Can the Quantum Vacuum be used as a propellant source?

by Harold White, Ph.D.

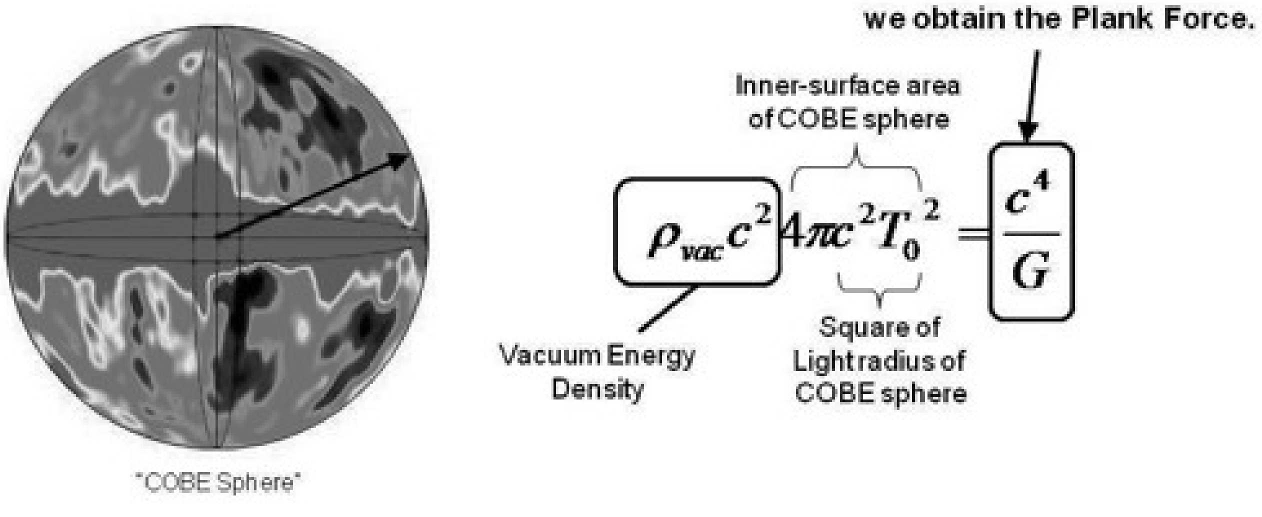
Imagine if it were possible to utilize the very vacuum of space as a source of propellant. If a spacecraft needed only to provide power, and not carry propellant, what would be the possibilities? A spacecraft equipped with such a propulsion system would have a Specific Impulse (ISP) that is many orders of magnitude higher than current propulsion technology. The limiting design parameter would then be the power density of the local power source. Mission planners could design reference missions to include multiple orbits and inclinations – the latter typically requiring the higher delta-v. A mission could incorporate multiple destinations. Perhaps most importantly for space exploration, transit times could be drastically reduced.

In order to enable bold exploration missions to Mars, the outer solar system, and beyond, advanced propulsion research must be undertaken with the goal of developing point solutions that are orders of magnitude more effective than the current arsenal of propulsion technologies. Propulsion and Power are the keys to exploration, utilization of the Solar System and beyond.

So, again, if it were possible to utilize the vacuum of space as a source of propellant, what would be the possibilities?

The physics community knows from experiments performed over the last ten years that the vacuum is anything but empty. Rather, it is a sea of virtual fields and particles (electron and positron pairs) that pop into and out of existence as they spontaneously create and annihilate. This is otherwise known as the quantum vacuum. Indeed, this phenomenon has been predicted for more than half a century. The substantive question is how can a spacecraft push off of the vacuum of space?

Figure 1. *Gedanken Experiment: Quantum Vacuum Fluctuations and Big-G. The sphere represents the light horizon of the universe with a radius of 13.7 billion light years. The nomenclature "COBE" Sphere is used since the radiation we see today as detected by the Cosmic Background Explorer represents the radiation that was emitted just after the universe transitioned from opaque hot gas to transparent allowing radiation to propagate. The equation on the right is the integral of the pressure over this spherical surface area shown.*



$$\boxed{\rho_{vac}c^2}\overbrace{4\pi c^2}^{\text{Inner-surface area of COBE sphere}}\underbrace{T_0^2}_{\text{Square of Light radius of COBE sphere}}=\boxed{\frac{c^4}{G}}$$

Some theoretical groundwork is in order to help illustrate how this can be done. Consider the following Gedanken experiment (a "thought" experiment). Imagine being an inertial observer in deep space. What happens if the vacuum energy density (energy density has the same units as pressure, N/m2) is integrated over the light horizon radius of the observable universe, or more simply over the surface area of the "COBE Sphere" with a radius of 13.7 billion light years? See Figure 1 for a cartoon depiction.

The vacuum energy density has been measured to be approximately 72% +/-3% of the critical density, r0, or rather 0.72 * 9.9x10-27 kg/m3, based on the apparent brightness of supernovae at red shifts of z ~ 1. The result is rather startling and can be re-arranged such that the gravitational constant can be shown to be a long wavelength consequence of the quantum vacuum rather than a fundamental constant. In this view, gravitation is an emergent force from the vacuum, and not a fundamental fourth force. The following equation is the more formal version that is produced after some effort from the cosmological Friedmann equation.

$$G = \left(4\pi \cdot t_H{}^2 \cdot \frac{2}{3} \rho_0 \right)^{-1}$$

It was just shown how the gravitational constant can be a long wavelength (Hubble time, tH) consequence of dark energy, or rather the quantum vacuum. It can be similarly shown that the Planck constant has a unique relationship with the Hubble time and dark energy by means of the Einstein tensor. In this instance, consider the 00th element corresponding to the energy density of space-time of the Einstein tensor for the same observer discussed earlier:

$$G^{\mu\nu} = R^{\mu\nu} - \tfrac{1}{2} g^{\mu\nu} R = -8\pi \frac{G}{c^4} T^{\mu\nu}$$

A quick note on nomenclature, the G with indices is the Einstein tensor, while the G without indices is the gravitational constant. After some work (which is omitted for brevity), it can be shown that the following relationship is numerically true:

$$G^{00} = \frac{-2}{c^2 t_H{}^2} = \frac{-h\upsilon_0 K}{4\pi}$$

The G00 element of the Einstein tensor produces the Planck constant times the lowest observable frequency, õ0. The constant, K, is of numerical value unity but with units of Joules-1*meter-2 for dimensional consistency. To illustrate the significance of this finding, the equation can be rearranged as follows (K omitted for clarity):

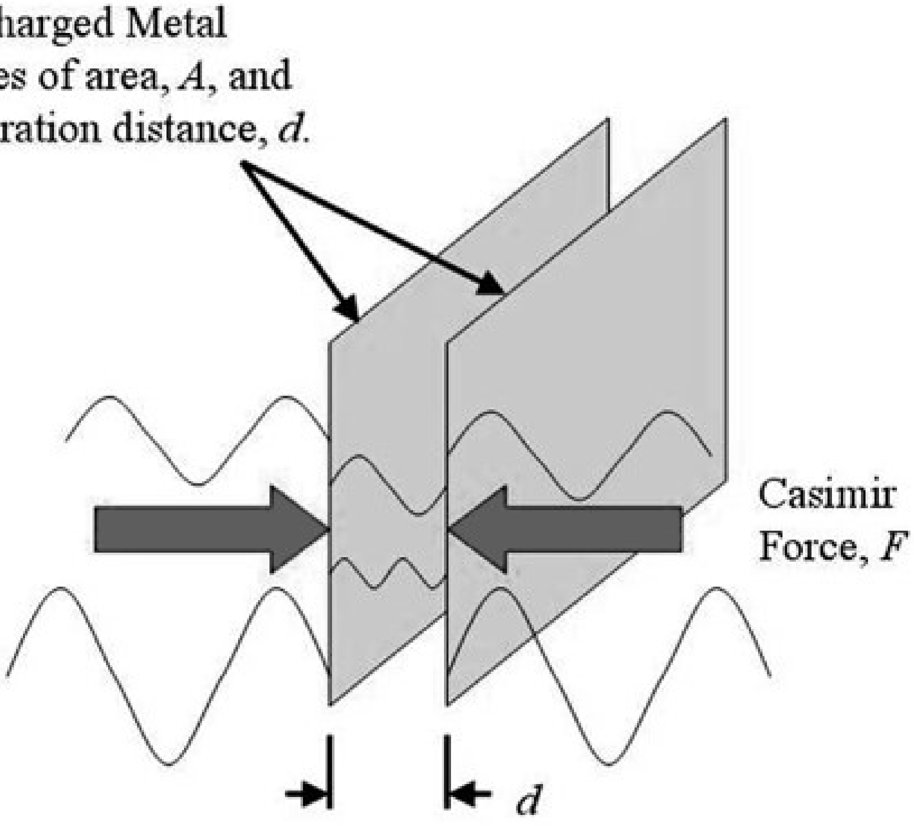
$$h = \frac{8\pi}{c^2 t_H}$$

All of this work is meant to illustrate the point that two physical constants, the gravitational constant G and the quantum mechanics physical constant h can both be shown to have a common mathematical/fundamental relationship to dark energy, or the quantum vacuum. Are there other characteristics of the quantum vacuum that give some insight on how to address the pinnacle objective of actually using it as a propellant source? Some more theoretical work must be presented to further frame the discussion. In Obousy's investigation into Casimir Energies and Phenomenological Aspects, it was shown that the dominant contribution to the density of the quantum vacuum comes from the electromagnetic force (QED Vacuum), by several orders of magnitude over either the electroweak force (Higgs Vacuum), or the strong force (QCD Vacuum). This suggests that it might be fruitful to further explore the electrodynamic characteristics of the vacuum.

But what makes up this quantum vacuum? As was stated earlier, the physics community knows from experiments performed over the last ten years that the vacuum is not empty, but rather a sea of electron and positron pairs that pop into and out of existence as they spontaneously create and annihilate, otherwise known as the quantum vacuum. Interestingly, the Dirac Sea approach (an earlier vacuum model) predicted the existence of the electron's antiparticle, the positron, in 1928. The positron was later confirmed in the lab by Carl Anderson in 1932.

Today, one of the most well known macroscopically observable characteristics of the quantum vacuum is the Casimir Force. Simply put, the Casimir Force is an attractive force between a pair of parallel uncharged metal plates. The Casimir force was first predicted by Casimir in 1948 when he realized that as two parallel uncharged metal plates are moved closer together, they only allow virtual photons of appropriate integer wavelength that fit within the gap between the plates. The net result is to reduce the energy density expectation value between the plates with respect to the free expectation value. Figure 2 demonstrates the concept and identifies the formula relating the pressure between the plates to the physical parameters. The Casimir Force was first tentatively measured in 1958 by Marcus Spaarnay, and the results generally agreed with prediction. It was subsequently measured more accurately in 1996 by Steven Lamoreaux. A historical, conventional analog to the idea behind the Casimir Force can be drawn considering training given to sailors of the tall-ship era who were instructed to not allow two ships to get too close to one another in choppy seas lest they be forced together by the surrounding waves requiring assistance to be pulled apart.

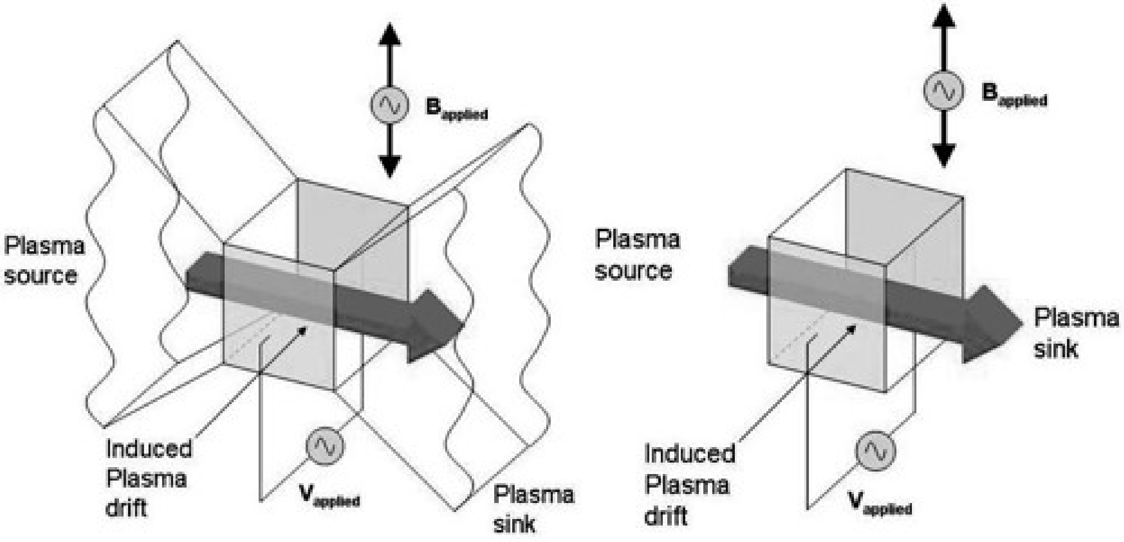
Figure 2. *Illustration of the Casimir Force*



$$\frac{F}{A} = -\frac{\hbar c \pi^2}{240 d^4}$$

So if the vacuum is never really empty, and the dominant density contribution to the quantum vacuum arises from the electrodynamic force, could the quantum vacuum be treated as a virtual plasma made up of electron- positron (e-p) pairs, and as such have the tools of Magneto-hydrodynamics (MHD) used to model it? If so, then an apparatus could be engineered that could act on the virtual plasma and use it as a propellant. For example, the virtual plasma could be exposed to a crossed electric field ***E*** and magnetic field ***B*** which would induce a plasma drift vp of the entire plasma in the ***ExB*** direction which is at right angles to the first two applied fields. The apparatus would be quite similar in construction to a conventional plasma thrust unit, only it would not need to carry a propellant tank along for the ride. This Quantum Vacuum Plasma Thruster (QVPT) would use the quantum vacuum as its source of propellant, which suggests much higher specific impulses (ISP) are available for QVPT systems, limited only by their power supply's energy storage densities. Figure 3 illustrates the conventional plasma thruster on the left, and a QVPT on the right.

Figure 3. *Plasma Thruster (left) and QVPT (right) are similar except the QVPT need not carry propellant.*



In practice, there are a number of engineering challenges to address, squeezing the vacuum to a density that can be used to produce a thrust that is both observable and useful is of primary interest. The preceeding equations can be used to derive an equation that relates the density (or squeezed state) of the quantum vacuum to local matter density:

$$\rho_{v\_local} = \rho_v \sqrt{\frac{\rho_m}{\rho_v}} = \sqrt{\rho_m \rho_v}$$

In this equation, rv_local is the local density of the vacuum, rm is the local matter density, and rv is the cosmological dark energy density. This equation suggests that a local matter density will result in a squeezed state of the quantum vacuum. The validity of this equation can be checked by considering the ground state of the hydrogen atom. The methodology will be to calculate a quasi-classical density for the hydrogen nucleus using experimental data which will serve as rm, calculate the predicted vacuum fluctuation density rv_local using the equation in question, and then derive the volume (radius) of vacuum energy density necessary to match the ground state of the hydrogen atom.

The ground state of the hydrogen atom is 13.6eV (2.18x10-18 N•m) which can be classically thought of as the sum of both the potential energy and kinetic energy for the electron in this orbit. The radius of the hydrogen atom nucleus is given as R0=1.2x10-15m (R=R0•A1/3 where R0 = 1.2x10-15m and A is the atomic number - these are experimentally determined by electron scattering). The radius can be used with the mass of a proton to calculate a quasi-classical density of the hydrogen nucleus:

$$\rho_m = \frac{m_p}{\frac{4}{3}\pi R_0^{\ 3}} = 2.31x10^{17}\frac{kg}{m^3}$$

Calculate equivalent local vacuum fluctuation density as a function of local matter density present using the dark energy density value ñv=2/3 * 9.9x10-27 kg/m3:

$$\rho_{v\_local} = \sqrt{\rho_m \rho_v} = 3.9046x10^{-5}\frac{kg}{m^3}$$

The next step is to determine the volume of this vacuum energy density necessary to sum to the hydrogen ground state of 13.6eV (2.18x10-18 N•m). To the point, what is the radius of the bubble of encapsulated vacuum energy density?

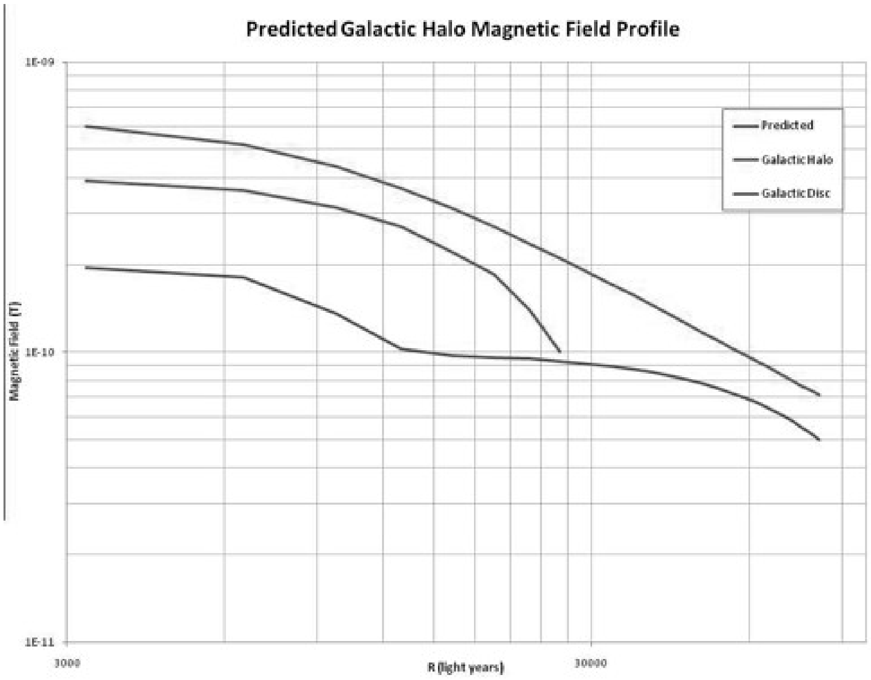
$$r = \left(\frac{E}{\rho_{v\_local} c^2 \frac{4}{3}\pi} \right)^{\frac{1}{3}}$$

The calculated or predicted radius is r = 5.29x10-11m, which turns out to be an exact match to the given value for the Bohr Radius, a0 = 5.29x10-11m. In the process of checking the validity of the equation, we have just derived the Bohr radius as a consequence of cosmological dark energy, and that the dark energy fraction should be exactly 2/3 in lieu of the 0.72 +/- 3%. Readers familiar with the history of the development of quantum mechanics will recognize the profound implications of the above findings.

Are there other methods by which the squeezed state of the vacuum can be altered to be of benefit as a propellant source? To answer this question, consider the extragalactic magnetic field which is estimated to be 1x10-12 Tesla. If the quantum vacuum can be treated as a virtual plasma, then the magnetic energy density (or pressure) should correlate to the plasma pressure. The magnetic pressure is calculated using the following equation: PB = B2/(2m0), B = 1x10-12T, m0 = 1.26x10-6 T2m3/J, PB = 3.98x10-19 N/m2. The plasma pressure can be calculated using the following equation: Pplasma = nekT. The electron-positron density ne can be found using ne = rc/me. The critical density is as stated before, rc = 9.9x10-27 kg/m3, and the temperature is T = 2.73K. Assuming an e-p plasma population, the plasma pressure is Pplasma = 4.09x10-19 N/m2.

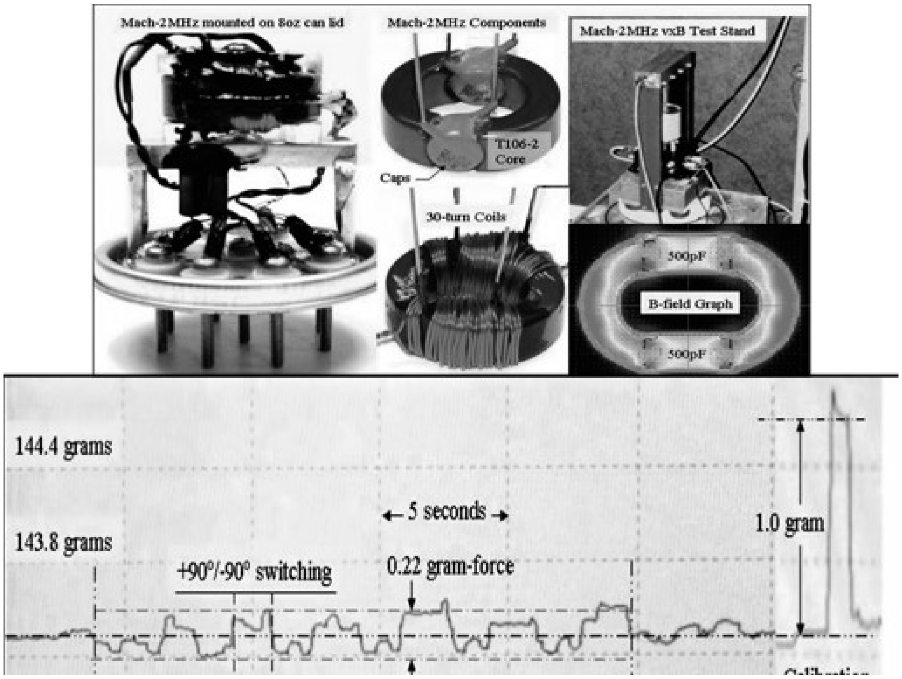
This relationship suggests that in the far field limit, the magnetic field squeezes the quantum vacuum. This same methodology can be applied to dark matter models for galaxies to see if there is a similar correlation when treating dark matter as a virtual e-p plasma. Current dark matter models for galaxies can be used to predict a galactic halo magnetic field as a function of galactic radius, and this magnetic field magnitude distribution can be compared to observation. Although galactic halo magnetic field strength and structure is not fully understood, the predictions can still be compared to the data and models available. Figure 4 shows the comparison. As with the extragalactic magnetic field, there is a very strong correlation for the galactic magnetic field. As a matter of caution, when considering conventional magnetic field strengths, Temperature must also be incorporated into the model. These findings also show that the tools of MHD can successfully be used to model quasi-classical behavior of the vacuum.

Figure 4. *Galactic Halo Magnetic Field*



A spectrum of high fidelity engineering tools have been developed to design and implement several thruster units for testing purposes. As it turns out, there are multiple input parameters that exhibit inherently nonlinear behavior when calculating thrust expectations. In many cases, certain input parameters work against one another in the process of trying to optimize a point design solution. Geometry, dielectric material, drive frequencies, peak field strengths, phase angles, and more have to be balanced for a given construction to provide predictions that are observable. To date, possible thrust levels in the 1000-3000 microNewton range have been observed with an equivalent specific impulse of 1x1012 seconds. Figure 5 depicts a test unit and a thrust trace. Toclearly establish the phenomenon, its scaling behavior, and make this technology relevant to the commercial satellite sector, the next test article currently under construction was designed to produce a thrust in the 0.1 to 1 Newton thrust range with an input power of ~1kW. Figure 6 shows the thrust predictions as a function of input power with an inset of the test article at the top left of the figure.

Figure 5. *1000-3000 microNewton class thruster with thrust trace*

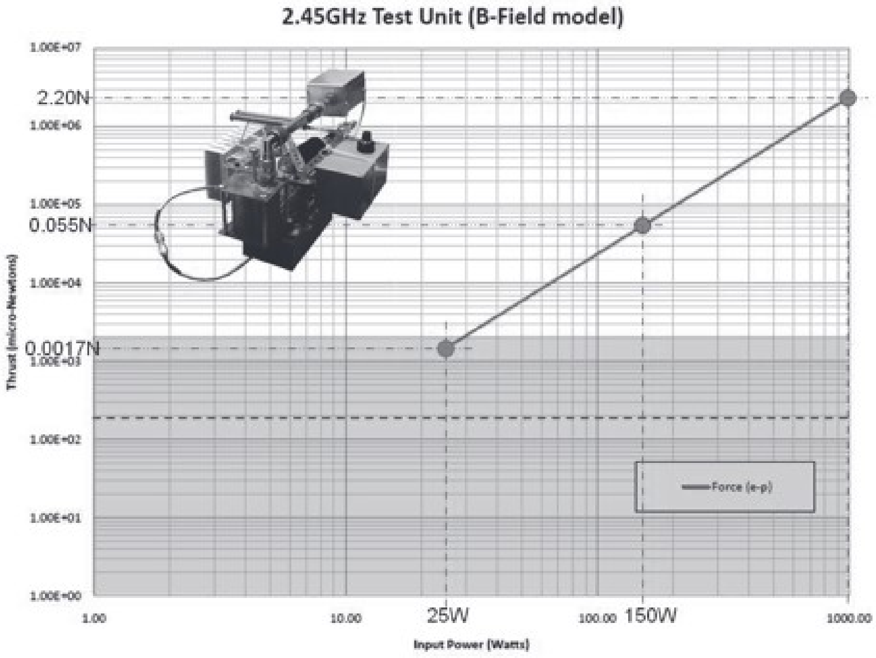


At this point, a few words should be spent to address the question of how the quantum vacuum communicates momentum information across a boundary constraint. For example, consider momentum information that has been imparted on a squeezed state of the vacuum by means of the noted crossed E and B fields within an enclosed region. The quantum vacuum is continuous, but has different density depending on multiple input parameters just discussed, one being the density of conventional matter such as the copper walls of a resonator unit. As the momentum information moves through this barrier, the density of the quantum vacuum within the copper walls is many orders of magnitude less than the squeezed state inside the enclosed region meaning any momentum information lost through a "collision" process with the copper lattice is many orders of magnitude less than the total momentum information gained by the source of the electric and magnetic fields (the copper thrust chamber). This means the departing momentum information will have a long range effect as the quantum vacuum field carrying this information is very weakly interacting with conventional matter due to the very low quantum vacuum densities. This is why we still feel gravity even though we put a thickplate of steel between us and the earth. A gravity well is a hydrostatic pressure gradient in the quantum vacuum, while a QVPT is a hydrodynamic pressure gradient in the quantum vacuum.

If the experimental effort can demonstrate that the thrust magnitude can be scaled to the 0.1 to 1 Newton range with an input power of ~0.1 to 1 kilo-Watt, this would establish the market entry-point for this technology. High power Hall-Effect Thrusters are used as station-keeping thrusters providing 0.5 to 1 Newton of thrust with 7 to 20 kilo-Watts of input power. Is there a business case that can adapt and employ the QVPTs to benefit the commercial satellite sector? Consider the following hypothetical business case.

Currently, there are 40-80 mini-satellites (~1000 pounds) per year that could utilize QVPTs in this size and power budget (see the Futron presentation, If you build it, who will come, presented to the 22nd AIAA/USU Conference on Small Satellites). If the test article were to generate the desired thrust levels, it is estimated that it would take about two years and approximately $10 million to design the first flight article. By producing equivalent thrust at a lower input power requirement, this would allow satellite designers to reduce the size of solar panels and thermal management systems. This translates into cost savings for satellite designers based on an industry metric of ~$500 per Watt. The power budget for a 0.1N Hall-Effect thruster would be ~ 1500 Watts, while an equivalent thrust level QVPT ~200 Watts, yielding a net savings of 1300 Watts power for a QVPT-equipped satellite design. This would result in a potential savings of ~$650K in the final design due to reduction in overall power level and reduced thermal management system. Assume that the flight QVPT articles could be manufactured for ~$500K per copy, and sold for ~$750K. The satellite designer saves the $650K in reduced thermal and power systems, and saves the cost of the equivalent Hall-effect thruster that was replaced by the QVPT, minus the $750K to purchase the QVPT. The net result is that the satellite manufacturer effectively gets a high performance engine for $100K. With these rough metrics, the design can become profitable within roughly forty sales, which is reasonable considering the annual market and cost savings for customers.

Figure 6. *2.45 GHz QVPT thrust predictions versus input power*



Note that in the above brief business case, we did not make use of the ultra-high ISP for the QVPTs, which will also result in the beneficial characteristics of the satellite system: A QVPT-equipped satellite can maintain position for life of hardware with no propellant limitations. Satellite missions can include servicing multiple orbits and inclinations which are precluded with other systems. Earth monitoring satellites and communications satellites could maintain a parked position in GEO, and change to different altitudes and/or inclinations based on transient and unpredictable events. Although this case study dealt with QVPTs, most forms of advanced propulsion research can likewise be shown to have beneficial characteristics back here at home. While the mention of advanced propulsion may invoke pictures of plucky little probes or vast crewed-spaceships headed off into the great unknown, advanced propulsion research can produce technology that can be matured within the crucible of the terrestrial commercial/civil/defense satellite sector. Thus the argument can be made that advanced propulsion research will not produce myopic point solutions with little-to-no intrinsic domestic value, rather these solutions will greatly improve the abilities and robustness of local space assets, while at the same time producing mission-enabling technology. ■

Dr. Harold White **currently serves as the Space Station Remote Manipulator System Manager for NASA in the Engineering Directorate at the Johnson Space Center. He is also a recognized expert and advocate of advanced propulsion research.**