Advanced Propulsion Physics: Harnessing the Quantum Vacuum. H. White[1] and P. March[2], [1]NASA JSC, NASA Pkwy, M/C EP411, Houston, TX 77058 harold.white-1@nasa.gov [2]NASA JSC paul.march-1@nasa.gov.

Introduction: Can the properties of the quantum vacuum be used to propel a spacecraft? The idea of pushing off the vacuum is not new, in fact the idea of a "quantum ramjet drive" was proposed by Arthur C. Clark (proposer of geosynchronous communications satellites in 1945) in the book Songs of Distant Earth in 1985: "If vacuum fluctuations can be harnessed for propulsion by anyone besides science-fiction writers, the purely engineering problems of interstellar flight would be solved." [1]. When this question is viewed strictly classically, the answer is clearly no, as there is no reaction mass to be used to conserve momentum. However, Quantum Electrodynamics (QED)[2], which has made predictions verified to 1 part in 10 billion, also predicts that the quantum vacuum (lowest state of the electrodynamic field) is not empty, but rather a sea of virtual particles and photons that pop into and out of existence stemming from the Heisenberg uncertainty principle. The Dirac vacuum [3], an early vacuum model, predicted the existence of the electron's antiparticle, the positron in 1928, which was later confirmed in the lab by Carl Anderson in 1932. Confirmation that the Quantum Vacuum (QV) would directly impact lab observations came inadvertently in 1948 while Willis Lamb was measuring the 2s and 2p energy levels in the hydrogen atom [4]. Willis discovered that the energy levels were slightly different, contrary to prediction, but detailed analysis performed within weeks of the discovery by Bethe at Cornell predicted the observed difference only when factoring in contributions from the QV field [5]. The Casimir force [6], derived in 1948 by Casimir in response to disagreements between experiment and model for precipitation of phosphors used with fluorescent light bulbs, predicts that there will be a force between two nearby surfaces due to fluctuations of the QV. This force has been measured and found to agree with predictions numerous times in multiple laboratories since its derivation.

What is the Casimir force? The Casimir force is a QV phenomenon such that two flat plates placed in close proximity in the vacuum preclude the appearance of particles, whose wavelength is larger than the separation gap, and the resultant negative pressure between the two surfaces is more negative than the pressure outside the two surfaces, hence they experience an attractive force. A historical, classical 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 and require assistance to be pulled apart. Although the forces have typically been small, from a practical perspective, micro-electromechanical systems (MEMS) are already utilizing this phenomenon in design application.

How much energy is in the Quantum Vacuum? The theoretical calculation for the absolute zero ground state of the QV can be calculated using the following equation[7]:

$$E_0 = \int_{\omega=0}^{\omega_{cutoff}} \frac{\hbar\omega^3}{2\pi^2 c^3} d\omega$$

Using the Plank frequency as upper cutoff yields a prediction of ~10^{114} J/m^3. Current astronomical observations put the critical density at $1*10^{-26}$ kg/m^3. The vast difference between QED prediction and observation is not currently understood.

Is there a way to utilize this sea of virtual particles and photons (radiation pressure) to transfer momentum from a spacecraft to the vacuum? A number of approaches have been detailed in the literature and synopsized in [8]: Vacuum sails that develop a net force by having materials on either side with different optical properties; Inertia control by altering vacuum energy density and reducing total spacecraft mass thus minimizing kinetic energy and amount of work needed to accelerate a spacecraft; and dynamic systems that make use of the dynamic Casimir force to generate a net force.

What is the dynamic Casimir force? The dynamic Casimir force arises as a result of Unruh radiation where an accelerated observer sees the vacuum as a higher temperature photon bath, and is the mechanism that facilitates Hawking radiation around a black hole where relativistic acceleration separates a virtual pair such that one particle goes in the horizon, while the other escapes. Recent findings reported earlier in 2011 show that the dynamic Casimir effect may have been detected in the lab [9]. The simplest mechanical construct to help visualize using the dynamic Casimir force to generate thrust is through the use of vibrating mirrors where the mirror trajectory is designed to generate radiation in a preferred direction. The magnitude of thrust arising from using the dynamic Casimir force derived numerous times in the literature has been shown to be very small in comparison with conventional propulsion systems, but has been clearly shown to be theoretically possible. As a classical construct to help with visualization, consider how a submarine uses a propeller to create a hydrodynamic pressure gradient that propels the sub forward while the receding water column carries the momentum information downstream. The sub does not carry a tank of water and then flow that water across the propeller; rather it uses the propeller to interact with the environment. The corollary is that there has to be a "wake" (conservation of momentum is required!).

Are there methods to increase net force? As the calculated energy density of the quantum vacuum versus observation shows, even though QED is one of the most experimentally successful theories to date, the community's understanding of the vacuum is only just beginning as this is a new field, and the study of the quantum vacuum is at the leading edge of science with a wide open horizon to explore. Recent models developed by White [10] suggests that there are ways to increase the net force, and these models have been validated against data at both the cosmological scale, the quantum level, and test devices have been fabricated/tested in the lab and found to agree with model predictions. Figure 1 depicts the principles of quantum vacuum plasma thrusters (Q-thrusters) in tabular form.

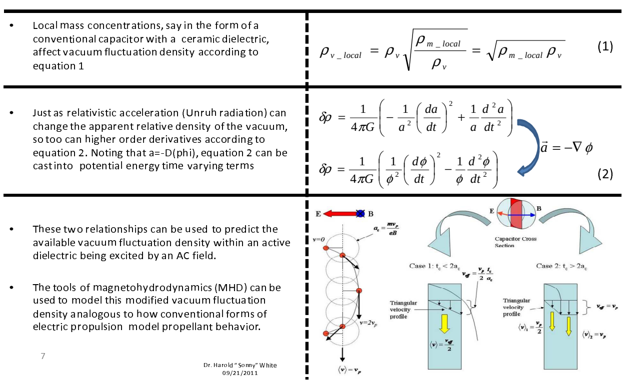

Figure 1: Principles of Q-thruster Operation

How does a Q-thruster work? A Q-thruster uses the same principles and equations of motion that a conventional plasma thruster would use, namely Magnetohydrodynamics (MHD), to predict propellant behavior. The virtual plasma is exposed to a crossed E and B-field which induces a plasma drift of the entire plasma in the ExB direction which is orthogonal to the applied fields. The difference arises in the fact that a Q-thruster uses quantum vacuum fluctuations as the fuel source eliminating the need to carry propellant. This suggests much higher specific impulses are available for QVPT systems limited only by their power supply's energy storage densities. Historical test results have yielded thrust levels of between 1000-4000 micro-Newtons, specific force performance of 0.1N/kW, and an equivalent specific impulse of ~1×10^{12} seconds. Figure 2 shows a test article and the thrust trace from a 500g load cell [11].

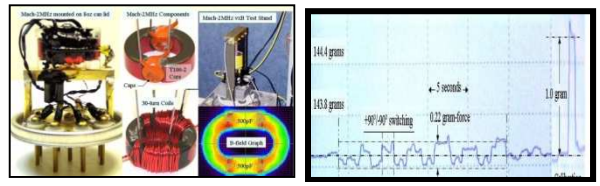

Figure 2: 2005 test article construction and results

The near term focus of the laboratory work is on gathering performance data to support development of a Q-thruster engineering prototype targeting Reaction Control System (RCS) applications with force range of 0.1-1 N with corresponding input power range of 0.3-3 kW. Up first will be testing of a refurbished test article to duplicate historical performance on the high fidelity torsion pendulum (1-4 mN at 10-40 W). The team is maintaining a dialogue with the ISS national labs office for an on orbit DTO.

How would Q-thrusters revolutionize human exploration of the outer planets? Making minimal extrapolation of performance, assessments show that delivery of a 50 mT payload to Jovian orbit can be accomplished in 35 days with a 2 MW power source [specific force of thruster (N/kW) is based on potential measured thrust performance in lab, propulsion mass (Q-thrusters) would be additional 20 mT (10 kg/kW), and associate power system would be 20 mT (10 kg/kW)]. Q-thruster performance allows the use of nuclear reactor technology that would not require MHD conversion or other more complicated schemes to accomplish single digit specific mass performance usually required for standard electric propulsion systems to the outer solar system. In 70 days, the same system could reach the orbit of Saturn.

References: [1] Clarke, A., Songs of Distant Earth, Ballantine Books, NY (1986). [2] Srednicki, M., Quantum Field Theory, Cambridge University Press (2007). [3] Available at http://www.nobelprize.org/nobel_prizes/physics/laureates/1933/dirac-lecture.pdf [4] Lamb, W., Phys. Rev., 72 (1947). [5] Bethe, H., Phys. Rev., 72 (1948). [6] Casimir, H., Koninklijke Nederlandse Akademie van Wetenschappen, 51 (1948). [7] Puthoff, H., Phys. Rev. D 35, 3266 (1987). [8] Millis, M., Davis, E., ed., Frontiers of Propulsion Science, AIAA (2009). [9] Available at: http://www.technologyreview.com/blog/arxiv/26813/. [10] White, H., et. al., 5th Spacecraft Propulsion Joint Subcommittee Meeting 2011. [11] March, P., Palfreyman, A., STAIF 2006.