Warp-Drives: The Dreams and Realities
Part I: A Problem Statement and Insights

P.A. Murad

Department of Defense
Paul.Murad@OSD.MIL

Abstract. Warp-drive feasibility and the theoretical basis for such devices are examined. A literature search reveals three basic schemes to travel faster than the speed of light. However, all of these violate various portions of Einstein's Theory of Special Relativity where they all require a negative stress-energy tensor to solve Einstein's field equations. To some, this infers the need for negative or exotic matter. Moreover, the amount of such matter is unrealistic preventing such schemes from operating within the realm of exploring the interstellar heavens so that mankind can become a true space-faring civilization. New formulations and suitable experiments to examine these premises are needed to validate that these shortcomings are real or imaginary. Even so, a potential way of remedying these stress-energy conditions may require using electromagnetic fields to produce a comparable effect as exotic matter. Moreover, an approach akin to the Yilmaz description to compensate for the shortcomings in Einstein's definition of gravity discussed in Part II may also provide some insights. The overall objective is to place these and other warp drive concepts on more of a stable scientific footing to resolve these issues.

INTRODUCTION

Science fiction is replete with Warp-drive driven spacecraft capable of traveling faster than the speed of light. To do so, however, would violate Einstein's Special Theory of Relativity. Some of these include multi-dimensional travel (Baker, 2003 and Seife, 2003, 2004) and other approaches. However, the objective of this paper is to review various warp-drive propulsion schemes and theories. Three basic concepts were identified that are:

- An Alcubierre warp-drive where space-time curvature is warped in front of and behind the spacecraft enshrouding the vehicle in a bubble where, relative to a fixed external observer, the vehicle and the bubble travel faster than the speed of light,
- The Krasnikov tube where a tunnel is created at very high sublight speeds, but a return through the same tunnel to the point of origin in the other direction is faster than the speed of light, and,
- A traversable Wormhole capable of connecting different portions of space-time curvature with a geometry that permits travel from one location to another at speeds that appear, to a fixed observer, to be faster than the speed of light.

All of these approaches attempt to satisfy the conventional wisdom despite some publications that examined Einstein's rationale that the speed of light may not be a real barrier as stipulated by the theory of relativity. There is another commonality in these three approaches, which is the need for negative mass. Negative mass is consumed in extremely large amounts to make these concepts feasible. It warps space-time in the first concept, creates the tunnel in the second, and in the third keeps the wormhole mouth open and large enough for the passage of a spacecraft. Even so with these difficulties, approaches may exist that can be used on the space-time metric to minimize the need for negative mass. Despite these shortcomings, a large body of information exists that supports the Alcubierre contention where analyses are evolved to the point that they also extend the notion and consider possible maneuvers or the impact of space debris at these relativistic conditions. However, no data was found that showed the successful implementation of these theoretical concepts into a practical device.

When the author initially approached this problem, it was with a huge level of skepticism. However, when notes and quotes from numerous references were compiled, it was realized that these individuals were very serious at looking at these issues both pro and con. If anything, their devotion and professionalism started to make the author

a believer that a warp drive could be possible and it was difficult to determine exactly where a contribution to this field could be seriously made. Clearly, there is a need for creating other theoretical approaches to achieve these aims. This may require expanding the conventional wisdom including the Theory of Relativity to treat a very different problem set as well as taking to an unconventional path of intellectual curiosity that is not often well-traveled.

This is not to say that these approaches in this paper are not valid, but the creation of large amounts of negative mass is clearly a compelling distraction. Moreover, very few individuals, with one exception seems to venture a guess on how to get such a light-speed spacecraft to reach high sublight velocity conditions in the first place or address the energy requirements to initiate these conceptual ideas. The sole exception is to generate a subluminal warp bubble, which by itself is a difficult task. On this basis, this author found enough material to write two papers. The first part involves results of the literature search where the background and crucial issues are hopefully identified to give the reader the depth of conviction that lies within this problem. In some previous efforts by the author, the concern about gravitational models was raised where an obvious bias led toward Jeffimenko's approach to account for relativistic conditions and that gravity is no longer a function of only position but both position as well as velocity. In addition to inducing a force, according to Jeffimenko's model gravity is an attractive force and can impart angular momentum to an attractive body. These issues should, if they are experimentally verified, be included in any navigation scheme at these conditions. Moreover, the author will discuss some findings that permit superluminal speeds in the context of Special Relativity and, as others have shown, this may not be a limitation. Finally, the author previously examined electric and magnetic fields with the objective of developing a traversable Black Hole using field propulsion. These field propulsion approaches would create electric, magnetic, or gravitational vortices and may have an application in part of this problem. If no solution is forthcoming it appears that such a task is beyond current or future technology and travel to the stars may be possible only at sub-light speeds. Are we with a deep desire to be a space-faring civilization, willing to accept such a premise?

DISCUSSION

Millis (1995) suggests that developing an interstellar propulsion system would require several breakthroughs. These are a means to exceed the speed of light, and discovery of a means of manipulating the coupling between mass and space-time. Such research would most likely introduce emerging technologies that could achieve these things while producing revolutionary consequences of enormous economic value. He implies that to develop a warp drive, all that is required is to contract space-time in front of a ship while expanding space-time at the rear. This 'warped' space-time would propel itself at arbitrarily large speeds. To do this and expand space-time in the rear of the ship would require a negative energy density or negative mass. Classical physics says this does not exist. Finally, will the warp move faster than light speed and how do you control it? Millis further asserts that wormholes may indicate a negative mass hole entrance and that a Casimir cavity may represent evidence of negative space energy.

Halerewicz, Jr. (2001) claimed that Alcubierre proposed a form of bipolar (or dual) gravitational waves as a potential propulsion scheme. In General Relativity, gravitational waves are planar and each wave expands and contracts. The Alcubierre metric suggests that such an effect could be bipolar possibly explaining the need for negative energy. The manipulation of space-time to propel a localized region of space or a warp bubble is by expanding and contracting the metric field. This is achieved with a 'Top Hat' function embedded into the metric. Thus, this principle is similar to gravitation as is the idea of how electric and magnetic fields cause electromagnetic radiation to propagate.

Space-time is given an intrinsic geometry dependent upon matter within the space according to Einstein's field equations and particles tend to follow geodesic paths within this space-time. Geodesic motion explains inertia and tends to replace the primitive notion that objects in motion tend to remain in a state at constant velocity. Assuming space-time can be manipulated by a warp drive, these conditions as well as the conventional wisdom change.

Lobo and Crawford (2002) suggest that recent solutions have been obtained to the Einstein Field Equations involving negative energy densities, or matter that violates the weak-energy-condition, have been obtained with

traversable wormholes, the Alcubierre warp drive, and the Krasnikov tube. These devices exceed the speed of light although the local speed of light is not violated. It is difficult to construct such metrics that allows superluminal travel that is in flat Minkowski space-times or space-times with no gravity. Negative energy density or exotic matter, which violates the weak energy condition (WEC), represents a severe drawback. The Alcubierre (1994) approach involves warping the space-time in a small bubble-like region such that the bubble may obtain arbitrarily large velocities. The approach is based upon the inflationary theory of the early universe and the expansion of space-time. Here, the distribution of negative energy density is concentrated in a toroidal region perpendicular to the direction of travel. Krasnikov (1998) suggests that an observer on a spacecraft cannot create nor control on demand an Alcubierre bubble with the velocity greater than light speed around the ship. The 2-dimensional model is reminiscent of an event horizon. The Krasnikov metric has the interesting property that the time on a one-way trip cannot be shortened, although the overall time on a round trip can be made arbitrarily small. With these brief discussions, let us look at these ideas in more detail.

Alcubierre Drive

Alcubierre (1994) states that by a purely local expansion of space-time behind a spaceship and an opposite contraction in front of it, faster than light speed motion as seen by stationary observers, is possible. The resulting distortion is from a warp-drive and, as with wormholes; exotic matter is needed to generate the distortion in space-time. He introduces a foliation of space-like hypersurfaces of constant coordinate time t and defines functions for an interval of proper time between the hypersurfaces and an Eulerian observer (whose four-velocity is normal to the hypersurface). The metric to the space-time can be written as:

$$ds^2 = -d\tau^2 = g_{\alpha\beta}\,dx^\alpha\,dx^\beta$$
$$ds^2 = -\left(\alpha^2 - \beta_i\beta^i\right)dt^2 + 2\beta_i\,dx^i\,dt + \gamma_{ij}\,dx^i\,dx^j\,.$$

(1)

Where the metric γ_{ij} is positive definite for all values of time and the space-time is globally hyperbolic with no closed casual curves. From these above expressions, he finds the top-hat function and rewrites the metric such that:

$$ds^2 = -dt^2 + (dx - v_s(t)f(r_s)dt)^2 + dy^2 + dz$$
$$\mathrm{where:}\quad f(r_s) = \frac{\tanh\left(\sigma\left(r_s + R\right)\right) - \tanh\left(\sigma\left(r_s - R\right)\right)}{2\tanh\left(\sigma R\right)}\,.$$

(2)

This 3-geometry of the hypersurface is always flat and that for certain values of these constants, the time-like curves normal to these hypersurfaces are geodesics and the Eulerian observers are in free-fall. The metric has a drawback in that it violates all three energy conditions (weak, dominant, and strong). Alcubierre looks at the Einstein tensor and finds that the energy density is given by:

$$T^{\alpha\beta}n_\alpha n_\beta = \alpha^2 T^{oo} = \frac{1}{8\pi}G^{oo} = -\frac{1}{8\pi}\frac{v_s^2\rho^2}{4r_c^2}\left(\frac{df}{dr_s}\right)^2\,.$$

(3)

The fact that this term is negative everywhere implies violation of the energy conditions. Moreover, the same happens with wormholes and that exotic matter is needed for faster than light travel. Furthermore, negative energy density may arise from the Casimir effect.

The Journal of Advanced Propulsion Methods, ISSN 1543-2661, indicates that in 1994 a Mexican mathematician, Miguel Alcubierre, discovered solutions to Einstein's equations that allow warps in space-time metric to travel faster than the speed of light. The proposal was unrealistic based upon:
1. It required a huge amount of negative energy,
2. It displayed no causality between the ship and the filed itself, and
3. The exotic energy states violated certain quantum energy conditions.

This reference also suggests that the issue of control at luminal speeds appears problematic and the need may require viewing null geodesics for control references. Moreover, Jose Natario showed that the energy of a photon distorted by a warp drive would be lethal at luminal speeds. The solution was to layer the warp bubble to deal with hazardous matter and radiation.

1258

Everett (1996) implies that Alcubierre recently exhibited space-time allows travel at superluminal speeds with a negative energy density and should be possible with closed causal loops that may involve cosmic strings. Moreover, this approach does not require using wormholes.

Hiscock (1997) finds the expected value of a stress-energy tensor for an Alcubierre drive. However, at the appropriate temperature, the stress-energy tensor diverges on past and future event horizons, which form the apparent velocity that the spaceship exceeds light. The use of exotic matter to generate a warp bubble around the spaceship is implausible. The warp-drive space-time is not spherically symmetric and cannot be reduced into two dimensions. The space-time is cylindrically symmetric about the axis where y = z = 0.

$$ds^2 = -(1 - v_o^2 f^2) dt^2 - 2 v_o f dt dx + dx^2. \tag{4}$$

Since the spaceship travels at constant velocity, there should exist a Lorentz-like transformation to a frame in which the ship is at rest. Hiscock determines this transformation and that near the horizon; the observed energy density is negative where a divergence occurs at both the past and future horizons. If this divergence is to be avoided, then the ship's drive must be presumably the source of the requisite stress-energy of the created particles and there would be a warp drag on the ship.

Pfenning and Ford (1997) apply a quantum-inequality type of restriction to Alcubierre's metric where the local space-time is flat. These restrictions reduce the negative energy requirement placing limits upon the warp bubble where the wall thickness is of the order of Plank's length. These restrictions and the energy restrictions make the thin walls physically unattainable. In this analysis, the spacecraft sits at rest with respect to the interior of the warp bubble and an observer may move through the interior of the bubble at constant velocity. The major issue is that of negative energy or exotic matter to produce space-time curvature in either the Alcubierre drive or a traversable wormhole. The solution to the Klein-Gordon equation would be needed to resolve the scalar field. Moreover, the Krasnikov metric also requires extremely thin walls to allow for superluminal travel. The wall thickness obviously reduces the amount of exotic matter required to achieve superluminal flight.

Pfenning (1998) reexamines the Alcubierre drive. Negative energy densities lead to several problems that demonstrate the failure of classical energy conditions, the production of closed time-like loops and faster than light travel violates the second law of thermodynamics, and the existence of naked singularities. Although quantum field theory does introduce negative energy, it also provides a constraint in the form of quantum inequalities. Moreover, the uncertainty principle limits the magnitude and duration of any negative energy. Pfenning goes on to indicate that the localized energy density in a quantized field theory is not always positive definite. The Casimir vacuum energy density for the quantized electromagnetic field between two perfectly conducting flat plates is constant and everywhere negative when the plates are forced to be attractive. Hawking, according to Pfenning, has shown that the vacuum energy around a black hole causes the black hole to evaporate with a flux of positive energy particles being radiated outward. The issue of negative energy density is not necessarily a problem but could be beneficial allowing time travel to be possible where mankind could construct a spacecraft that could warp space-time around them to travel around the universe faster than light speed. Even wormholes would represent self-consistent solutions to Einstein's equation. Pfenning also addresses the issue of average energy as a means of bypassing the negative energy argument. He concludes that even here, negative energy fluxes do not appear to work as well.

Van Den Broeck (1999) demonstrates that a minor modification of the Alcubierre geometry can dramatically reduce the energy requirements to maintain a warp bubble. This places the energy requirements on the same mass scale of large transversable wormholes. He mentions that the Krasnikov tube was an attempt to improve upon the Alcubierre geometry; the latter of which would deform space-time in the spacecraft's immediate vicinity such that the curve becomes a timelike geodesic while still keeping most of the space-time Minkowskian. The Alcubierre geometry is defined as:

$$ds^2 = -dt^2 + (dx - v_s(t) f(r_s) dt)^2 + dy^2 + dz$$

$$where: r_s(t, x, y, z) = \sqrt{(x - x_s(t))^2 + y^2 + z^2}. \tag{5}$$

Unfortunately, the geometry violates strong, dominant and especially the weak energy condition. A macroscopically large bubble must contain an unphysically large amount of negative energy and this requires that the bubble wall is

extremely thin. The 'f' term disappears outside of the bubble and the geometry is Minkowskian. He makes a modification to this geometry such that:

$$ds^2 = -dt^2 + B^2(r_s)\left[(dx - v_s(t)f(r_s)dt)^2 + dy^2 + dz \right].$$ (6)

The B term must be twice differentiable. Ford and Pfenning calculate the minimum negative energy with a warp bubble, which is reduced while still maintaining all of the advantages of the original geometry. "However, the warp drive has a trivial topology, which makes it an interesting space-time to study."

Everett (1996) implies that Alcubierre recently exhibited space-time allows travel at superluminal speeds with a negative energy density and should be possible with closed causal loops that may involve cosmic strings. Moreover, this approach does not require suing wormholes.

Van Den Broeck (1999b) implies Hiscock argued that the energy density due to fluctuations of conformally coupled quantum fields diverges at particle horizons within the bubble at superluminal speeds. Although these calculations were for 2-dmensions, it is reasonable that this phenomenon would occur in four dimensions. It is questionable that such a divergence would be present if the warp bubble went superluminal and developed horizons a finite time in the past, a situation comparable to a newly formed black hole that is not in thermal equilibrium with the field at infinity.

Van Den Broeck (1999b) examines objections raised concerning the Alcubierre geometry. These suggest the geometry is unlikely within the framework of general relativity and quantum field theory although subluminal bubbles are feasible. Another objection claims the divergence of quantum fluctuations on a warp drive background is not valid. The major issue is the amount of negative energy required. He mentions that the well-known Casimir effect also violates the Weak Energy Condition (WEC). Recently a class of theoretical wormholes was found that were self-stabilizing in that the negative energy density (exotic matter) needed to sustain the wormhole geometry would arises from vacuum fluctuations of conformal fields due to the curvature of the wormhole geometry itself.

The total energy is reduced dramatically by keeping the surface area of the warp bubble microscopically small while at the same time expanding the spatial volume inside the bubble. A problematic feature is the behavior of the negative energy in the warp bubble wall. If tachyonic motion is interpreted as meaning that part of the exotic matter is not able to keep up with the bubble when it goes superluminal, the outer shell could be left behind destroying the warp effect. This induces a naked curvature singularity in front of the bubble. Due to the lack of horizons, potential problems due to diverging vacuum fluctuations will not arise and there will be no tachyonic motion of exotic matter if the geometry is correctly chosen.

Loup et al (2002) claim that horizons did not exist for warp drive space-times traveling at subluminal velocities that asymptotically approached luminal velocities. They claim that a control region of a warp drive ship may lie within a warped region casually connected to the ship even at superluminal speeds that will allow the ship to slow to subluminal velocities. A skeptical physicist regarding warp drives would be concerned about the appearances of horizons when the ship reaches superluminal velocities. How is the ship controlled when the bubble detaches or is casually disconnected from the ship and the bubble is not turned off to reduce velocity? This effort examines what occurs regarding the bubble at subluminal speeds. The paper introduces the Hiscock horizon, the 'top hat' function associated with the Alcubierre drive, and the Pfenning piecewise function. It is concluded that the Pfenning function provides the ingredients for the control of the warp bubble.

Is there a different approach toward resolving the negative stress-energy or exotic matter issue? Desiato and Storti (2003) compare the Alcubierre 'warp drive' space-time metric to an electric field superimposed onto an array of time varying 4-current density sources. The energy condition violation required by this metric is provided by the interaction term of the Lagrangian density. Although E-M fields are created by real sources of charge and currents, a negative potential energy density can be formulated. Negative energy density exists as the relative potential between sources. The interaction results in a macroscopic quantum phase shift similar to the Bohm-Aharonov Effect, manifested as a Lorentz force. For the Bohm effect, each field emitter possesses a 4-current density that is a function of time and the coordinates relative to the center of mass and the other field emitters. Fields involved do not need to be necessarily strong. The superimposed fields control the Lorentz force exerted on each field emitter and EM fields are orders of magnitude stronger than gravitational fields. Although the energy density is positive in a vacuum, using a polarizable vacuum approach, this energy may be interpreted as negative

resulting from a relative negative permitivity. Conservation laws than allow for a free electromagnetic field as a propulsion system reaction force radiating away from the sources allowing speeds greater than light. Exotic matter is required for all space-time shortcuts. Desiato also suggests that for identical field emitters, coherent waves represent a flux linkage similar to an electric induction motor. If all field emitters are thus coupled, a relative phase displacements in both space and time could control the speed of the array.

Desiato and Storti in this crucial reference claim no exotic mass is required and derive equations that imply the Lorentz force does work to move the field emitters forward. Moreover, an E-M field is radiated behind the emitters thereby conserving both energy and momentum (the reaction field is radiated in the –z direction). The author concludes that the EGM metric is not the same as the Alcubierre metric and that space-time curvature emerges from a phase shift induced by a gauge phase factor by semi-exotic matter. Superimposing a strong E-M field on this matter exerts strong Lorentz forces and not weak gravito-magnetic accelerations. The negative density of exotic matter in the Alcubierre metric results because it is assumed to exist as a free-field. Here, negative matter is not found in free space but in the relative potentials between field emitters.

Szpir (2001) states that the warp drive as envisioned by Alcubierre would create a disturbance in space-time directly in front of the spaceship that is contracted and one that is expanded directly behind the craft. This distortion in space-time would propel a spacecraft forward like a surfer riding the crest of a breaking wave. Although it violates Einstein's special theory of relativity, the violations lead to casual paradoxes where actors in the present can alter their past. Alcubierre claims his idea does not lead to such violations. Because time flows at different rates, the passengers on such a craft will not feel any acceleration and would be weightless. Although it needs negative energy, Hendrik Casimir was the first to predict that one could observe the effects of negative energy densities by allowing two closely-spaced parallel plates to be attracted to each other.

Hart et al. (2002) suggests that if we assume that space-time could be influenced by a warp drive, the need exists to deflect matter in the form of meteors, away from the ship. Intrinsic properties of the space-time metric can be used to deflect matter. If one created a static warp field, meteors could be deflected from planets by using a fleet of subluminal ships. Hazardous radiation and collisions with matter on a warp drive ship pose serious obstacles to interstellar travel. The Broeck metric offers a potential solution to both challenges and the horizon problem no longer exists. These problems could, for example, include photons at the front of the ship that are blue-shifted to lethal very high energies and radiation due to the Pfenning warped region. The Pfenning warped region is described by the top hat function going from 1 to 0, and the Broeck warped region that contains two warped regions. Photons emitted in the forward direction, seen by the ship, change sign in the horizon and will loose contact with the ship. The remote frame will see photons emitted by the ship, crossing the horizon, and emerge outside similar behavior to the event horizon of black holes. Here, a remote observer never sees the photons crossing the event horizons but an observer inside the hole will see the photons going to a singularity. The ship loses contact with photons in the horizon, but an outside observer in front of the ship will see those that carry information as emerging from the warp bubble and reaching external space-time. Hart claims that for a rigid body, the gravitational gradients in the Broeck regions have the property to tidally disrupt and deflect hazardous matter in the ship's vicinity. Pieces of matter too small to be disrupted by the tidal forces will be slowed down by the Broeck warped region potentially, impacting the ship at low speeds. Larger pieces of matter will be tidally interrupted in the Broeck region and are not expected to hit the ship. Krasnikov demonstrated that a Broeck warp drive could be obtained with –10 kg of exotic matter using classical scaling fields in lieu of quantum fields. This considerably lower value of exotic matter requires a microscopic size radius for the warp field. The authors claim that warp drive space-times cannot be ruled out due to limitations from energy, blue shifts, or horizons.

Krasnikov Tube

Krasnikov (1998) examines if a traveler could reach a destination faster than a photon considering that the traveler can control his space-time geometry. Results indicate that the traveler could make a round trip within an arbitrarily short time based upon observations from a stationary observer. This assumes that a beam of test particles are sent to a location moving at sub-luminal speed and that they do not influence any effect on the surrounding environment. Upon reaching its destination, the light is reflected and some portion heads back to earth, the starting point. It is conceivable that the particles that reach a wormhole should shorten the time to the

original location. Suppose now a spaceship is launched under similar conditions. By space-time, we are talking about a smooth Lorentzian connected global manifold with no restrictions placed upon the matter field. The interaction of the spaceship with the environment may not be weak because of a small expenditure of energy that could influence equilibrium. Moreover, it is assumed tachyons do not exist to maintain causality. On a one-way trip:

$$\mathbf{ds}^2 = -\mathbf{dt}^2 + (\mathbf{dx} - \mathbf{v_s(t)f(r_s)dt})^2 \ . \tag{7}$$

This resembles Alcubierre's space-time. However, during the round-trip, the metric becomes:

$$\mathbf{ds}^2 = -(\mathbf{dt} - \mathbf{dx})(\mathbf{dt} + \mathbf{k(t,x)\ dx}). \tag{8}$$

Here, k is a function that considers propagation within light cones. When it is unity, the space-time is flat and not influenced by gravity. A result of his analysis implies violation of the weak energy conditions and that an exorbitant amount of negative energy is required during the superluminal return.

Pfenning (1998) indicates that the Krasnikov space-time occurs when a spaceship travels to a distant star at subluminal velocity creating a tube of negative energy behind it thereby altering space-time as it goes. When it reaches its destination and turns around, to observers at the point of departure, the time that elapses between the departure and return can be arbitrarily small or even zero.

Low (1998) claims it is well known that linear perturbations of a metric on an Einstein vacuum satisfy a wave equation. Moreover, the bicharacteristics of this wave equation are the null geodesics of the background space-time. Thus finite perturbations in a gravitational field travel along null geodesics or no faster than light and that constructing an Alcubierre warp drive is impossible without exotic matter. Low suggests it is difficult that the metric of space-time in general relativity should be fixed; how could one make a decision that would change the metric in one's future? It may be possible to arrange a space-time such that a slower spaceship can arrive with less lapsed time in such a way that the return trip may be made short, as seen by a stationary observer, as mentioned in Krasnikov in 1998. Thus, we may want to change the metric if matter satisfies an evolution equation allowing faster than light travel. Without exotic matter, the speed of light is a speed limit in general relativity.

Halerewicz, Jr (2001) suggests that the Krasnikov Tube generates an exotic energy field that causes space-time coordinates to rearrange themselves according to a projection scheme. It is the simplest warp drive concept because it does not suffer from 'horizon' problems although it requires a spacecraft that travels near the speed of light. Due to no real reference, the pilot has very little means to control the warp drive. This is related to the Cosmological Constant based upon an expanding universe and that gravity appears to both repel as well as attract. The model is also known as the *"Subway to the Stars"* where no special space-time constructions are needed. However, exotic matter is needed to generate the shortcut within global space-time resulting in an Alcubierre-type warp drive during the return trip.

Traversable Worm Holes

Krasnikov (2000) looks at a class of wormholes with wide throats where the sources for the WEC violations are required by the Einstein equations describing the vacuum stress-energy of the neutrino, electromagnetic, or massless scalar field. A wormhole is basically a tunnel that connects a part of the universe with another sufficiently remote part disconnected from the initial region. If a signal is transmitted through the wormhole then it is called transversable. Krasnikov examines the Morris-Thorne wormhole who's metric is:

$$\mathbf{ds}^2 = -\mathbf{e}^{2\Phi(r)}\mathbf{dt}^2 + (1-\mathbf{b(r)/r})^{-1}\mathbf{dr}^2 + \mathbf{r}^2(\mathbf{d\theta}^2 + \sin^2\theta\,\mathbf{d\varphi}^2),$$
$$\mathbf{where:\ \Phi, b/r\ and\ all\ derivatives} \to 0\ \mathbf{as\ r} \to \pm\infty.. \tag{9}$$

As the radius goes to infinity, the metric becomes a Minkowski metric. The stress-energy tensor of a quantum field need not obey the WEC. However, this tensor is not arbitrary for a specified metric so this condition still holds. The author writes Einstein's equations separating the total stress-energy tensor and neglecting the interaction of the field with other matter. He defines some inequalities and determines that the resulting expressions hold for neutrino, electromagnetic, and massless scalar (uniformly coupled) fields. This term is subtracted from the total stress-energy tensor to satisfy the WEC for a wormhole. Thus if wormholes are theoretically possible, an experiment for finding a

macroscopic wormhole would be examining the gravitational microlensing of a background bright sources such as a quasar. The gravitational field of a wormhole is assumed to be clumps of exotic matter having a stellar-scale negative mass although this was not considered in this paper. Moreover, a wormhole should generate a well-collimated beam of high-energy photons. If such a beam sweeps over the earth, it could be detected as a flash or a gamma ray burst. Finally, note that no velocity appears in these expressions except through b(r); hence there is no way to easily describe the velocity of a particle within a traversable wormhole.

CONCLUSIONS

As these efforts show, the warp drive concept is an intellectual and technological challenge. There are real problems regarding negative or exotic matter and how it becomes part of this issue. Many investigators have given these concepts very serious thought as well as tried to understand the first and second tier problems that would allow a spacecraft to travel at or greater than the speed of light. They do so in the fear of not violating special relativity while still desiring to achieve capabilities that are outside of the realm of special relativity. Some efforts involve diminishing the size of the problem by using a multiplier that essentially reduces the amount of exotic matter required. Others look directly at the Einstein equations and have found some ways of circumventing this problem. Despite these theories, however, the need exists to provide a means of experimental verification that these problems are real and resolvable. For example, no one can define an adequate means of reaching near light speed before creating a warp bubble. This is also a crucial problem that is unfortunately ignored because of technology limitations. Identifying meaningful experiments is yet to be achieved and some of these issues will be discussed in Part II.

—————————————————————————

"Views expressed in this article are those of the author and do not reflect the official policy or position of the U.S. Government."

REFERENCES

Alcubierre, Miguel, "The Warp Drive: Hyper-Fast Travel Within General Relativity," Class. Quantum Grav. 11-5, L73-L77 (1994).

Baker, R. M. L., Jr. and Murad, Paul A., "Cosmology and the Door to Other Dimensions and Universes," proceedings of the 39th AIAA/ASME/SAE/ASEE Propulsion Conference, Huntsville, Ala. 2003.

Desiato, T. J., Storti, R. C., "Warp Drive Propulsion with Maxwell's Equations", 2003.

Everett, A. E., "Warp Drive and Causality," PHYSICAL REVIEW D, Vol. 53, No. 12, 1996.

Halerewicz, Jr., E., "WDT- The Basics of Warp Drive Physics," 2001.

Hart, B. B., Held, R., Hoiland, P. K., Jenks, S., Loup, F., "On the Problem of Hazardous Matter and Radiation at Faster than Light Speeds in the Warp Drive Space-time," arXiv:gr-qc/0207109 v1, 2002.

Hiscock, W. A., "Quantum Effects in the Alcubierre Warp-Drive Spacetime," Letter to the Editor, Class. Quantum Grav. 14 (1997) L183-L188.

Krasnikov, S. V., "Hyperfast Interstellar Travel in General Relativity," gr-qc/9511068 v6, 1998.

Krasnikov, S., "A Traversable Wormhole", gr-qc/9909016 v4, 2000.

Lobo, Francisco and Crawford, Paulo, "Weak Energy Condition Violation and Superluminal Travel," arXiv:gr-qc/0204038 v2, 2002.

Loup, F., Held, R., Waite, D., "A Causally Connected Superluminal Warp Drive Space-time", arXiv:gr-qc/0202021 v1, 2002.

Low, Robert J., "Speed Limits in General Relativity", gr-qc/9812067 v1, 18 Dec. 1998.

Millis, Marc G., "Emerging Possibilities for Space Propulsion Breakthroughs," The Interstellar Propulsion Newsletter, Vol. 1, No. 1, 1995.

Pfenning, M. J., "Quantum Inequality Restrictions on Negative Energy Densities in Curved Spacetimes", Ph.D. Dissertation for Tufts University, 1998.

Pfenning, M. J. and Ford, L. H., "The Unphysical Nature of 'Warp Drive'," Class. Quantum Grav. 14 (1997) 1743-1751.

Seife, C., "Polyhedral Model Gives the Universe an Unexpected Twist," Science 302, p. 209 (2003)

Seife, C., "Physics Enters the Twilight Zone," Science 305, pp. 464-466 (2004)

Szpir, M., "Space Time Hypersurfing", (American Scientist V82), 2001.

Van Den Broeck, Chris, "A 'Warp Drive" with more Reasonable Total Energy Requirements," Class. Quantum Grav. 16 (1999) 3973-3979, Printed in the UK.

Van Den Broeck, Chris, "On the (im) possibility of Warp Bubbles," KUL-TF-99/22 gr-qc/9906050,LANL.