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PROPULSIVE FORCES USING HIGH-Q ASYMMETRIC HIGH ENERGY LASER RESONATORS

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Recent analyses of spacecraft flyby, Galileo, NEAR, Cassini, and Rosetta spacecraft suggest unusual short-lived changes in their inertia and, likewise, unexplained accelerations. One theory which possibly explains these anomalies assumes the inertial changes are due to Unruh radiation modified by a Hubble-scale Casimir effect. Laboratory scale experiments to demonstrate and verify this theory turn out to be in the form of an asymmetric microwave resonator, also known as, the EmDrive. Various experiments have been performed and are ongoing to verify the validity of the EmDrive using microwaves, but none have been reported in the optical regime. According to the physics of the Unruh radiation and modified inertia due to Hubble-scale Casimir effect theory the net propulsive force generated is a function of the cavity Q and input power. It is proposed in this paper that a high-Q asymmetric, but stable, Fabry-Perot laser resonator should produce very large propulsive forces if the theory is correct. Experiment design to demonstrate the concept is given.

Keywords: Modified inertia, Casimir effect

1. INTRODUCTION

On December 8, 1990 the Galileo spacecraft did a flyby maneuver using the Earth as a gravitational assisting body. During this near Earth encounter there was a very brief, and unexpected, Doppler shift of 66 millihertz in the telemetry transmissions [1]. This change in the radio signals corresponds to a delta-v of 3.92 mm/s having been imparted to the spacecraft. While the small change in velocity to Galileo didn't impact the mission, it is completely unexplained and should not have occurred. Interestingly enough, the NEAR, Cassini, and Rosetta spacecraft flyby maneuvers have demonstrated signs of unusual and unexpected accelerations [2, 3]. These spacecraft each experienced an anomalous delta-v during their close encounters with the Earth: Near Earth Asteroid Rendezvous (NEAR) of 13.46 mm/s, Cassini–Huygens 0.11 mm/s, and Rosetta 1.82 mm/s.

Seemingly unrelated to the flyby anomalies is the large-scale dynamical anomalies of galaxy rotation also known as the galaxy rotation problem. Since the early 1930s until present day astronomers and astrophysicists have noted that many galaxies both nearby and far away tend to have a higher rotation rate about their respective centers than they should when conducting a mass-to-luminosity ratio analysis [4-11]. In other words, these galaxies appear to rotate as if they were more massive than the number of stars within them suggests they are.

While the two phenomena seem to be unrelated it is quite possible that there is a much deeper cosmological connection between them that might explain them. In fact, Anderson, *et al*, [1-3] as well as others [12-14] have suggested that the phenomena might all be explained by some type of "new physics". While some of the concepts that invoke dark matter/dark energy or modified Newtonian Dynamics (MOND) can explain some of the phenomena they cannot explain both while at the same time describing why the motion of the planets and other spacecraft within our own solar system are not likewise affected. There is also some issue with developing experiments to test some of the theories.

NOMENCLATURE

m_i	is the modified inertial mass in kg
c	is the speed of light in m/s
Θ	is the distance to the Rindler horizon which is twice the Hubble distance ($\sim 8.8 \times 10^{26}$ m)
a	is the acceleration of an object relative to surrounding matter in m/s^2
λ	is the wavelength of the Unruh radiation in meters
F	scalar propulsive force in Newtons
P	is power in Watts
Q	is the quality factor of the cavity
l	is the cavity length measured in meters
W_{big}	large diameter of the frustrum end measured in meters
W_{small}	small diameter of the frustrum end measured in meters
f_o	is the resonant frequency of the cavity in hertz
E	is the energy in Joules
ξ	is the cavity loss per oscillation
Δt	is the round trip time for a photon to traverse the cavity measured in seconds

One possible approach to describing the three anomalies is to consider that the unexplained accelerations in all cases are due to some type of modification to the inertia of the spacecraft or galaxies due to an added force or drag due to Unruh radiation that is only present during accelerations [14, 15]. McCulloch has proposed a model known as the Modified Inertia due to a Hubble-scale Casimir effect (MiHsC), also sometimes refered to as "quantized inertia", which proposes that inertia is actually due to Unruh radiation and its affects as set up within a large-scale cavity Casimir effect. McCulloch suggests that when an object accelerates, from left to right, that [16]:

"a dynamical (Rindler) event horizon forms to its left, reducing the Unruh radiation on that side by a Rindler-scale Casimir effect whereas the radiation on the other side is only slightly reduced by a Hubble-scale Casimir effect. This produces an imbalance in the radiation pressure on the object, and a net force that always opposes acceleration, like inertia."

McCulloch goes on to suggest that [16]:

"This model for inertia suggests that if some way could be found to damp the Unruh waves on one side of an object, or create an artificial event horizon on that side (perhaps using metamaterials), the object could then be accelerated in a new way."

It is this statement that suggests this theory of inertia (that would explain the three gravitational anomalies mentioned previously) can possibly be tested by laboratory experiment. In order to do so, a so-called "imbalanced" Casimir effect would have to be demonstrated. As it turns out, new unexplained experimental data from advanced propulsion research into what is known as the EmDrive might be just such a demonstration of an "imbalanced" Casimir effect.

In 2008 Shawyer [17] reported that when microwaves resonate within a truncated cone-shaped cavity, called a frustrum, a small, and heretofore unexplained, acceleration occurs towards the small end. Shawyer claims to have generated as much as 16 mN of thrust from 850W of power being introduced into his frustrum cavity with end diameters of 16 and 12 cm, and which had a cavity Q value (dissipation constant) of 5900 [17]. Figure 1 is a drawing of the typical EmDrive experiment configuration. While no theory as to why this propulsive force is generated has yet to be accepted, the presence of the force has been repeated by multiple researchers around the world including at NASA Eagleworks [18] and in China [19].

According to the MiHsC theory an ordinary inertial mass, m, under acceleration can be described as [16]

$$m_i = m\left(1 - \frac{2c^2}{|a|\Theta}\right) = m\left(1 - \frac{\lambda}{4\Theta}\right) \tag{1}$$

where m_i is the modified mass, c is the speed of light, Θ is the distance to the Rindler horizon which is twice the Hubble distance (~8.8×10^{26} m), and a is the magnitude of the relative acceleration of the object relative to surrounding matter, and λ is the wavelength of the Unruh radiation present. Figure 2 is a graph of Equation (1) and from inspection of the graph it becomes clear that as the acceleration of the mass is on the order of an Earth gravity the right side of the terms in parentheses approaches zero and standard mass is observed. Likewise, with small accelerations the right side terms grow large and dominate and therefore the observed mass is something other than usual. This MiHsC theory can describe the dynamical anomalies mentioned herein and can be tested and experimented within the laboratory via the EmDrive.

Other than astronomical observations testing MiHsC at a cosmological scale is almost impossible because the large distances of Θ makes the accelerations extremely tiny as would be expected out in deep space where the Pioneers and the edge of galaxies are. It has been suggested by McCulloch [20] that the trick needed for a laboratory device is to somehow reduce

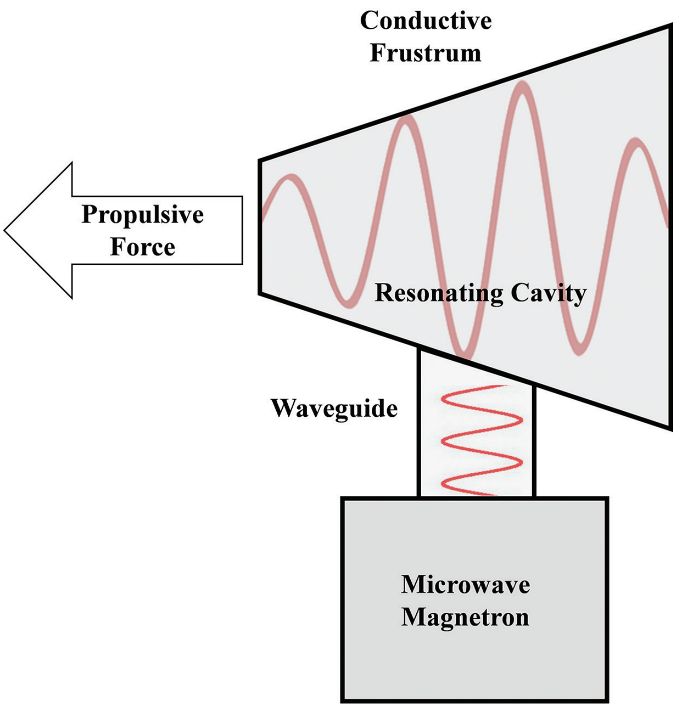

Fig. 1 Typical EmDrive experiment configuration.

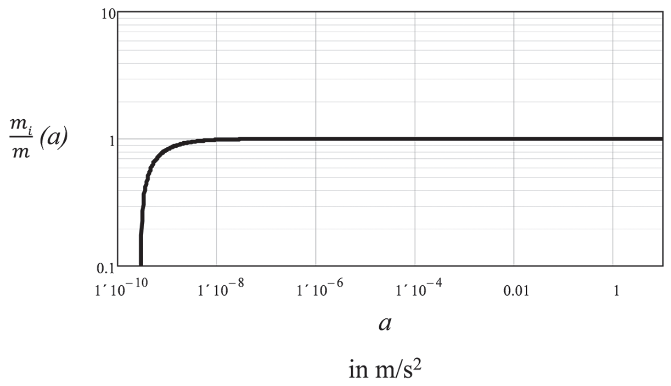

Fig. 2 Inertial mass adjustments predicted by MiHsC model as a function of acceleration.

the distance to the Rindler event horizon and that the EmDrive might be doing just this. McCulloch explains [20]:

"…and this is what the emdrive may be doing since the radiation within it is accelerating so fast that the Unruh waves it sees will be short enough to be limited by the cavity walls in a MiHsC-like manner."

In other words, the microwave resonator is creating the asymmetric Casimir effect cavity at or near the ends of the frustrum structure. McCulloch then goes on to show that following the MiHsC theory an equation for the scalar propulsive force, F, can be derived as [20]

$$F = \frac{-P_{in}Ql}{c}\left(\frac{1}{W_{big}} - \frac{1}{W_{small}}\right) \tag{2}$$

where P_{in} is the microwave input power in Watts, Q is the quality factor of the cavity, l is the cavity length, and W_{big} and W_{small} are the diameters of the ends of the frustrum. Using Equation (2) to calculate results from actual experiment data as discussed in [17, 18, 19] shows close enough agreement as to warrant further investigation [20].

2. METHOD

Consider Q in Equation (2). This quality factor of an electromagnetic resonator cavity is a dimensionless parameter that is used to describe the damping of an oscillator, bandwidth of the resonator about its center frequency, and the level of losses or gains within the cavity. A resonator with a high Q will have less energy loss and will therefore oscillate longer. The Q of an electromagnetic resonator cavity is typically measured but can be calculated by [21]

$$Q = \frac{2\pi f_o E}{P} \tag{3}$$

where f_o is the resonant frequency of the cavity, E is the energy stored in the cavity, and P is the power dissipated from the cavity. Realizing that the magnitude of P is

$$P = \frac{dE}{dt} = \frac{\Delta E}{\Delta t} \tag{4}$$

then Equation (3) can be rewritten as

$$Q = \frac{2\pi f_o E}{P} = \frac{2\pi f_o E \Delta t}{\Delta E} = \frac{2\pi f_o \Delta t}{\hat{\imath}} \tag{5}$$

Here ξ is the cavity loss per oscillation or the energy lost divided by the energy initially stored, and Δt is the time for the one oscillation in the cavity. In an optical cavity Δt would be considered to be the round trip time for a photon to travel from one end of the cavity to the other and back again.

Inserting Equation (5) into Equation (2) results in

$$F = \frac{-P_{in} l}{c} \frac{2\pi f_o \Delta t}{\xi} \left(\frac{1}{W_{big}} - \frac{1}{W_{small}} \right) \tag{6}$$

Realizing that Δt is $2l/c$ and f_o is c/λ_o, where λ_o is the center wavelength of the electromagnetic oscillation in the cavity, then Equation (6) becomes

$$F = \frac{-4\pi P_{in} l^2}{\lambda_o c \xi} \left(\frac{1}{W_{big}} - \frac{1}{W_{small}} \right) \tag{7}$$

Equation (7) is the MiHsC propulsion force equation simplified to parameters that are easily measured and understood about an electromagnetic resonant cavity. The key design parameters are the diameters of the ends, or reflectors, of the cavity frustrum, the center wavelength of the electromagnetic oscillation, the input power to the cavity, and the length of the cavity. The loss per trip of the cavity can be determined quite readily through an energy in versus energy out measurement.

Figures 3 through 7 show graphs of Equation (7) with the propulsive force as a function of one of the parameters, P_{in}, l, λ_o, ξ, and W_{small}, varying respectively. While varying the length gives nonlinear gains, at some point increasing the length of an oscillator cavity will become troublesome as the coherence length of the system is approached.

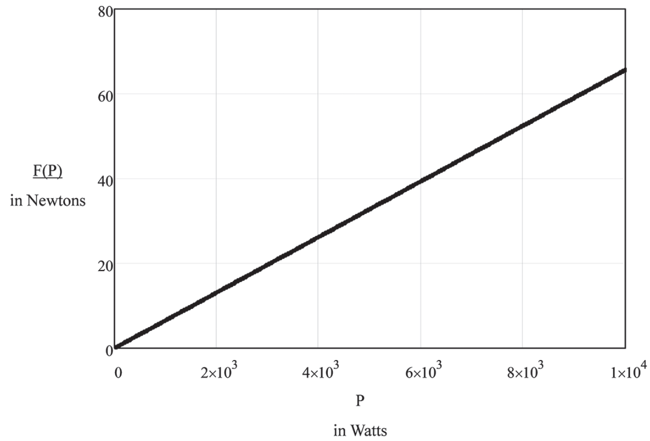

Fig. 3 Predicted propulsive force versus cavity power.

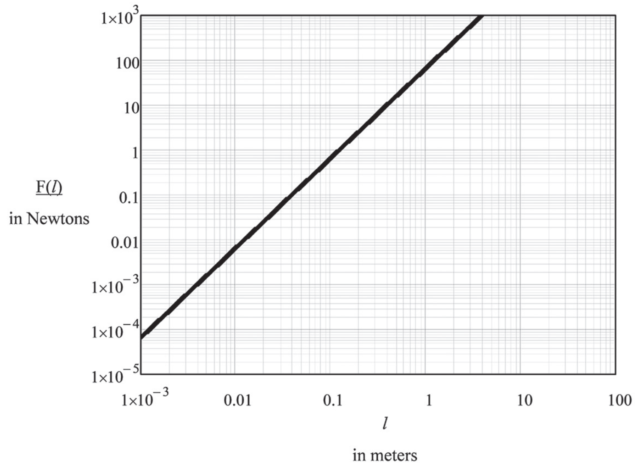

Fig. 4 Predicted propulsive force versus cavity length.

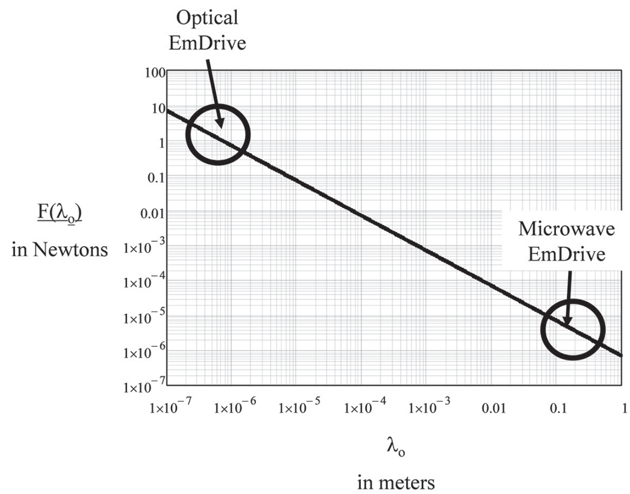

Fig. 5 Predicted propulsive force versus wavelength.

One point to be noted is that as the wavelength becomes smaller the force should increase. To date, and to the author's knowledge, no experiments with the EmDrive have been performed outside of the microwave regime likely because the transmitters are readily available from microwave oven magnetrons and the frustrums are mechanically straightforward to construct. However, following the MiHsC

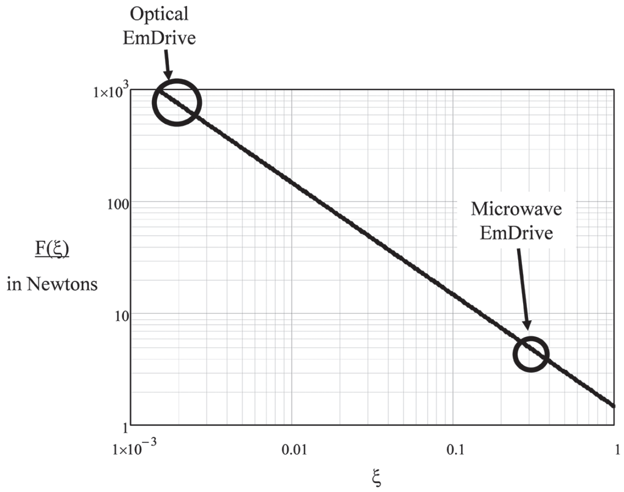

Fig. 6 Predicted propulsive force versus cavity loss.

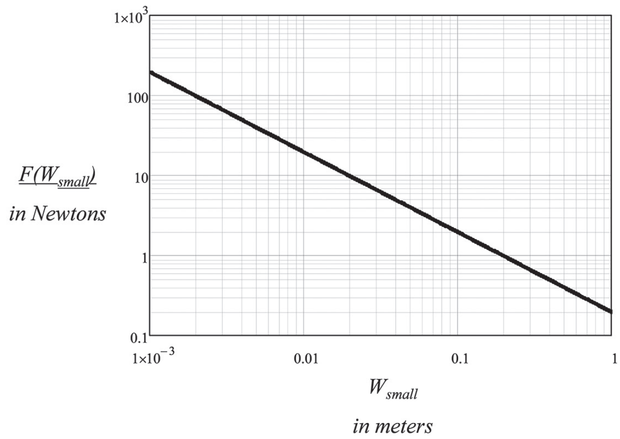

Fig. 7 Predicted propulsive force versus small end of cavity diameter.

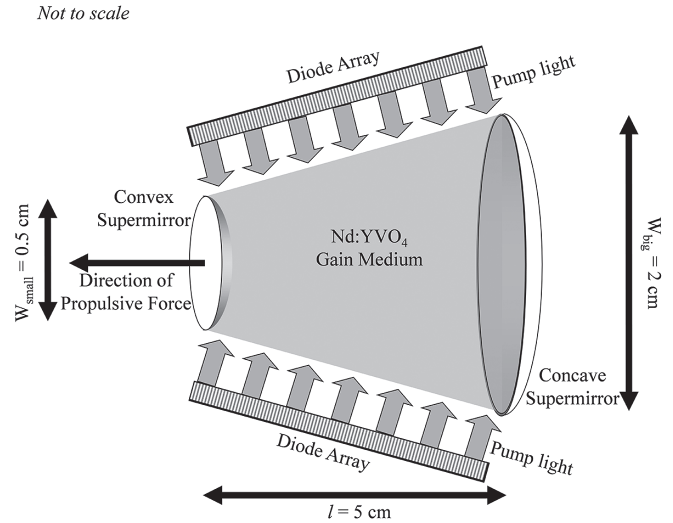

Fig. 8 Concept for testing the MiHsC model using an asymmetric laser resonator cavity.

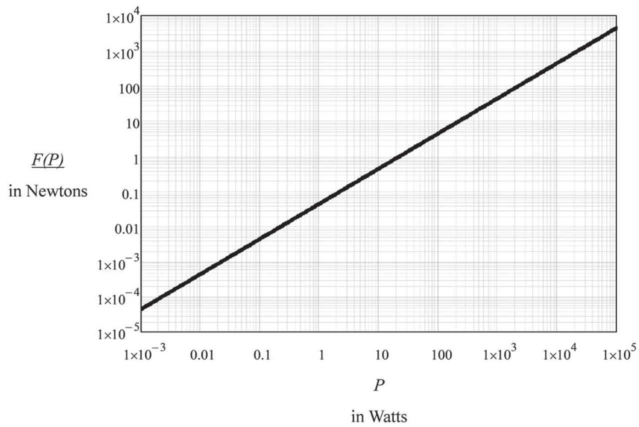

Fig. 9 Predicted propulsive force versus laser cavity power.

model and the derivation given above an electromagnetic resonator of the asymmetric design at any center wavelength should demonstrate similar propulsive forces as described by Equation (7).

Also note that the loss of the cavity is of particular interest for the optical regime. Super reflective mirrors for high Q laser resonators have been realizable for many decades with modern so-called "supermirrors" having reflectivity as high as 99.99965% [22]. Therefore, it is likely that a properly designed asymmetric Fabry-Perot laser cavity with very high reflectivity mirrors, and likewise a high Q, would enable an experiment to demonstrate this theory in a completely new energy regime.

Figure 8 shows a concept for testing the MiHsC model using an asymmetric laser resonator cavity. The laser cavity implements two supermirrors coated for high reflectivity on both ends. The small mirror will be a convex optic and the larger mirror will be concave. Located between the mirrors is an optical gain medium with ends anti-reflection coated. It has been suggested that adding a dielectric between the cavity ends of the microwave experiments would improve performance [20]. In a laser cavity a dielectric might simply be the gain medium. It is proposed here to construct the frustrum from a neodymium-doped yttrium orthovanadate ($Nd:YVO_4$) crystalline material for the gain medium. The cavity will be transversely excited with several linear arrays of 808 nm pump diodes located about the circumference of the frustrum.

Figure 9 shows a graph of the propulsive force as a function of the laser cavity power as calculated using Equation 7. The calculation assumes a λ_o = 1064 nm, ξ = 0.1, l = 5 cm, W_{big} = 2 cm, and W_{small} = 0.5 cm. This is a fairly straightforward and very realizable laser cavity, whereas, a 10 mW laser cavity should produce a propulsive force on the order of 1 to 2 mN if the model is correct. This level of thrust can easily be measured via a load cell thrust measurement stand. It is recommended that for initial measurements the power levels be low in order to reduce extraneous noise sources from cooling fluids, thermal expansion, and lab bench vibrations. Care must be taken to account for and correlate all vibration signals so multiple load cells should be considered.

3. DISCUSSION

While the experiment described here implements a laser in the milliwatt scale, from Fig. 9 it is clear that, if the MiHsC theory turns out to be correct, then the use of high energy lasers in similar frustrum configurations could produce very large thrusts. A laser cavity with only 10 W of output power (trapped within the cavity) would produce on the order of 1 N of thrust. This suggests a relationship of about 100 N/kW of laser cavity power. If we assume a so-called "wall plug" efficiency for the

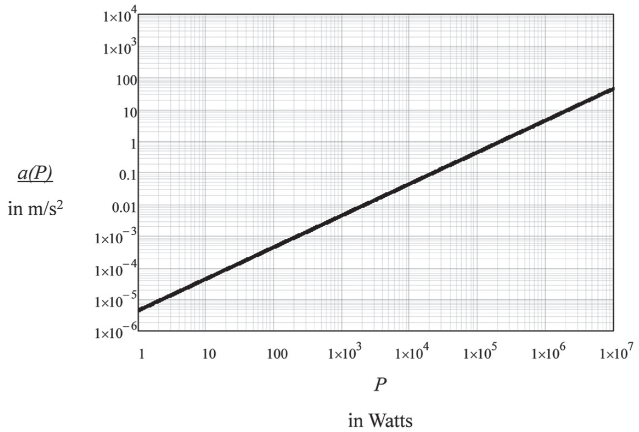

Fig. 10 Predicted acceleration of a 10,000 kg mass versus wall plug power.

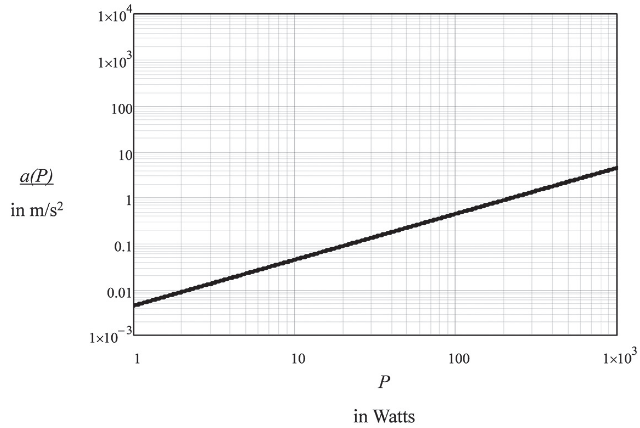

Fig. 11 Predicted acceleration of a 10 kg mass versus wall plug power.

laser of 30% (possibly could be as high as 50%) [23, 24] then our system can produce on the order of 30 N thrust per kW of electrical power. In other words, one kW of electrical power will supply roughly 3 gee acceleration to a one kilogram mass.

Figure 10 shows a graph of the acceleration of a 10,000 kg mass versus wall plug power input. A supplied power of about 2 MW would generate 1 gee of acceleration. This level of power is possible from small fission reactors. NASA reported the Safe Affordable Fission Engine 4 (SAFE-400) had a total mass of about 700 kg and produced about 100 kW of electrical power [25]. Two of these reactors could supply enough power to produce about a tenth of a gee of acceleration continuously as long as power could be supplied and the laser system functioned. If this model holds true the ramifications for deep space travel are quite significant.

Figure 11 shows a smaller scale of this concept using a 10 kg mass, which is similar in scale to so-called cubesats, A power source supplying 100 W could supply a continuous 6 mN thrust or an acceleration on the order of 0.3 m/s^2. This amount of power could be supplied by roughly one square meter of solar panels.

4. CONCLUSION

An asymmetric laser resonator is proposed to test the Modified inertia due to Hubble-scale Casimir effect. Recent research suggests that microwave resonators can be used for such an experiment but the theory does not seem to limit itself to the microwave regime. If the propulsive force is as predicted by the MiHsC theory then extrapolating to higher wavelength photons should provide higher thrust. The experimental configuration proposed in this paper is a small transversely diode pumped frustrum shaped Nd:YVO_4 crystal within a convex-concave stable laser resonator with high reflectivity mirrors.

While the ramifications of this concept for spacecraft propulsion could be significant, first things should be put first. The proposed experiment must be conducted to determine if the MiHsC theory and model extrapolates to the optical regime. If so, the next step might be to push to shorter optical wavelengths to optimize the thrust per power ratio. Simply by going to a blue laser or near ultraviolet laser the thrust to power ratio would be tripled or more.

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