Interstellar Travel by Means of Wormhole Induction Propulsion (WHIP)

Article · October 2011

DOI: 10.1063/1.54779

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INTERSTELLAR TRAVEL BY MEANS OF WORMHOLE INDUCTION PROPULSION (WHIP)

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Abstract

Space flight by means of wormholes is described whereby the traditional rocket propulsion approach can be abandoned in favor of a new paradigm involving the manipulation of spacetime. Maccone (1995) extended Levi-Civita's 1917 magnetic gravity solution to the Morris and Thorne (1988) wormhole solution and claimed that static homogeneous magnetic/electric fields can create spacetime curvature manifesting itself as a traversable wormhole. Furthermore, Maccone showed that the speed of light through this curvature region is slowed by the magnetic (or electric) induced gravitational field there. Maccone's analysis immediately suggests a way to perform laboratory experiments whereby one could apply a powerful static homogeneous magnetic field in a vacuum, thereby creating spacetime curvature, and measure the speed of a light beam through it. Magnetic fields employed in this scenario must achieve magnitudes > 10^{10} *Tesla* in order for measurable effects to appear. Current magnetic induction technology is limited to static fields of ~ *several x* 10^{3} *Tesla*. However, destructive chemical (implosive/explosive) magnetic field generation technology has reached peak rate-of-rise field strengths of ~ 10^{9} *Tesla/s*. It is proposed that this technology be exploited to take advantage of the high rate-of-rise field strengths to create and measure spacetime curvature in the lab.

INTRODUCTION

Rapid interplanetary and interstellar space flight by means of spacetime wormholes is possible, in principle, whereby the traditional rocket propulsion approach can be abandoned in favor of a new paradigm involving the use of spacetime manipulation. In this scheme, the light speed barrier becomes irrelevant and spacecraft no longer need to carry large mass fractions of traditional chemical or nuclear propellants and related infrastructure over distances larger than several astronomical units (AU). Travel time over very large distances will be reduced by orders of magnitude. Einstein published his General Theory of Relativity (GTR) in 1915. In 1917, physicist Tullio Levi-Civita read a paper before the Academy of Rome about creating artificial gravitational fields (spacetime curvature) by virtue of static homogeneous magnetic or electric fields as a solution to the GTR equations. This paper went largely unnoticed. In 1988, Morris and Thorne published an exact solution to the GTR equations which describe the creation of traversable wormholes in spacetime by virtue of exotic (*mass-energy* ρc^2 < *stress-energy* τ) matter-energy fields. Visser (1995) has extended and added to the knowledge base of this research. The essential features of these solutions are that wormholes possess a traversable throat in which there is no horizon or singularity. For the purpose of this study, we also impose the additional constraint that travel through the wormhole is causal, although, this is not a necessary constraint in general. When these properties are employed together with the GTR field equations, it becomes necessary to introduce an exotic material in the wormhole's throat which generates its spacetime curvature.

Maccone (1995) extended and matched Levi-Civita's solution to the Morris and Thorne solution and claimed that the earlier describes a wormhole in spacetime. More specifically, Maccone claims that static homogeneous magnetic/electric fields with cylindrical symmetry can create spacetime curvature which manifests itself as a traversable wormhole. Although the claim of inducing spacetime curvature is correct, Levi-Civita's metric solution is not a wormhole. A near-term lab experiment based on Maccone's analysis will be discussed. It is my intent to introduce a new space propulsion concept which employs the creation of traversable wormholes by virtue of ultrahigh magnetic fields in conjunction with exotic matter-energy fields. I call this propulsion concept "Wormhole Induction Propulsion" or WHIP. It is speculated that future WHIP spacecraft could deploy ultrahigh magnetic fields along with exotic matter- energy fields (e.g. radial electric or magnetic fields, Casimir energy field, etc.) in space to create a wormhole and then apply conventional space propulsion to move through the throat to reach the other side in a matter of minutes or days, whence the spacecraft emerges several AU's or light-years away from its starting point. The requirement for conventional propulsion in WHIP spacecraft would be strictly limited by the need for short travel through the wormhole throat as well as for orbital maneuvering near distant worlds. The integrated system comprising the magnetic induction/exotic field wormhole and conventional propulsion units could be called WHIPIT or "Wormhole Induction Propulsion Integrated Technology."

THEORETICAL BRIEF

Levi-Civita's spacetime metric for a static uniform magnetic field was originally conceived by Pauli (1981):

$$ds^2 = (dx^1)^2 + (dx^2)^2 + (dx^3)^2 + \frac{(x^1dx^1 + x^2dx^2)^2}{a^2 - \left[(x^1)^2 + (x^2)^2\right]} - \left[c_1 \exp\left(\tfrac{x^3}{a}\right) + c_2 \exp\left(\tfrac{-x^3}{a}\right)\right]^2 (dx^4)^2 , \qquad (1)$$

where c_1 and c_2 are integration constants which are determined by appropriate boundary conditions and $x^1 \ldots x^4$ are Cartesian coordinates ($x^1 \ldots x^3$ = *space*, x^4 = *time*) with orthographic projection. The important parameter in (1) is:

$$a = c^2\left(\frac{4pG}{m_0}\right)^{-\frac{1}{2}} B^{-1} = 3.4840x10^{+18} B^{-1} , \qquad (2)$$

which measures the radius of spacetime curvature induced by a homogeneous magnetic field with cylindrical symmetry (axis, $x^3 = z$) about the direction of the field. From the coefficient of dx^4 in (1), Maccone derived the "speed of light function" which gives the gravitationally induced variation of light speed within the curvature region:

$$v(z) = 2c\left[\exp\left(\tfrac{L}{2a}\right)\right]\left[\exp\left(\tfrac{L}{a}\right) + 1\right]^{-1} \cosh\left(\tfrac{z}{a}\right) . \qquad (3)$$

At the center of this region ($z = 0$), this becomes:

$$v(0) = 2c\left[\exp\left(\tfrac{L}{2a}\right)\right]\left[\exp\left(\tfrac{L}{a}\right) + 1\right]^{-1} = 2c\left[\exp\left(\tfrac{LB}{2K}\right)\right]\left[\exp\left(\tfrac{LB}{K}\right) + 1\right]^{-1} , \qquad (4)$$

for $0 < L << a$, where $K = c^2\left(\frac{4pG}{m_0}\right)^{-\frac{1}{2}} = 3.4840x10^{+18}$ is the radius of curvature constant. Equation (4) is based on the assumption that the magnetic field is created by a solenoid of length *L* oriented along the *z*-axis, and that $c = 3x10^8$ *m/sec* at the solenoid's ends ($z = \pm L/2$), while at $z = 0$, c slows down according to (4) because of the presence of the artificially induced spacetime curvature. Further, Maccone inverted equation (4) and solved for *B* to get:

$$B = \frac{2K}{L} \ln\left[\frac{c \pm \sqrt{c^2 - v^2(0)}}{v(0)}\right]. \qquad (5)$$

Equations (2), (4) and (5) are formulae to use for creating and detecting spacetime curvature in the lab.

Technical Issues

Traversable wormholes are creatures of classical GTR and represent non-trivial topology change in the spacetime manifold. This makes mathematicians cringe because it raises the question of whether topology can change or fluctuate to accommodate wormhole creation. Black holes and naked singularities are also creatures of GTR representing non-trivial topology change in spacetime, yet they are accepted by the astrophysics and mathematical communities - the former by Hubble Space Telescope discoveries and the latter by theoretical arguments due to Kip

Thorne, Stephen Hawking, Roger Penrose and others. The Bohm-Aharonov effect is another example which owes its existence to non-trivial topology change in the manifold. The topology change (censorship) theorems discussed in Visser (1995) make precise mathematical statements about the "mathematician's topology" (topology of spacetime is fixed!), however, Visser correctly points out that this is a mathematical abstraction. In fact, Visser (1990) proved that the existence of an everywhere Lorentzian metric in spacetime is not a sufficient condition to prevent topology change. Furthermore, Visser (1990 and 1995) elaborates that physical probes are not sensitive to this mathematical abstraction, but instead they typically couple to the geometrical features of space. Visser (1990) also showed that it is possible for geometrical effects to mimic the effects of topology change. Topology is too limited a tool to accurately characterize a generic traversable wormhole; in general one needs geometric information to detect the presence of a wormhole, or more precisely to locate the wormhole throat (Visser 1997).

Landis (1997) has made technical criticisms of Maccone's (1995) work suggesting that the Levi-Civita metric in the presence of a uniform magnetic field does not form a wormhole within the Morris and Thorne (1988) framework. While the latter view is correct, the technical arguments are not accurate or complete. Changing the coordinate system from Cartesian to cylindrical ($x^1 = r\cos\varphi$, $x^2 = r\sin\varphi$, $x^3 = z$, let $x^4 = t$) puts equation (1) into the form (Maccone 1995):

$$ds^2 = -\left[c_1 \exp\left(\tfrac{z}{a}\right) + c_2 \exp\left(\tfrac{-z}{a}\right)\right]^2 dt^2 + \left(1 - \tfrac{r^2}{a^2}\right)^{-1} dr^2 + r^2 d\varphi^2 + dz^2 . \tag{6}$$

This is a cleaner form, but what is the Levi-Civita metric really? We can find out from making a change of (radial) variable by letting $r = a\sin\theta$, $dr = a\cos\theta\, d\theta$ and substituting these into equation (6):

$$ds^2 = -\left[c_1 \exp\left(\tfrac{z}{a}\right) + c_2 \exp\left(\tfrac{-z}{a}\right)\right]^2 dt^2 + a^2\left[d\theta^2 + \sin^2\theta\, d\varphi^2\right] + dz^2 , \tag{7}$$

where a is the constant radius defined by equation (2). The spatial part of (7), $d\sigma^2 = a^2\left[d\theta^2 + \sin^2\theta\, d\varphi^2\right] + dz^2$, is recognized as the three-metric of a hypercylinder $S^2 \times \Re$ So equation (7) shows that Levi-Civita's spacetime metric is simply a hypercylinder with a position dependent gravitational potential: no asymptotically flat region, no flared-out wormhole mouth and no wormhole throat. Maccone's equations for the radial (hyperbolic) pressure, stress and energy density of the "magnetic wormhole" configuration are thus incorrect.

In addition, directing attention on the behavior of wormhole geometry at asymptotic infinity is not too profitable. Visser (1997) and Hochberg and Visser (1997) demonstrates that it is only the behavior near the wormhole throat that is critical to understanding what is going on, and that a generic throat can be defined without having to make all the symmetry assumptions and without assuming the existence of an asymptotically flat spacetime to embed the wormhole in. One only needs to know the generic features of the geometry near the throat in order to guarantee violations of the null energy condition (NEC) (Hawking and Ellis 1973) for certain open regions near the throat (Visser 1997). There are general theorems of differential geometry that guarantee that there must be NEC violations (meaning exotic matter-energy is present) at a wormhole throat. In view of this, however, it is known that static radial electric or magnetic fields are borderline exotic when threading a wormhole if their tension were infinitesimally larger, for a given energy density (Herrmann 1989 and Hawking and Ellis 1973). Other exotic (energy condition violating) matter-energy fields are known to be squeezed states of the electromagnetic field, Casimir (electromagnetic zero-point) energy and other quantum fields/states/effects. With respect to creating wormholes, these have the unfortunate reputation of alarming physicists. This is unfounded since all the energy condition hypotheses have been experimentally tested in the laboratory and experimentally shown to be false - 25 years before their formulation (Visser 1990). Violating the energy conditions commits no offense against nature.

EXPERIMENTAL APPROACH

Table 1 below shows the radius of curvature generated by a range of magnetic field strengths via equation (2). Equations (2), (4) and (5) suggest a way to perform a laboratory experiment whereby one could apply a powerful static homogeneous (cylindrically symmetric) magnetic field in a vacuum, thereby creating spacetime curvature in principle, and measure the speed of a light beam through it. A measurable slowing of c in this arrangement would demonstrate that a curvature effect has been created in the experiment. The achievable precision in measuring this

TABLE 1. Radius of Spacetime Curvature Induced by B-Field.

B **(x 3.484 *Tesla*)**	***a*** **(*m*)**
1	10^{18} **(105.7 *ly*)**
10^{2}	10^{16} **(1.06 *ly*)**
10^{3}	10^{15} **(0.11 *ly*)**
10^{5}	10^{13} **(66.7 *AU*)**
10^{7}	10^{11} **(0.67 *AU*)**
10^{9}	10^{9} **(1.44 *Solar Radii*)**
10^{12}	10^{6} **(0.16 *Earth Radii*)**
10^{15}	10^{3}
10^{18}	**1**

would be $c - v(0)$ or $c^2 - v^2(0)$ as seen from equation (5). Electric fields could also be used to create the same effect, however, the field strengths required to accomplish the same radius of curvature or slowing of c is seventeen times larger than magnetic field strengths (Maccone 1995).

From Table 1, it is apparent that laboratory magnetic field strengths would need to be > 10^9 - 10^{10} *Tesla* so that a significant radius of curvature and slowing of c can be measured. Experiments employing chemical explosive/implosive magnetic technologies would be an ideal arrangement for this. The limit of magnetic field generation for chemical explosives/implosives is ~ *several x* 10^3 *Tesla* and the quantum limit for ordinary metals is ~ 50,000 *Tesla*. Explosion/implosion work done by Russian (MC-1 generator, ISTC grant), Los Alamos National Lab (ATLAS), National High Magnetic Field Lab and Sandia National Lab (SATURN) investigators have employed magnetic solenoids of good homogeneity with lengths of ~ 10 cm, having peak rate-of-rise of field of ~ 10^9 *Tesla/s* where a few nanoseconds is spent at 1000 *Tesla*, and which is long enough for a good measurement of c (Solem 1997). Further, with picosecond pulses, c could be measured to a part in 10^2 or 10^3. At 1000 *Tesla*, $c^2 - v^2(0) \approx 0\ m^2/s^2$ and the radius of curvature is 0.368 *light-years*. If the peak rate-of-rise of field (~ 10^9 *Tesla/s*) can be used, then a radius of curvature ≤ *several x* 10^6 *km* can be generated along with $c^2 - v^2(0) \geq$ *several x* $10^4\ m^2/s^2$. In general, we can use Table 1 and equation (4) to see that for $B \leq 10^8$ *Tesla* we obtain $c^2 - v^2(0) \approx 0\ m^2/s^2$, and for $B \sim 10^9 - 10^{18}$ *Tesla* we obtain $c^2 - v^2(0) \sim 10^4 - 10^{14}\ m^2/s^2$. It can be seen from this result that the use of ultrahigh magnetic fields will be necessary to obtain measurable consequences of any spacetime effects which may occur in a laboratory experiment.

It will be necessary to consider advancing the state-of-art of magnetic induction technologies in order to reach static field strengths that are > 10^9 - 10^{10} *Tesla*. Extremely sensitive measurements of c at the one part in 10^6 or 10^7 level may be necessary for laboratory experiments involving field strengths of ~ 10^9 *Tesla*. Magnetic induction technologies based on nuclear explosives/implosives may need to be seriously considered in order to achieve large magnitude results. An order of magnitude calculation indicates that magnetic fields generated by nuclear pulsed energy methods could be magnified to (brief) static values of ≥ 10^9 *Tesla* by factors of the nuclear-to-chemical binding energy ratio (≥ 10^6). Other experimental methods employing CW lasers, repetitive-pulse free electron lasers, neutron beam-pumped UO_2 lasers, pulsed laser-plasma interactions or pulsed hot (zeta pinch) plasmas generate insufficient magnetic field strengths for our purpose. Table 2 shows the currently available (high and ultrahigh) magnetic field generation technologies. However, it will be shown in the next section that several technologies listed in Table 2 are more than adequate for generating magnetic fields which could create and stabilize very large wormholes.

TABLE 2. Current High and Ultrahigh Magnetic Field Generation Technologies.

Magnetic Field Strength (*Tesla*)	Field Generation Technology
10 - 300	**Superconductivity, Hybrid Magnets, Pulsed Magnets**
360	**Magnetic flux compression by electromagnetic force**
400	**One-turn coil connected to strong laser produced plasma**
~ 10^3	**High powered pulsed lasers**
1000 - 3000	**Magnetic flux compression by chemical explosion**
10^2 - 10^5	**White Dwarf stars**
10^7 - 10^9	**Neutron stars**
$\geq 10^9$	**Magnetic flux compression by nuclear explosion**

WHIP SPACECRAFT CONCEPT

WHIP spacecraft will have multifunction integrated technology for propulsion. The Wormhole Induction Propulsion Integrated Technology (WHIPIT) would entail two modes. The first mode is an advanced conventional system (chemical, nuclear fission/fusion, ion/plasma, antimatter, etc.) which would provide propulsion through the wormhole throat, orbital maneuvering capability near stellar or planetary bodies, and spacecraft attitude control and orbit corrections. An important system driver affecting mission performance and cost is the overall propellant mass-fraction required for this mode. A desirable constraint limiting this to acceptable (low) levels should be that an advanced conventional system would regenerate its onboard fuel supply internally or that it obtain and process its fuel supply from the in situ space environment. Other important constraints and/or performance requirements to consider for this propulsion mode would include specific impulse, thrust, energy conversion schemes, etc. Further discussion of these is beyond the scope of this paper and is left for the reader to explore on their own.

The second WHIPIT mode is the stardrive component. This would provide the necessary propulsion to rapidly move the spacecraft over interplanetary or interstellar distances through a traversable wormhole. The system would generate a static, cylindrically symmetric ultrahigh magnetic field to create a hypercylinder curvature envelope (gravity well) near the spacecraft to pre-stress space into a pseudo-wormhole configuration. The radius of the hypercylinder envelope should be no smaller than the largest linear dimension of the spacecraft. As the spacecraft is gravitated into the envelope, the field-generator system then changes the cylindrical magnetic field into a radial configuration while giving it a tension that is greater than its energy density. A traversable wormhole throat is then induced near the spacecraft where the hypercylinder and throat geometries are patched together. The conventional propulsion mode then kicks on to nudge the spacecraft through the throat and send its occupants on their way to adventure. This scenario would apply if ultrahigh electric fields were employed instead.

After a wormhole is created, it will be important to stabilize it against collapse by threading it with matter or energy fields of stupendous negative (outward) tension. If *b* denotes the size of the wormhole throat (minimum radius), then the tension (outward radial pressure) at the throat must be at least (Morris and Thorne 1988):

$$\tau = \left(8\pi G c^{-4} b^2\right)^{-1} \approx 5.0\,x\,10^{40}\left(\frac{10\,m}{b}\right)^2 . \qquad (8)$$

Table 3 below shows the tension required to induce and stabilize a range of wormhole throat sizes. By inspecting Table 3, it becomes apparent that the calculated tensions are indeed stupendous. One can see that for wormhole throats smaller than 0.11 *ly*, the required tension will be greater than 5.0 x 10^{12} N/m^2 which exceeds the tensile strength of steel or tungsten (~ *several x* 10^{11} N/m^2). Indeed, for a 1000 *m* wormhole throat, the required tension of 5.0 x 10^{36} N/m^2 has the same magnitude as the pressure at the center of the most massive neutron star. However, if we make a very large wormhole of 1.0 *ly* in size, then we can use non-material fields to do the job. The outward tension required to open and stabilize a 1.0 *ly* wormhole is 5.59 x 10^{10} N/m^2. This is achievable by threading the wormhole throat with a magnetic field of only 118.5 *Tesla*. One can see in Table 2 that magnetic generation technologies based on superconductivity, hybrid or pulsed magnets can easily achieve this field strength. For magnetic field strengths of ~

10^2 - 10^3 *Tesla*, the corresponding magnetic field tension and wormhole size is ~ 10^{10} - 10^{12} N/m^2 and ~ 1 - 10^{-1} *ly*, respectively. It is apparent from Table 2 that there are technologies which can meet these requirements.

TABLE 3. Wormhole Throat Size Induced by Applied Tension.

b (m)	**τ (x 5.0 N/m^2)**
10^{18} (105.7 *ly*)	**10^6**
10^{16} (1.06 *ly*)	**10^{10}**
10^{15} (0.11 *ly*)	**10^{12}**
10^{13} (66.7 *AU*)	**10^{16}**
10^{11} (0.67 *AU*)	**10^{20}**
10^9 (1.44 *Solar Radii*)	**10^{24}**
10^6 (0.16 *Earth Radii*)	**10^{30}**
10^3	**10^{36}**
1	**10^{42}**

If optimization of wormhole throat (geometry) creation and hyperspace tunneling distance requires a fully exotic energy field to thread the throat, then the propulsion system would need to be capable of generating and deploying a Casimir (or other exotic) energy field. Although exotic field generation schemes are speculative, further discussion is beyond the scope of this paper and will be left for future work.

CONCLUSIONS

A candidate for breakthrough propulsion physics has been identified in the form of a traversable wormhole created by virtue of ultrahigh magnetic or electric fields with an additional exotic energy component. Maccone (1995) claimed that cylindrically symmetric ultrahigh magnetic (electric) fields can create a traversable wormhole in the Morris and Thorne (1988) framework. It has been shown that this is incorrect. Instead, a hypercylinder curvature effect having a position dependent gravitational potential is induced. This effect can be used to create a wormhole by patching the hypercylinder envelope to a throat that is induced by either radially stressing the ultrahigh field or employing additional exotic energy. Maccone correctly showed that the speed of light through the hypercylinder region is slowed by the magnetic induced gravitational field there. This suggests a way to perform laboratory experiments whereby one could apply an ultrahigh magnetic field in a vacuum, thereby creating a hypercylinder curvature effect, and measure the speed of a light beam through it. While chemical explosive/implosive magnetic induction technology has achieved static field strengths of ~ *several* x 10^3 *Tesla*, the peak rate-of-rise of field is ~ 10^9 *Tesla/s*. Field strengths > 10^9 - 10^{10} *Tesla* would need to be generated to impart a measurable slowing of light speed in this scenario. It is proposed that the peak rate-of-rise of field be exploited as a means to achieve this goal in the near-term. Magnetic induction technologies based on nuclear explosives/implosives may need to be considered in order to achieve results of larger magnitude. Further, it has been shown that it is possible, in the Morris and Thorne (1988) framework, to create very large (~ 10^{-1} - 1 *ly*) traversable wormholes in principle. These large wormholes require fields with outward tensions of < 10^{13} N/m^2 to create and stabilize them against collapse. High magnetic field strengths of ~ 10^2 - 10^3 *Tesla* were shown to be adequate for inducing the required tension. There are several magnetic field generation technologies available which are capable of attaining these field strengths. A Wormhole Induction Propulsion system has been introduced to exploit the possibilities of traversable wormholes that are created by high or ultrahigh magnetic induction systems.

Acknowledgments

I wish to thank Marc Millis for allowing me to use WHIP and WHIPIT which he coined at the February, 1997 NASA Breakthrough Propulsion Physics Regional Brainstorming Workshop at Austin, TX. My gratitude to Matt Visser for his many valuable suggestions and comments on this work. I also thank Alan Holt, Dean Judd, Johndale Solem, George Hathaway and John Alexander for their technical contributions and remarks. This research is partially supported by the National Institute for Discovery Science.

References

Hawking, S. W. and G. F. R. Ellis (1973) *The Large-Scale Structure of Space-Time*, Cambridge Univ. Press, Cambridge, 4:88-91 and 95-96.

Herrmann, F. (1989) "Energy Density and Stress: A New Approach to Teaching Electromagnetism," *Am. J. Phys.*, 57:707-714.

Hochberg, D. and M. Visser (1997) "Geometric Structure of the Generic Static Traversable Wormhole Throat," *LANL Abstract* gr-qc/9704082, to appear in *Phys. Rev. D*.

Landis, G. (1997) "Magnetic Wormholes And The Levi-Civita Solution To The Einstein Equation," *JBIS*, 50:155-157.

Levi-Civita, T. (1917) "Realtà fisica di alcuni spazi normali del Bianchi", in *Rendiconti della Reale Accademia dei Lincei, Series 5*, 26:519-533.

Maccone, C. (1995) "Interstellar Travel Through Magnetic Wormholes," *JBIS*, 48:453-458.

Morris, M. and K. Thorne (1988) "Wormholes in Spacetime and their use for Interstellar Travel: A Tool for Teaching General Relativity," *Am. J. Phys.*, 56:395-412.

Pauli, W. (1981) *Theory of Relativity*, Dover reprint, New York, 171-172.

Solem, J. (1997) Personal Communication, Los Alamos National Lab, Los Alamos, NM, February, 1997.

Visser, M. (1990) "Wormholes, baby universes, and causality," *Phys. Rev. D*, 41:1116-1124.

Visser, M. (1995) *Lorentzian Wormholes - From Einstein to Hawking*, AIP Press, Woodbury, NY.

Visser, M. (1997) Personal Communication, Washington University, St. Louis, MO, July, 1997.

--Nomenclature--

a: Radius of Spacetime Curvature (m)
c: Speed of Light in Vacuum (3.00×10^{8} m/s)
G: Universal Gravitational Constant (6.673×10^{-11} Nm^2/kg^2)
μ_0: Permeability of Free Space ($4\pi \times 10^{-7}$ H/m)
AU: Astronomical Unit (1.50×10^{11} m)
B: Magnetic Field Intensity (*Tesla*)
$v(z)$: Speed of Light Function (m/s)
L: Length of Magnetic Solenoid (m)
K: Radius of Curvature Constant (3.4840×10^{18} *Tesla•meter*)
ly: Light-Year (9.46×10^{15} m)
τ: Outward Field Tension (N/m^2)
b: Wormhole Throat Radius (m)
