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New frontiers in space propulsion sciences

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Abstract

Mankind's destiny points toward a quest for the stars. Realistically, it is difficult to achieve this using current space propulsion science and develop the prerequisite technologies, which for the most part requires the use of massive amounts of propellant to be expelled from the system. Therefore, creative approaches are needed to reduce or eliminate the need for a propellant. Many researchers have identified several unusual approaches that represent immature theories based upon highly advanced concepts. These theories and concepts could lead to creating the enabling technologies and forward thinking necessary to eventually result in developing new directions in space propulsion science. In this paper, some of these theoretical and technological concepts are examined – approaches based upon Einstein's General Theory of Relativity, spacetime curvature, superconductivity, and newer ideas where questions are raised regarding conservation theorems and if some of the governing laws of physics, as we know them, could be violated or are even valid. These conceptual ideas vary from traversable wormholes, Krasnikov tubes and Alcubierre's warpdrive to Electromagnetic (EM) field propulsion with possible hybrid systems that incorporate our current limited understanding of zero point fields and quantum mechanics.

Keywords: Space propulsion; Warp drive; Worm Holes; EM propulsion

1. Introduction

Technical challenges placed before mankind today are slowly revealing what we believe to be nature's most deep and darkest secrets. Much of this is attributed to the fact that decades ago adequate theories were developed for the four fundamental forces of nature: the so-called "strong" and "weak" nuclear forces which operate on subatomic scales, and the electromagnetic forces responsible for most of what we experience in everyday life. The first three of these are built on a foundation of quantum field theory and have been so successful in matching theory with experimental data that it has become the "Standard Model" of particle physics. This model ranks as one of the premier scientific accomplishments of the twentieth century. However, new developments in particle physics are routinely taking place (e.g., the study of neutrino properties). These developments strain the conventional wisdom and raise questions regarding the uniqueness and validity of the Standard Model. As with Einstein's development of the modern theory of gravity (i.e., general relativity with its spacetime curvature), which improved upon the Newtonian theory, the Standard Model will also eventually be improved upon over time to treat newer developments as well as any valid anomalies that might appear along the way.

Perhaps the greatest enigma remaining is the search for an understanding of how gravity fits together with the other three fundamental forces. Within the confines of space propulsion science, this lack of understanding has made gravity "a burden to overcome"; rather than a

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science to embrace. Further, with the exception of nuclear propulsion and some limited attempts at antimatter approaches [1], very little, if any, of these new theories have been applied to the research and development of new propulsion models and literally no serious consequential experimentation has been performed [2]. Therefore, space beyond our solar system is outside our reach within our limited knowledge of the space propulsion sciences of today. As today's space propulsion science is based upon outmoded century old ideas; basically ($\sim$300 yr old) Newtonian physics with a little general relativity thrown in for minor trajectory corrections of long range probes and in recent years for creating extremely accurate timing signals from Global Positioning Satellites.

It can only be concluded that "*without more aggressive research* [3]" to incorporate new physical theories into future space propulsion, mankind's destiny will be chained to the continued use of modern brute force rocketry, developed over the approximately 70 years since WWII; closer to several hundred years, if you include the early Chinese efforts upon discovering gun powder, a truly sad state of affairs.

This paper presents and discusses potential approaches and ways for extending knowledge in developing space propulsion sciences beyond the concepts of today's thinking. It is hoped that others will step forward to meet this crucial challenge and help create new propulsion models and maturate promising embryonic technologies beyond their current limitations.

2. Expanding the physics

In an attempt to broaden the mindset before presenting new areas of space propulsion science, it is worth noting that: *Physics is not a finished logical system. Rather, at any moment it spans a great confusion of ideas, some that survive like folk epics from the heroic periods of the past, and others that arise like utopian novels from our dim premonitions of a future grand synthesis* [4].

In this respect it is important to note that the work of physicists does not aim to place limits on the potential scope of engineering, except where violations of "*well-tested and accepted laws of physics*" are involved [5]. However, many problems arise because scientist and engineers alike believe that theories satisfy "*accepted laws of physics*" that cannot be broken, when they are in fact just that – theories. For example, it is important to realize that the laws of gravity, in general, belong in the class of Newtonian theory, which was replaced by General Relativity, which is being replaced by quantum theory, which maybe replaced by string-Brane theory which . . ... and so forth as time goes on. Further, when trying to interpret between theories, one quickly fines that you are dealing with apples and oranges. That is for example, relativity and quantum mechanics cannot prove the same thing by virtue of differences in scale lengths, astronautical distances versus the Planck length. Therefore, limiting ourselves to any one set of theoretical concepts keeps us from sketching our imagination, but more importantly, it forbids us from embracing far thinking ideas and concepts as the older theories become entrenched into the mainstream science and engineering thinking; giving rise to the conventional wisdom of today, which when entirely different from the emerging theories halts any progress from pushing forward until the new theories begin to replace the older ones.

A truly fundamental theory of gravity is thought to be quantum in nature. However, despite decades of effort, little is new to our understanding about the nature of quantum gravity. Should gravity be able to stand alone in a separate quantum theory, independent of other fields that constitute nature, or can gravity only be understood in terms of a unified theory that attempts to handle all aspects of matter and its interactions at once? M-theory, a modified string theory, is a bold attempt at being a theory of everything, solving the problems of both the quantum theory of gravity by merging all matter and interactions into a single theory where the fundamental objects of interest are not point particles, but are higher-dimensional objects such as loops of "superstrings".

In ordinary matter, quantum effects become quite evident when one reaches the atomic scale, at $\sim 10^{-10}$ m. Today's high-energy particle accelerators allow us to study the behavior of matter and energy at scales as small as 10^{-17} m, where the existence of particles such as quarks, gluons, and W and Z bosons are evident and completely invisible at the atomic scale. However, quantum gravitational effects are not expected to become important until one reaches the Planck scale, about 10^{-35} m, the size of a typical loop of superstring material. The large difference in scale between the Planck scale of superstrings and today's experiments – some 18 orders of magnitude, a billion–billion – is one reason why it is so difficult for physicists working on superstring models to make experimental predictions from their theory that can be tested using the present level of physical understanding and contemporary technology. This leads many to believe that string related theories border purely on philosophy.

This large span between the scales at which quantum effects become evident in matter and the Planck scale of quantum gravity is a realm where the semi-classical theory of gravity may be reasonable to help us understand how to marry gravity and quantum physics. In semi-classical gravity, the gravitational field is still treated in a classical sense, being described by the spacetime curvature of general relativity. The matter that creates the spacetime curvature, however, is treated using quantum field theory. The resulting theory is not ultimately acceptable, since it mixes classical and quantum physics, but should still remain a valuable tool for providing an approximate description of nature's behavior over length scales (and energy scales) that reach down towards the realm where string theory may provide an ultimate exegesis.

Theoretical physicists expand their understanding of the strengths, limitations, weakness and behavior of a particular theory by "pushing" the theory to its extremes. For example, general relativity is understood much better by studying spacetime geometries for such things as black hole solutions to the Einstein equations than by restricting attention to the tiny differences between predictions of Newtonian gravity and general relativity, for say planetary orbits. These tiny differences, when detected, provide valuable experimental tests of general relativity, since black holes are not observed in our near-field neighborhood. Understanding the full range of behavior allowed by the theory that provides the best predictions for situations that are far from "normal" – e.g., for black holes, and much more speculative solutions to the equations such as so-called "wormholes", "warp drives" and other concepts that can potentially lead to possible forward or backward time travel.

If one postulates a spacetime geometry with some exotic property (e.g., a wormhole), then it is likely that "exotic" matter is necessary to generate that geometry per Einstein's field equations [6]. This assumes these equations are correct in the absence of any other approach. By "exotic matter" we mean matter that has properties not usually seen in ordinary situations – such as using negative mass or energy densities. Such properties are far from those exhibited by normal matter that we must seriously ask whether such behavior is compatible with the quantum field theory description of matter. This then provides a link between extreme quantum behavior of matter and exotic geometries, and hence insight into quantum gravity.

If we accept the premise that Einstein's Theory of Relativity is really a geometric theory, then the goal is to continue to make the geometry model more realistic. Thus, adding more aspects of physics to its description and determining whether the original exotic geometry is compatible with such a more realistic treatment, becomes a consequence of physical reality. If physics rules such features out, then no amount of *clever* engineering can turn science fiction into fact; thus, if no incompatibility exists within the known or experimentally proven physics, then it might be possible for future engineers to create such geometric constructs in spacetime.

In the next section, some particular spacetime geometries that represent mathematical solutions to Einstein's field equations are identified. In fact, any four-dimensional geometry for a spacetime can be termed a solution of Einstein's theory. Thus, the question physics must answer is whether matter or a field necessary to curve spacetime into a particular "shape" is compatible with our current understanding of nature or does it defy our understanding thereby requiring a change to our current thinking and understanding.

3. Windows on future space propulsion sciences

Although new physical theories affect many areas of science, they form the basis for "New Frontiers in Space Propulsion Sciences," where the goal is to create motivation for the continual development of realistic propulsion models within these new theories. More importantly, experimental validation of these models is a prerequisite to accepting these new notions as valid ideas and concepts. This broadens the physics in its description whether the original model is compatible with this more realistic treatment. Should no incompatibility with known or new physics results from these new theories, then it might be possible for future engineers to create new space propulsion systems only previously dreamt by visionaries such as Robert Forward [7] embedded into the realms of science friction. As such, the following contains a review of some of the most interesting space propulsion models and concepts to surface outside the annals of fiction and into the journals of science.

3.1. Fast-than-light travel in spacetime

Miguel Alcubierre [8] has published a spacetime metric that is a mathematical description of a hyper-fast spacetime geometry for Faster-than-Light (FTL) or superluminal travel within the General Theory Relativity (GTR) that embodied properties usually associated with the "warp drive" of science fiction. The Alcubierre spacetime metric was constructed to allow an object to travel at superluminal (FTL) velocities (faster than light) by manipulating spacetime in such a way that the object never locally exceeds the speed of light, but in a manner identical to the inflationary stage of the universe, the object has a relative speed defined by the change of proper spatial distance compared to a stationary observer, over proper spatial time faster than the speed of light. This is described by a warp bubble as illustrated in Fig. 1 where the center of the bubble corresponds to the object's position.

Numerous solutions to the GTR field equations are known that theoretically allow 'effective' superluminal travel [9]. Despite the use of the term superluminal, it is not 'really' possible to travel faster than light, in any *local* sense that is known today. The general *global* definition of superluminal travel is due to nontrivial matter [10,11]. It is; however, clear that spacetimes may allow 'effective' superluminal travel that generically suffers from a severe drawback that they also involve significant amounts of negative energy densities.

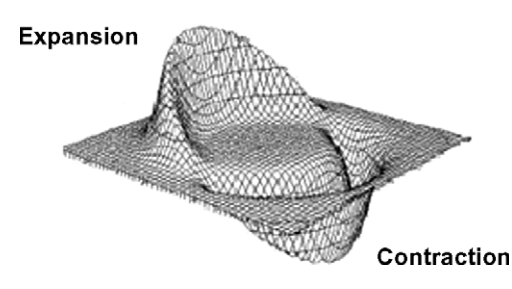

Fig. 1. The Alcubierre Warp Bubble describes a volume whose spacetime elements expand behind the object (residing in the center flat region) and contract in front of it; producing motion in the direction of the contraction.

More precisely, superluminal effects are associated with *exotic* matter (see Section 3.4), that is, matter that violates the null energy condition (NEC). In fact, superluminal spacetimes violate all known energy conditions; making negative energy densities and superluminal travel intimately related [12]. Although most classical forms of matter supposedly obey the energy conditions, they are certainly violated by certain quantum fields [13]. Certain classical systems (such as non-minimally coupled scalar fields) exist, which violate the null and the weak energy conditions [14,15]. Exotic matter-negative energy is discussed in more detail in Section 3.4.

Further for Alcubierre-like warp drive spacetimes using the 'quantum inequality (QI)' deduced by Ford and Roman [16], it was verified that enormous amounts of energy are needed to sustain superluminal warp drive spacetimes [17,18]. This is due to the fact that QI restricts the bubble wall to be very thin to lower the amount of exotic material needed. For a macroscopic bubble the energy is roughly proportional to the square of the bubble radius divided by the wall thickness. It was shown that a very thin walled bubble with a radius of 100 m would require a total negative energy of at least $E \simeq -6.2 \times 10^{62} v_s^2$ kg, which is, for an object velocity v_s equal to that of light, ten orders of magnitude greater than the total positive mass of the entire visible Universe. Quantum inequality (QI) is discussed in more detail in the next session.

Chris Van Den Broeck [19] proposed a slight modification of the Alcubierre spacetime metric that considerably reduces the energy requirements of the warp bubble. He accomplished this by keeping the *surface area* of the warp bubble itself microscopically small while at the same time expanding the spatial *volume* inside the bubble. Essentially he incorporated a multiplication factor on Alcubierre's metric that decreased the size of the warp bubble thereby decreasing the amount of negative energy required to sustain it.

Large amounts of negative energy are not the only problem with the Alcubierre spacetime metric and its incarnations. Lobo and Visser [9] points out that these spacetime models by definition define a point at the center of the warp bubble, which moves along a geodesic and is 'massless.' That is, in the usual sense the object is always treated as a test particle with no real mass. Consequently these metrics have become useful 'gedanken-experiments' – they are useful primarily as a theoretician's probe into the basic foundations of general relativity; therefore *they do not provide a realistic engineering model*. To illustrate this, Lobo and Visser [9] corrected this flaw by constructing a more realistic model by applying linearized gravity to the weak-field warp drive case testing the energy conditions to first and second order of warp velocity. The fundamental basis of their model is that it specifically includes a finite mass spaceship that interacts with the warp bubble. Their results verified that all warp drive spacetimes violate the energy conditions and will continue to do so for arbitrarily low warp bubble speeds. They also found that the energy condition violations in this class of spacetimes is generic to the form of the geometry under consideration and is not a side-effect of superluminal properties. Based upon these efforts [20], it appears that for all conceivable laboratory experiments in which negative energy is created in very small amounts, the warp bubble speed will be absurdly low. It appears unlikely that warp drives that require Alcubierre-like warp bubble geometries will prove to be technically feasible let alone practical unless new geometries or ways to generate astronomical amounts of negative energy are found.

3.1.1. A word about quantum inequalities

Puthoff [21] has shown that the Alcubierre drive is a particular case of a broad, general approach that is called "metric engineering," providing support for concepts that reduce the time for interstellar travel that is not fundamentally constrained by physical principles. The most fundamental is the concept of Quantum Inequalities (QI) [16]. The third author indicates that the Quantum Inequalities (QI) conjecture is an ad hoc extension of the Heisenberg Uncertainty Principle to curved spacetimes [63]. The QI conjecture relates the energy density of a free quantum field and the time during which this energy density is observed (via model dependent time integrals of the energy density along geodesics). This conjecture was devised as an attempt to quantify the amount of negative energy or energy condition violations required to build a FTL spacetime. Investigators invoked the QI to rule out many of the warp drive spacetimes and macroscopic wormholes.

When generating negative energy, the QI postulate states that:

1. The longer the pulse of negative energy lasts, the weaker it must be,
2. A pulse of positive energy must follow and its magnitude must exceed that of the initial negative pulse, and
3. The longer the time interval between the two pulses, the larger the positive pulse must be.

However, the Casimir Effect and its non-Maxwellian quantum field analogs [22] violate all three conditions. There are also a number of squeezed vacuum sources and Dirac field states that manifestly violate all three conditions. Cosmological inflation, cosmological particle production, the conformal anomaly, and gravitational vacuum polarization also violate the QI conjecture. Visser [23,24] also points out that observational data indicate that large amounts of "exotic matter" need to exist in the universe to account for the observed cosmological evolution parameters. Most important, the QI requirements have not been verified by laboratory experiments. Therefore, the assumptions used to derive the QI conjecture and their derivation for various cases has been called into question by numerous investigators. For example, Krasnikov [25] has constructed an explicit counter-example for generalized FTL spacetimes showing that the relevant QI breaks down even in the simplest FTL cases. Therefore, the QI conjecture is flawed.

On another note, Borde et al. [26] recast the QI conjecture into a new program that studied the spatial distributions of negative energy density in quantum field theory. Their study modeled free (massless) scalar fields in flat two-dimensional Minkowski spacetime. Several explicit examples of spacetime averaged QI were studied to allow or rule out some particular model (spatial) distributions of negative energy. Their analysis showed that some geometric configurations of negative energy can either be ruled out or else constrained by the QI restrictions. And their investigations found allowable negative energy distributions where observers did not encounter the positive energy distribution previously mentioned. The extent of these results generalized to four-dimensional curved spacetime remains unresolved and it is not yet clear if this can be solved. Thus, the implication is that at least for now, the QI conjecture can be ignored.

A more effective way to quantify the amount of negative energy or energy condition violation required for a FTL spacetime has been developed [9,27–29], which proposes a quantifier of a spatial volume integral with an appropriate choice of the integration measure. The amount of energy condition violation is defined where this integral can be negative. The value of the integral provides information about the total amount of energy condition-violating matter that must exist for any given FTL spacetime. This integral can be adjusted to become vanishingly small by an appropriate choice of parameters. That is, examples can be constructed where the energy condition violation can be arbitrarily small, but cannot be made to entirely vanish.

3.2. D-Brane warp drive in spacetime

The warp drive spacetime metric is based largely on the Einstein Field equations with quantum mechanics thrown in to interpret the energy requirements through the QI conjecture, which as previously mentioned may be based on flawed assumptions. Thus, extending the warp drive concept to the newly developed D-Brane theory only seems to be a natural next step. For example, White [30] and White with the third author [31] shows how Alcubierre's drive can be reinterpreted in extra-dimensional D Brane theory as a spacetime expansion boost (i.e., like a scalar multiplier) acting on the initial spacecraft speed. This mechanism recasts the warp drive energy requirement into an equation of state for dark energy (a.k.a. as the cosmological vacuum (scalar) energy) where there is no negative energy density, but only negative pressure in the scalar energy field, required to sustain the warp drive bubble.

Obousy [32] gives another example whereby Alcubierre's warp drive can be engineered via effective Casimir energy (see Section 4.1.3), but with broken super-symmetry in the extra-dimensional D-Brane theory. By utilizing a recent model that relates the cosmological constant to the Casimir energy of the extra dimensions in brane-world theories, Obousy shows that by manipulating the radius of the extra dimension, a local adjustment of the cosmological constant could be created. This provides a mechanism for expanding/contracting spacetime around a spacecraft creating an exotic form of field propulsion. This notion is analogous to the

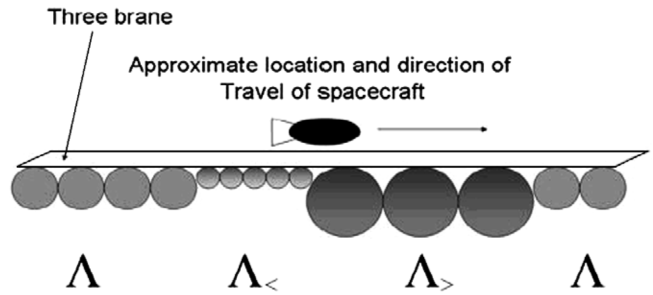

Fig. 2. This image represents a spacecraft with the capability to increase the radius of the extra dimension at its front and decrease the radius at its rear. The relative radius is shown graphically as circles of smaller/larger radius when compared against the unchanged extra dimension [32].

Alcubierre bubble, but differs entirely in the approach, using the physics of higher-dimensional quantum field theory, instead of general relativity. This is illustrated in Fig. 2.

3.3. Fast-than-light travel using wormholes

Traversable wormholes represent a different class of FTL solutions in General Relativity theory, where unlike the warp bubble surrounding the object, a wormhole is produce in some manner forward of the object, such that the object may enter into it. For a stable traversable wormhole one needs to define the desirable physical requirements to achieve the desired benefits of FTL travel. The requirements we desire are that travelers entering a wormhole throat should not encounter any adverse gravitational tidal forces and be able to traverse the throat at sub-light speeds while taking no more than a year of travel time. And wormholes must not possess any black hole-like event horizons and singularities [33,34]. These requirements define a spherically symmetric Lorentzian spacetime metric (i.e., invariant distance function in spacetime) that prescribes the required traversable wormhole geometry.

There are several variations of traversable wormhole geometries that have different properties [34]. Fig. 3a shows an embedding diagram for a traversable wormhole that connects two different universes (i.e., an inter-universe wormhole). Fig. 3b is an intra-universe wormhole with a throat that connects two distant regions of our own universe. These diagrams serve in visualizing traversable wormhole geometry and are merely a geometrical exaggeration. It has been shown that a generic traversable wormhole throat can be defined without having all the symmetry assumptions and assuming the existence of an asymptotically flat spacetime to embed the wormhole in [35]. Additionally, a number of different traversable wormhole throat designs, such as cubic shaped, polyhedral shaped, flat-face shaped, generic shaped, etc., have been developed [34].

3.4. Faster-than-light requires exotic energies

In classical physics the energy density of all observed forms of matter (and fields) is positive. What is exotic

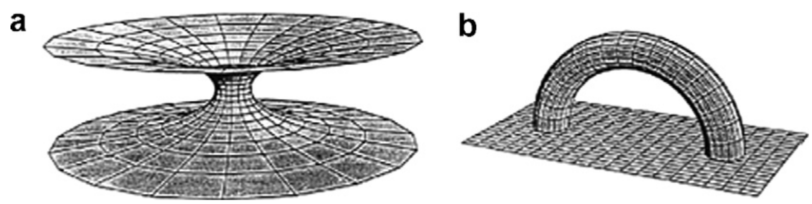

Fig. 3. (a) Inter-Universe and (b) intra-universe wormhole [63].

about matter used to generate FTL spacetimes is that it must have a negative energy density and/or negative flux to satisfy Einstein's field equations [6]. The energy density is "negative" in the sense that the configuration of matter fields must generate and thread the interior of a traversable wormhole throat or a warp drive bubble have an energy density that is less than or equal to its pressure [33,34]. In many cases, these equations of state are also known to possess an energy density that is algebraically negative, i.e., the energy density and flux are less than zero. On the basis of these conditions we call this material property exotic. The condition for ordinary, classical (non-exotic) forms of matter that we are all familiar with in nature is that the energy density > pressures and/or $\geqslant 0$. These conditions represent two examples of what are variously called the "standard" energy conditions: weak energy condition (WEC), null energy condition (NEC), dominant energy condition (DEC) and strong energy condition (SEC). These energy conditions forbid negative energy density between material objects to occur in nature. However, take note that *these energy conditions are but mere hypotheses at* (*t*) *his point in time and are yet to be verified.*

The bad news is that real physical matter is not "reasonable" because the energy conditions are violated by semi-classical quantum effects occurring on the order of the Planck constant $\hbar$ [34]. More specifically, quantum effects generically violate the average NEC (ANEC). Moreover, Epstein et al. [36] discovered that quantum field theory has the remarkable property for allowing states of matter to exist containing local regions of negative energy density or negative fluxes. This violates the WEC. There are also more general theorems of differential geometry that guarantee that there must be a violation of one, some, or all of the energy conditions (meaning exotic matter is present) for all FTL spacetimes. Finally, all of the energy condition hypotheses that have been tested in the laboratory and experimentally are shown to be *false* – 25 years before their formulation [37]. Further investigation showed that violations of the energy conditions are widespread for all forms of both "reasonable" classical and quantum matter [13,24,38]. Moreover, Visser [34] showed that all (generic) spacetime geometries violate all the energy conditions.

3.4.1. Exotic energies found in nature

The exotic (energy condition-violating) fields that are known to exist in nature are:

1. Static radial electric or magnetic fields. These are borderline exotic if their tension were infinitesimally larger, for a given energy density [39,40].
2. Squeezed quantum vacuum states: electromagnetic and other non-Maxwellian quantum fields. [33,41].
3. Gravitationally squeezed vacuum electromagnetic zero-point fluctuations. [42].
4. Casimir Effect(s), i.e., the Casimir vacuum in flat or curved space. [43–48,22].
5. Other quantum fields/states/effects. The local energy density in quantum field theory can be negative due to quantum coherence effects [36]. Other examples that have been studied are Dirac field states: the superposition of two single particle electron states and the superposition of two multi-electron–positron states [49,50]. In the former (latter), the energy densities can be negative when two single (multi-) particle states have the same number of electrons (electrons and positrons) or when one state has one more electron (electron–positron pair) than the other.

In addition, cosmological inflation, cosmological particle production, the conformal anomaly, and gravitational vacuum polarization also violate the energy conditions, since the laws of quantum field theory place no strong restrictions on negative energies and fluxes. *Therefore, it might be possible to produce exotic phenomena such as warp drives* [8,12,51] *and traversable wormholes* [33,34].

4. Stretching space propulsion sciences within current theories

There are realms within science that stretch the boundaries of known theories. Many of these attempts incorporate electromagnetism or the quantum vacuum energies into the gravity equation, while others attempt to rewrite existing theories. Although much can be found in the literature, the following present some interesting examples. We leave it up to the interested reader to search the literature for more examples.

4.1. Propulsion using the quantum vacuum field

The Russian physicist Sakharov created quite a controversy during the sixties when he suggested that the vacuum was not empty [52]. Those in Russia took this to mean that the vacuum consisted of spinors having an electric, magnetic, gravitic, and spin fields; spinors are a short-hand notation used by physicists to characterize tensors for solving Einstein's field equations. Shipov [53] published work suggesting that this was a homogeneous condition. To better understand anomalies, Dyatlov [54] claimed that anomalies represented regions of an inhomogeneous vacuum where a boundary separated regions of the vacuum having different electric, magnetic, gravitic, and torsion field strengths. Moreover, Dyatlov was able to identify, due to natural symmetry, different types of particles and vacuums that existed under unique conditions. By contrast those in the West took Sakharov's words as signifying something closer to a Dirac model where the vacuum consists of particles instantaneously created and destroyed with their electric, magnetic, and gravitational fields. This schema became the foundation for a quantum theory representation of the vacuum.

4.1.1. The quantum vacuum field

The third author indicates that quantum theory evolved and predicts that the vacuum of space in the universe is filled with electromagnetic waves, random in phase and amplitude and propagating in all possible directions [63]. This is different from the cosmic microwave background radiation and is referred to as the electromagnetic quantum vacuum since it is the lowest state of otherwise empty space. When integrated over all frequency modes up to the Planck frequency, v_p ($\sim 10^{43}$ Hz), this represents an enormous potential source of energy with a density of as much as $\sim 10^{113}$ J/m^3 which is far in excess of any known energy source even if only an infinitesimal fraction of it is accessible. This is also several tens of orders of magnitude greater than the energy density needed for matter–antimatter annihilation reactions. Even if we are constrained to integrate over all frequency modes up to the nucleon Compton frequency ($\sim 10^{23}$ Hz), this energy density is still enormous ($\sim 10^{35}$ J/m^3). And we have not taken into account the fact that the electromagnetic quantum vacuum is not alone by itself. On the contrary, it intimately couples to the charged particles in the Dirac sea of particle–antiparticle pairs and to the other interactions of the Standard Model (weak and strong force vacua). So all the numbers we just mentioned admit of some further adjustment.

This energy is so enormous that most physicists believe that even though zero-point energy (ZPE) seems to be an inescapable consequence of quantum field theory, it cannot be physically real, and so is eliminated in calculations by ad hoc means. A minority of physicists do, however, accept it as a real energy source which we cannot directly sense since it is the same everywhere, even inside our bodies and inside measuring devices. Moreover, the zero point field does not appear to have a theoretical gradient which can have unusual implications from a propulsion perspective. Here, the ordinary world of matter and energy is like foam placed atop the quantum vacuum sea. It does not matter to a ship how deep the ocean is as long as the ship is enmeshed in this surface foam. If the ZPE is real, then it can be tapped as a source of power harnessed to generate a propulsive force for space travel. Moreover, this energy may not really be negative but measured to a reference such as the cosmic background noise. That is, negative energy could still remain a positive quantity but represents a value lower than this reference.

4.1.2. Casimir force

There is a force associated with the electromagnetic quantum vacuum: the Casimir force [55]. This force is an attraction between parallel uncharged metallic plates that has now been well measured [56–58] and can be attributed to a minute imbalance in the zero-point energy density inside the cavity between the plates versus the region outside the plates as shown in Fig. 4a. However, this is currently not useful for propulsion since it symmetrically pulls on the plates. If some asymmetric variation of the Casimir force could be identified, though, then one could in effect sail through space as if propelled by a kind of fluctuating quantum wind.

Interestingly, the Casimir force can also be repulsive. This is less understood but whether attractive or repulsive, there is a strong dependency upon the geometry of the objects. For example, perfectly flat plates are attractive where the force varies like $1/r^4$ whereas a flat plate and a sphere the force varies like $1/r^3$. However, the force between two spheres may be repulsive. This simply demonstrates our lack of understanding of this important effect

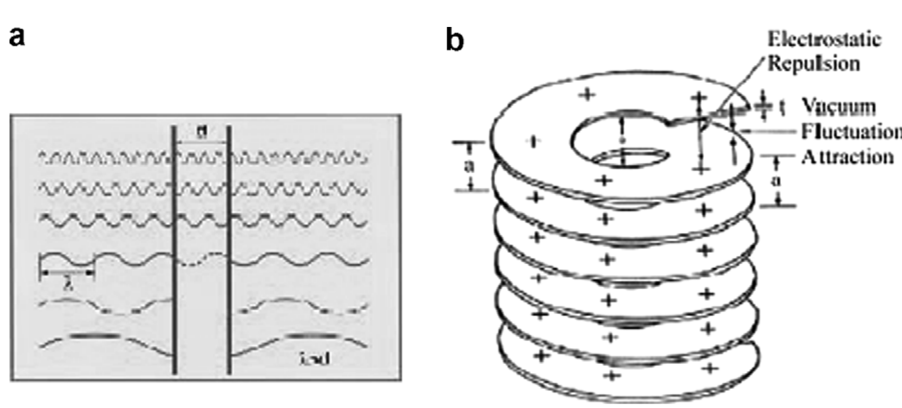

Fig. 4. (a) Casimir Effect (d = cavity wall separation, = ZPF mode wavelength); (b) vacuum-fluctuation battery [20].

and that there is a realistic lack of theoretical understanding of even the most basic phenomenon that warrants additional or continuing research.

4.1.3. Zero-point energy

The other requirement for space travel is ample energy. It is sometimes assumed that attempting to extract energy from the vacuum zero-point field (ZPF) would somehow violate the laws of thermodynamics. Fortunately, it turns out that this is not the case. A thought or "gedanken experiment" published by Forward [59,60] demonstrated how the Casimir force could theoretically extract energy from the vacuum. He showed that any pair of conducting flat plates at close approximate distance experiences an attractive Casimir force due to the electromagnetic ZPF. A "vacuum-fluctuation battery" can be constructed by using the Casimir force to do work on a spiral stack of charged conducting plates (see Fig. 4b). By applying a charge of the same polarity to each conducting plate, a repulsive electrostatic force will be produced that opposes the Casimir force. If the applied electrostatic force is adjusted to be slightly less than the Casimir force, the plates will move toward each other and the Casimir force will add energy to the electric field between the plates. The battery can be recharged by making the electrical force slightly stronger than the Casimir force to re-expand the foliated conductor.

Cole and Puthoff [61] verified that (generic) energy extraction schemes are not contradictory to the laws of thermodynamics. For thermodynamically reversible processes, no heat will flow at a reference temperature $T = 0$. However, for thermodynamically irreversible processes, heat can be produced and made to flow, either at $T = 0$ or at any other $T > 0$ situation by taking a system out of mechanical equilibrium. Moreover, work is performed by or on physical systems, either at $T = 0$ or $T > 0$ situations, whether for a reversible or irreversible process. However, if one considers a net cyclical process of, say, the Casimir Effect, then energy would not be continually extracted without violating the second law of thermodynamics. Thus, Forward's process cannot be cycled to yield a continuous extraction of energy. Here, recharging the battery would, owing to frictional losses, require more energy than gained from the ZPF. There is no net energy production in this process. Nonetheless, the plate-contraction phase of the cycle does demonstrate the ability to cause "extraction" of energy from the ZPF. It does reflect work done by the ZPF on matter.

Another illustrative example of a scheme for extracting energy from the ZPF is a patent by Mead and Nachamkin [62]. They propose that a set of resonant dielectric spheres are used to extract energy from the ZPF and convert it into directly into electrical power. They consider the use of resonant dielectric spheres, slightly detuned from each other, to provide a beat-frequency downshift of the more energetic high-frequency components of the ZPF to a more easily captured form.

4.1.4. Other experiments

In a series of experiments, Koch et al. [64–66] measured voltage fluctuations in resistive wire circuits that are induced by the ZPF. The Koch et al. result is striking confirmation that the ZPF can do real work (at least cause measurable currents). Although the Koch et al. experiment detected miniscule amounts of ZPF energy, it shows the principle of ZPF energy circuit effects to be valid and opens the door to consideration of means to extract useful amounts of energy.

Blanco et al. [67] have proposed a method for enhancing the ZPF-induced voltage fluctuations in circuits. Treating a coil of wire as an antenna, they argue that antenna-like radiation resistance of the coil should be included in the total resistance of the circuit, and suggest that it is this total resistance that should be used in the theoretical computation of the ZPF-induced voltage fluctuations. Because of the strong dependence of the radiation resistance on the number of coil turns (scaling quadratically), coil radius (quartic scaling), and frequency (quartic scaling), these enhanced ZPF-induced voltage fluctuations should be measurable in the laboratory at accessible frequencies (100 MHz compared to the 100 GHz range necessary uncovered in the Koch et al. experiments). The third author provides a further discussion on experiments elsewhere [75].

5. Emerging EM propulsion experiments and theories

In this section, we present a few propulsion theories and experiments that may prove to validate EM propulsion. Section 5.1 has roots in Oliver Heaviside's 1889 divergence of the Maxwell stress tensor but generally relates to the differences between the 1910 results of Minkowski [68] and Abraham [69] and has recently been applied to verify Mach's principle [70]. Section 5.2 dates to the 1959 work of Heim [71], where recently Droscher and Hauser [72,73] applied this theory to propulsion. Section 5.3 discusses an EM velocity profile derived by David Maker with help from the first author [74–76] from Maker's previous work on his novel ungaged Einstein equations [77,78]. Section 5.4 discusses the consequence of Jefimenko's gravity model [79,80], which the second author has indicated could produce a gravitational vortex [52] as this model suggest that gravity is not only an attractive force but also one that also induces angular momentum. Although, much of the presented material is highly speculative, they represent a class of theories and experiments, which could lead to useful EM propulsion in the future.

5.1. Electromagnetism (EM) impulse momentum

The notion of electromagnetic propulsion from $E \times H$ fields date back to Joseph Slepian in 1949 who proposed a momentum drive based on Heaviside's 1889 expression obtained from the divergence of the Maxwell stress tensor [81,82]. Since then many experiments addressing the momentum transfer between matter (dielectric medium) and electromagnetic fields have arisen from the discrepancy [83] between the 1910 results of Minkowski [68] (also Einstein and Laub [84]) and Abraham [69]. Their difference is significant: while Minkowski's momentum is directly proportional to the refractive index of the medium, Abraham's momentum possesses inverse proportionality [84].

The model visualized by Slepian [81] was of an EM drive that employs an RF source to drive a parallel-plate capacitor between two solenoids electrically wired in series as shown in Fig. 5. Here, current passing through the coils must also cross the capacitor. The Slepian inductive–capacitive system, if properly phased, is uniquely suited for studying EM effects as the electric E and magnetic field B both change directions together such that $E \times H$ always points in the same direction and is mathematically positive.

In the late 1960's, Corum [86] gave rise to his so-called Heaviside force density equation by assuming that there could be nonlinear electromagnetic interactions, which arise within selected materials, to provide an efficient force rectification mechanism. The Heaviside force density equation is generally the same as Minkowski's results.

In the 1980s, Graham and Lahoz [87], reported experiments composed of a cylindrical vacuum capacitor using Natural Magnetite, Ni–Zn ferrite or barium–ferrite between the electrodes and exposed to an axial magnetic field. Their experiments showed that torque resulting form the impulse–momentum effect was consistent with the Livens [88] results.

The Graham and Lahoz results are not surprising as EM field momentum can give rise to mechanical motion due to internal $E \times H$ interactions with the macroscopic medium (dielectric) or with the electrical wiring. Momentum can also arise from radiation (photons). Generally, the total momentum is a small impulse force of short duration that time averages to zero and has little useful value in practical impulse–momentum systems (i.e., propulsion). With respect to generally accepted theories, Jackson [85] gives some latitude by his assumption that the macroscopic medium is linear in its electric and magnetic properties, which is above and beyond normal losses or dispersion – a change of the index of refraction with frequency. This allows for additional momentum through some characteristic property of the macroscopic medium.

5.1.1. Dielectric nonlinearity

In the early 2000s, Brito [89–93] began reporting experiments using a ring shaped barium titanate-based dielectric medium in a magnetic field produced by a toroidal coil about the ring dielectric. His experiments showed forces in the low μ-Newton under time varying $E \times H$ fields with a frequency of ~40 kHz and an applied voltage of ~200 V. In 2004, Woodward [70,94–97] reported a variation on the Brito design by using a circular arrangement of commercially available barium titanate-based capacitors. His experiments showed forces in the tens of μ-Newton under time varying $E \times H$ fields with frequency of ~60 kHz and applied voltages of ~1300 V. Of note, this design also used a ferrite material between each capacitor to enhance the magnetic field within the dielectric medium in the capacitors. However, no electrodes were placed about the ferrites as with the Graham and Lahoz experiments [87]. In 2005, March [98] took the Woodward design and exposed it to a time varying $E \times H$ field with a frequency of ~2200 kHz (2.2 MHz) with an applied voltage of ~67 V. His experiments showed forces up to a few milli-Newtons, roughly three orders of magnitude above those shown by Brito with roughly three orders of magnitude difference in the applied frequency. Although not necessarily stated by these authors, these experiments are toroidal variations of the 1949 Slepian model. The difference being that the current feeds to the capacitor and inductive coil were separated so that the relative phase between E and H could be adjusted to solve phasing issues.

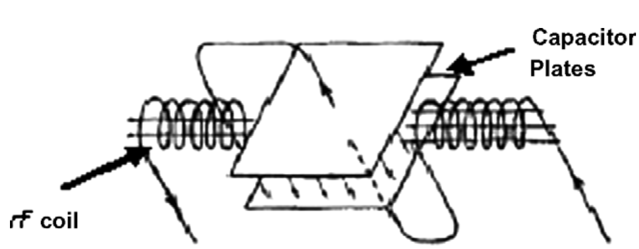

Fig. 5. A schematic diagram of the "Slepian" drive [99].

In 2006, the first author [99], derived an empirical correlation among the Brito [93], Woodward [96] and March [98] experiments by modifying the electromagnetic field (volume) momentum equation given in Jackson [92] to incorporate the concept of nonlinear electromagnetic interactions as noted by Corum [80]. This provided some measure of agreement between experimental and calculated results of these experiments as they all used a (pseudo) magnetoelectric dielectric medium – barium titanate, which behaves differently from normal dielectric materials. That is, the magnetoelectric dielectric medium exhibits nonlinear magnetoelectric effects arising from the interplay of piezomagnetism and piezoelectricity [100]. The premise that magnetoelectric materials are nonlinear in the applied EM fields was taken from Feigel [83] (but not necessarily his thesis of vacuum energy [101]).

This assumption is valid for experiments using barium titanate as barium titanate-based capacitors are known to be nonlinear in voltage and temperature. Further this barium titanate is a piezoelectric material that exhibits magnetoelectric properties when combined with other materials [102]. Moreover, residual magnetoelectric effects cannot be ruled out as contaminates could exist in the material matrix due to the attached electrodes or improper handling during fabrication. These residual magnetoelectric effects would be enhanced due to time varying applied electric and magnetic fields within the dielectric. As a result, the nonlinearity in the data is independent of the applied electric and magnetic field intensities; extra momentum shows up in test data as an electromagnetic nonlinearity of the macroscopic or dielectric medium with respect to the applied frequency of the applied power.

5.1.2. The chameleon model

The first author connected his nonlinear model [99] to work by Khoury and Weltmann [103] who describe a scalar field they called the Chameleon as it takes on the properties of the surrounding medium [104]. The Chameleon model presents an alternative mechanism for circumventing the constraints from local tests of gravity by mediating a fifth force for cosmological expansion. Khoury and Weltmann propose that this could result in experimental signatures detectable through modest improvements of current laboratory set-ups in the vicinity of oscillating matter. This is accomplished through a thin-shell mechanism about an object. The first author proposes that the oscillation of a dielectric by a crossed EM field affects an object's thin-shell producing a force differential in the Chameleon field about an object; field momentum. Further he derives an equation that not only predicts the EM momentum work of Brito [89–93], Woodward [70,94–97] and March [98], but also predicts the experimental data from work conducted by Walker, et. al. [105], where either the electric or magnetic field was time varied; all using the barium titanate-based dielectric material.

5.2. The heim quantum theory of EM propulsion

The Heim's quantum theory (*HQT*) of gravity is based on the geometric view of Einstein, namely that geometry itself is the cause of all physical interactions, but it uses the structure of Einstein's field equations only as a *template* for describing physical interactions in a higher-dimensional discrete space, and extends them also to the microcosm. The theory utilizes an *8-dimensional discrete space 4* in which a smallest elemental surface, the so-called *metron*, exists. This theory was first developed by Heim in the fifties and sixties and partly published in the following three decades of the last century, seems compliant with these modern requirements and makes a series of predictions with regard to cosmology and high-energy physics [106] that should be checked by experiment.

Heim [70] first published his theory of a higher-dimensional discrete spacetime in an obscure German journal in a series of four articles. In 1977, following the advice of Heisenberg's successor, H. P. Dürr, Heim published an article entitled *Vorschlag eines Weges zur einheitlichen Beschreibung der Elementarteilchen* (Recommendation of a Way to a Unified Description of Elementary Particles) [107] as a summary of his unified field theory including quantum gravity. Later on, he wrote two text books *Elementarstrukturen der Materie* (Elementary Structure of Matter) [108,109] that were eventually published by A. Resch. However, to be fair, the Heim's publications are difficult to read and required being modified and extended in several ways, for instance [110].

Most important, Heim's extended theory predicts two additional interactions [73,108,109,111] identified as *quintessence*, a weak *repulsive gravitational*-like interaction (*dark energy*) and *gravitophoton interaction* that enables the conversion of electromagnetic radiation into a gravitational-like field, represented by the two hypothetical gravitophoton (negative and positive energy) particles. The interpretation of the physical equations for the gravitophoton field suggests that this field could be used to both *accelerate* a material body and to cause a transition of a material body into some kind of *parallel space*; possibly allowing for superluminal speed that could serve as the basis for advanced space propulsion technology [74].

Accordingly to Heim's theory, gravitation, as we know it, is comprised of *three* interactions, namely by *gravitons*, the postulated *gravitophotons*, and by the *quintessence* particle. This means that the gravitational constant G contains contributions from all three fields. The quintessence interaction, however, is much smaller than the first two contributions. It is interesting that the mass spectrum for elementary particles, calculated from Heim's mass formula as taken from [106], is very sensitive to G. A corrected value of G was obtained and accounting for the contribution of the gravitophoton field, led to substantially improved results of mass values when compared to experimental data. In Heim's theory the existence of matter as an independent entity is replaced by the features of a dynamic eight-dimensional discrete space, and as such is created by space itself. In other words, matter is caused by a non-Euclidean metric in an 8 *dimension Heim space*, comprised by a large number of elemental *space atoms* or *metrons*, interacting in a dynamic and highly complex way.

Droscher and Hauser [112] indicate that the *HQT* implies that field propulsion can be applied to a superconductor gravitomagnetic field experiment similar to that conducted by Tajmar et al. [113]. However, the Tajmar et al. experiment generates an azimuthal gravitational field, and thus is not suitable for propulsion. The lesson learned from the experiment is that coupling to *bosons* (Cooper pairs) is of prime importance. Whereby applying the general Heim–Lorentz force equations to the experimental setup as seen in Fig. 6, Heim–Lorentz force now produces force components in the radial r and z- directions. If theoretical predictions are correct, the realization of a *workable space propulsion device that can lift itself from the surface of the Earth* seems feasible.

5.3. EM propulsion implications as a new source term for the einstein equations

In 1999, Maker [77] introduced a new E&M source term for the Einstein Equations to derive a new Dirac equation. He explains that this is plausible in light of implications for the standard model, especially in regards to quantum electrodynamics (QED). He presents all of this within the framework of a "dialogue" to facilitate understanding his theory by writing down a Generally Covariant Lagrangian that leads to these results and indicates how the metric formulations can be derived by E&M fields. Maker indicates

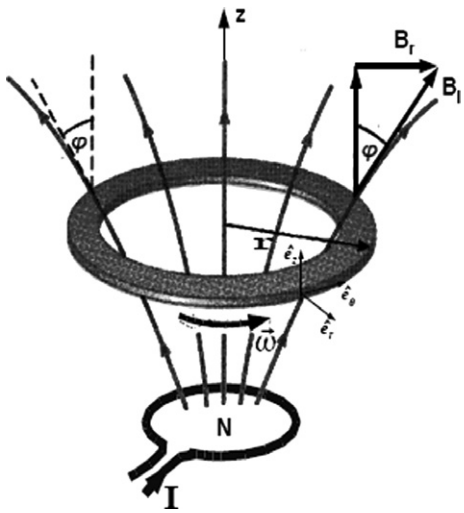

Fig. 6. This picture shows the physical principle of the experimental setup to generate a gravitational field in the z-direction (upward, above rotating disk) by the Heim–Lorentz force using a superconducting coil (boson coupling) and a rotating disk or ring. The actual experiment would be somewhat different to be practical [112].

that the results of his theory are relevant to propulsion through a coordinate transformation from this E&M source to a gravity source, which is shown to "cancel out" the coordinate transformation effects. That is, this cancels out the gravity contribution to produce a propulsion result. This gravity annulment term has a shape function as illustrated in Fig. 7.

An impulse velocity equation based upon Maker's earlier work [77,78] was developed with the help of the first author [74–76]. This impulse velocity equation predicts the data from the 2000–2001 Podkletnov superconductor impulse experiments [114] and has a form similar to the right side of Fig. 7 with the center spike representing a voltage of ~512 kV, the electron destruction/creation voltage. Also of note is that the left side of Fig. 7 is similar to the thrust profile derived by the first author [99] for the inductive capacitor experiments (see Section 4.2), which uses voltages <512 kV. From this, it can be speculated that the profile of Fig. 7 represents an increasing thrust to the center, where a maximum thrust is obtained (speculatively imposed by the surrounding environment, e.g., earth). Beyond this the thrust is constant with respect to the (negative) velocity, which can be imposed to approach the speed of light as the profile approaches zero on the right.

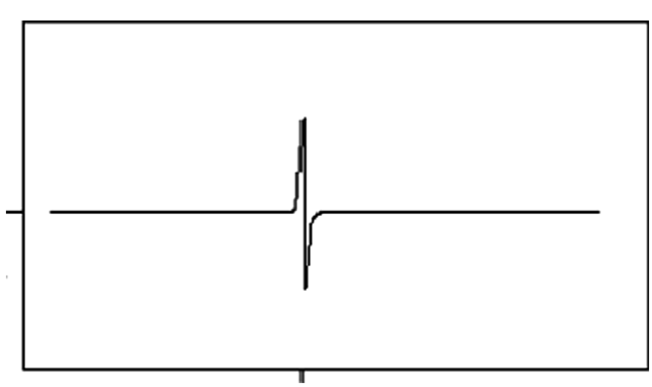

Fig. 7. Maker's gravity annulment profile [74].

5.4. Vortex gravity model

Aside from these constructs, there is a need to more closely examine gravitational effects, in general, in the hopes that some propulsive advantage may be revealed that is outside the current mindset [114–117]. As one example, Jefimenko [79,80] created a gravitational model resulting in partial differential wave equations defining both gravity and co-gravity to treat relativistic effects within a gravity model in lieu of a mass model. This model was predicated upon the Lorentz force with the consequence that gravity is not only an attractive force but also one that also induces angular momentum. The second author [52,115] makes the conjecture that Jefimenko's co-gravity is the elusive spin or torsion field identified in Russian scientific literature. That is, if one looked at specific gravity models as well as Newtonian theory, one point becomes very apparent, the terms in these equations involve a Laplace operator acting on gravity. A similar mathematic term also occurs in the equations governing both the EM fields about a body. In hydrodynamics, such a term implies various interesting fluid dynamic processes. This includes linear flow, separated flow as well as the creation of vortices, which induce effects impacting continuity, momentum and energy considerations. The only analogous vortices that have been detected to date regarding electric or magnetic fields are microscopic electrical vortices involving electron pairs that occur in superconductors creating a quantized magnetic flux.

This leads to the emphasis on how to create a gravitational vortex. Mathematically, this possibility exists and offers many interesting insights for future propulsion concepts. For example, anomalies like the Gerschtenstein effect [118] indicate that there exists a coupling between gravity and electromagnetic waves. However, if true, then it is entirely feasible that a rotating electromagnetic vortex could induce a gravitational vortex. Such a vortex may induce a flow of gravitons that would travel along the axis of the vortex and generate thrusts, not only on the basis of momentum considerations, but also due to field interactions with the Earth and solar system's gravity field.

6. Forging new space frontiers toward a realistic space drive

Each day we see on television or read in the papers about some new advance in technology. In most cases we take the news in stride, for we have heard of similar things. But for our ancestors of only a few generations ago, these new technological achievements would have been thought to be magic (Dr. Robert L. Forward) [119].

We are very uncertain of how many of the concepts, technologies and/or theories presented in this paper and the many others presented throughout current literature will be attained or progress over time; that is to turn them from wishful thinking into a hard concrete and realistic space drive system. Moreover, the theories on which some of these imagined concepts are based upon may be wrong or the technology needed to achieve the eventual goal of space travel may require materials or energy density levels that do not currently exist in today's reality. It may be we are just too busy exploring other realms of science that are more pressing – than – we are to take the time to ponder such far stretched space drive concepts. These realities however do not change the dilemma we face in our understanding of current physical laws, which indicate that rockets in space have nothing to push against, and so it needs to carry propellant to eject mass in the absence of pushing against a medium.

The space drive breakthrough one wishes to obtain is to overcome the need to carry any propellant. Within the new frontiers in space propulsion sciences discussed, there may be clues to a roadmap to a space drive in the future. Even if the specific technology proves unattainable, the study thereof may provide clues needed to forge forward in a new direction in space propulsion. The key challenge here, in addition to the daunting physics, is dealing with such visionary topics in a credible, impartial, and productive manner. That is, when considering future prospects, a management challenge should take into account genuine, reliable progress as well as the associated risk assessment [120,121] and must balance progress with far reaching goals.

The necessity for forging new frontiers (aka: breakthroughs) within the space propulsion sciences was made apparent in the 2002 Walker et al. Aerospace Commission Report [122], which made the following policy recommendations:

- "Achieve Breakthroughs in Propulsion and Space Power." – Executive Summary
- "New propulsion concepts based on breakthrough energy sources... could result in a new propulsion paradigm that will revolutionize space transportation." (p. 9–5)
- "In the longer-term, breakthrough energy sources that go beyond our current understanding of physical laws, ... must be credibly investigated in order for us to practically pursue human exploration of the solar system and beyond. These energy sources should be the topic of a focused, basic research effort." (p. 9–6)
- In Figure 9–3 on page 9–9, "zero-point" is listed under "Breakthrough Energy Sources."

These roadmap recommendations point the way to achieve successful breakthroughs within the frontiers of science and propulsion science so that we can move forward in a meaningful way. In the following we discuss the propellant mass and energy problem that point to more promising concepts and discuss how these new frontiers in space propulsion science could fit into the future of space propulsion.

6.1. Propellant-based rocketry verse the space drive

Interstellar space travel will pose many difficult scientific challenges. For example, defining the mass/energy requirements needed for propellant-based interstellar travel is nothing less than "astronomical." The fundamental propellant problem is that a propellant-based, deep space rocket would have to start with all the propellant it will ever need. For example, in order to send a vehicle using chemical propellant with the mass of a space shuttle to our nearest star at the leisurely pace of a 1000 year-trip time would require 10^{119} kg of propellant [123].

It may seem that the solution to the propellant mass problem is simply just a matter of developing more efficient rockets. Unfortunately, exhaust cannot leave a rocket with a velocity that exceeds the velocity of light in a vacuum. This upper theoretical limit to the speed of kinetic objects in the universe imposed by relativistic dynamics places a serious constraint on how efficient a rocket can be. For example a perfect propellant-based rocket would have a propellant of matter and anti-matter that react in a controlled way producing a photon exhaust. A fuel of anti-matter and ordinary matter to react would have the smallest ratio of stored energy E, to total mass m, that is physically possible, namely $E/m = c^2$. The problem that still arises is that a typical interstellar mission will require at least four phases for a round trip: two phases where acceleration is required and two phases where deceleration is required. Calculations using the rocket equation obeying relativistic dynamics show that the amount of anti-matter required for an interstellar mission with a perfect rocket will be very difficult to produce using contemporary technology [124].

It is easily argued that the successful production of anti-matter is more important than researching the theories and conceptual technologies presented in this paper. As most of these aforementioned approaches require that space must have some kind of dynamic structure that can react against an energy stream to satisfy the Law of Conservation of Momentum. However, space drive techniques might achieve this through the application of exotic or specially conditioned electromagnetic fields to potentially reduce or diminish gravitational inertia. Such techniques could come from a better understanding of the quantum vacuum field as discussed in Section 4 or from the EM propulsion experiments and theories discussed in Section 5. Even if obtainable, we still must address conservation of energy, which indicates that large amounts of electrical power will be required.

Conservation of energy rules in propellant-based propulsion and in all the new frontiers in propulsion science, which could produce a specific space drive. That is, energy is really the key to space travel. It is the energy requirement that leads us to nuclear concepts – fission, fusion, and anti-matter. For years we have listed the energy sources per unit mass for propulsion starting with various chemicals, metastable materials, and proceeding all the way to antimatter or $E = mc^2$. In this regard, tremendous amounts of energy will be needed to power such star ships of the future based on the theories and concepts presented in this paper. This energy requirement is what drives our interest in the zero point energy (ZPE) or the vacuum fluctuations of the electromagnetic field as discussed in Section 4. The kind of energy theoretically available from ZPE would really make interstellar travel a reality. But there are other high payoff energy sources that ought to be considered, which are not considered in this paper. In fact, some thought ought to be given to searching for advanced energy sources rather than putting all our emphasis on advanced space drive concepts, which requires new methods for abundant on-board energy creation, conversion, and storage. However, given the apparent magnitude of the energy requirements to create perceptible effects toward a space drive within the new frontiers in propulsion science, it seems unlikely that high thrust space drive experimental work will be forthcoming in the near future without the development of high density-high power subsystems to complement them.

6.1.1. Limits of rocketry analyses on space drives

Millis [125] points out that when using the metrics of current propulsion technology to assess the potential of a concept technology within a specific new area of propulsion science, results can be misleading. As demonstrated by his hypothetical inertial example that illustrated how different assumptions of inertial control can lead to very different answers. Millis also states that another misleading use of the rocket equation is the common practice of assigning an infinite specific impulse to describe a propellantless space drive. Although based on a reasonable extrapolation, where higher specific impulse leads to less propellant, this leads to the conclusion that a propellantless space drive would require infinite energy, which is not necessarily the case. Furthermore, since specific impulse is a measure of the thrust per propellant weight flow rate, it has no real meaning if there is no propellant flow, such that, using the rocket equation to describe something that is not likely to involve a rocket is about as misleading as using the metrics of sailing ships to assess steamships [126]. Therefore, comparisons built on the incumbent methods might be useful for introductory purposes, but for spaceflight, whether via rockets or space drives, vehicle specific energy and/or specific power is a better basis for comparison. This is specifically useful for a space drive, which is defined as "an idealized form of propulsion where the fundamental properties of matter and space time are used to create propulsive forces anywhere in space without having to carry and expel a reaction mass [127]."

6.2. Earth-to-orbit (ETO) and planetary propulsion

Several ETO field propulsion or space drive concepts have been envisioned. Such concepts indicate that an aerospace vehicle could use specially engineered vacuum or EM energy fields to modify the local gravity field to be lifted from the Earth's surface and propelled up to orbit without having to necessarily engage any FTL motion. These approaches obviously require further research as well as discovery of physical evidence regarding the interaction between EM radiation, the vacuum field and gravity. For example, the motion of nonlinear capacitors manipulated by an electric and magnetic field, as discussed in Section 5, and created through purely energy interactions is of some interest. However, current demonstrations are at relatively low values comparable to present day values competitive with using simple ion engines. Theoretically, this new technology has a potential for higher thrust capability, which would scale with the input power. Thus further testing could offer potential breakthroughs in thrust capability. Although, defining a space drive for ETO propulsion would clearly be a very challenging situation that could induce new interesting propulsion concepts and open very unusual doors to the propulsion community.

6.2.1. Fluid dynamic simulation of FTL space drive

Aside from the FLT space drive concepts, an understanding of the environment such as a spaceship might encounter is also of importance before pushing forward to actual trials (assuming of course that such a space drive is realistic). For example, Froning and Roach [128,129] discuss similarities in air densities associated with thermal energy fluctuations from air molecule collisions in planetary atmospheres and vacuum densities associated with zero-point energy fluctuations from virtual particle pair creation and annihilation in space. Therefore, just as aerodynamic pressure gradients form in air disturbed by a moving aircraft, so zero-point radiation pressure gradients should form in the quantum vacuum perturbed by field-propelled ships.

Just as a craft's gravitational presence determines what paths (geodesics) passing space particles must follow in their warped spacetime, so to a craft's outer skin determine what paths (streamlines) passing air particles must also follow in their disturbed airflow. And just as stresses formed in warped spacetime cause pressures, which exert forces on bodies in space, so stresses formed in disturbed airflow also induce pressures, which exert forces on aircraft in the air. In this respect, there is a similar increase in flight resistance as an accelerating spacecraft approach an electromagnetic disturbance propagation speed in space and accelerating aircraft approach acoustic propagation speed in air.

Recently Froning and Roach [130] extended their analysis to include the Zero-point radiation pressures in the vicinity of an accelerating warp drive-driven ship by simulating it as a 2D inviscid CFD computation of aerodynamic pressures in the vicinity of an accelerating aircraft of much smaller size. Fig. 8a shows the simulated zero-point radiation pressures in the vicinity of a large warp drive-driven ship at 0.99 and 2.0c, based upon pressures about a smaller ship at Mach 0.99 and 2.0 shown in Fig. 8b.

This fluid dynamic approximation of accelerated flight of a warp drive-driven craft through a compressible

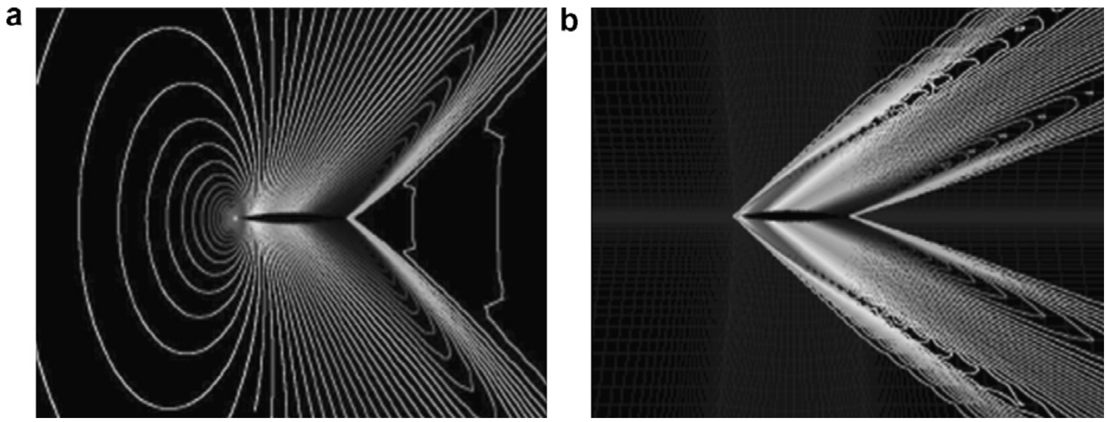

Fig. 8. Comparison of zero-point radiation pressures: (a) zero-point radiation pressure gradient caused by accelerating ship at 0.99 speed of light and (b) zero-point radiation pressure gradient caused by accelerating ship at 2.0 speed of light [130].

negative pressure vacuum is not yet refined enough to provide quantitative results. But it has revealed some trends similar to some of those already predicted by warp drive solutions to Einstein's General Theory of Relativity. One similar prediction is that appropriate warp drive energy transfer into a negative pressure zero-point quantum vacuum forms pressure gradients that can accelerate ships from slower-than-light (STL) to faster-than-light (FTL) speed.

6.3. Interstellar propulsion

The ultimate challenge to interstellar travel is to become a viable economic entity. It requires exploring the possibility of hyper-fast space drive to exceed the speed of light in which the antimatter propulsion system previously discussed could not even achieve. Have any of the EM field propulsion concepts been applied to the FTL problem? The answer requires that we focus our attention toward other more exotic concepts such as wormholes and warp drives as discussed in Section 3. These concepts could fundamentally provide a means of curtailing the propellant mass problem, plus eliminate the enormous round-trip time required for missions to the distant stars at "sub-light" speeds.

The first question that needs to be solved is "*how* one could reach a suitable initial condition to initiate a FTL drive." Such a problem has yet to be seriously addressed. Some supporters of the warp drive imply that a sub-light version could achieve this using the current understanding provided by the theoretical physics model. Although at present, there is no known successfully conducted experiment that has demonstrated the disturbance of spacetime by either a warp drive or wormhole configuration. Even though these notions are theoretically sound; without any realistic experimental data, these ideas remain only as remnants of theoretical concepts or artifacts providing no real propulsion engineering solutions at this time.

Further, one must realize that even FTL theoretical concepts are extremely unlikely to be engineered in the near future. However theories toward FTL concepts can at least be useful as teaching tools to more thoroughly explore the intricacies of Einstein's General Relativity, which then could lead to more realistic FTL space drive systems. Such research could build on experiments like hyper-fast travel involving the quantum mechanical tunneling of light through a potential barrier with an apparent super-luminal speed. Although, research that could develop some means to achieve near-light or relativistic speeds for molecular structures beyond that of purely information exchange, e.g., electron exchange is a good next step and is an important challenge before mankind can pursue faster than light travel for interstellar mission.

7. Conclusions

We discussed the underlying principles that inhibit the current progress of the space propulsion sciences and some of the theories and concepts that have emerged over the last twenty or so years from science fiction to the science journals, to include warp drive, wormholes, vacuum zero point propulsion and energy and EM propulsion theories and concepts. Admittedly many if not all these theories and concepts stretch the imagination. Unfortunately, even the most promising of these may soon be forgotten until the physics catches up to them. For those concepts that survive, the question remains: "How do we apply some or even all of these theoretical concepts into a useful device so that clear-cut engineering principles could apply? Further, could a new propulsion system consist of a hybrid system that incorporates portions of many of these theories and concepts? Even so, what is the grand principle that allows us to engineer such a device?

We conclude that a new breed of propulsion scientists is required as they will need to be cross disciplined into a variety of the physical sciences to include: electromagnetism, spacetime and string-brane theory to but name only a few.

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