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Destination Universe: Some Thoughts on Faster-Than-Light (FTL) Travel

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Faster-than-light (FTL) travel is a staple of science fiction and it has been seriously investigated by a number of physicists. Despite the challenges both theoretical and practical, the idea of FTL travel is intriguing because if it can be achieved it offers the human race the chance to travel to the stars within the lifetimes of the crew. Three of the principal FTL concepts are discussed in this paper: (1) tachyons which are hypothetical FTL particles with properties consistent with the special theory of relativity; (2) wormholes which offer a window to distant star systems using general relativity; and (3) warp drives which employ general relativity to modify spacetime to get around the velocity of light speed limit. Issues facing hypothetical FTL travelers are discussed.

In space there are countless constellations, suns and planets; we see only the suns because they give light; the planets remain invisible, for they are small and dark. There are also numberless earths circling around their suns, no worse and no less than this globe of ours. For no reasonable mind can assume that heavenly bodies that may be far more magnificent than ours would not bear upon them creatures similar or even superior to those upon our human earth.

---Giordano Bruno
(1548 – 1600)
Burned at the stake for heresy (17 February 1600)

1. Introduction

The stars have beckoned the human race since before the dawn of history. Sometimes thought to be deities, other times guides, their apparent movements were studied by early "astronomers" in such places as China, Mesopotamia and Egypt. The early speculations of Lucretius (c. 90s BCE to c. 50 BCE) and Giordano Bruno (1548-1600) have come to pass – there are, as of 03 June 2016, 3,272 confirmed exoplanets.[1]

Can we travel to these planets? That is an age-old question, one that is of more than academic interest. There is the undeniable urge to see firsthand what is "out there" ("over the next mountain"). One can argue that humans share the same biological urge that has enticed creatures from the sea to the land to the air, now into near Earth space and perhaps to Mars as Dr. Chris McKay has suggested.[2] Shall we carry it to the stars and, if so, how will we travel across the vast interstellar distances?

Two methods of interstellar transportation immediately suggest themselves. One approach is to "upgrade" our existing means of interplanetary travel by using "… very large starships moving at relatively low velocities and therefore taking long periods to reach their stellar destinations".[3] "The second approach" astronomy writer John Macvey suggested "is to think in terms of rapid interstellar travel".[3] Three such "rapid-travel" approaches will be qualitatively discussed in this paper: (1) tachyons (hypothetical FTL particles); (2) wormholes; and (3) warp drives.

(To aid the reader a list of key acronyms used in this paper is presented in Appendix A at the end of the paper.)

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The first method (low velocity starship) listed by John Macvey runs into an immediate problem: for example, traveling at the speeds of the two Voyager spacecraft it would take almost 75,000 years to reach the Alpha Centauri system (the nearest star system).[4] If we try to speed up the spacecraft the problem becomes almost intractable. For example, Robert Frisbee has calculated that to move a payload mass of 100 metric tons (approximately the mass of a Space Shuttle Orbiter) at 50% the speed of light (0.5 c) would require an energy "… about 2.7 years worth of the annual energy production of human civilization".[4] Furthermore, Frisbee noted that "… adding the required propulsion system to reach interstellar transportation speeds results in vehicle systems with dimensions on the order of planetary diameters, masses of hundreds of billions of tons and power levels thousands of time that of human civilization".[4] Thus, we need to think "… in terms of rapid interstellar travel".[3]

Speeds at or beyond the speed of light ($c \approx 2.998 \times 10^8$ m/s) for objects with mass have often been described as impossible, as violations of the "laws of physics". Fortunately for our descendants there may be some ways around this "speed limit" which will be briefly discussed or listed in this paper.

2. The Speed Limit

In 1887, Albert A. Michelson and Edward W. Morley conducted an experiment to measure the speed of the ether, the assumed material through which Earth moved and which was thought to be the medium that allowed the propagation of light. What they found was an absence of an "inter-molecular ether" and that the speed of light was a constant.[5]

In explaining this new view of the Universe, Albert Einstein later established two postulates[6]

1. The laws of nature and the results of all experiments performed in a given frame of reference are independent of the translational motion of the system as a whole.

2. The speed of light (c) is independent of the motion of its source.

Einstein concluded "… that in the theory of relativity the velocity *c* plays the part of a limiting velocity, which can neither be reached nor exceeded by any real body".[6]

The barrier facing us for rapid interstellar travel can be seen by looking at the classical example of a propagating spherical wave observed from the reference frame of the source and from a reference frame (prime) moving with respect to the source[7]

$$x^2 + y^2 + z^2 - c^2t^2 = x'^2 + y'^2 + z'^2 - c^2t'^2 \qquad (1)$$

Contrary to popular belief, Einstein did not make the Universe relative; Equation (1) expresses the conservation of the four-dimensional volume of an object. But his "Special Theory of Relativity" (SRT) leads to some curious physical effects which need to be highlighted if we are to understand what constrains us.[7]

For example, consider a rigid rod lying at rest along the z-axis in the unprimed system with length $l = z_2 - z_1$. An observer moving with velocity v will see an apparent length of[7]

$$z'_2 - z'_1 = l(1 - \beta^2)^{1/2} \qquad (2)$$

where $\beta = v/c$.

Time suffers a similar "distortion" that depends on velocity. An observer in the moving primed system will measure this dilated time interval for a clock in the unprimed system[7]

$$t'_2 - t'_1 = \frac{t_2 - t_1}{(1 - ß^2)^{1/2}} \tag{3}$$

And finally we come to the relativistic "*coup de grâce*" that seems to shoot down any hope of traveling at or beyond the speed of light: the increase in the mass of a moving object[7]

$$m_r = \frac{m_0}{(1 - ß^2)^{1/2}} \tag{4}$$

where m_r is the "relativistic mass" associated with the moving object.[7] Figure 1 illustrates the extraordinary increase in the relativistic mass as the velocity of the object approaches the speed of light, c. Where will the energy come from to push an infinitely massive object beyond the light barrier?

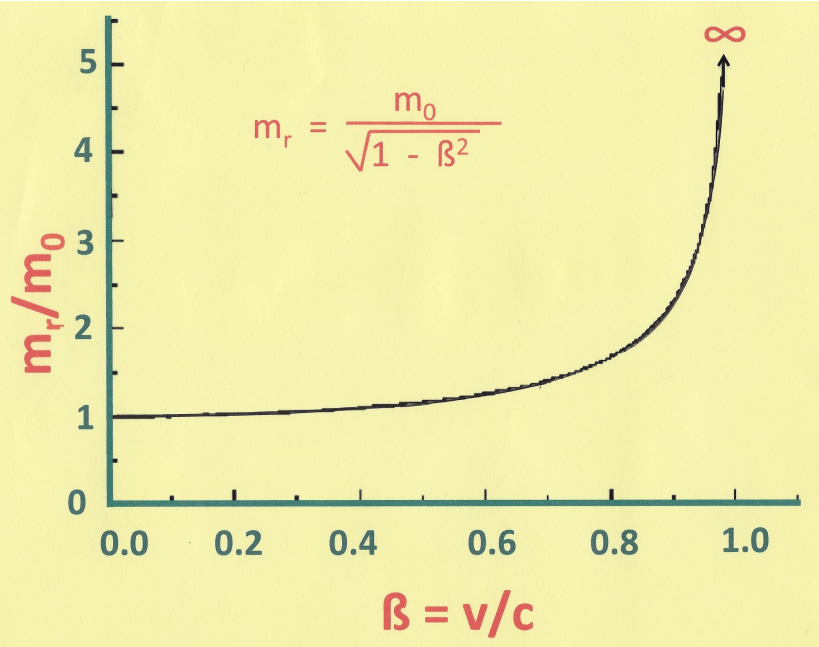

Figure 1. Variation in mass as a function of velocity.

Worse for the interstellar traveler approaching the speed of light, Equation 3 shows the traveler's time will slow to zero and Equation 2 shows the traveler's length will decrease to zero as well. These are not constraints like the sound barrier that can be overcome with some clever engineering; these are constraints built into the very fabric of the Universe. These relativistic effects have been seen experimentally (see, for example References 8-10 for starters). As the T-shirt slogan says, "It's all fun and games until someone divides by zero".

Still, as Nick Herbert has pointed out, there are some things that theoretically move faster than light (FTL).[11] For additional details, the interested reader is referred to Reference 12.

Scissor-blade intersection	Marquee lights
Searchlight beam	Comet tail
Eclipse shadow	Riptide
Perfectly rigid rod	Oscilloscope trace
Galloping waves	Neptune and Pluto
Quasar expansion	Expansion of spacetime
Plasma phase velocity	"Practical speed" of NAFAL ship

[NAFAL means "nearly-as-fast-as-light"]

Unfortunately none of these theoretical actions allow the transmission of information, mass or energy at FTL speeds.

And it must be noted that it is possible to travel faster than light in a medium where the speed of light is less than that *in vacuo*. The classic example usually given is that of Cherenkov radiation emitted when charged particles (e.g., electrons) travel faster than light in a medium (such as water shown in the nuclear reactor photograph in Figure 2 where the speed of light is about 75% that *in vacuo*).

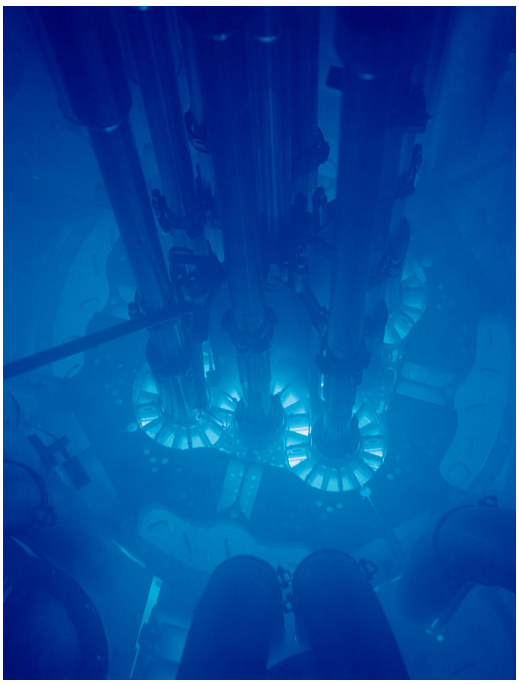

Figure 2. Observed "Faster-Than Light Travel":
Cherenkov radiation emitted in the Advanced Test Reactor.
The blue glow is from the electromagnetic radiation (Cherenkov radiation)
emitted by charged particles traveling faster than the speed of light in the water.
(Source: U.S. Nuclear Regulatory Commission)

Theoretical proposals for overcoming the light barrier (sometimes called the "luxon barrier") have been grouped into one or more of four general categories as illustrated in Figure 3.

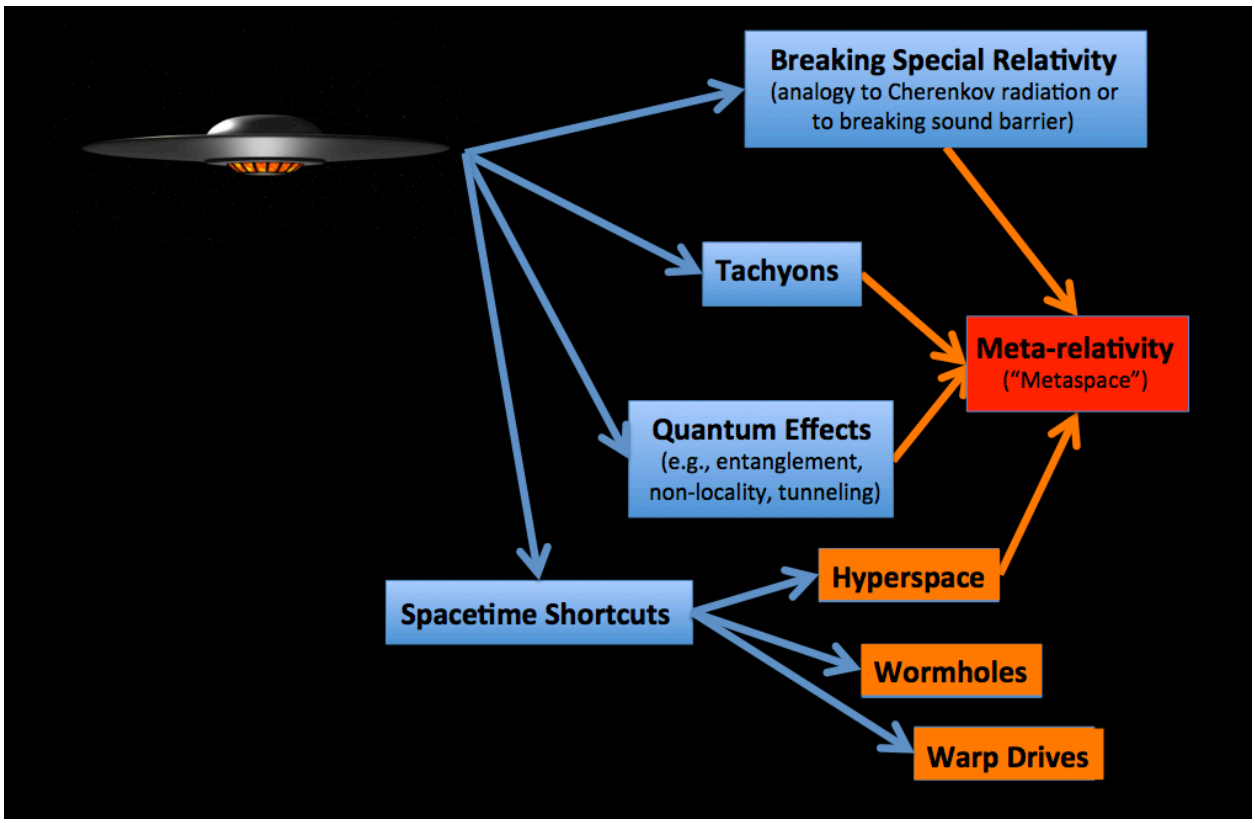

Figure 3. Diagram of general concepts for achieving faster-than-light (FTL) travel.
(After M. G. Millis and E. W. Davis, "Warp Drives & Wormholes, Exploiting the Boundaries of Physics", Tau Zero Foundation, 2013)

This paper, which is a spinoff of Reference 13, will qualitatively consider three of these concepts (tachyons, wormholes and warp drives) followed by a discussion of some other concepts along with an argument for why FTL interstellar travel is needed.

3. Tachyons – Particles Beyond The Light Barrier

Contrary to popular belief, the equations of special relativity do allow faster-than-light particles as a number of researchers have pointed out (See Section 3.1). But such particles (if they exist) have some strange properties. And if they don't exist, the question becomes, why don't they exist if the mathematics allows their existence?

3.1 Tachyon History (Brief)

In a 1962 paper on what they termed "meta relativity", O. M. P. Bilaniuk, V. K. Deshpande, and E. C. G. Sudarshan investigated the implications of hypothetical particles ("meta particles") created at superluminal velocities.[14] Such particles had to satisfy two criteria:[14]

1. In any frame of reference the energy of a particle must be positive.

2. Laws of particle dynamics must be independent of the frame of reference.

In order for such meta particles to have real energy

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

and real momentum

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

the rest mass (m_0) must be imaginary. Similarly, from Equations 2 and 3, the proper length (ℓ) and the proper time (t) must be imaginary. Bilaniuk et al., suggested that if such meta particles were charged, they might be detected in the Cherenkov radiation.[14] To date such searches have come up negative – or with a low probability of FTL particle interactions (see, for example, References 15-18).

Gerald Feinberg developed a quantum field theory of noninteracting, spinless, FTL particles which he called "tachyons" from the Greek word **ταχὺς** (tachys) meaning swift or rapid.[19]

3.2 Tachyon Propulsion

In order to be consistent with the special theory of relativity, tachyons are assumed to be created traveling faster than the speed of light. This presents a problem – how do we subluminal creatures take advantage of a possible FTL means of travel or communication?

Takaaki Musha has suggested using quantum tunneling to move subluminal particles to FTL speeds.[20] Recall from nuclear physics that the explanation for how alpha particles, which have a wavelike property, can overcome the Coulomb barrier of the nucleus is by tunneling through the barrier as shown in Figure 4.

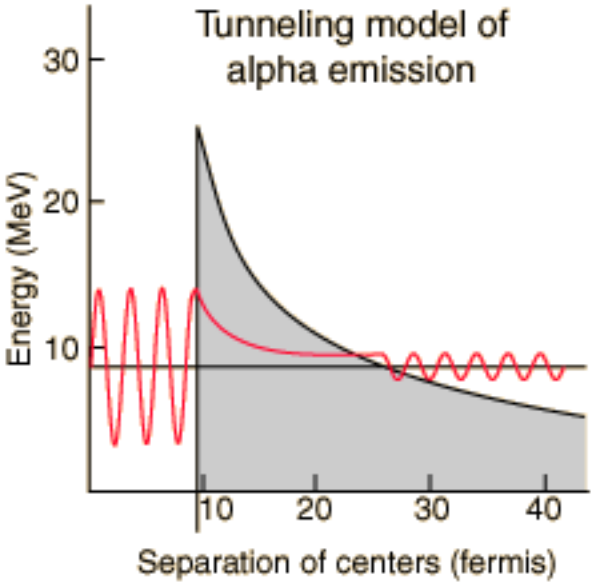

Figure 4. Alpha tunnel model.
The illustration models how an alpha particle with its wavelike properties can escape from the 26-MeV Coulomb barrier of polonium-210.
(Source: hyperphysics.phy-astr.gsu.edu/hbase/nuclear/alptun.html)

Since the alpha particle has wavelike properties it is possible for it to "leak" through the barrier with a probability, P, of

$$P = \exp \{ - (2/\hbar) (2m)^{1/2} \int (U - E_\alpha)^{1/2} \, dr \}$$

where $\hbar = h/2\pi$, m is the mass of the α–particle, and the integral is taken over the entire region in which $U(r) > E_\alpha$.[21]

Musha has proposed a similar tunneling through the light barrier.[20] By manipulating the zero-point field (ZPF, the lowest energy state of a particular field), Musha derived this approximation for the transmissivity *T* of tunneling through the barrier[22]

$$T \approx \exp\left[\frac{\sqrt{1-\beta^2}}{2\beta}\frac{m_0 c^2 \omega^2}{\hbar\omega_c}\frac{\Delta t}{\Delta\omega}\log\left(m_0 c\frac{\omega^2}{\omega_c^2}\right)\right]$$

where $\omega = 2\pi f$ (f is the frequency of the quantum harmonic oscillator associated with the field) and ħ is Planck's constant divided by 2π (h/2π).

Because this tunneling involves generating a negative energy field to reduce the ZPF frequency around the ship in order to accelerate to FTL speeds it could also be termed a "warp drive"; however, Musha terms it "FTL travel in a tachyonic mode".[22] Even though tachyons are not involved, tunneling to the tachyon side of the light barrier avoids the infinities in Einstein's equations.[20] (I have to confess that tunneling was one of the several mechanisms I invoked to achieve FTL travel in my novel *The Star Sailors*.[23])

John G. Cramer has described a tachyon drive in which tachyons are created and exhausted from the rocket engine to produce thrust.[24] In his description, neutrino-antineutrino pairs would be used to produce tachyons. Producing the neutrino-antineutrino pairs at the desired flux and direction were issues that Cramer said would have to be addressed. Still, the idea of having a tachyon drive without tunneling through the light barrier is intriguing.[24]

4. Wormholes

Wormholes, those short cuts through space, are often invoked in science fiction as a way to achieve FTL travel. Figure 5 illustrates in a two-dimensional way the basic concept of a wormhole in which a three-dimensional tunnel (or "mouth") connects two different regions of the two-dimensional space.

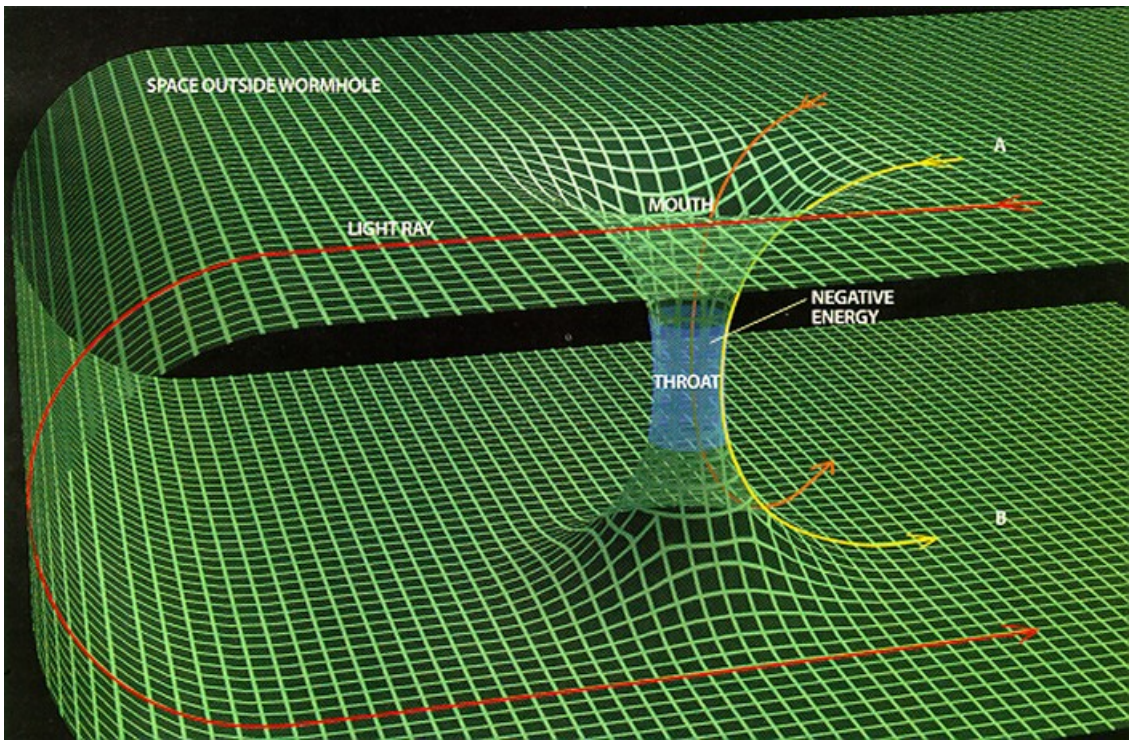

Figure 5. Wormhole bridge connecting two mouths with a single throat or tunnel.
(Source: Wikipedia)

4.1 Traversable Wormholes

While wormholes are an attractive method of traveling vast interstellar distances in a short (to the traveler) time, they have the theoretical problem of closing down quite rapidly.[25] The trick, then, is to thread the throat with something that will hold the tunnel open long enough for travel. The desirable properties of traversable wormholes include[26,27]

- The wormholes have to have small tidal forces
- The wormholes have to be two-way, which means they cannot have a horizon
- Transit times through them have to be reasonable, both from the points of view of the traveler and the people outside the tunnel
- Radiation effects have to be minimal
- The wormhole should be capable of being constructed with reasonable materials and within a reasonable period of time

To these five desirable properties, E. W. Davis has listed eight "primary general requirements for putative FTL space warps" (some of which overlap the five above):[28]

- The rocket equation no longer applies
- The starship travel time via the FTL space warp should take ≤ 1 year as measured by the starship passengers and outside remote static observers
- Proper time as measured by starship passengers should not be dilated by relativistic effects
- The FTL space warp-induced tidal-gravity accelerations acting between different parts of the starship passengers' bodies should be $\leq 1\ g_{\oplus}$ inside the FTL space warp
- The speed of the starship while inside the FTL space warp should be $<c$
- The starship (made of ordinary matter) must not couple strongly to the material that generates the FTL space warp

- The FTL space warp should not have an event horizon
- There should be no singularity of infinitely collapsed matter residing inside or outside of the FTL space warp

Creating a wormhole might be achieved by tearing two hole in space and sewing them together or by grabbing one of the tiny wormholes thought to pop into existence in the quantum foam that is believed to exist at or less than Planck-Wheeler length scales (~1.62 x 10^{-33} cm).[25,26] As Kip Thorne has noted, this may require an "infinitely advanced civilization".[25] Such an infinitely advanced civilization would have to create a tension in the wormhole's throat that has the same magnitude (~10^{37} dyn/cm^2) as the pressure at the center of the most massive neutron stars.[26]

4.2 Natural Wormholes

Theoretically, it may be possible for wormholes to exist naturally. This would certainly overcome the problem we face of not being an "infinitely advanced civilization". Now we just need to find them.

Gravity, particularly near compact gravitational objects like black holes, may produce regions of "squeezed vacuum" the could correspond to the negative energy within which natural wormholes might form.[29] Such "squeezed vacuum" might have resulted from any quantum black holes possibly created in the Big Bang.

The idea that there might be natural wormholes led six physicists who participated in the 1994 NASA/Jet Propulsion Laboratory (JPL)-sponsored workshop on FTL communication and/or travel[30] to see if such wormholes could be detected by gravitational lensing.[31] What the physicists discovered is that the negative matter required to hold open a wormhole tunnel should bend gravitationally lensed starlight differently from positive matter. They urged astronomers to consider such lensing effects and not discard lensing that doesn't fit with traditional lensing caused by positive mass.[31]

5. Warp Drives

Warp drives, which are another staple of science fiction,[32] involve altering spacetime and/or mass-energy to achieve FTL speeds. In science fiction, warp drives have been given names such as "overdrive" (A. E. van Vogt, Murray Leinster), "star drive" (*Space Patrol*) and "hyperdrive" (*Star Trek*, where one often hears the term "warp factor"). (In *The Star Sailors*, I referred to the FTL transportation as "metadrive" in recognition of the early study of "meta relativity" by Olexa-Myron Bilaniuk, V. K. Deshpande, and E. C. George Sudarshan.[14,23]) Essentially the same desirable properties listed in Section 4.1 apply to warp drives as well.

5.1 Alcubierre Drive

An often cited warp drive concept is that proposed by Miguel Alcubierre in which he argued that "… it is possible to modify spacetime in a way that allows a spaceship to travel with an arbitrarily large speed" "… within the framework of general relativity and without the introduction of wormholes".[33] In essence, as shown in Figure 6, the space in front of the spaceship is contracted and the space behind is expanded to allow FTL travel even though the spaceship travels at sublight velocities inside the bubble. A potential drawback that Alcubierre noted is that "… just as it happens with wormholes, exotic matter will be needed in order to generate a distortion of spacetime …" like the Alcubierre drive.[33]

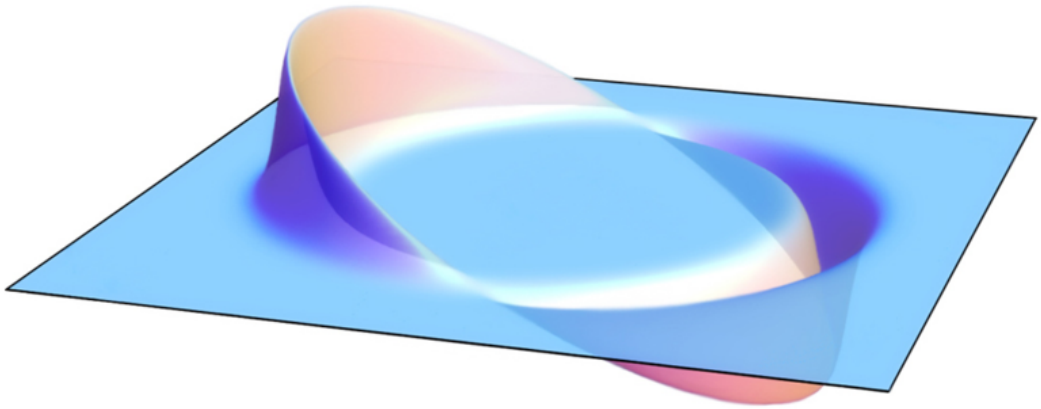

Figure 6. Two-dimensional visualization of an Alcubierre drive showing the opposing regions of expanding and contracting spacetime that displace the central region.
In this diagram the starship would be moving from left to right.
Source: Wikipedia

5.2 Alcubierre Warp Drive Benefits and Issues

To motivate us to continue studying the Alcubierre warp drive as a means of achieving interstellar travel, Kelvin Long has listed these six benefits:[34]

- Removal of the interstellar distance barrier
- Conventional transport system (no wormholes)
- No time dilation effects
- No relativistic mass increase with velocity
- No requirement for rocket-type propulsion to achieve near light speed
- Technological and economic benefits to humanity

Among the issues listed by Long are the requirement for large negative energy densities (perhaps approaching solar mass sizes); the possibility that the starship could become causally disconnected from the surrounding warp bubble; the need to create the geometric structure ahead of the starship; and the production of harmful energetic radiation in front of the warp bubble.[34] The need to create the geometric structure ahead of the starship may require an FTL construction mode; in essence, to go faster than light may require one to have a spacetime modification system that travels faster than light – a sort of "Catch-22".

5.3 Wormholes and Warp Bubbles – An Energy Comparison

As a means of getting a handle on the difficulties of constructing a wormhole and a warp bubble, Eric Davis has estimated the negative equivalent mass required for each.[35] Davis calculated that the negative equivalent mass for a wormhole throat size of 1 km to be -709.9 M_J, about -1.2 x 10^{47} J (where M_J = 1.90 x 10^{27} kg is the mass of Jupiter), or about the same order of magnitude as the mass of the Sun. A warp bubble with radius R = 50 m would require a negative energy ranging from -3.30 x 10^{52} J for a velocity v = 10 c, to -3.30 x 10^{54} J for a velocity v = 100 c.[35] Based on Davis's analysis the negative energy requirements for a warp bubble are greater than those for a traversable wormhole. Davis has concluded that "A detailed energy analysis showed that warp drives are not technologically practical to implement due to their requirement for extremely large amounts of negative energy (in order to achieve absurdly low 'warp speeds'), while traversable wormholes appear to be the most practical to implement because of their very minimal negative energy requirement".[35]

6. FTL Miscellany

In addition to the three types of FTL transportation concepts discussed in the previous sections there are others which have been proposed and there are issues with FTL travel.

6.1 Some Other FTL Concepts

In preparation for the 1994 NASA/JPL Workshop on Advanced Quantum/Relativity Theory Propulsion[30], Robert L. Forward assembled a summary of possible FTL phenomena that has been publicly summarized in Ref. 36. Forward divided his survey into four subject areas: (1) space and time tunnels (e.g., wormholes); (2) transrelativistic physics (e.g., tachyons); (3) space-time structures and (4) quantum phenomena.

Some other possible FTL concepts include[13,36]

- Twistor theory in which space may be distorted such that rapid travel is possible[36,37,38,39]
- Extra dimensions (e.g. branes) in which a traveler moves to a dimension in which the speed of light can be exceeded [40,41,42,43]
- Quantum mechanics contains concepts (e.g., entanglement) which appear to be FTL[44-51]
- Variable speed of light[52,53]

6.2 Some FTL Issues

Theories regarding FTL phenomena eventually encounter one or more of the following issues:[13]

- Time travel paradoxes (reference frames can be found in which backward time travel occurs.[26,54,55] Appendix B describes one of these FTL time travel paradoxes.
- Radiation effects either from the propulsion mode or from galactic cosmic rays and blue-shifted light
- Relativistic effects that distort the appearance of the Universe[56]
- Galactic debris – a starship traveling at the speed of light and hitting a 1-gram particle would be subjected to an impact energy on the order of 9×10^{13} J (ignoring relativistic effects). This corresponds to the energy equivalent of a small nuclear weapon.[57]

7. FTL – Why Do It?

Sten Odenwald has pointed out that just traveling to another star doesn't make much sense.[58] "There are three simple questions that drive exploration of any kind: Where are we going to go, what are we going to do when we get there, and how will it benefit people back home?"[58]

While Odenwald's questions would certainly need to be addressed in arguing for an interstellar mission and his concerns about spending billions of dollars to explore the Alpha Centauri system are valid, I would argue that we aren't even at the Wright brothers stage of development of FTL interstellar transportation so plans for interstellar exploration are a bit premature. At this time, it is more important to be working on the theory and the technology. But as to why develop FTL transportation, there are two immediate answers: exploration and survival.

7.1 FTL For Exploration

In his paper on the scientific benefits of rapid ($v \geq 0.1$ c) interstellar spaceflight, I. A. Crawford has written that "Significant benefits are identified in the fields of interstellar medium studies, stellar astrophysics, planetary science and astrobiology".[59] Should the exoplanet searches find a habitable world, the impetus to send probes there will be almost unstoppable.

7.2 FTL For Survival

Some 65 million years ago, according to a hypothesis advanced by Luis W. Alvarez and co-investigators, the impact of a large Earth-crossing asteroid caused the mass extinction that wiped out the non-avian dinosaurs in what is now called the Cretaceous-Paleogene extinction event.[60] Larry Niven has summarized this situation best in his famous quote, "The dinosaurs became extinct because they didn't have a space program".[61]

As if the asteroid impact weren't enough, more recently Blair Schoene and colleagues have dated the Deccan Traps continental basalt eruption precisely enough to argue "… that the Deccan Traps contributed to the latest Cretaceous environmental change and biologic turnover that culminated in the marine and terrestrial mass extinctions".[62] It's possible that Earth suffered a one-two punch: the asteroid impact and the basalt eruption.[63]

Long term (billions of years from now), of course, the Sun will burn its hydrogen and helium fuel, ballooning out into a red giant that will engulf and destroy Earth.[64] A sufficiently advanced civilization might move Earth[65] but it seems to this author that long before that our descendants should have moved off the planet.

Climate change or other environmental catastrophe or a pandemic or overpopulation could force humanity to leave Earth. And, as Tom Purdom warned in the 1950s, there is always the danger of a global dictatorship.[66] Having an independent, self-supporting colony sufficiently far from Earth may be the astronomical equivalent of 17th-century America in the face of European monarchies.

More recently, researchers have discovered 28 mantle plumes rising from the Earth's core.[67] Venus, Earth's so-called "twin", was roasted 800 million years ago.[68]

Robert A. Heinlein summed up the situation facing us: "The Earth is just too small and fragile a basket for the human race to keep all its eggs in".[69]

8. FTL – Where Are We?

In the foregoing sections, a little of the progress that is being made on FTL theories has been presented. Perhaps the greatest breakthrough is conceptual, that is, that scientists have some theoretical basis to suppose that the speed of light may not be a limiting constraint. But to this writer, it appears that we are still no further along than Bishop John Wilkins who wrote in 1648: "There are four several ways whereby this flying in the air hath been or may be attempted. Two of them by the strength of other things, and two of them by our own strength: (1) By spirits, or angels. (2) By the help of fowls. (3) By wings fastened immediately to the body. (4) By a flying chariot".[70] The invoking of wormholes and warp drives may someday be seen as the equivalent of invoking spirits or fowls.

To provide some perspective, consider these past visions of interplanetary travel in the context of how it was actually done.[71]

- A whirlwind conveys people to the Moon (Lucian, *True History*, 2nd century CE)
- Spirits convey people to the Moon (Kepler, *Somnium*, 1608, published in 1634)

- Wild swans carry the traveler to the Moon (Bishop Francis Godwin, *The Man in the Moone*, 1638)
- Bottles of dews, lodestones and powder rockets (Cyrano de Bergerac, *A Voyage to the Moon*, 1649)
- An electric-powered aircraft (large ball of sulfur) (Louis-Guillaume de la Follie, *The Philosopher without Pretension, or the Rare Man,* 1775)

With the various concepts of FTL transport that have been published, we may be like Cyrano de Bergerac who accidentally hit upon the right concept (rocket) for traveling to the Moon. But we will have to weed out the FTL equivalents of the bottles of dew and lodestones to get there!

9. Some Possible FTL-Related Research Projects

In various workshops, researchers have identified a number of experiments or studies that could help answer the question: Is faster-than-light (FTL) travel possible? [cf., e.g., 30, 31, 34, 35, 36, 72, 73, 74, 75]. Among the topics that should be addressed are these

- Astronomical search for possible gravitationally anomalous halo objects by examining any gravitational lensing effects on light emitted by distant stars. This would help address the question about the existence of negative matter, a key concept in certain wormhole and warp drive concepts.
- Good measurements of the velocity of light perpendicular to the Casimir plates to determine if the speed of light is increased as predicted.
- High-energy experiments to determine if there are any nonlinearities in quantum mechanics (such as those proposed by Steven Weinberg[50]) that could be exploited for FTL communication.
- Use of a laser to focus enough energy in "empty" space to determine if negative-energy virtual pairs can become positive-energy pairs thereby proving the existence of virtual particles.
- Good, time-phased studies of cosmic ray showers to determine if tachyons are present.
- Measuring the frequency of the acoustical modes of a neutron start to determine if the speed of sound in neutron star matter is greater than the speed of light (as predicted by some equations of state for neutron stars).

Several organizations have been championing the cause of interstellar travel (see Appendix C). What may be needed next is the occasional informal gathering of a small number of theoreticians to brainstorm what has been learned and what may need to be done.

As we strive to push back the frontiers of science let us be mindful of the pitfalls of pseudoscience.[76]

Concluding Remarks

A quick survey of the physics literature will show (as I hope this brief discussion has) that there are ways, in theory, to travel to the stars. With more and more planets being discovered, it seems almost inevitable that one will be like Carl Sagan's "pale blue dot", a world waiting patiently in the cosmos.

Writing in the May 2016 issue of *Astrobiology*, Adam Frank and Woodruff Sullivan used the Drake equation to estimate the number of extraterrestrial civilizations that could have existed over the lifetime of the Milky Way Galaxy. Depending on the assumptions made about the lifetime of technological civilizations, Frank and Sullivan calculated the number of civilizations that could have existed to be on the order of tens of thousands to a trillion civilizations that could have appeared over cosmic history.[77,78]

The possibility of many extraterrestrial civilizations gives added emphasis to James Strong's 1965 observation that the universe of stars is "… an arena that has been set for countless eons, patiently awaiting all comers. At any moment in time, any race—human or alien—that feels moved to pick up the gauntlet may do so. To whoever wins, the reward is survival".[79]

Imagine what awaits our species if we develop star travel; to see directly what Tennyson could only imagine[80]

> Many a night from yonder ivied casement, ere I went to rest,
> Did I look on great Orion sloping slowly to the West.
>
> Many a night I saw the Pleiads, rising thro' the mellow shade,
> Glitter like a swarm of fire-flies tangled in a silver braid.
> …
>
> For I dipt into the future, far as human eye could see,
> Saw the Vision of the world, and all the wonder that would be;
>
> Saw the heavens fill with commerce, argosies of magic sails,
> Pilots of the purple twilight dropping down with costly bales;

In quantum mechanics, we are the observers. In some quantum concepts, our very act of measuring brings things into existence. We need to understand dark matter and dark energy, the force that is driving the Universe to a cold death. Can this increasing expansion be stopped?

And finally, going back to where we started, consider c, that ultimate speed limit which still confronts us. What if c is the escape velocity from the Universe?[81]

If the human race is to achieve FTL travel to the stars we will have to heed the advice of "Dr. Morbius" in the movie *Forbidden Planet*: "Prepare your minds for a new scale of physical scientific values, gentlemen".

Appendix A

List of Acronyms

ß	=	Ratio of the velocity of an object to the speed of light (v/c)
BPP	=	Breakthrough Propulsion Physics
c	=	Speed of light (299,792,458 m/s or $\approx 3 \times 10^8$ m/s)
cm	=	centimeter
DARPA	=	(U.S.) Defense Advanced Research Projects Agency
dyn	=	Dyne
E_α	=	Disintegration energy of alpha (α) particle
FTL	=	Faster Than Light
GRT	=	General Relativity Theory
ħ	=	Planck's constant (h) divided by 2π
J	=	Joule
M_J	=	Mass of Jupiter (1.8991×10^{27} kg or $\approx 1.9 \times 10^{27}$ kg)
NAFAL	=	Nearly As Fast As Light
P	=	Probability
R	=	Radius of warp bubble
SRT	=	Special Relativity Theory
T	=	Transmissivity
U	=	Potential energy of nucleus
v	=	Velocity
ZPF	=	Zero Point Field

Appendix B

Time Travel Paradox With FTL Communication

The issue of time travel paradoxes inevitably arises when faster-than-light travel or communication is invoked. For example, consider the paradox that arises when one person sends a message to another using a signal that travels faster than light as illustrated in the two examples shown in the Minkowski diagrams of Figure B-1. In the left-hand side of Figure B-1, the reference frame B is moving away from the reference frame A at a high rate of speed. The effects of the high speeds on lengths and times (Eq. 2 and 3) are represented by the slanting of the B axes. The line OP represents A sending a signal from O to P at a speed faster than the speed of light.[54]

In the reference frame of A the event O occurs before P. But in the reference frame of B, the event P occurs before O as indicated by the dotted coordinate lines. To B the signal is received before it is sent![54] (A and B would also disagree about the order of events in the FTL signal B sends from O to Q.)

Another aspect of this time travel paradox is illustrated on the right-hand side of Figure B-1. If A and B agree that A will send an FTL signal at a certain time unless A receives an FTL signal from B and B agrees to send a signal when he/she receives an FTL signal from A then the diagram illustrates, if A sends a signal at the designated time B will end up sending an FTL signal to A before A's designated time to send a signal. But if A receives a signal from B before the designated time then A won't send a signal to B which means B won't send a signal which means that A will send a signal – one is clearly faced with a circular problem![54]

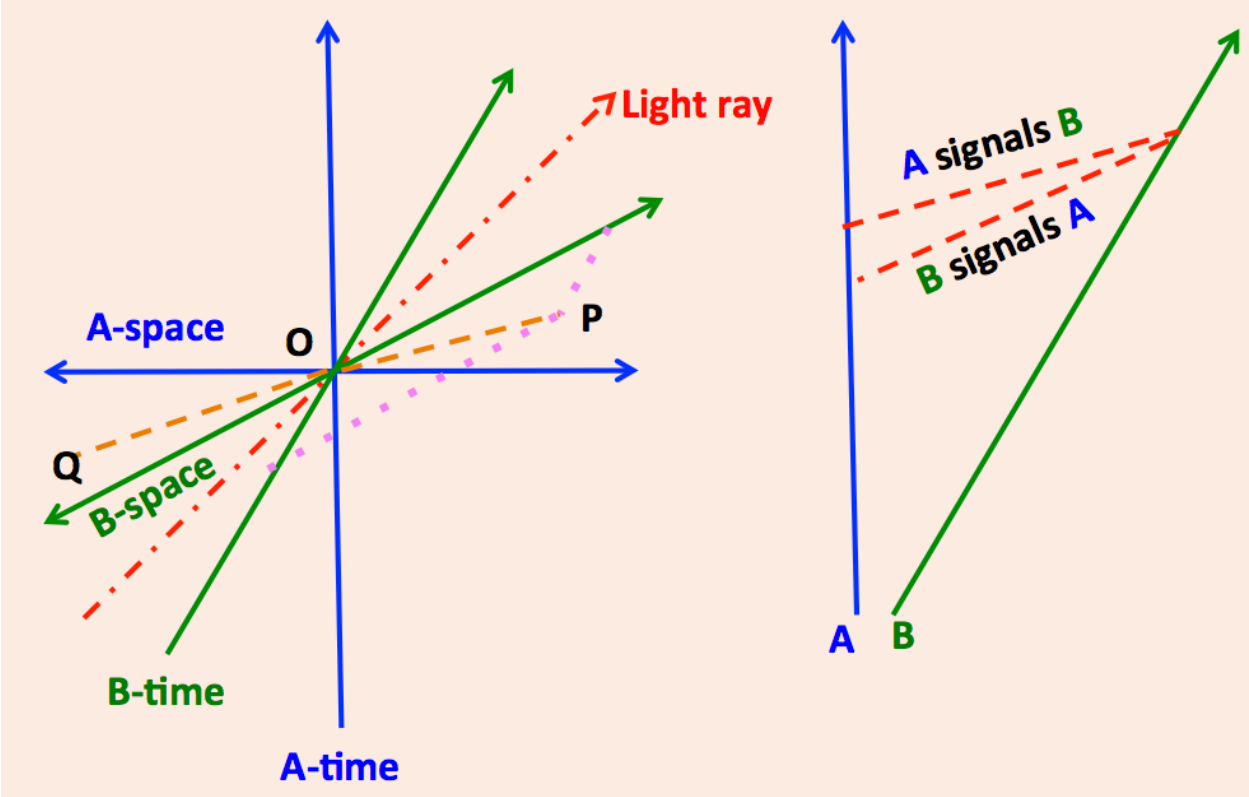

Figure B-1. Minkowski diagrams of faster-than-light (FTL) signals.
The left-hand side illustrates what happens when A sends an FTL signal (OP) which is observed by B in a frame moving away from A at a high rate of speed. The right-hand side illustrates the paradox of A and B signaling back-and-forth with FTL speeds. (After Ref. 54)

Appendix C

Organizations Studying Interstellar Flight

Breakthrough Starshot (http://breakthroughinitiatives.org/About)

Breakthrough Starshot is a $100 million research and engineering program aiming to demonstrate proof of concept for a new technology, enabling ultra-light unmanned space flight at 20% of the speed of light; and to lay the foundations for a flyby mission to Alpha Centauri within a generation.

British Interplanetary Society (www.bis-space.com)

The British Interplanetary Society (BIS) has long been a supporter of and publisher of research on FTL transportation. On 15 November 2007, for example, BIS sponsored a symposium on warp drives under the chairmanship of K. F. Long. The results were published in a special issue of the *Journal of the British Interplanetary Society* (Volume 61, Number 9, September 2008).

Centauri Dreams (www.centauri-dreams.org)

At the Centauri Dreams Web site, Paul Gilster discusses peer-reviewed research on deep-space exploration, with an eye toward interstellar possibilities. Centauri Dreams serves as the news forum for the Tau Zero Foundation (see below).

Initiative for Interstellar Studies (i4is) (www.i4is.org)

Founded in 2012, "The mission of the *Initiative for Interstellar Studies (i4is)* is to foster and promote education, knowledge and technical capabilities which lead to designs, technologies or enterprise that will enable the construction and launch of interstellar spacecraft".

100 Year Starship (100yss.org)

The 100 Year Starship is an outgrowth of 2011 conference sponsored by the U. S. Defense Advanced Research Projects Agency (DARPA). The program exists "… to make the capability of human travel beyond our solar system a reality within the next 100 years".

Tau Zero Foundation (www.tauzero.aero/)

The Tau Zero Foundation grew out of NASA's Breakthrough Propulsion Physics (BPP) Program (1996-2002) to advocate research into interstellar travel. The Tau Zero Foundation is not affiliated with NASA but it is connected to Centauri Dreams (see above).

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