Warp Field Mechanics 101

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Abstract:

This paper will begin with a short review of the Alcubierre warp drive metric and describes how the phenomenon might work based on the original paper. The canonical form of the metric was developed and published in [6] which provided key insight into the field potential and boost for the field which remedied a critical paradox in the original Alcubierre concept of operations. A modified concept of operations based on the canonical form of the metric that remedies the paradox is presented and discussed. The idea of a warp drive in higher dimensional space-time (manifold) will then be briefly considered by comparing the null-like geodesics of the Alcubierre metric to the Chung-Freese metric to illustrate the mathematical role of hyperspace coordinates. The net effect of using a warp drive “technology” coupled with conventional propulsion systems on an exploration mission will be discussed using the nomenclature of early mission planning. Finally, an overview of the warp field interferometer test bed being implemented in the Advanced Propulsion Physics Laboratory: Eagleworks (APPL:E) at the Johnson Space Center will be detailed. While warp field mechanics has not had a “Chicago Pile” moment, the tools necessary to detect a modest instance of the phenomenon are near at hand.

Keywords: warp, boost, York Time, bulk, brane

Introduction

How hard is interstellar flight without some form of a warp drive? Consider the Voyager 1 spacecraft [1], a small 0.722 mT spacecraft launched in 1977, it is currently out at ~116 Astronomical Units (AU) after 33 years of flight with a cruise speed of 3.6 AU per year. This is the highest energy craft ever launched by mankind to date, yet it will take ~75000 years to reach Proxima Centauri, the nearest star at 4.3 light years away in our neighboring trinary system, Alpha Centauri. Recent informal mission trades have been assessing the capabilities of emerging high power EP systems coupled to light nuclear reactors to accomplish the reference Thousand Astronomical Units (TAU) [2] mission in ~15 years. Rough calculations suggest that such a Nuclear Electric Propulsion (NEP) robotic mission would pass Voyager 1 in just a few years on its way to reaching 1000 AU in 15 years. While this is a handy improvement over Voyager 1 statistics - almost 2 orders of magnitude, this speedy robotic craft would still take *thousands* of years to cross the black ocean to Proxima Centauri. Clearly interstellar flight will not be an easy endeavor.

Background

The study of interstellar flight is not a new pursuit, and there have been numerous studies published in the literature that consider how to approach robotic interstellar missions to some of our closest stellar neighbors, with the objective of having transit times closer to the 100 year mark rather than thousands of years. One of the most familiar studies is Project Daedelus [3] sponsored by the British Interplanetary Society in 1970. The Daedelus study's objective was to consider a 50-year robotic mission to Barnard's star, which is ~6 light years away. The spacecraft detailed in the report was quite massive weighing in at 54000 mT, 92% of which was propellant for the fusion propulsion system. For comparison, the International Space Station is a "modest" ~400 mT, thus the Daedelus spacecraft is nearly the equivalent of 150 International Space Stations. Project Longshot [4], a joint NASA-NAVY study in the late 1980's to develop a robotic interstellar mission to Alpha Centaury, produced a 400 mT (67% propellant) robotic spacecraft that could reach Alpha Centaury in 100 years. At one ISS of mass, this vehicle is easier to visualize than its heftier older cousin, Daedelus. There are many other studies that have been performed over the years each having slight permutations on the answer, primarily depending on the integrated efficiency of converting propellant mass directly into spacecraft kinetic energy (matter-antimatter being among the best). All results are of course bounded by the speed of light, meaning earth-bound observers will likely perceive interstellar transit times of outbound spacecraft in decades, centuries, or more.

Alcubierre Metric

Is there a way within the framework of current physics models such that one could cross any given cosmic distance in an arbitrarily short period of time, while never breaking the speed of light? This is the question that motivated Miguel Alcubierre to develop and publish a possible mathematical solution to the question back in 1994 [5]. Since the expansion and contraction of space does not have a speed limit, Alcubierre developed a model (metric) within the domain of general relativity that uses this physics loop hole and has almost all of the desired characteristics of a true interstellar space drive, much like what is routinely depicted in science fiction as a "warp drive".

The metric that is discussed in the paper is presented in equation 1. This uses the familiar coordinates, (t, x, y, z) and curve $x = x_s(t)$, $y = 0$, $z=0$ where x is analogous to what is commonly referred to as a spacecraft's trajectory.

$$ds^2 = -c^2dt^2 + [dx - v_s(t)f(r_s)dt]^2 + dy^2 + dz^2 \tag{1}$$

In this metric, v_s is defined as the velocity of the spacecraft's moving frame, dx_s/dt, and r_s is the radial position in the commoving spherical space around the spacecraft's origin. The $f(r_s)$ term is a "top hat" shaping function that is defined as:

$$f(r_s) = \frac{\tanh\big(\sigma(r_s + R)\big) - \tanh\big(\sigma(r_s - R)\big)}{2\tanh(\sigma R)}$$

The parameters σ and *R* when mapped into the metric given in equation 1 control the wall thickness and radius of the warp bubble respectively. For very large σ, the wall thickness of the bubble becomes exceedingly thin, approaching zero thickness in the limit. The driving phenomenon that facilitates speedy travel to stellar neighbors is proposed to be the expansion and contraction of space (York Time) shown in equation 2. Figure 1 shows several surface plots of the York Time surrounding the spacecraft. The region directly in front of the spacecraft experiences the most contraction of space, while the region directly behind the spacecraft experiences the most expansion of space. The phenomenon reverses sign at the $x = x_s$ symmetry surface. As the warp bubble thickness is decreased, the magnitude of the York Time increases. This behavior when mapped over to the energy density requirements will be discussed in the next section.

$$\theta = v_s \frac{x_s}{r_s} \frac{df}{dr_s} \tag{2}$$

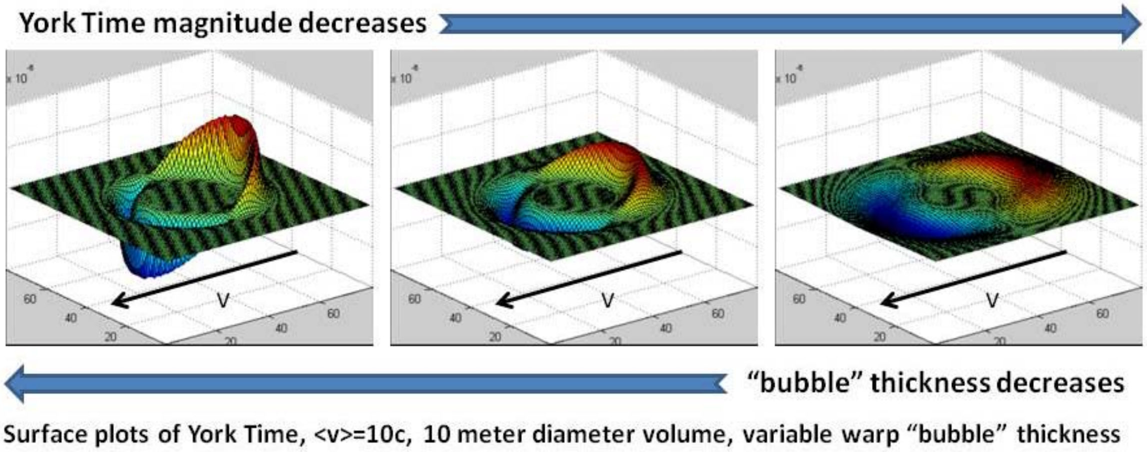


Figure 1: York Time, θ, is depicted for several different warp bubble wall thicknesses, σ.

The energy density shown in equation 3 for the field has a toroidal form that is axisymmetric about the x-axis, and has a symmetry surface at $x = x_s$. The energy density is exactly zero along the x-axis. For a fixed target velocity v_s and warp bubble radius *R*, varying the warp bubble thickness σ changes the required peak energy density for the field at a fixed velocity. Figure 2 shows the relative change in energy density for several warp bubble wall thicknesses. As is evident when comparing the magnitudes, as the warp bubble is allowed to get thicker, the required density is drastically greatly reduced, but the toroid grows from a thin equatorial belt to a diffuse donut. The advantage of allowing a thicker warp bubble wall is that the integration of the total energy density for the right-most field is orders of magnitude less that the left-most field. The drawback is that the volume of the flat space-time in the center of the bubble is reduced. Still, a minimal reduction in flat space-time volume appears to yield a drastic reduction in total energy requirement that would likely outweigh reduced real-estate. Sloppy warp fields would appear to be "easier" to engineer than precise warp fields. Some additional appealing characteristics of the metric is that the proper acceleration α is zero, meaning there is no acceleration felt in the flat space-time volume inside the warp bubble when the field is turned on, and the coordinate time t in the flat space-time volume is the same as proper time τ, meaning the clocks on board the spacecraft proper beat at the same rate as clocks on earth.

$$T^{00} = -\frac{1}{8\pi}\frac{{v_s}^2\rho^2}{4{r_s}^2}\left(\frac{df}{dr_s}\right)^2 \tag{3}$$

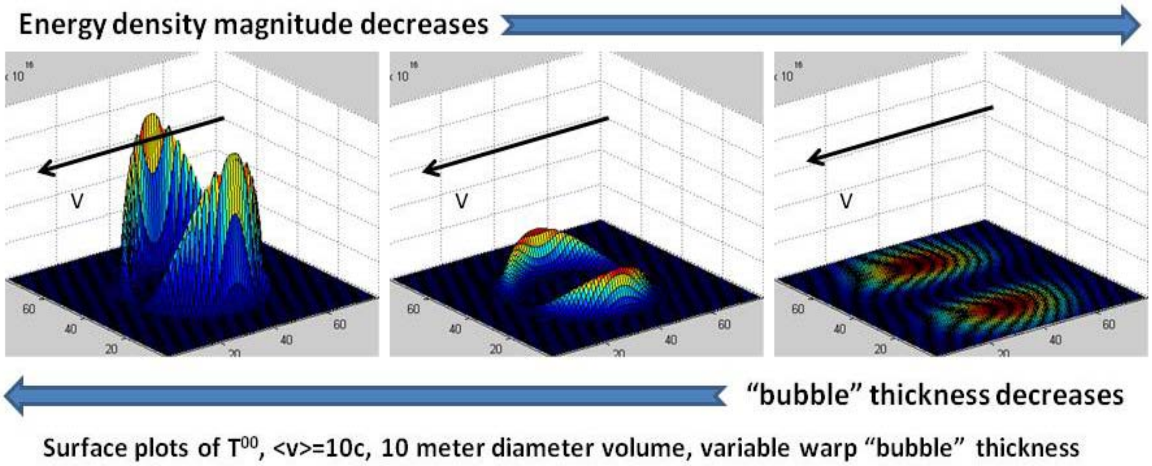


Figure 2: Energy density, T^{00}, is depicted for several different warp bubble wall thicknesses, σ.

The concept of operations as described by Alcubierre is that the spacecraft would depart the point of origin (e.g. earth) using some conventional propulsion system and travel a distance d, then bring the craft to a stop relative to the departure point. The field would be turned on and the craft would zip off to its stellar destination, never locally breaking the speed of light, but covering the distance in an arbitrarily short time period of time just the same. The field would be turned off a similar standoff distance from the destination, and the craft would finish the journey conventionally. This approach would allow a journey to say Alpha Centauri as measured by an earth bound observer (and spacecraft clocks) measured in weeks or months, rather than decades or centuries.

A paradox identified in [6] is an issue that arises due to the symmetry of the energy density about the $x = x_s$ surface. When the energy density is initiated, the choice in direction of the +x-axis is mathematically arbitrary, so how does the spacecraft “know” which direction to go? Comparing Figure 1 to Figure 2 visually displays the asymmetry of the York Time and the symmetry of the energy density. Both sets of three frames were purposely aligned to make direct comparison easier. This asymmetry/symmetry paradox issue can be potentially resolved when considering the canonical form of the metric derived by using a gauge transformation in [6] as shown in equation 4.

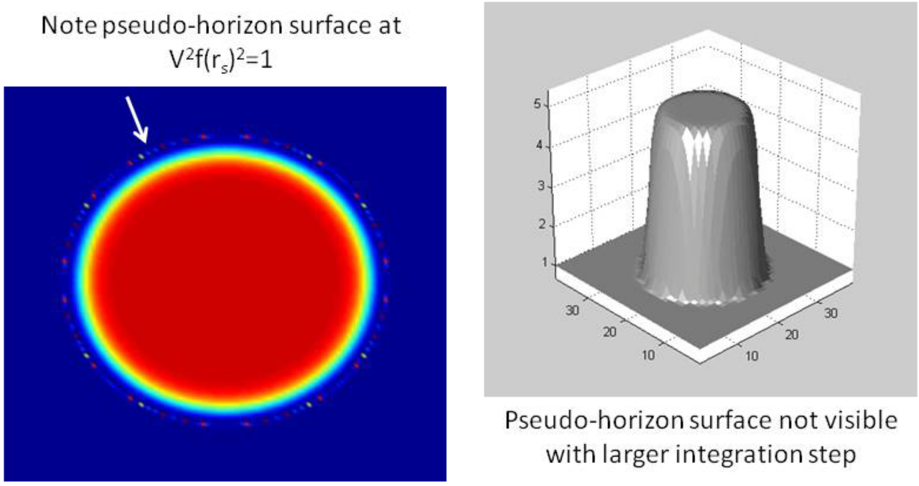
$$ds^2 = ({v_s}^2 f(r_s)^2 - 1)\left(dt - \frac{v_s f(r_s)}{{v_s}^2 f(r_s)^2 - 1}dx\right)^2 - dx^2 + dy^2 + dz^2 \tag{4}$$

Using this canonical form, the field potential ϕ and the boost γ can be determined using the standard identity $\gamma = \cosh(\phi)$. They are, respectively:

$$\phi = \frac{1}{2}\ln|1 - v_s{}^2 f(r_s)^2| \qquad \text{and trivially,} \qquad \gamma = \cosh\left(\frac{1}{2}\ln|1 - v_s{}^2 f(r_s)^2|\right)$$

Using this new information, a modified concept of operations is proposed that may resolve the asymmetry/symmetry paradox. In this modified concept of operations, the spacecraft departs earth and establishes an initial sub-luminal velocity v_i, then initiates the field. When active, the field's boost acts on the initial velocity as a scalar multiplier resulting in a much higher apparent speed, $<v_{eff}>= \gamma v_i$ as measured by either an earth bound observer or an observer in the bubble. Within the shell thickness of the warp bubble region, the spacecraft never locally breaks the speed of light and the net effect as seen by earth/ship observers is analogous to watching a film in fast forward. Consider the following to help illustrate the point – assume the spacecraft heads out towards Alpha Centauri and has a conventional propulsion system capable of reaching 0.1c. The spacecraft initiates a boost field with a value of 100 which acts on the initial velocity resulting in an apparent speed of 10c. The spacecraft will make it to Alpha Centauri in 0.43 years as measured by an earth observer and an observer in the flat space-time volume encapsulated by the warp bubble. While this line of reason seems to resolve the paradox, it also suggests that the York Time may not be the driving phenomenon, rather a secondary result. In this physical explanation of the mathematics, the York Time might be thought of as perhaps a Doppler strain on space as this spherical region is propelled through space. A pedestrian analog to use to help envision this concept would be to consider the hydrodynamic pressure gradients that form around a spherical body moving through a fluid – the front hemisphere has a high pressure region while the rear hemisphere has a low pressure region. Analogously, the warp bubble travelling through space-time causes space to pile up (contract) in front of the bubble, and stretch out (expand) behind the bubble. Figure 3 depicts the boost field for the metric, and shows that the toroidal ring of energy density creates spherical boost potentials surrounding a flat space-time volume. Also note pseudo-horizon at $v^2 f(r_s)^2=1$ where photons transition from null-like to space-like and back to null like upon exiting. This is not seen unless the field mesh is set fine enough. The coarse mesh on the right did not detect the horizon.

Surface plots of boost, <v>=10c, 10 meter diameter volume



Note pseudo-horizon surface at $V^2 f(r_s)^2=1$

Pseudo-horizon surface not visible with larger integration step

Figure 3: Boost plots for the field

Chung-Freese Metric

Additional work has been published that expands the idea of a warp drive into higher dimensional space-times. In 2000, Chung and Freese [7] published a higher dimensional space-time model that is a modified Friedmann-Robertson-Walker (FRW) metric as shown in equation 5. The idea of a higher dimensional model is that the standard 3+1 subspace exists as a "brane" embedded in this higher dimensional space-time labeled the "bulk." The size and number of extra dimensions are not explored in this paper; rather the discussion will stick to the original form of the published metric.

$$ds^2 = -c^2dt^2 + \frac{a^2(t)}{e^{2kU}}dX^2 + dU^2 \tag{5}$$

The dX^2 term represents the 3+1 space (on the brane), while the dU^2 term represents the bulk with the brane being located at U=0. The $a(t)$ term is the scale factor, and k is a compactification factor for the extra space dimensions. A conventional analogy to help visualize the brane-bulk relationship, consider a 2D sheet that exists in a 3D space. The 2D inhabitants if the "flat-land" subspace have a manifold that is mapped out with the simple metric, $dx^2 + dy^2$, where this can be viewed as being analogous to the dX^2 term in equation 5. The remainder of the 3D bulk space is mapped by the z-axis, and anything not on the sheet would have a non-zero z-coordinate. This additional dz^2 term is, from the perspective of the 2D inhabitants, the dU^2 term in equation 5. Anything not on the 2D sheet would be labeled as being in the bulk with this simplified analogy.

In order to illustrate the mathematical relationship between a "hyper drive" and a warp drive, the null-like geodesics for the Chung-Freese metric will be considered and compared to the conjectured driving phenomenon in the Alcubierre metric, the boost. The equation for the null-like geodesics for equation 5 is (setting c=1):

$$\frac{dX}{dt} = \frac{e^{kU}}{a(t)}\sqrt{1 - \frac{dU^2}{dt^2}}$$

If dU/dt is set to 1, then a test photon that has a velocity vector orthogonal to the brane would have a zero speed as measured on the brane, dX/dt=0. If a test photon has dU/dt=0, but arbitrarily large U coordinate, dX/dt will be large, possibly >>1. Remember that c was set to 1, so dX/dt >1 is analogous to the hyper-fast travel character of the Alcubierre metric. The behavior of the null-like geodesics in the Chung-Freese metric becomes space-like as U gets large. The null-like geodesics in the Alcubierre metric become space-like within the warp bubble, or where the boost gets large. This suggest that the hyperspace coordinate serves the same role as the boost, and the two can be informally related by the simple relationship $\gamma \sim e^U$. A large boost corresponds to an object being further off the brane and into the bulk.

Mission Planning with a Warp-enabled System

To this point, the discussion has been centered on the interstellar capability of the models, but in the interest of addressing the crawl-walk-run paradigm that is a staple of the engineering and scientific disciplines, a more “domestic” application within the earth’s gravitational well will be considered. As a preamble, recall that the driving phenomenon for the Alcubierre metric was speculated to be the boost acting on an initial velocity. Can this speculation be shown to be consistent when using the tools of early reference mission planning while considering a warp-enabled system? Note that the energy density for the metric is negative, so the process of turning on a theoretical system with the ability to generate a negative energy density, or a negative pressure as was shown in [8], will add an effective negative mass to the spacecraft’s overall mass budget. In the regime of reference mission development using low-thrust electric propulsion systems for in-space propulsion, planners will cast part of the trade space into a domain that compares a spacecraft’s specific mass α to transit time. While electric propulsion has excellent “fuel economy” due to high specific impulses that are measured in thousands of seconds, it requires electric power measured in 100’s of kW to keep trip times manageable for human exploration class payloads. Figure 4 shows a notional plot for a human exploration solar electric propulsion tug sized to move payloads up and down the earth’s well – to L1 in this case. If time were of no consequence, then much of this discussion would be moot, but as experience shows, time is a constraint that is traded with other mission constraints like delivered payload, power requirements, launch and assembly manifest, crew cycling frequency, mission objectives, heliocentric transfer dates, and more.

The specific mass of an element for an exploration architecture or reference mission can be determined by dividing the spacecraft’s beginning of life wet mass by the power level. Specific mass can also be calculated at the subsystem level if competing technologies are being compared for a particular function, but for this exercise, the integrated vehicle specific mass will be used. The transit time for a mission trajectory can then be calculated and plotted on a graph that compares specific mass to transit time. This can be done for a few discrete vehicle configurations, and the curve that fits these points will allow mission planners to extrapolate between the points when adding and subtracting mass, either in the form of payload or subsystem, for a particular power level. Figure 4 shows a simple plot of this approach for two specific impulse/efficiency values representing notional engine choices. It is apparent from the graph that lower specific impulse yields reduced trip times, but this also reduces delivered payload. However, if negative mass is added to the spacecraft’s mass budget, then the effective specific mass and transit time are reduced without necessarily reducing payload. A question to pose is what effect does this have mathematically? If energy is to be conserved, then $\frac{1}{2} mv^2$ would need to yield a higher *effective* velocity to compensate for apparent reduction in mass. Assuming a point design solution of 5000kg BOL mass coupled to a 100kW Hall thruster system (lower curve), the expected transit time is ~70 days for a specific mass of 50 kg/kW without the aid of a warp drive. If a very modest warp drive system is installed that can generate a negative energy density that integrates to ~2000kg of negative mass when active, the specific mass is dropped from 50 to 30 which yields a reduced transit time of ~40 days. As the amount of negative mass approaches 5000 kg, the specific mass of the spacecraft approaches zero, and the transit time becomes exceedingly small, approaching zero in the limit. In this simplified context, the idea of a warp drive may have some fruitful domestic applications “subliminally,” allowing it to be matured before it is engaged as a true interstellar drive system.

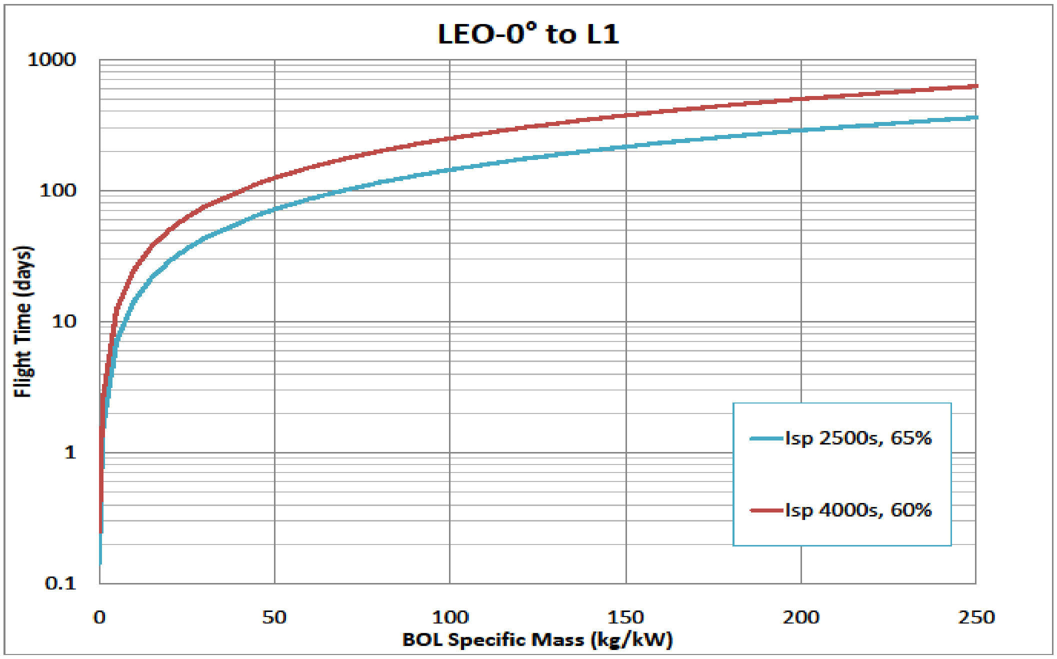
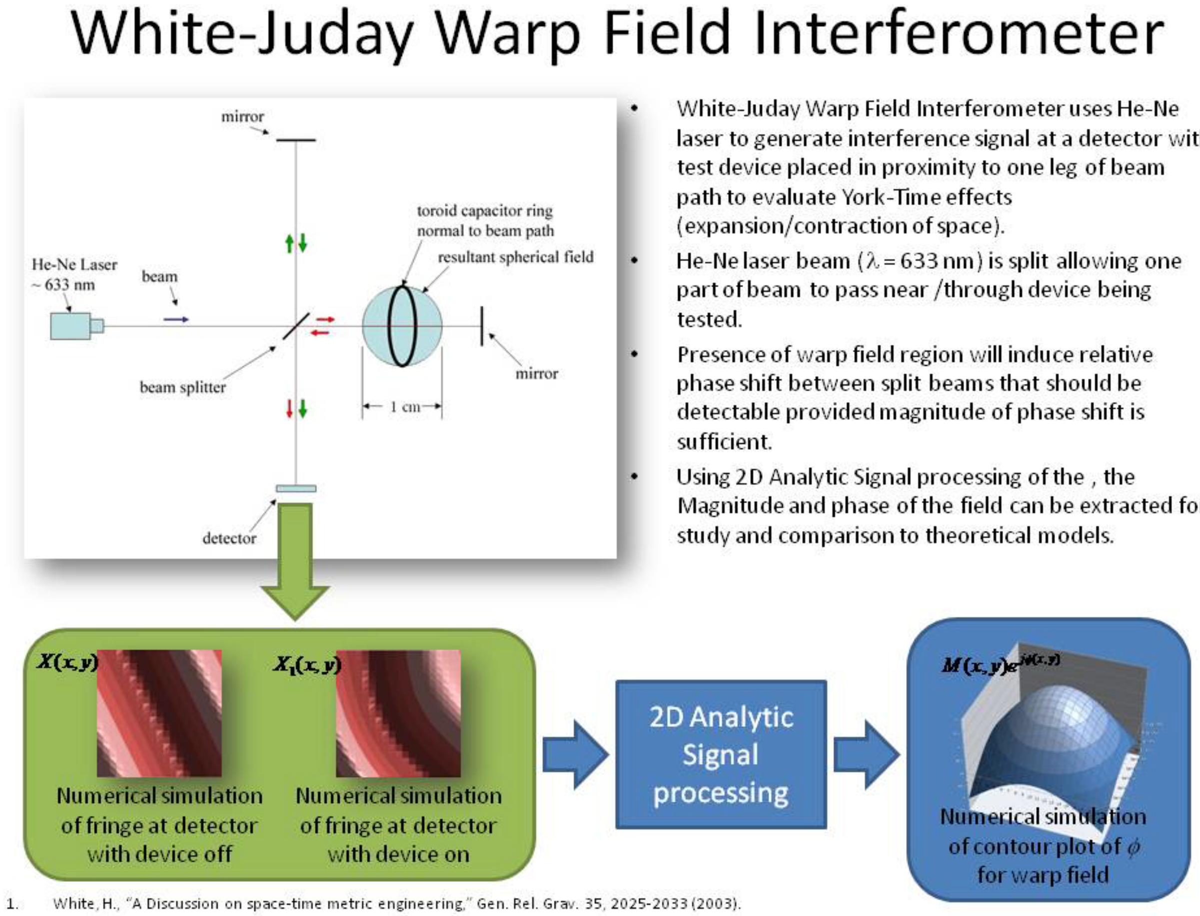


Figure 4: Trip time to L1 as a function of Beginning of Life (BOL) specific mass.

Advanced Propulsion Physics Lab: Eagleworks

A good question to ask at the end of this discussion is can an experiment be designed to generate and measure a very modest instantiation of a warp field? As briefly discussed by the author in [9], a Michelson-Morley interferometer may be a useful tool for the detection of such a phenomenon. Figure 5 depicts a warp field interferometer experiment that uses a 633nm He-Ne laser to evaluate the effects of York Time perturbations within a small (~1cm) spherical region. Across 1cm, the experimental rig should be able to measure space perturbations down to ~1 part in 10,000,000. As previously discussed, the canonical form of the metric suggests that boost may be the driving phenomenon in the process of physically establishing the phenomenon in a lab. Further, the energy density character over a number of shell thicknesses suggests that a toroidal donut of boost can establish the spherical region. Based on the expected sensitivity of the rig, a 1cm diameter toroidal test article (something as simple as a very high-voltage capacitor ring) with a boost on the order of 1.0000001 is necessary to generate an effect that can be effectively detected by the apparatus. The intensity and spatial distribution of the phenomenon can be quantified using 2D analytic signal techniques comparing the detected interferometer fringe plot with the test device off with the detected plot with the device energized. Figure 5 also has a numerical example of what the before and after fringe plots may look like with the presence of a spherical disturbance of the strength just discussed. While this would be a very modest instantiation of the phenomenon, it would likely be Chicago pile moment for this area of research.



White-Juday Warp Field Interferometer

- White-Juday Warp Field Interferometer uses He-Ne laser to generate interference signal at a detector with test device placed in proximity to one leg of beam path to evaluate York-Time effects (expansion/contraction of space).
- He-Ne laser beam ($\lambda = 633$ nm) is split allowing one part of beam to pass near /through device being tested.
- Presence of warp field region will induce relative phase shift between split beams that should be detectable provided magnitude of phase shift is sufficient.
- Using 2D Analytic Signal processing of the , the Magnitude and phase of the field can be extracted for study and comparison to theoretical models.

1. White, H., "A Discussion on space-time metric engineering," Gen. Rel. Grav. 35, 2025-2033 (2003).

Figure 5: Warp Field Interferometer layout (here, ϕ is the phase angle).

Conclusion

In this paper, the mathematical characteristics of the Alcubierre metric were introduced and discussed, the canonical form was presented and explored, and the idea of a warp drive was even considered within a higher dimensional manifold. The driving phenomenon was conjectured to be the boost field as opposed to purely the York Time which resolved the asymmetry/symmetry paradox. An early idea of a warp drive was briefly discussed within the context of mission planning to elucidate the impact such a subsystem would have on the mission trade space. Finally, a laboratory experiment that might produce a modest instantiation of the phenomenon was discussed. While it would appear that the model has nearly all the desirable mathematical characteristics of a true interstellar space drive, the metric has one less appealing characteristic – it violates all three energy conditions (strong, weak, and dominant [9]) because of the need for negative energy density. This does not necessarily preclude the idea as the cosmos is continually experiencing inflation as evidenced by observation, but the salient question is can the idea be engineered to a point that it proves useful for exploration. A significant finding from this effort new to the literature is that for a target velocity and spacecraft size, the peak energy density requirement can be greatly reduced by allowing the wall thickness of the warp bubble to increase. Analysis performed in support of generating the plots shown in Figures 1 and 2 also indicate a corresponding reduction in total energy when converted from geometric units (G=c=1) to SI units, but still show that the idea will not be an easy task. So it remains to be seen if the evolution of the phrase penned by J. M. Barrie in the story *Peter Pan* will ever be uttered on the bridge of some majestic starship just embarking on a daring mission of deep space exploration taking humanity beyond the bounds of this solar system and boldly going out into the stars: "2^{nd} star to the right, straight on till morning…"

Godspeed…

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Picture courtesy of NASA,
http://www.nasa.gov/centers/glenn/technology/warp/warpstat.html

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09/02/2011

PUTTING THINGS IN PERSPECTIVE…

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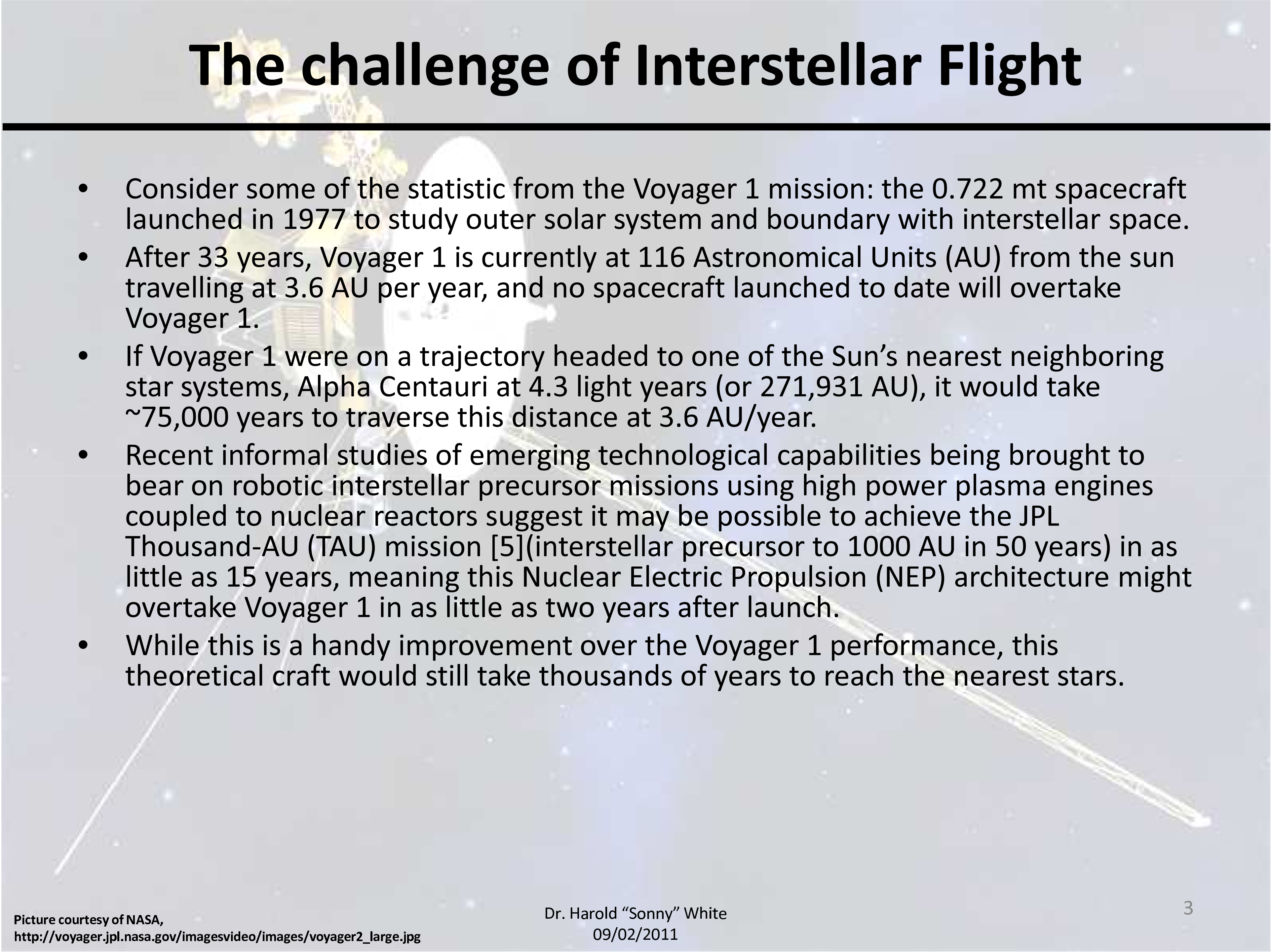
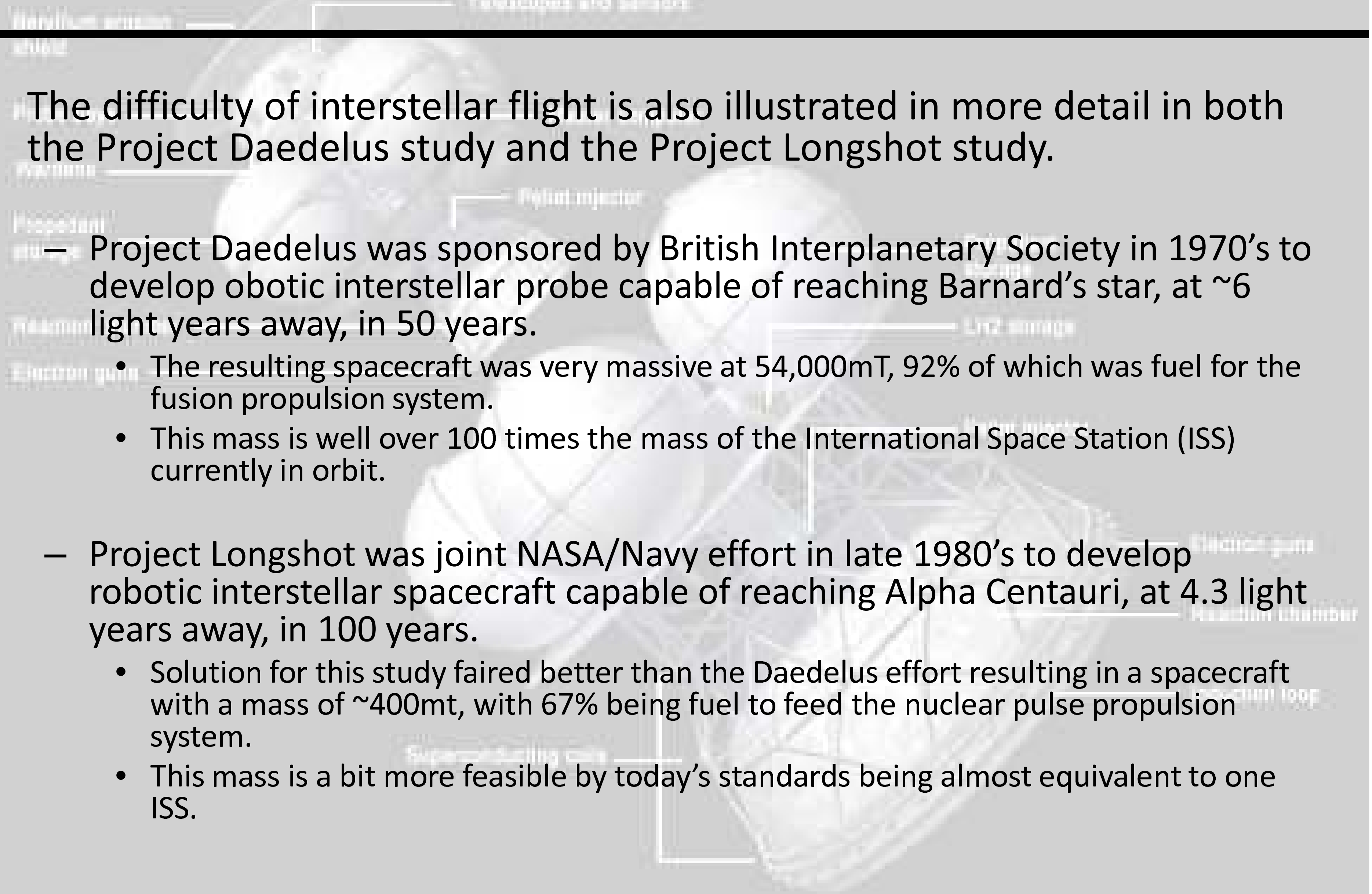
The challenge of Interstellar Flight



- Consider some of the statistic from the Voyager 1 mission: the 0.722 mt spacecraft launched in 1977 to study outer solar system and boundary with interstellar space.
- After 33 years, Voyager 1 is currently at 116 Astronomical Units (AU) from the sun travelling at 3.6 AU per year, and no spacecraft launched to date will overtake Voyager 1.
- If Voyager 1 were on a trajectory headed to one of the Sun’s nearest neighboring star systems, Alpha Centauri at 4.3 light years (or 271,931 AU), it would take ~75,000 years to traverse this distance at 3.6 AU/year.
- Recent informal studies of emerging technological capabilities being brought to bear on robotic interstellar precursor missions using high power plasma engines coupled to nuclear reactors suggest it may be possible to achieve the JPL Thousand-AU (TAU) mission [5](interstellar precursor to 1000 AU in 50 years) in as little as 15 years, meaning this Nuclear Electric Propulsion (NEP) architecture might overtake Voyager 1 in as little as two years after launch.
- While this is a handy improvement over the Voyager 1 performance, this theoretical craft would still take thousands of years to reach the nearest stars.

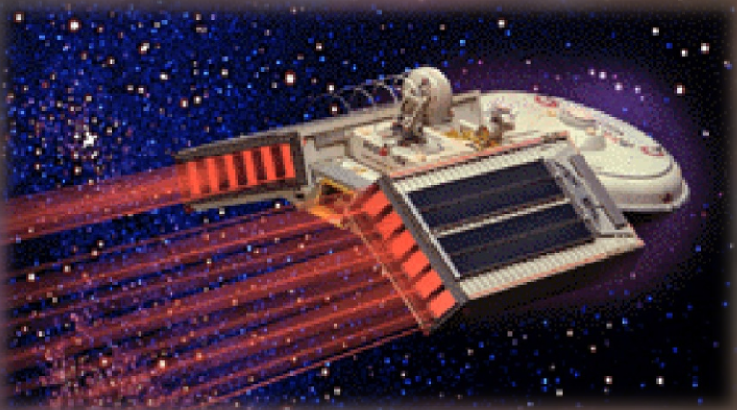
Picture courtesy of NASA,
http://voyager.jpl.nasa.gov/imagesvideo/images/voyager2_large.jpg

Interstellar Flight (Past Studies)



- The difficulty of interstellar flight is also illustrated in more detail in both the Project Daedelus study and the Project Longshot study.
  - Project Daedelus was sponsored by British Interplanetary Society in 1970's to develop obotic interstellar probe capable of reaching Barnard's star, at ~6 light years away, in 50 years.
    - The resulting spacecraft was very massive at 54,000mT, 92% of which was fuel for the fusion propulsion system.
    - This mass is well over 100 times the mass of the International Space Station (ISS) currently in orbit.
  - Project Longshot was joint NASA/Navy effort in late 1980's to develop robotic interstellar spacecraft capable of reaching Alpha Centauri, at 4.3 light years away, in 100 years.
    - Solution for this study faired better than the Daedelus effort resulting in a spacecraft with a mass of ~400mt, with 67% being fuel to feed the nuclear pulse propulsion system.
    - This mass is a bit more feasible by today's standards being almost equivalent to one ISS.

Picture courtesy of Adrian Mann www.bisbos.com, used with permission



Is there another way?

"Originally an experimental craft to test the new "Diametric Induction Drive", the XCC-05 was later sold to a multi-national consortium of asteroid prospectors, and christened the "Earth Space Ship Lewis & Clark." With its new propulsion this ship was able to reach and survey the "Transition Zone" at the extreme boundaries of the Solar System. Fifteen months into its survey mission it transmitted the following message: 'Long range scans indicate an unidentified ship beyond 175 AU. Definitely a maneuvering ship. Setting course to investigate, will advise.'" It was never heard from again." -- **Fictional** vehicle, Marc Millis Design, courtesy of NASA

Inflation: Alcubierre Metric

- In 1994, Alcubierre published a paper[1] exploring the consequences of inflation within the context of General Relativity.
  - Paper derived inflation-based metric allowing for rapid transit times between points without locally violating the speed of light.
  - Working mechanism was proposed to be the York Time (inflation).
  - Alcubierre metric requires a halo of negative energy density which violates several energy conditions and is considered to be classically non-physical.
- Concept of Operation
  - Spacecraft departs earth using conventional propulsion system and travels distance *d*, where spacecraft is brought to stop relative to earth.
  - Field is turned on and craft zips off to interstellar destination, never locally breaking the speed of light, but covering the distance *D* in an arbitrarily short period of time.
  - Field is turned off at standoff distance *d* from the destination, and craft finishes journey conventionally.
  - This approach would allow journey to Alpha Centauri in weeks or months, rather than decades or centuries as measured by an earth bound observer (and spacecraft clocks).

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1. Alcubierre, M., "The warp drive: hyper-fast travel within general relativity," Class. Quant. Grav. 11, L73-L77 (1994).

Inflation: Alcubierre Metric

Warp Drive Metric:

$$ds^2 = -dt^2 + \left(dx - \underset{\uparrow}{v_s} f(r_s)dt\right)^2 + dy^2 + dz^2$$

Apparent speed

Shaping Function:

Shell thickness parameter

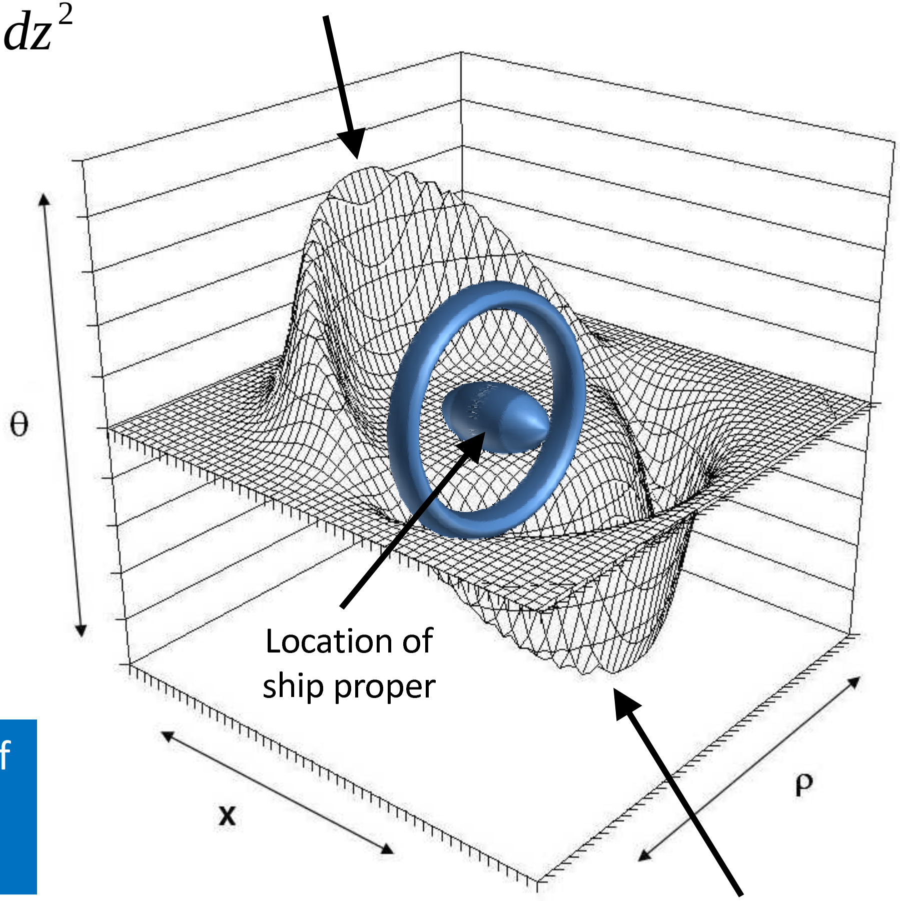
Shell size parameter

$$f(r_s) = \frac{\tanh\left(\overset{\downarrow}{\sigma}(r_s + \overset{\downarrow}{R})\right) - \tanh\left(\sigma(r_s - R)\right)}{2\tanh(\sigma R)}$$

York Time:

$$\theta = v_s \frac{x_s}{r_s} \frac{df(r_s)}{dr_s}$$

York Time is measure of expansion/contraction of space



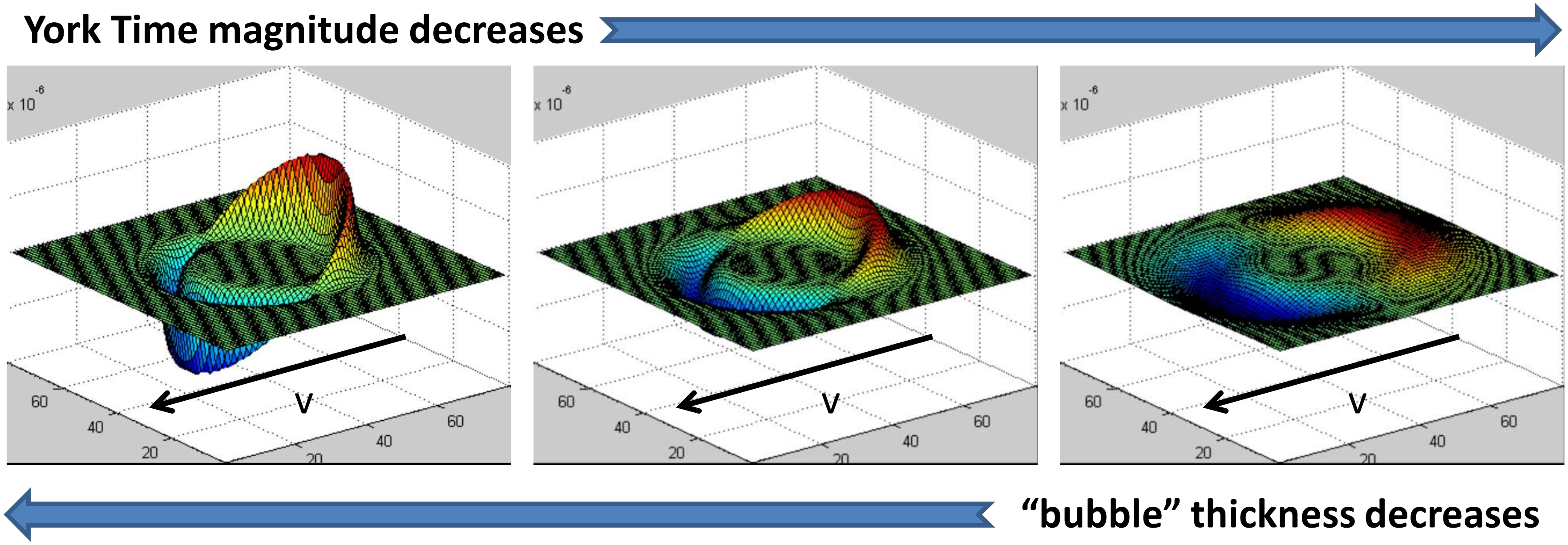
Space expansion behind ship

Location of ship proper

Space contraction in front of ship

York Time Behavior

- Allowing the thickness of the warp bubble to get thicker greatly reduces the required York Time magnitude, while still achieving desired v_s.
- The flat space-time region inside the bubble is slightly reduced, but manageable considering benefits.



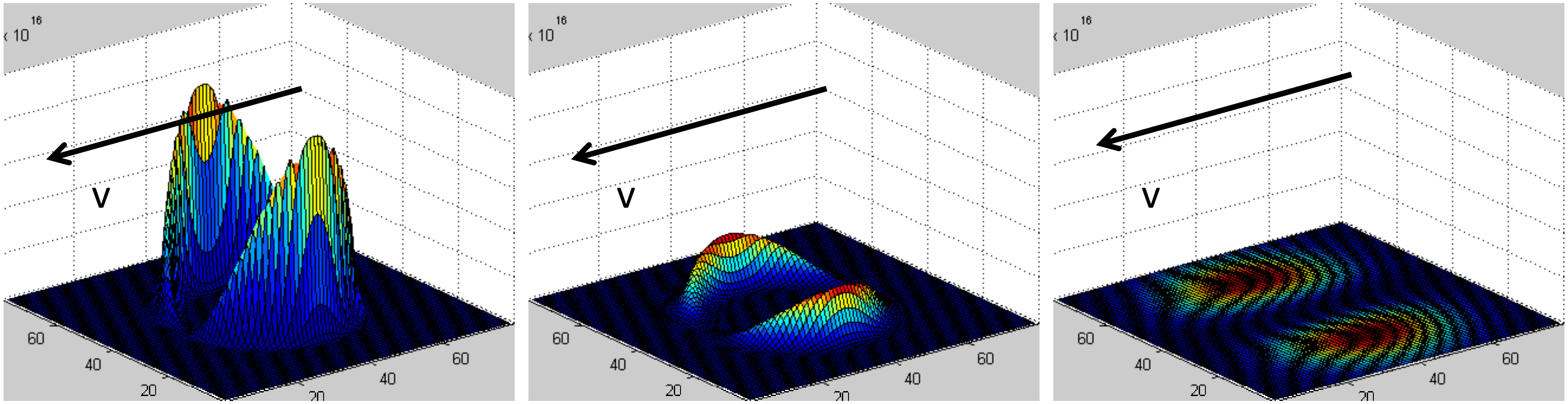
York Time magnitude decreases

"bubble" thickness decreases

Surface plots of York Time, <v>=10c, 10 meter diameter volume, variable warp "bubble" thickness

Energy Density Behavior

Energy density magnitude decreases →



← **"bubble" thickness decreases**

Surface plots of T^{00}, <v>=10c, 10 meter diameter volume, variable warp "bubble" thickness

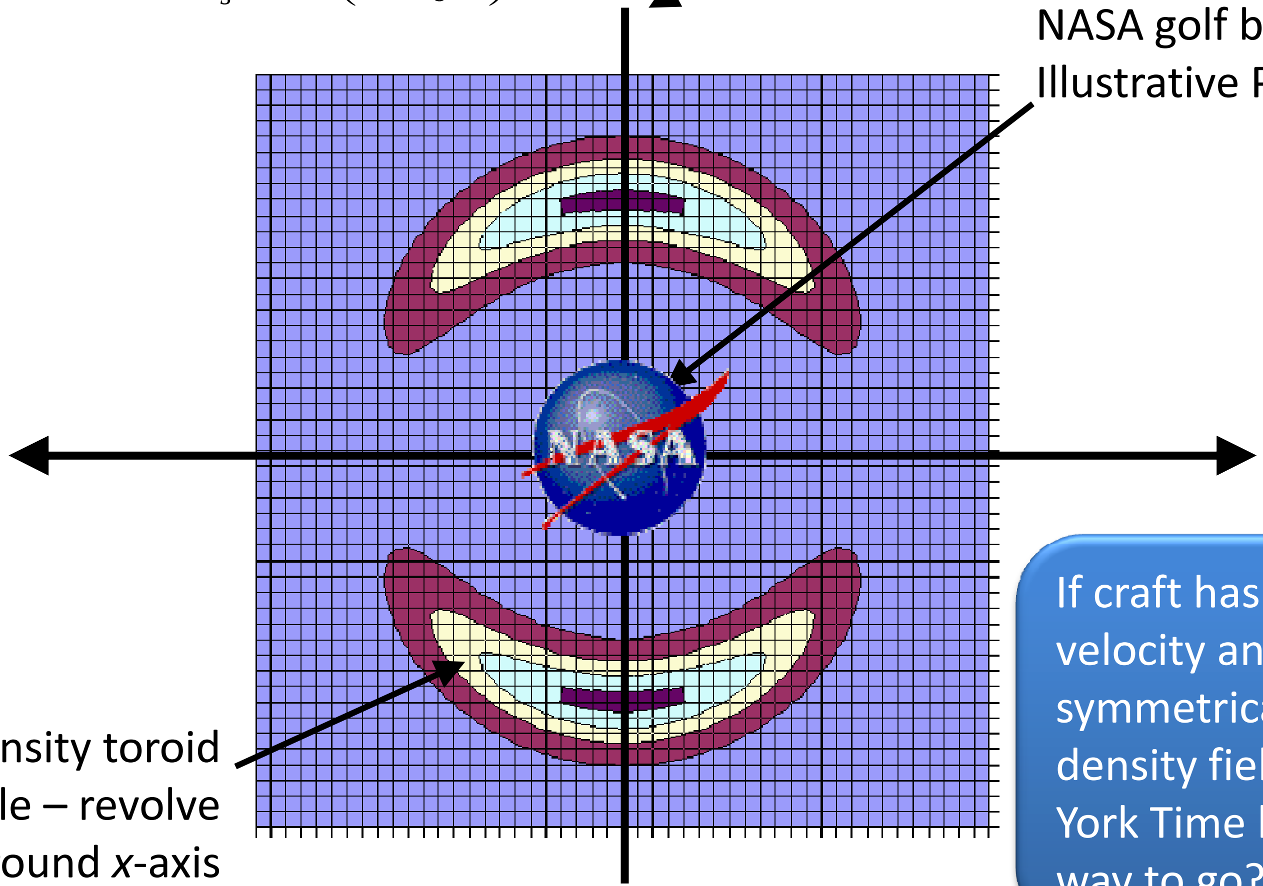
- As the warp bubble gets thicker, the peak energy density is greatly reduced.
- Similarly, the total energy (integration of field) is also reduced, but to a point. Early indications suggest there is an optimal thickness that minimizes total energy for craft size and target velocity.

Takeaway: sloppy bubbles appear to be "easier" than precise ones.

Symmetry/Asymmetry Paradox

Energy Density:

$$\frac{1}{8\pi}G^{00} = -\frac{1}{8\pi}\frac{v_s^2\left(y^2+z^2\right)}{4r_s^2}\left(\frac{df(r_s)}{dr_s}\right)^2$$



Symmetry Surface

Gedanken experimental NASA golf ball ship. Illustrative Purposes Only

Energy density toroid profile – revolve around *x*-axis

If craft has zero initial velocity and initiates symmetrical energy density field, how does York Time know which way to go?

Canonical Form of Alcubierre Metric

- In 2003, this author published a paper[1] that derived the canonical form of the Alcubierre metric allowing for a better understanding of the physical nature, and how it might be manifested (at least mathematically).
  - Canonical form mitigated energy density symmetry paradox and showed that working mechanism might be the boost sphere (resulting from halo) acting on initial velocity (e.g boost = 2, initial v = 27,500mph, apparent v = 55,000mph).
  - Boost is something that can be readily engineered, while the notion of inflation is less tangible.
  - This model by itself was still a mathematical toy, unless the need for negative energy density issue could be addressed.

---

1. White, H., "A Discussion on space-time metric engineering," Gen. Rel. Grav. 35, 2025-2033 (2003).

Canonical Form of Alcubierre Metric

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---

1. White, H., "A Discussion on space-time metric engineering," Gen. Rel. Grav. 35, 2025-2033 (2003).

Canonical Form of Alcubierre Metric

Canonical Form of Alcubierre metric:

$$ds^2 = \left[v_s{}^2 f(r_s)^2 - 1\right]\left\{dt - \frac{v_s f(r_s)}{v_s{}^2 f(r_s)^2 - 1}dx\right\}^2 - dx^2 + dy^2 + dz^2$$

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

Since the equation is now in canonical form, the boost can be derived:

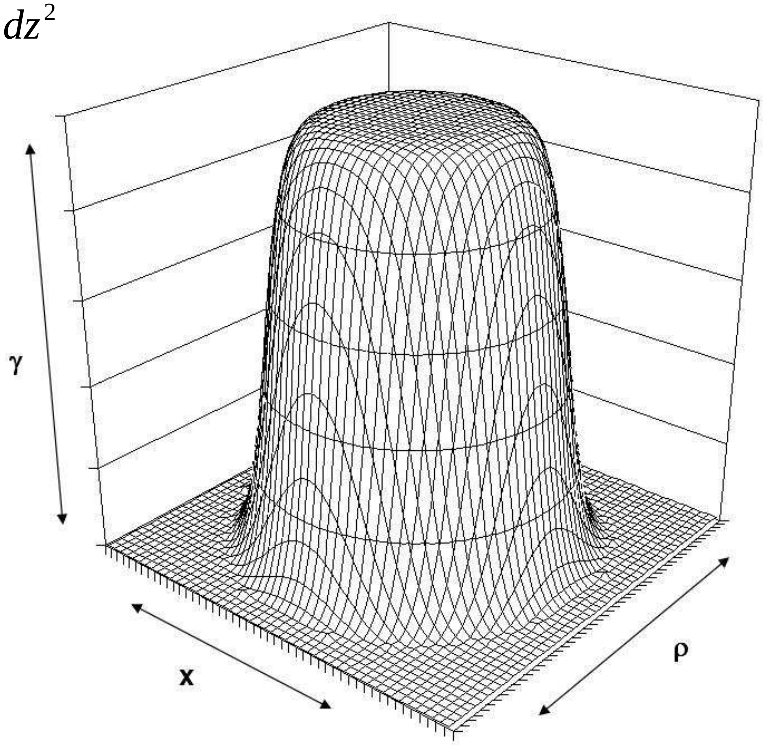
$$-e^{\frac{2\Phi}{c^2}} = \left[v_s{}^2 f(r_s)^2 - 1\right]$$

Or taking c = 1…

$$\Phi = \frac{1}{2}\ln\left[\left|1 - v_s{}^2 f(r_s)^2\right|\right]$$

Trivially, the Lorentz Transform or boost field is: $\gamma_\Phi = \cosh(\Phi)$

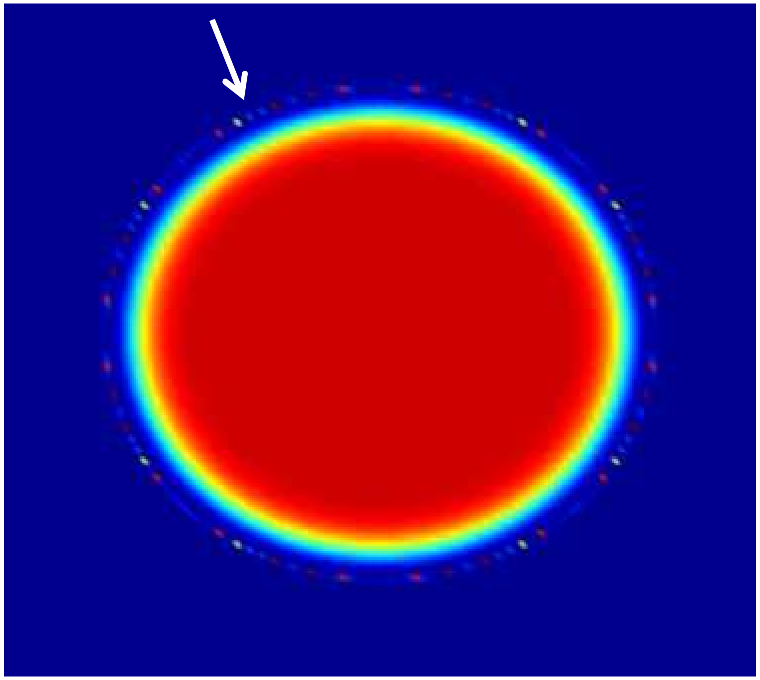
Boost Field:

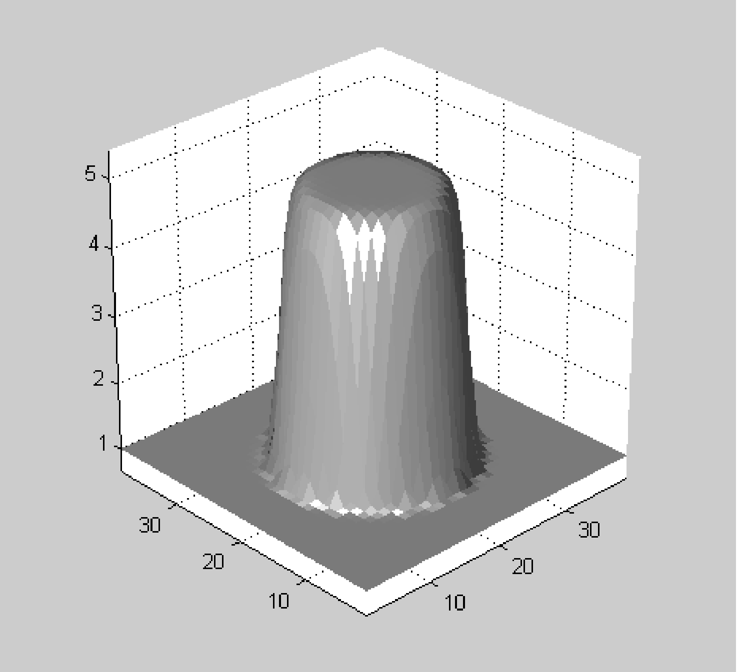


Boost Field

Surface plots of boost, <v>=10c, 10 meter diameter volume

Note pseudo-horizon surface at $V^2 f(r_s)^2=1$





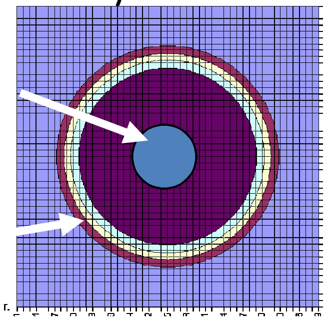
Pseudo-horizon surface not visible with larger integration step

Note pseudo-horizon at $v^2 f(r_s)^2=1$ where photons transition from null-like to space-like and back to null like upon exiting. This is not seen unless the field mesh is set fine enough. The coarse mesh on the right did not detect the horizon.

Dr. Harold “Sonny” White
09/02/2011

Modified Concept of Operations

- A modified concept of operations is proposed that may resolve symmetry/symmetry paradox.
- Spacecraft departs earth and establishes an initial sub-luminal velocity vi, then initiates field.
- When active, field's boost acts on initial velocity as a scalar multiplier resulting in a much higher apparent speed, $\langle v_{eff} \rangle = \gamma v_i$ as measured by either an earth bound observer or an observer in the bubble.
- Within shell thickness of the warp bubble region, the spacecraft never locally breaks the speed of light and the net effect as seen by earth/ship observers is analogous to watching a film in fast forward.
- Consider the following to help illustrate the point –
  - Assume the spacecraft heads out towards Alpha Centauri and has a conventional propulsion system capable of reaching 0.1c.
  - The spacecraft initiates a boost field with a value of 100 which acts on the initial velocity resulting in an apparent speed of 10c.
  - The spacecraft will make it to Alpha Centauri in 0.43 years as measured by an earth observer



Gedanken experimental NASA golf ball ship.

Boost Shell

Brane Cosmology: Chung-Freese metric

- In 2000, Chung and Freese published a paper[1] that mapped a Friedmann-Robertson-Walker (FRW) metric into a higher dimensional manifold to address the cosmological horizon problem (e.g. COBE sphere smoothness).
  - In this model, our 3 + 1 universe exists as a brane imbedded in a higher dimensional bulk.
  - By considering the null solutions for the metric (e.g. light rays), thermodynamic information can be communicated over vast distances without violating causality by means of transiting through the bulk.
  - Model can be generalized to represent an n-dimensional space, and compactification can be included if desired.

---

1. Chung, D. J. H., and Freese, K., "Can geodesics in extra dimensions solve the cosmological horizon problem?," Phys. Rev. D 62, 063513 (2000).

Brane Cosmology: Chung-Freese metric

Chung Freese metric:

$$ds^2 = -c^2 dt^2 + \frac{a^2(t)}{e^{2\mathrm{kU}}} dX^2 + dU^2$$

- The dX^2 term represents the 3+1 space (on the brane).
- The dU^2 term represents the bulk with the brane being located at U=0.
- The $a(t)$ term is the scale factor, and k is a compactification factor for the extra space dimensions.
- A conventional analogy to help visualize the brane-bulk relationship, consider a 2D sheet that exists in a 3D space:
  - The 2D inhabitants of the “flat-land” subspace have a manifold that is mapped out with the simple metric, $dx^2 + dy^2$, where this can be viewed as being analogous to the dX^2 term
  - The remainder of the 3D bulk space is mapped by the z-axis, and anything not on the sheet would have a non-zero z-coordinate.
  - This additional dz^2 term is, from the perspective of the 2D inhabitants, the dU^2 term.
  - Anything not on the 2D sheet would be labeled as being in the bulk with this simplified analogy.

Comparison of null geodesics (e.g. light rays)

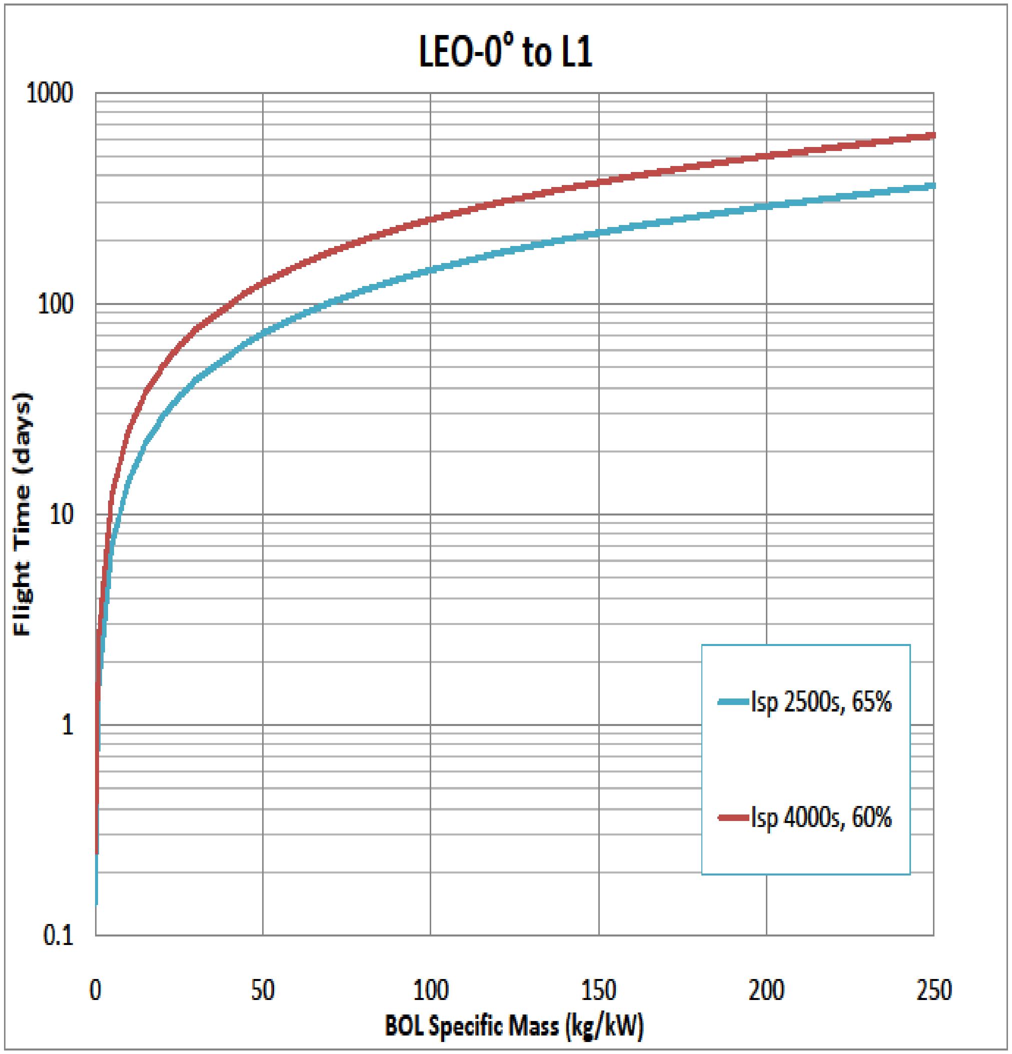
$$\frac{dX}{dt}=\frac{ce^{\mathrm{kU}}}{a(t)}\sqrt{1-\frac{dU^{2}}{c^{2}dt^{2}}} \quad \Longrightarrow \quad \gamma \approx e^{U}$$

- *dX/dt* is the speed of a photon in coordinate space.
- For *U* = 0, *dX/dt* = 1 as expected
- If *dU/dt* is set to 1, then test photon that has a velocity vector orthogonal to the brane would have a zero speed as measured on the brane, *dX/dt*=0.
- If a test photon has *dU/dt*=0, but arbitrarily large *U* coordinate, *dX/dt* will be large, possibly >>1. Remember that c was set to 1, so *dX/dt* >1 is analogous to the hyper-fast travel character of the Alcubierre metric.
- The behavior of the null-like geodesics in the Chung-Freese metric becomes space-like as *U* gets large.
- The null-like geodesics in the Alcubierre metric become space-like within the warp bubble, or where the boost gets large.
- This suggest that hyperspace coordinate serves same role as boost, and the two can be informally related by simple relationship above.

A large boost corresponds to an object being further off the brane and into the bulk.

Cis-lunar Mission Planning

- To this point, discussion has been centered on interstellar capability , but a more “domestic” application within the earth’s gravitational well will be considered.
- Energy density for metric is negative, so process of turning on a theoretical system with ability to generate negative energy density, or a negative pressure as shown in [1], will add an effective negative mass to the spacecraft’s overall mass budget.
- In reference mission development using low-thrust electric propulsion systems for in-space propulsion, planners will cast part of trade space into domain that compares specific mass a to transit time. (see LEO to L1 inset)
- Specific mass of an architecture element can be determined by dividing spacecraft’s beginning of life wet mass by the power level.
- Transit time for a mission trajectory can be calculated and plotted on graph that compares specific mass to transit time.
- If negative mass is added to spacecraft’s mass budget, then the effective specific mass and transit time are reduced without necessarily reducing payload.
- A question to pose is what effect does this have mathematically? If energy is to be conserved, then ½ mv^2 would need to yield a higher *effective* velocity to compensate for apparent reduction in mass.



<u>EXAMPLE:</u>

- Assuming a point design solution of 5000kg BOL mass coupled to a 100kW Hall thruster system (lower curve), expected transit time is ~70 days for a specific mass of 50 kg/kW without the aid of a warp drive.
- If a very modest warp drive system is installed that can generate a negative energy density that integrates to ~2000kg of negative mass when active, the specific mass is dropped from 50 to 30 which yields a reduced transit time of ~40 days.
- As the amount of negative mass approaches 5000 kg, the specific mass of the spacecraft approaches zero, and the transit time becomes exceedingly small, approaching zero in the limit.
- In this simplified context, the idea of a warp drive may have some fruitful domestic applications “subliminally,” allowing it to be matured before it is engaged as a true interstellar drive system.

---

1. White, H., Davis, E., “The Alcubierre Warp Drive in Higher Dimensional Space-time,” in proceedings of Space Technology and Applications International Forum (STAIF 2006), edited by M. S. El-Genk, American Institute of Phys$_{IC}$s, Melville, New York, (2006).

NASA EAGLEWORKS LABORATORIES

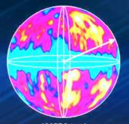
Humanity should explore and colonize the Solar System in the next fifty years, while making human-crewed and robotic interstellar flights a real possibility by the end of the 21st Century. To that end, many dedicated teams and individuals are actively working to research and develop both the science and technology (propulsion & power) required to accomplish these goals. Propulsion and Power are the keys to exploration and utilization of the Solar System and beyond. Godspeed!

Derivation of Gravitational Constant

Quantum Vacuum Fluctuations and Big-G

Gedanken Experiment

- Imagine being an inertial observer in deep space...
- The longest path a quantum vacuum fluctuation can travel for any inertial observer is the radius of the observable universe, or more simply, the radius of the "COBE Sphere" at ~13.7 billion light years.
- The vacuum energy density has been measured to be approximately 72% +/-3% of the critical density, or rather 0.72 * 1x10^{-26} kg/m^3, based on the apparent brightness of supernovae at red shifts of z ~ 1.
- If we integrate the vacuum energy density over the surface area of the COBE sphere, we arrive at a startling conclusion...



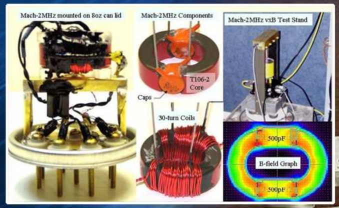
"COBE Sphere"

we obtain the Plank Force.

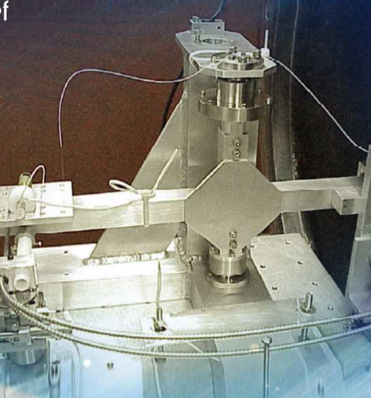
$$\underbrace{\boxed{\rho_{vac}c^2}}_{\text{Vacuum Energy Density}}\overbrace{4\pi \underbrace{c^2 t_H{}^2}_{\text{Square of Light radius of COBE sphere}}}^{\text{Inner-surface area of COBE sphere}}=\boxed{\frac{c^4}{G}}$$

Harold White, Ph.D.
League City, TX

1000+μN Thruster (4x Force density of leading EP tech, I_{8P} ~1x10^{12} s)

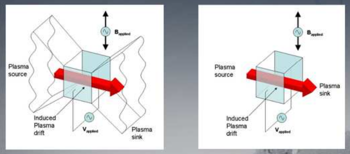


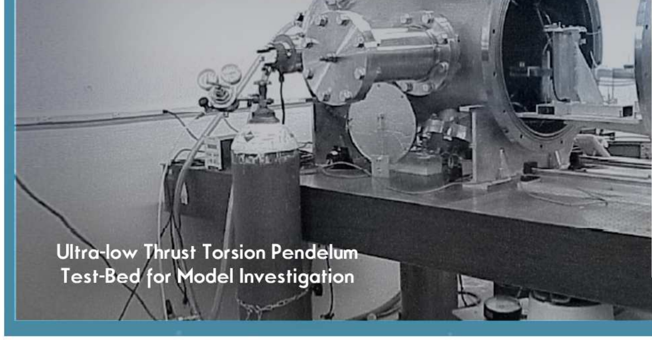
Test Results



2.45GHz Quantum Vacuum Plasma Thruster

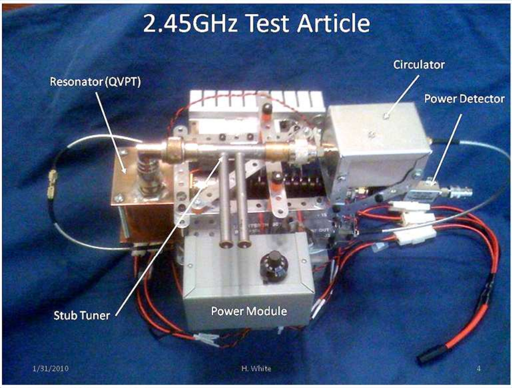
How It Works





Ultra-low Thrust Torsion Pendelum Test-Bed for Model Investigation

2.45GHz Test Article



Inflation: Alcubierre Metric

Warp Drive Metric:

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

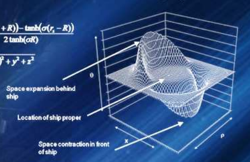
$$v_s=\frac{dx_s(t)}{dt}$$

$$f(r_s)=\frac{\tanh(\sigma(r_s+R))-\tanh(\sigma(r_s-R))}{2\tanh(\sigma R)}$$

$$r_s(t)=\sqrt{(x-x_s(t))^2+y^2+z^2}$$

York Time:

$$\theta=v_s\frac{x_s}{r_s}\frac{df(r_s)}{dr_s}$$



Spacetime Metric Engineering

Inflation: Alcubierre Metric, Canonical Form

Canonical Form of Alcubierre metric:

$$ds^2=\left[v_s^2 f(r_s)^2-1\right]\left\{dt-\frac{v_s f(r_s)}{v_s^2 f(r_s)^2-1}dx\right\}^2-dx^2+dy^2+dz^2$$

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

Since the equation is now in canonical form, we can extract the boost:

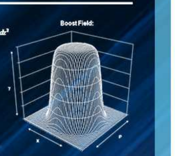
$$-e^{\frac{2\Phi}{c^2}}=\left[v_s^2 f(r_s)^2-1\right]$$

Or taking c = 1... $\Phi=\frac{1}{2}\ln\left[1-v_s^2 f(r_s)^2\right]$

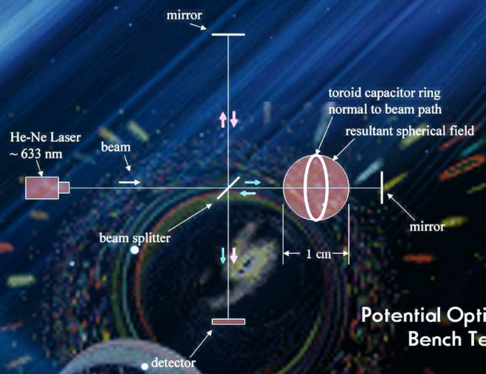
We will then use the following identity to extract the Lorentz Transform equation for the field:

$$\gamma_\Phi=\cosh(\Phi)$$

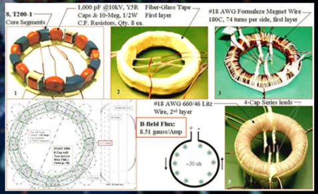
Boost Field:



Canonical Form

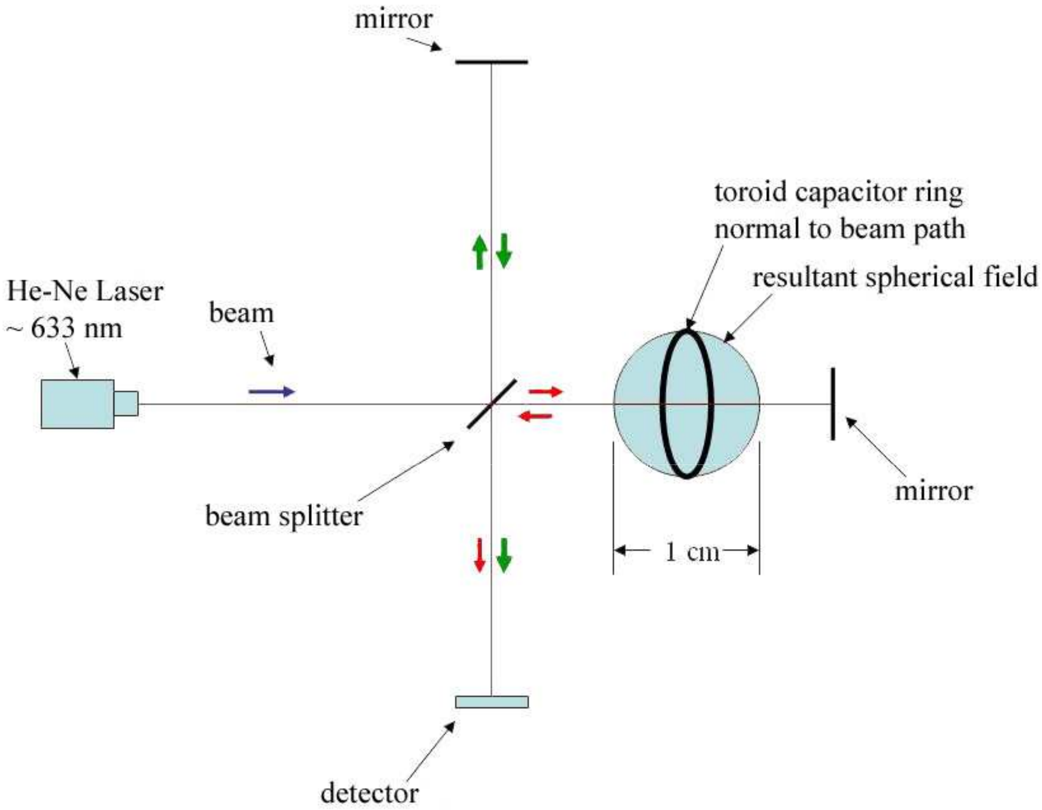


Potential Optics Bench Test



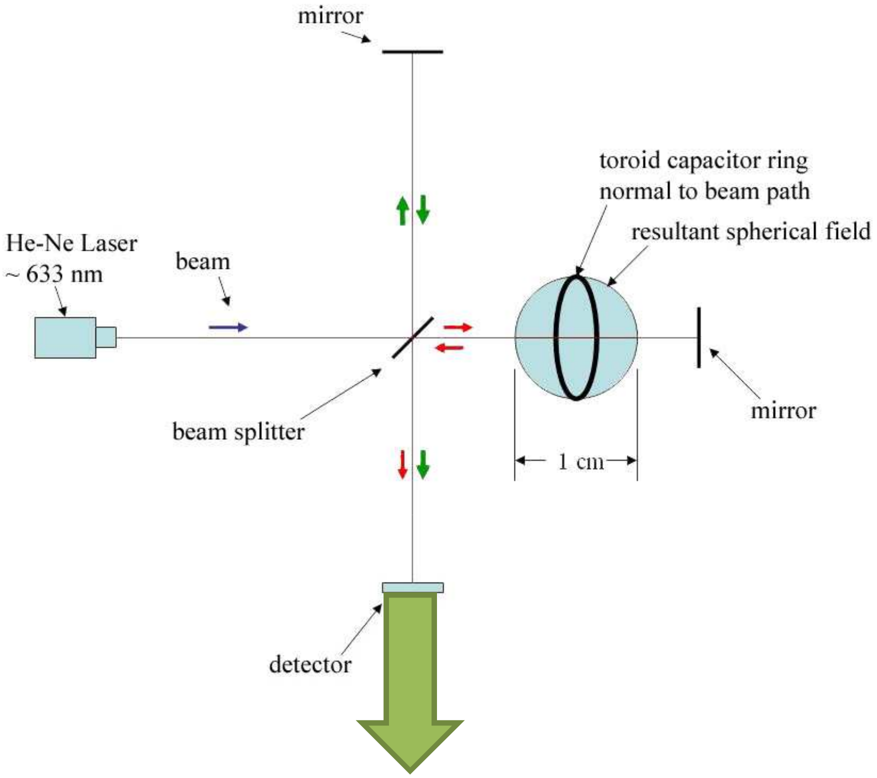
Potential Warp Field Experiment

- Since we know how to make a large spacetime expansion boost value, a test configuration could be invoked conceptually as shown.
- The figure depicts a modified Michelson-Morley Interferometer setup that makes use of a 1 cm diameter toroidal-ring of positive energy density on one leg of the interferometer.
- A He-Ne laser beam (λ = 633 nm) is split allowing one part of the beam to pass through the center of the ring and hence the spherical warp field region.
- This warp field region will induce a relative phase shift between the split beams that could be detectable provided the magnitude of the phase shift is sufficient.
- If the desired phase shift goal were set to be roughly 1/4th wavelength (reasonable expectation), then the necessary boost field is on the order of 1.0000001 to 1.0000002.

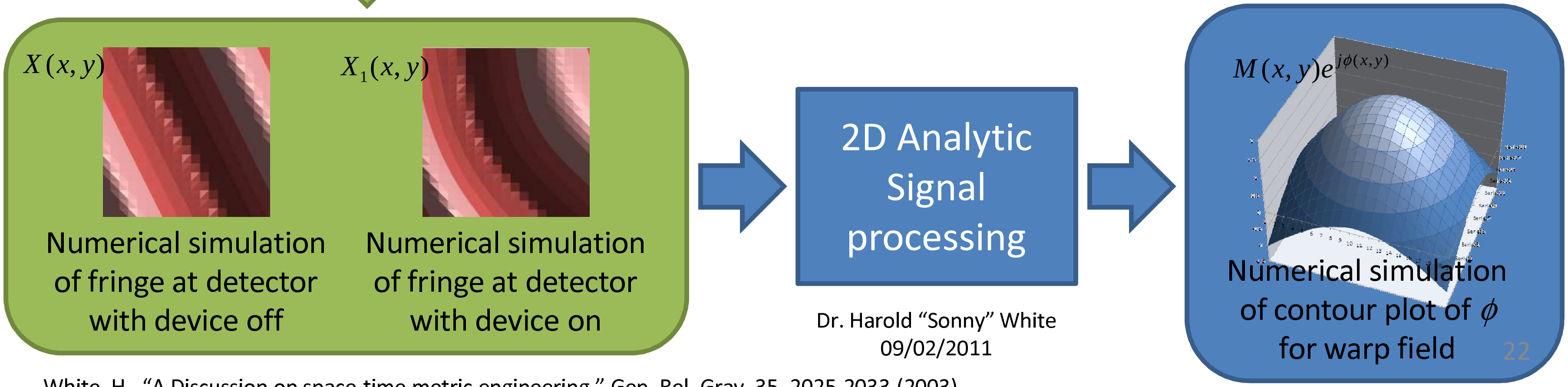


From a purely Special Relativistic perspective, this equates to a velocity of ~ 0.0004c which could be achieved potentially with a toroidal ring of plasma. Additionally, we could take the route of acting on the boost by means of the potential or gauge, $\gamma = \cosh(\phi)$. In this scenario, we would employ a ring of capacitors driven at high voltage and possibly moderately high frequencies to act on the potential (ϕ) of the ions within the dielectric.

White-Juday Warp Field Interferometer



- White-Juday Warp Field Interferometer uses He-Ne laser to generate interference signal at a detector with test device placed in proximity to one leg of beam path to evaluate York-Time effects (expansion/contraction of space).
- He-Ne laser beam (λ = 633 nm) is split allowing one part of beam to pass near /through device being tested.
- Presence of warp field region will induce relative phase shift between split beams that should be detectable provided magnitude of phase shift is sufficient.
- Using 2D Analytic Signal processing of the , the Magnitude and phase of the field can be extracted for study and comparison to theoretical models.



$X(x,y)$

Numerical simulation of fringe at detector with device off

$X_1(x,y)$

Numerical simulation of fringe at detector with device on

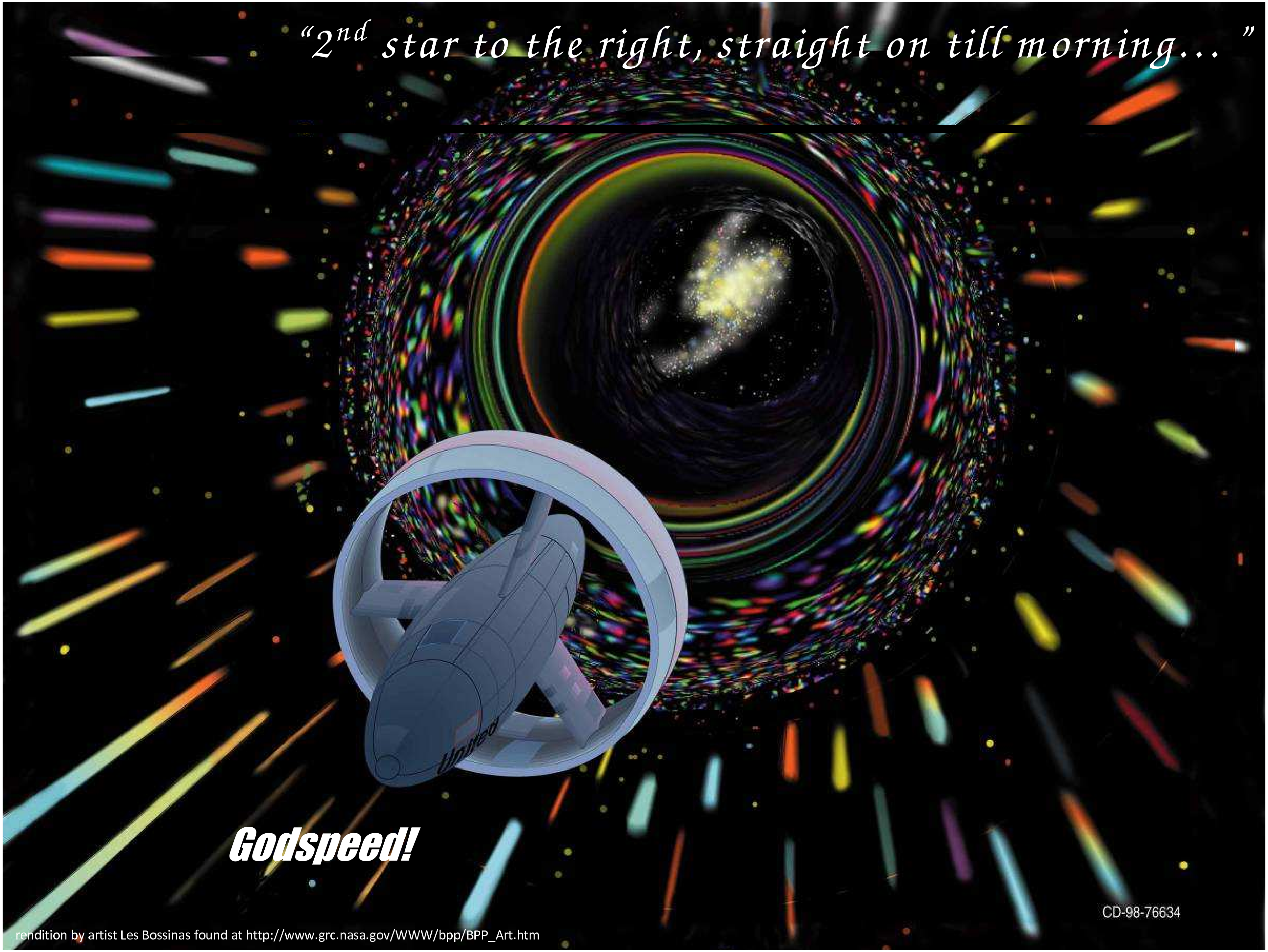
2D Analytic Signal processing

$M(x,y)e^{j\phi(x,y)}$

Numerical simulation of contour plot of ϕ for warp field

Dr. Harold “Sonny” White
09/02/2011

1. White, H., “A Discussion on space-time metric engineering,” Gen. Rel. Grav. 35, 2025-2033 (2003).



“2nd star to the right, straight on till morning… ”

Godspeed!

rendition by artist Les Bossinas found at http://www.grc.nasa.gov/WWW/bpp/BPP_Art.htm