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Overview of the Current State of Understanding of the EMDrive

Jonathan Card
Build an EM Drive (www.buildanemdrive.org)
69 Merriam St. Apt 3, Somerville, MA 02143; 303-916-3966
jcard@buildanemdrive.org

ABSTRACT

The controversial EMDrive propulsion technology is currently supported by experimental evidence from multiple sources, and it enjoys multiple proposed theoretical explanations, but all the explanations are radical explanations requiring significant changes to existing physical theories. I would expect this: such a radical phenomenon unexpected by currently known physics is more and more likely to require a radical explanation as more conventional explanations continue to fail to explain it. I outline here the major theories and testable predictions that would advance the state-of-the-art.

OVERVIEW

The EMDrive is an invention of Roger Shawyer of Britain that, in essence, proposes that a microwave resonance cavity in a non-standard shape (a frustum, where classical designs for such a cavity are a cylinder or a box), the cavity will experience thrust towards one end without a reaction mass. Because of the obvious difficulties such a device would have with respect to the conservation of momentum, this device was considered improbable, and likely fanciful.

A thorough history of the experimental evidence in support of this phenomenon is not in this paper. It is a complicated history of publications, retractions, reductions of strongly worded support, and other ups and downs as scientists have struggled with the difficulty of how strongly to endorse such a radical proposal. For the purposes of this paper we are taking the experimental evidence, in particular the paper published in the November 2016 issue of the Journal of Propulsion and Power, authored by Dr. White, et al, to be, at this time, supportive that an unexplained thrust is produced by the device, at least within test conditions, connected to testing and measuring equipment, on the surface of the Earth, within the magnetosphere, etc.1 The source of this thrust is not explained, though there are several proposed theories that will be summarized here, along with experiment proposals to attempt to determine which, if any, can be used to understand it.

ROGER SHAWYER

Pride of place must be given to the inventor, Roger Shawyer. As the inventor, it is significant that he predicted the phenomenon and developed the technology to exploit it. However, there remain significant questions about his explanation of the phenomenon.

Theory

Mr. Shawyer's explanation revolves around an accepted, non-controversial phenomenon known as "guide wavelength". This states that within a waveguide, such as a fiber optic cable, a wave is observed with a frequency equal to the electromagnetic wave being conducted along the waveguide, but with a longer wavelength than that frequency would normally expect to have, implying a phase velocity faster than the speed of light (the rule against faster-than-light travel is preserved, as that rule specifically refers to *information* not being able to propagate faster than lightspeed, and the group velocity, that is changes in the frequency, are conducted down the waveguide at the speed of light or slower). In his Lectures on Physics, Vol. 2, Richard Feynman gives the following intuition to understand this: imagine a wavelength in the shape of a box. It has a rectangular cross section, a near end with a microwave emitter in the center, and it is very long, so long that the other end is unimportant. We can imagine that the "signal" from the reflection of the emitter in one wall and the "signal" from the reflection of the emitter in the other wall interfere with each other and produce some field strength where those two signals intersect each other in the center of the waveguide. This interference would stretch out along the entire length of the box, it would be in the shape of a wave, and it would appear to travel down the waveguide as the "signals" from the reflections of the emitter oscillate. The photons themselves are not adopting this wavelength, but the field strengths of multiple photons interacting produce an interference pattern like this. This guide wavelength is related to the cross-section of the waveguide. The narrower the waveguide, the longer the guide wavelength. Eventually, if you make the waveguide too narrow, the guide wavelength becomes infinity; beyond this point, the waveguide cannot transmit waves of that frequency. This is known as the

"cut-off diameter" for that frequency, or as it is more commonly stated in the literature, the lowest frequency that can be transmitted down a given waveguide is the "cut-off frequency" of that waveguide.

Mr. Shawyer suggests that this guide wavelength can be converted to kinetic energy according to the energy-momentum relation in the same way that force is exerted on solar sails. However, because in a frustum one end of the cavity has a smaller radius than the other, the guide wavelength is longer, this translating to greater momentum being imparted to the small end of the cavity than to the large end.

Criticism of this model is extensive. An intuition of the conservation of momentum suggests Mr. Shawyer's explanation cannot be true and that conservation of energy suggests that the energy of the longer wavelength at one end of the frustum must match the energy in the shorter wavelength at the other end of the frustum. I would normally argue that, because the guide wavelength is not the wavelength of a photon but rather of the interaction of the waves of multiple photons resonating in the cavity, this does not allow for the application of equations that are usually meant for the conversion of the frequency and wavelength of a photon into a measure of the energy in the waves to be used to convert the frequency and guide wavelength of this interference pattern to the energy in the interference pattern. Mr. Shawyer's explanations for this disparity in momentum rest on the cavity not being considered a closed system and so conservation of momentum is not necessary, but his explanation of why this is so does not match with the understanding of relativity as it is shared by other physicists, and there does not seem to be a good explanation of what the boundaries of the closed system would be. There are sections in his theory paper about the efficiency of the device during use that suggest a preferential reference frame in contradiction with the general application of Special Relativity,2 and there is discussion in his recent patent application involving the second generation of this device where the Doppler Effect is invoked to explain interactions between items that are not in motion relative to each other,3 which is outside the current understanding of this effect.

However, the supremacy of experimental evidence over theory requires us to take seriously his prediction of thrust from the cavity that is not predicted by other models, as there is now growing evidence that it exists.

In his theory paper available at emdrive.com,2 he derives a thrust equation that is referenced here as Figure 1. This paper does not reference the final equation derived by Mr. Shawyer, but an equation only part-way through the derivation. This is the final step in his derivation that I feel comfortable with his interpretation of relativity, and this seems to be the equation most often referenced by others investigating this phenomenon.

$$T = \frac{2P_0}{c}\left(\frac{\lambda_0}{\lambda_{g1}} - \frac{\lambda_0}{\lambda_{g2}}\right)$$

Figure 1. Shawyer Thrust Equation – P_0 = term related to power defined elsewhere in his paper, c = speed of light, λ_0 = wavelength of microwave in free space, λ_{g1} = guide wavelength near the large plate, λ_{g2} = guide wavelength near the small plate

Testable Predictions

Most published research into this phenomenon has been based on verifying or replicating this theory. Tests of this prediction in relation to the other theories presented here will be presented in the sections devoted to those theories. However, I will outline what I believe to be the salient points of this equation, and defer the discussion of why they are salient to later sections.

This equation can be interpreted in two parts: the power term and the efficiency term, the multiplier being the power term and the multiplicand being the efficiency term. There is no mention in this equation regarding the optimal the height of the cavity (that is, the distance between the large plate and the small plate that are parallel to each other at the ends of the frustum). The height needs to be an integer multiple of the half-wavelength of the resonating frequency, but there is no prediction of an optimal multiple. Apocryphally, it has been suggested that a multiple of 2 or 3 times the half-wave length has yielded best results, but it is not clear that this has ever been documented in a published paper and there is no clear prediction of that in Shawyer's equation. This may be relevant to the prediction made by Dr. McCulloch of the University of Plymouth discussed in the third theory section of this paper. Additionally, we should take note of the boundary conditions of the efficiency term. The first term (the minuend) is the potential maximum efficiency, dictated by the size of the large end of the frustum; this suggests that maximum efficiency is achieved when the large end is infinitely large, i.e., the size of the universe. The second term, the subtrahend, is the efficiency penalty enacted by the small end of the frustum. In this equation, there is no efficiency penalty evoked from a small plate that is equal to the cut-off diameter of the resonating frequency, because that is when the term λ_{g2} becomes infinite and the efficiency penalty becomes 0%. Beyond cut-off, this term becomes undefined. It is

also relevant that the cut-off diameter is calculated in relation to the mode in with the electromagnetic waves resonate in the cavity. This is not immediately obvious, but the equation to calculate λ_{g1} and λ_{g2} are functions of the cut-off frequency at that diameter, and that cut-off frequency is calculated using a different set of constants depending on whether it is resonating in the TE or TM modes.

DR. WHITE AND EAGLEWORKS

Dr. Harold White was the lead investigator for the experiment at NASA's Eagleworks that has provided the strongest experimental evidence to-date of the existence of the EMDrive phenomenon. They propose an alternative explanation of the phenomenon based on Dr. White's work regarding the quantum vacuum.1,4,5

Theory

Dr. White's theory of the quantum vacuum suggests that, contrary to generally accepted theory of the quantum vacuum as a zero-energy ground state for all other oscillation phenomenon and energy states, the quantum vacuum is a mutable and degradable medium. This has suggested some interesting results, such as providing a possible theoretical basis for the mass of an electron, which had not previously been derived and is currently believed to be a universal constant.

The implications of this for the EMDrive is the possibility that the conservation of momentum problem is solved by suggesting that the magnetic fields within the EMDrive cavity are accelerating these fluctuations in the quantum vacuum in a way that is difficult, if not currently impossible, to detect. It is therefore not "reactionless" as it is often described, but the reaction mass is taken from the environment in the same way as a boat impeller or, in their preferred analogy, a magnetohydrodynamic drive (MHD drive).6 This has led the authors of the Eagleworks paper to suggest that the aspect of the device that has primary importance is the orientation of the magnetic fields in the cavity, and not the guide wavelength phenomenon at all. The orientation of the magnetic fields, and the expected interaction between magnetic fields and the quantum vacuum, is expected to be able to accelerate the fluctuations in the quantum vacuum as a reaction mass.

This model of the behavior of the drive would require expressing the quantum vacuum as a compressible fluid or plasma, and I have not seen a proposed equation to model this behavior. This is presumably because it would require more characterization of this vacuum in a way that has not yet been explored. However, this theory does provide for a few predictions that would not be expected from the other proposed theories, which will be explored later in this section.

This theory is not without its detractors. The notion that the quantum vacuum is a mutable and degradable medium is a significant departure from traditional physical understanding. And there remain further questions that I am not qualified to suggest are problems with the theory, but remain unanswered at the time of writing. To wit: 1. it is not clear to me why, if the primary source of the thrust is the interaction of the quantum vacuum with the magnetic fields within the cavity, why the frustum shape of the cavity is necessary, or for that matter 2. why the thrust when resonating in the TE mode continues to be along the longitudinal axis when the magnetic fields would be expected to be either misaligned for it to work at all or to be attempting to accelerate the cavity sideways rather than longitudinally.

Testable Predictions

The qualitative nature of the Eagleworks explanation is, I think, reasonable and responsible, but it still suggests experiments that could be explored to confirm, though maybe not disconfirm, their explanation. The primary experiment at this time is in relation to their prediction in their paper of a wake effect that should come out of the EMDrive.

If it is true that there is a mostly undetectable reaction mass rooted in the quantum vacuum being accelerated by the EMDrive cavity, and if this behaves as other fluids have under similar conditions, then this stream should interact with a second EMDrive device placed in series with the first. The second drive can expect to perceive cavitation or other disruptions in its behavior as a result of the wake produced by the first device. In correspondence with Dr. Paul March, formally of the Eagleworks team, he shares my suspicion that this effect could be observed. Detecting that behavior would be major supporting evidence both of the explanation of the EMDrive and of Dr. White's theory of the nature of the quantum vacuum.

DR. MCCULLOCH AND QUANTIZED INERTIA

Dr. Michael McCulloch of the University of Plymouth in Plymouth, England, has proposed a theory of inertia called MiHsC or "quantized inertia" that he believes also has implications on the EMDrive phenomenon. While a detailed description of the theory is not in the scope of this paper, my best attempt to summarize it is that he suggests that inertia is caused by a kind of "back pressure" similar to the Casmir effect but which is derived from the interaction of Unruh radiation with the Hubble horizon. An accelerating object experiences a variance between the Hubble horizon in front of it and the Hubble horizon behind it which results in a countervailing force against the acceleration, resulting

in what we experience as "inertia". The implications of this are an explanation of the faster-than-expected rotation of distal stars in large galaxies without resort to Dark Energy or Dark Matter. He posits that all objects must be undergoing a minimum amount of acceleration at all times in order for their Unruh radiation to be contained within the Hubble horizon, and therefore the low accelerations predicted pre-Dark Matter orbital mechanics for the orbit of distal stars around a galaxy cannot be achieved. Therefore, their angular velocity must be faster than those theories would predict, explaining their observed orbits without requiring additional gravity from Dark Matter. Additionally, it provides an explanation of phenomena like the "flyby anomaly," which has not been explained satisfactorily to-date.7,8

Theory

Dr. McCulloch has proposed a solution to the EMDrive phenomenon related to MiHsC, speculating that the metallic cavity is creating a localized Hubble horizon and that the thrust experienced by the cavity as a whole is similar to the unexpected acceleration of the distal stars in large galaxies. He solves the question of conservation of momentum by side-stepping around it: by relating the phenomenon to the nature of inertia itself, perhaps the question of momentum has become a definitional problem and the behavior is indicative of a mistake in our understanding of momentum itself. If the inertial mass, as opposed to the gravitational mass, can change depending on the environment, momentum itself is more mutable than expected.10

This theory is considered extremely speculative and would constitute an even greater upheaval of the current understanding of the physical world than Dr. White's. His theory would overturn Dark Matter, overturn General Relativity (though not Special Relativity), and revolutionize our understanding of acceleration and inertia itself. It relies on the acceptance of Unruh radiation, which has not been reliably observed despite being proposed by in the early 1970s, over 40 years ago. It is presented here because there are few good theories for the EMDrive phenomenon, at all. If an explanation is not possible for the phenomenon in physical theories currently accepted, then it is only to be found in physical theories not currently accepted.

Testable Predictions

The chief-most prediction to come out of the application of MiHsC to the EMDrive phenomenon is that he has introduced an alternative mathematical model of the behavior that, he claims, matches all existing experimental data gathered to-date. (And, as a side-note, according to his blog, allowed him to predict that the Eagleworks team had made use of dielectrics that he had not observed in a first reading of their published studies. I personally find that an interesting anecdote when assessing this theory, though it be self-reported.)

$$F = -\frac{6PQL}{c}\left(\frac{1}{L+\omega_s} - \frac{1}{L+\omega_b}\right)$$

Figure 2. McCulloch Thrust Equation – P = power, Q = resonance quality, L = height of the cavity, c = speed of light, ω_s = diameter of the small plate, ω_b = diameter of the large plate

There are two important observations in comparing this equation to Mr. Shawyer's: 1. there is a presence in the equation of the height of the cavity, which is not considered a relevant term in Shawyer's equation, and 2. the minimum efficiency penalty introduced by the design of the small plate in the first term of the efficiency term (here, not presented as a percentage but more as a scaling factor) is not 0.

For the first observation, McCulloch's equation has been presented in an alternative form by Igor Kaporin of the Russican Academy of Science in Moscow to determine the maximum thrust across various heights,9 shown here in Figure 3, and (while respecting the limitation that the height must be integer multiples of the half-wavelength of the resonating wave), the maximum thrust is found in fairly high multiples of the half-wavelength (in my exploration of the equation, using a specific set of assumptions of frequencies and geometries, I found the maximum thrust to be 9 times the half-wavelength). I find this relevant given the persistent stories in the community that cavities with a height of more than 1 half-wavelength perform better. This effect should also be testable and observable, and is worth exploring.

$$L = 4\sqrt{\omega_s \omega_b}$$

Figure 1. Kaporin optimization of the McCulloch equation – ω_s = diameter of the small plate, ω_b = diameter of the large plate

Regarding the second observation, the impact of this difference is that the Shawyer equation suggests that a cavity in TE mode optimized for that mode will create equal thrust to a cavity in TM mode optimized for that mode but the McCulloch equation would not, because what is important in McCulloch's equation is the absolute size of the small plate, rather than the difference in size between the small plate and the cut-off diameter of the resonating frequency in that mode. A cavity optimized for resonance in the TM mode

would have a larger small plate than on optimized for resonating in the TE mode. Dr. McCulloch's equation suggests that maximum efficiency is reached when the small plate is infinitely small, and the cut-off diameter is an unavoidable boundary that cannot be eliminated. The Eagleworks team had previously documented thrust differences in cavities based on the mode in which it resonates (TE vs. TM).10 However, this has not been compared to the predicted behavior of the cavities by other theorists. The Shawyer equation predicts that a cavity that is capable of resonating in both TE and TM modes would have greater thrust in the TM mode, when controlled for power and Q; the McCulloch equation does not. Additionally, the Shawyer equation predicts that a cavity resonating in the TM mode with a small plate size close to the cut-off diameter for the resonating frequency in the TM mode should provide equal thrust to a cavity resonating in the TE mode that has a small plate size close to the cut-off diameter for the resonating frequency in the TE mode. The Eagleworks team found greater thrust originating from a cavity in the TE mode, but it was resonating with a greater Q value as well, and was more difficult to maintain proper resonance and tuning than when operating in the TM mode. An experimental regime that compared a single cavity resonating in two different modes, and two cavities, each resonating in the mode it is optimized for, and controlled for power and Q, could provide important insight into which of these models, if any, could explain the phenomenon. Mr. Shawyer would predict equal thrust, McCulloch would predict that the cavity in the TE mode would produce more thrust as the small plate would be smaller, and I believe that Dr. White would predict the cavity in the TM mode would produce more thrust as the magnetic fields are properly aligned.

On a self-serving note, I will note here that the cut-off diameter equations in the classical literature, which is based on cylindrical cavities, have proven by others to be unreliable in the TM mode.11 However, I have proposed a possible solution for calculating the cut-off diameter in a frustum that may serve to relate the Shawyer equation to the Eagleworks results.12

OTHERS

There are other theories, such as a paper by Grahn, et al, at the University of Helsinki,12 but I have not explored them as thoroughly. These would no doubt provide additional avenues of exploration if the tests provided here produce results that defy explanation.

CONCLUSION

Ultimately, the most important conclusion to reach regarding the current state-of-the-art of the EMDrive phenomenon is that there are a number of clearly defined experiments, in addition to actual spaceflight of a test article, that should be done to further explore this phenomenon, and now that multiple groups have been able to reproduce the thrust predicted by Mr. Shawyer, it is important to explore the phenomenon with determination. Outlined above are a series of accomplishable experiments, with expected results and possible interpretations, that would produce important insight.

Resources

I would like to include a section on resources for inquiring minds who wish to better understand this phenomenon and the community of people that are investigating it.

1. NASA Spaceflight Forum – This community has been discussing this phenomenon for several years and is a gathering place for many of the most experienced people investigating it. https://forum.nasaspaceflight.com/index.php?topic=42978.0
2. emdrive.wiki – This wiki is available with links to many of the teams interested in constructing cavities to replicate Mr. Shawyer's discovery and with experimental data from those teams.
3. www.emdrive.com – This is Mr. Shawyer's website, containing his original theory paper.
4. physicsfromtheedge.blogspot.com – Dr. McCulloch's blog.

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References

1. White, Harold, Paul March, James Lawrence, Jerry Vera, Andre Sylvester, David Brady and Paul Bailey. Measurement of Impulsive Thrust from a Closed Radio-Frequency Cavity in Vacuum. Retrieved from https://arc.aiaa.org/doi/pdf/10.2514/1.B36120

2. Shawyer, Roger. A Theory of Microwave Propulsion for Spacecraft. Retrieved from http://www.emdrive.com/theorypaper9-4.pdf

3. Link to the UK patent office document: https://www.ipo.gov.uk/p-find-publication-getPDF.pdf?PatentNo=GB2537119&DocType=A&JournalNumber=6647

4. White, Harold, Jerry Vera, Paul Bailey, Paul March, Tim Lawrence, Andre Sylvester, David Brady. Dynamics of the Vacuum and Casimir Analogs to the Hydrogen Atom. Journal of Modern Physics, 2015, 6, 1308-1320. Published online August 2015 in SciRes. http://dx.doi.org/10.4236/jmp.2015.69136

5. White, Harold "Sonny". A Discussion on Characteristics of the Quantum Vacuum. Published at: https://physicsessays.org/browse-journal-2/product/1396-11-harold-sonny-white-a-discussion-on-characteristics-of-the-quantum-vacuum.html I believe this is the original publication location, though I read an electronci copy of the document from another source.

6. For those unfamiliar with this term, here is an article detailing one of the most famous instanes of this device: https://en.wikipedia.org/wiki/Yamato_1

7. McCulloch, Michael Edward (2014). Physics from the Edge: A New Cosmological Model for Inertia. World Scientific Publishing Company; 1 edition

8. https://arxiv.org/abs/1604.03449

9. McCulloch, Michael. (2017, January 6) Emdrives, dielectrics, & the Kaporin optimization. Retrieved from http://physicsfromtheedge.blogspot.com/2017/01/emdrives-dielectrics-russian.html

10. Brady, David A., Harold G. White, Paul March, James T. Lawrence, and Frank J. Davies. Anomalous Thrust Production from an RF Test Device Measured on a Low-Thrust Torsion Pendulum. Retrieved from: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140009930.pdf

11. The NASA Spaceflight Forum is a regular discussion thread on the topic of the EMDrive. When sharing attempt to derive an equation for the cut-off diameter in a TM mode, this gentleman shared his own efforts on the subject that I think valid to include as a counter to my own: https://forum.nasaspaceflight.com/index.php?topic=37642.msg1392223#msg1392223 with in-depth description here: https://forum.nasaspaceflight.com/index.php?action=dlattach;topic=37642.0;attach=1030954;sess=45576

12. Card, Jonathan. Derivation of an Equation for the Cut-Off Diameter of a Frustum-Shaped Cavity at a Specific Resonant Frequency. Access at: https://www.buildanemdrive.org/blog/derivation-equation-cut-diameter-frustum-shaped-cavity-specific-resonant-frequency This link is not active at the time of this writing, but will become active and the content frozen by the time of publication.

13. Grahn, Patrick, Arto Annila, and Erkki Kolehmainen. On the exhause of electromagnetic drive. AIP Advances 6, 065205 (2016); doi; 10.1063/1.4953807. View online: http://dx.doi.org/10.1063/1.4953807