is unknown if they could be a source of energy. For FTL purposes, the question would be, as Morris and Thorne have wondered, could quantum wormholes be "grown" large enough to provide a mechanism for FTL travel?

4.1.4 CPT "Space" Asymmetries

Forward reviewed CPT (charge-parity-time) symmetry theory which says there should be symmetry in particle behavior when charge, parity and time are interchanged. He observed that experiments have not borne out the symmetry predicted by the theory. Forward called the group's attention to the charge asymmetry between protons and anti-protons; the neutrino parity asymmetry; and the K^0 (neutral kaon) particle time asymmetry, asking if these asymmetries might provide a handle on time that could lead to time travel or if some particles (e.g. neutrinos) occupy a different "space" from other particles (e.g. photons).

4.1.5 Point Particles

Forward reviewed a number of experimental and theoretical results showing that

- quarks, muons, and electrons are points (e.g., the radius of the electron must be less than 10^{-20} cm)
- black holes are point-like (finite circumference and area with zero radius and volume)

and reminded everyone that point charges produce infinities. The question, then, is: are point charges warping spacetime? Could point particles be quantum black holes? Forward noted that the hyperfine structure of a hydrogen atom agrees to within an almost exact factor of two with the hyperfine structure one would get if the proton was replaced by a theoretical subatomic version of the Kerr-Newman black hole. Forward has asked: "Do we need quantum gravity to understand elementary particles? Is nature trying to tell us something?"¹³

4.1.6 Spin Space

Forward briefly reviewed the concept of spin as applied to elementary particles, noting that spin is not the same as the classical angular momentum of a rotating object. In particular, particles with a spin of $1/2$ ($h/2\pi$) (e.g., electrons, protons, neutrons and neutrinos) have some very peculiar properties. As an example, they must be rotated 720° in order to be turned completely over. Forward wondered if this implied the existence of a "half" dimension for these particles. What is spin space?

4.2 HMM Discussion of Physics of Additional Space Dimensions

Matt Visser suggested that instead of having the extra dimensions rolled up into Planck-length dimensions, these dimensions could form a bowl in which our universe lies at the bottom. Somehow energy or momentum would have to be added to a spaceship to move it out of this well but if such a well existed it may be that the velocity of light would be different from "c". Using five-dimensional Kaluza-Klein models it might be possible to develop a 5-D drive that operates by jumping out of this 4-D "ground state" into a "higher state", allowing access to the fifth dimension, traveling in that dimension, then dropping back into our 4-D spacetime.

5. SOME OPEN ISSUES IN PHYSICS

Over the course of the two-day workshop the participants identified a number of "open issues" in physics. As one participant commented these "embarrassing unsolved physics problems . . . may prove to be chinks in the FTL armor". The issues or problems (many of which have been summarized in the preceding sections) are summarized below:

- "Point-like" (zero dimensional) properties of electrons, muons, and quarks.
- Lack of a quantum theory of gravity.
- FTL "quantum connectedness" of distant entangled particles.
- Extreme predicted (but unobserved) densities for vacuum fluctuations.
- Existence of spin.
- Internal structure of elementary particles.
- CPT asymmetries.
- Lack of a theory of inertia.
- Missing mass in the Milky Way Galaxy, galactic clusters, and the universe.
- Excess of matter over antimatter in the universe.
- Non-zero cosmological constant.
- Gamma-ray bursters.
- CENTAUROS.
- FTL-appearing blobs emitted from quasars. (One participant commented that the involved geometry being used to explain why the FTL effect is not real FTL movement was beginning to look like the "cycles within cycles" of Ptolemaic cosmology.)
- Lack of cosmic censorship of naked singularities in existing theories of gravity.
- Existing theories allow time machines.
- Heavy-ion collisions produce e^+e^- pairs 100 angstroms away, implying an intermediate neutral particle. What is it?
- Positronium decay into two and three gamma rays does not agree with theory.
- Failure to detect the gamma ray bursts from the final stages of evaporation of the predicted miniature primordial black holes.

6. CONCLUDING REMARKS

After considering three principal FTL scientific windows (wormholes, FTL particles, and higher dimensional spaces) the participants were not able to identify a specific or obvious method to achieve FTL travel or communication. However, the participants noted that there are enough cracks in the armor of physics that FTL travel or communication could not be ruled out. Moreover,

the participants identified a number of experiments, which have been summarized in Appendix 2, that could help elucidate possible FTL-related phenomena.

The odd aspect of postulated FTL travel is that it is the reverse of the normal interplay between theory and experiment. In the past our theories have been the limiting statements which were eventually overthrown or expanded by subsequent experiments that pressed beyond the boundaries of known physics. In the case of FTL phenomena the reverse seems to be true: our theories permit such phenomena but our experiments don't find them. Even if we find that the speed of light is the ultimate speed limit, theoretical and experimental studies of FTL-related phenomena, which represent a frontier in quantum and relativity theories, should help us better understand the universe.

In conclusion we offer the words of Henry Margenau: "If the history of science teaches anything at all it is that there are no eternal verities which man can grasp and hold forever. Science is a flux of understanding, deepening and yielding ever greater satisfaction, it appears, but the river of discoveries is never dammed and made into a stagnant pool . . . [the philosopher or the scientist] must swim with the flow and try, if possible, to be abreast of it. He may be able to judge for some distance ahead where he is moving, but his final destination is also unknown".²⁹

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APPENDIX 1:
LIST OF ATTENDEES/PARTICIPANTS AT THE
WORKSHOP ON ADVANCED
QUANTUM/RELATIVITY THEORY
PROPULSION

(Organizational affiliations listed for identification purposes only)

Dr. John L. Anderson
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Dr. Gary L. Bennett
NASA Headquarters (now retired)

Dr. John G. Cramer
University of Washington

Dr. Pauline B. Cramer
Boeing Commercial Airplane Group

Dr. Robert L. Forward
Forward Unlimited

Dr. Robert H. Frisbee
Jet Propulsion Laboratory

Dr. H. B. Knowles
H. B. Knowles Physics Consulting

Dr. Geoffrey A. Landis
NYMA, Inc. (Lewis Research Center)

Dr. Franklin B. Mead, Jr.
Phillips Laboratory

Dr. Marc G. Millis
Lewis Research Center

Dr. Michael S. Morris
Butler University

Mr. Roy Patrick Rawlings
Science Applications International Corporation

Dr. Matt Visser
Washington University

APPENDIX 2:
SUMMARY OF EXPERIMENTS PROPOSED BY THE
WORKSHOP PARTICIPANTS TO ELUCIDATE
POSSIBLE FASTER-THAN-LIGHT (FTL) PHENOMENA

Wormhole Physics

- Astronomical search for possible gravitationally negative anomalous compact halo objects (GNACHOs) by examining any gravitational lensing effects on light emitted by distant stars. (This would be an adjunct experiment to the search for massive compact halo objects [MACHOs].)

Physics Where the Velocity of Light is a Lower Bound

- Good, confirmatory, unambiguous measurements of the mass of the three flavors of neutrinos (electron, muon, and tau neutrinos) to clarify whether or not the neutrino is a tachyon.
- Good measurements of the velocity of light perpendicular to the Casimir plates to determine if the speed of light is increased as predicted.
- High-energy experiments to determine if there are any Weinberg-type nonlinearities in quantum mechanics that could be exploited for FTL communication.
- Use of a laser to focus enough energy in “empty” space to determine if negative-energy virtual pairs can become positive-energy pairs thereby proving the existence of virtual particles.
- Good, time-phased studies of cosmic ray showers to determine if tachyons are present (see Figure 5).
- Search for neutrinos from a nearby black hole since if neutrinos are being emitted they must be tachyons because only FTL particles can escape from a black hole.
- Measuring the frequency of the acoustical modes of a neutron star to determine if the speed of sound in neutron star matter is greater than the speed of light (as predicted by some equations of state for neutron stars).

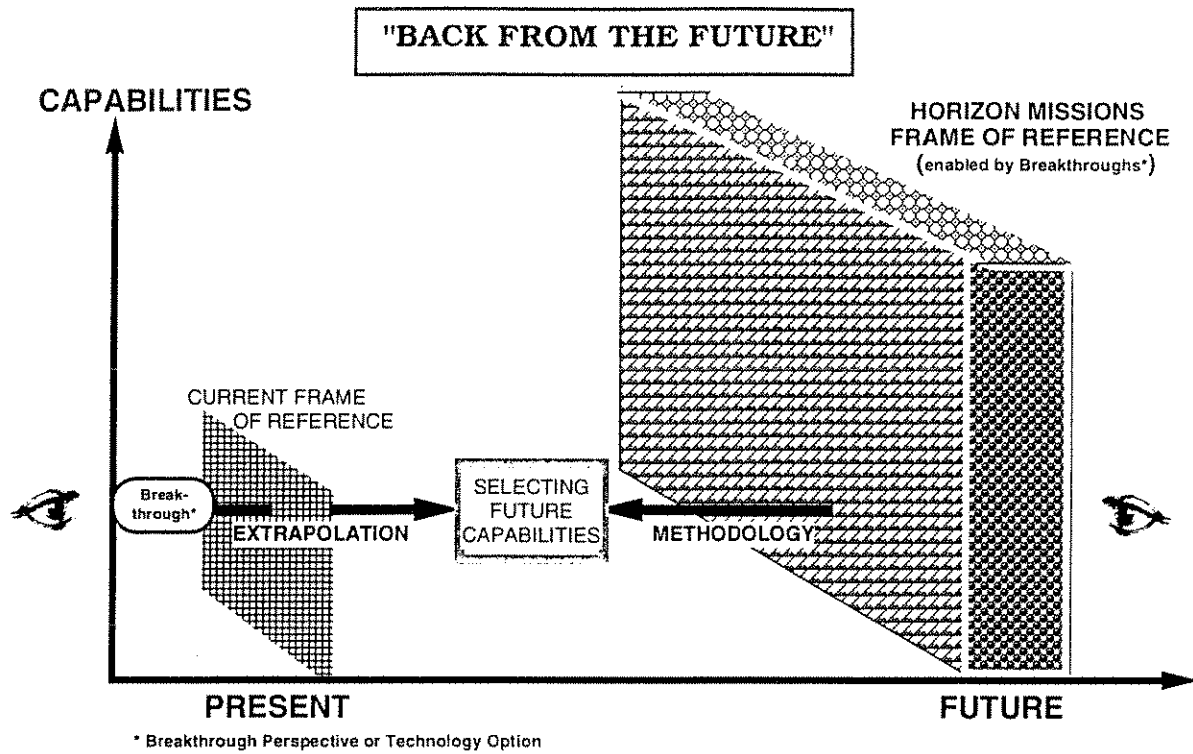


Figure 1. Diagram of the Horizon Mission Methodology (Ref. 8).

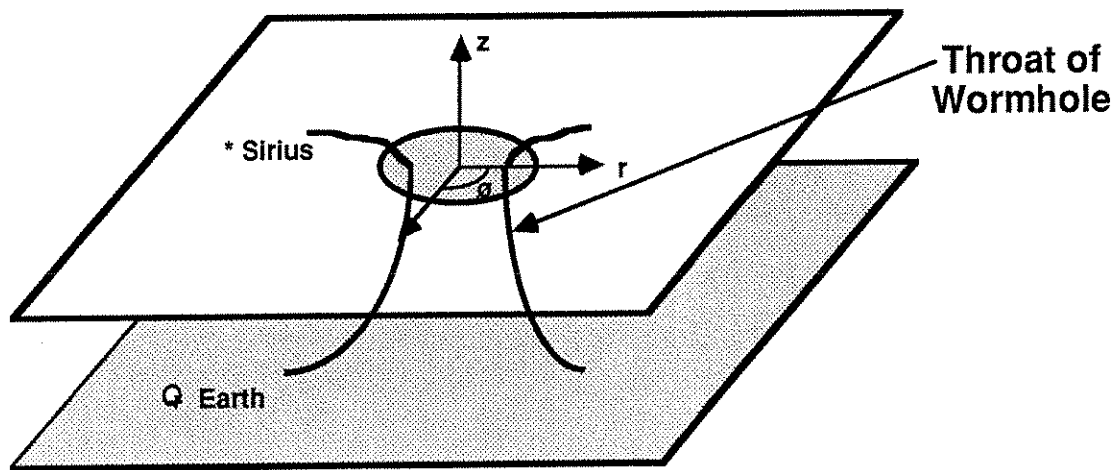


Figure 2. Diagram of a Wormhole Tunnel Without Horizons Connecting the Region Near Earth With the Region Near the Star Sirius (after M. S. Morris).

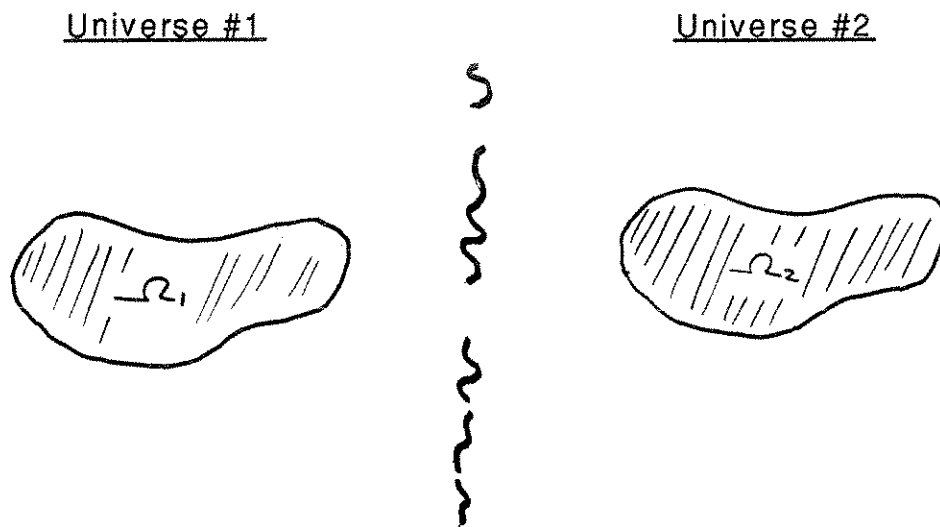


Figure 3. Diagram of Two Compact Regions of Minkowski Space (With Time Suppressed) Used to Create the Throat of a Wormhole (after M. Visser).

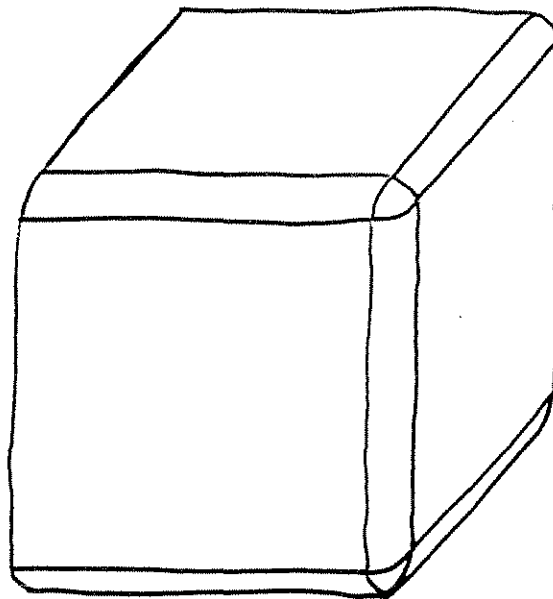


Figure 4. Sketch of a Wormhole Throat in the Form of a Cube With Rounded Edges and Rounded Corners (after M. Visser). The Struts are Built Out of Negative Tension Classical Strings.

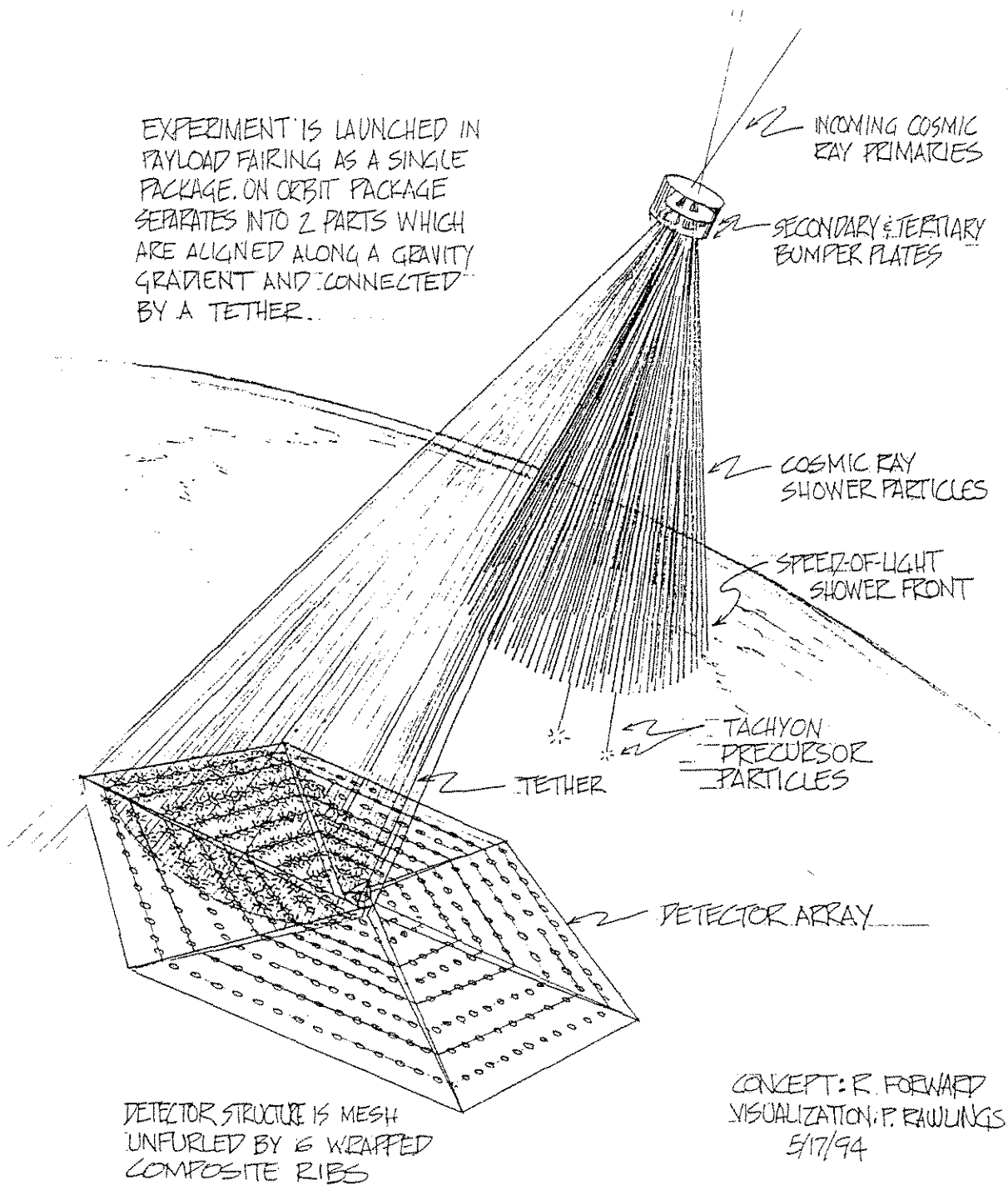


Figure 5. Sketch of a Satellite-Based Experiment Designed to Search for Tachyons in Cosmic Ray Showers (Visualization by Pat Rawlings from a Concept Proposed by Robert L. Forward).