Mini-Magnetospheric Plasma Propulsion (M2P2): Prospects for Long-Distance Space Flight

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1. Introduction

Long-distance human spaceflight to the outer planets and beyond has been a goal of mankind since the first manned mission into space. With all of the goals that have been achieved since the dawn of space flight, it now seems natural for the next progressive step to be human exploration of space beyond our own Earth-moon system. Reaching farther distances, however, is no easy task. The most significant problem faced when considering such missions is finding a propulsion system that is technologically feasible, cost-effective and low-risk. Current proposed methods often lack in one or more of these contexts, making the desire for new and innovative propulsion systems strong.

Moreover, it is suggested that missions to remote destinations perform their duties within a 10 year post-launch period for optimal scientific return. For missions to the edge of the solar system, this restriction would require the spacecraft to move at speeds greater than 50 km/s – an extremely high speed. For traditional propulsion systems, this is just not feasible; a new method is clearly needed. One such method, known as Mini-Magnetospheric Plasma Propulsion, is presented here.

2. Mini-Magnetospheric Plasma Propulsion (M2P2)

M2P2 is an advanced propulsion concept proposed by geophysicist Robert Winglee at the University of Washington. The system is modeled after the magnetic sail technique, in which a magnetic field on the spacecraft deflects charged particles radiated by the Sun to impart momentum and acceleration. The M2P2 design calls for inflation of this sail by the injection of plasma into the magnetic field, expanding the field to a bubble with widths as large as 15-30 km. This technique reduces the size and weight of the magnet used to generate the initial field, lowering the overall mass while largely increasing performance.

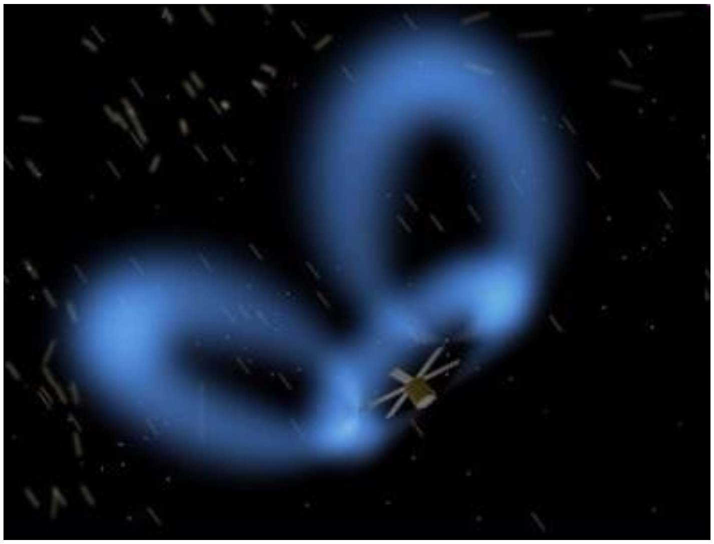

Figure 1: An illustration of solar wind particles interacting with the M2P2 mini-magnetosphere (figure courtesy of official M2P2 website).

3. M2P2 Design

The design of the M2P2 system is similar to that of a magnetic sail propulsion system, but with the incorporation of plasma to increase the size of the field. In normal magnetic sail systems, a magnetic field is created using a loop of superconducting wire, and the field interacts with the solar wind to impart accelerations on the spacecraft (in much the same way solar sails interact with photon radiation pressure from the Sun). The wind contains protons moving at speeds of 350-800 km/s, and the protons' momentum is transferred to the spacecraft upon being deflected by the field. However, the intensity of the field in normal magnetic sail designs decreases inversely as the cube of the distance from the coil center. This leaves a smaller, less-efficient field with which to interact with the solar wind.

In the M2P2 design, solar cells power a solenoid on the spacecraft, which generates a magnetic field. Plasma is then injected into a plasma chamber (roughly the size of a mason jar) and kept highly magnetized at high density, causing its currents to interact with and expand the magnetic field to distances as large as 15-30 km. This newly-enlarged field interacts with the solar wind just as a normal magnetic sail would, but on a much larger scale due to the exceedingly large volume of the field.

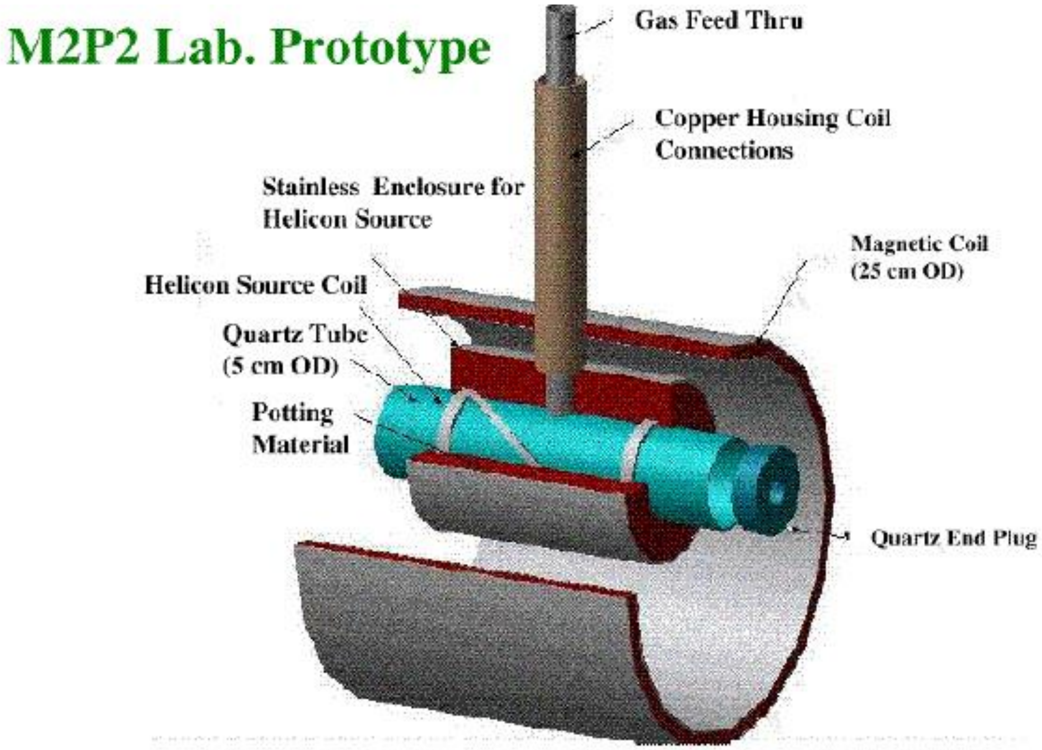

Figure 2: The M2P2 testing prototype (figure courtesy of official M2P2 website).

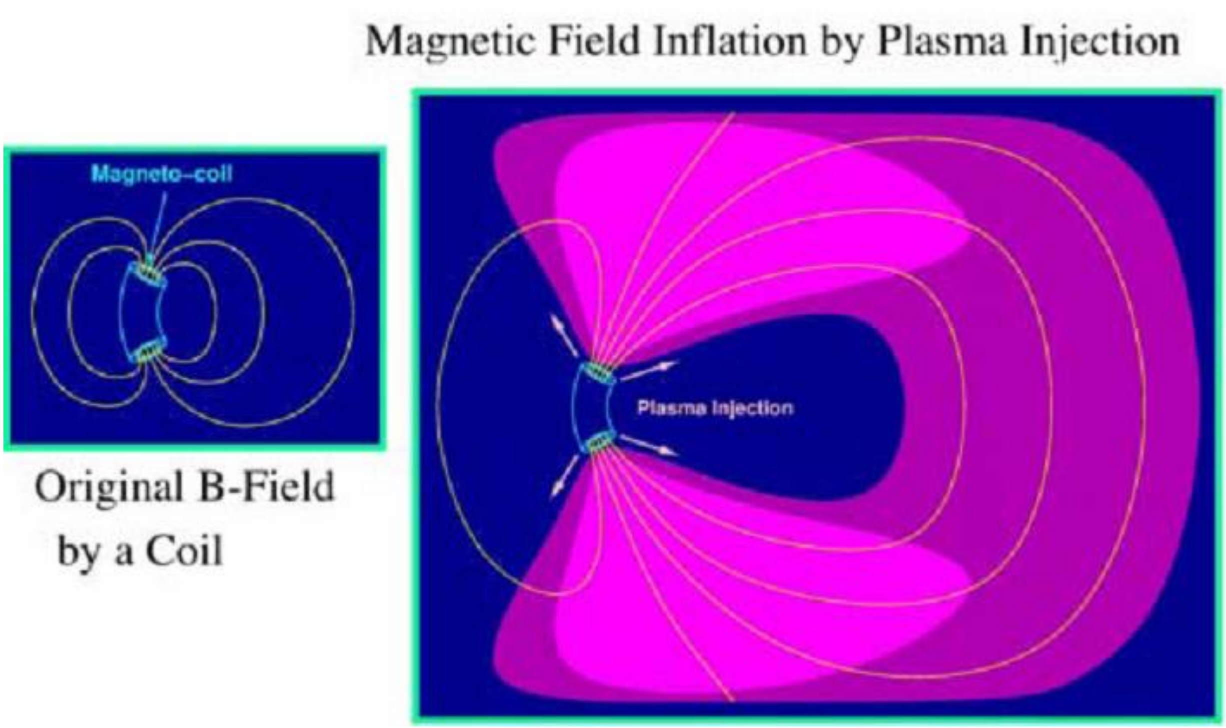

Figure 3: Magnetic field inflation by plasma injection (figure courtesy of Funaki et al.).

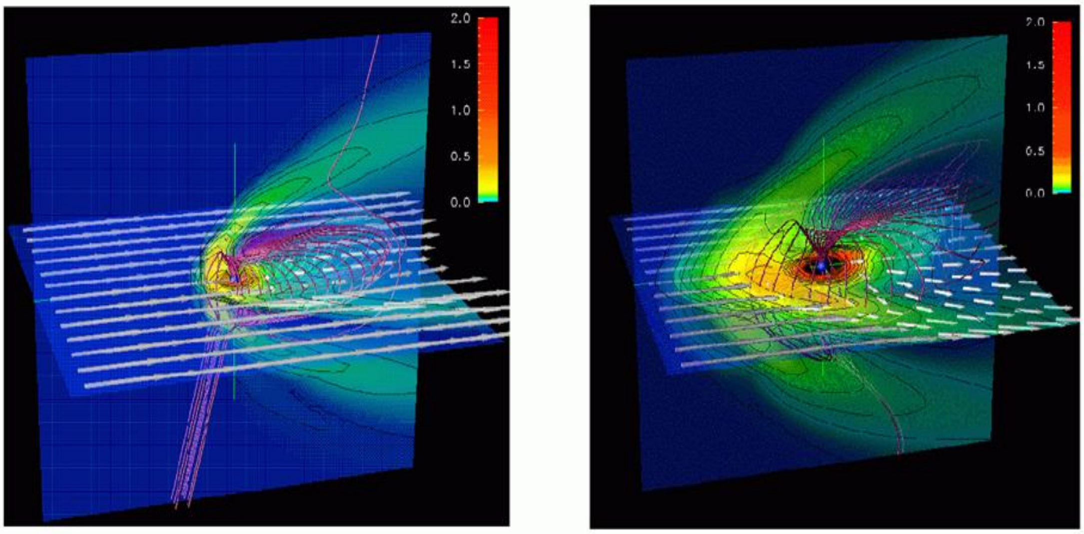

Figure 4: Comparison of a normal magnetic sail field and a plasma-enlarged field (figure courtesy of official M2P2 website).

The electric current in the solenoid must be maintained to keep the plasma from deionizing and escaping. With plasma escaping, the enlarged magnetic field would shrink until the leaked ions are restored to the plasma. Therefore, a source of gas must be stored on the spacecraft. Virtually any ionizable gas could be used, but an ideal choice would one with less massive ions (so the ions move more quickly) and ease of containment. In an Earth-based prototype being tested by Dr. Winglee, Argon has been used because of its relatively easy containment properties, as well as Helicon. However, it is thought that Helium may be a better choice for future space-based implementations of M2P2 because of its low mass and higher "velocity per kilogram" yield. More work is being done to study better containment methods for certain gases, to prevent potential leakage and field shrinking.

As an example, a weak, 50 nT starting field (which is strong enough to support itself against the plasma wind flow) could be expanded to a radius of 26km. Since the thrust is calculated by:

$$F = \frac{1}{2}\rho u^2 * S_{eff},$$

where $\frac{1}{2}\rho u^2$ represents the dynamic pressure of the solar wind and S_{eff} is the effective area that deflects the plasma flow of the solar wind, a thrust of 1N would be obtained. With a 20% efficiency for the conversion of plasma energy to magnetic field energy, roughly 4 kW of electric power would be needed to maintain the field. This gives a thrust/power ratio of 1N/4 kW, a relatively large number when compared to other low-thrust propulsion systems.

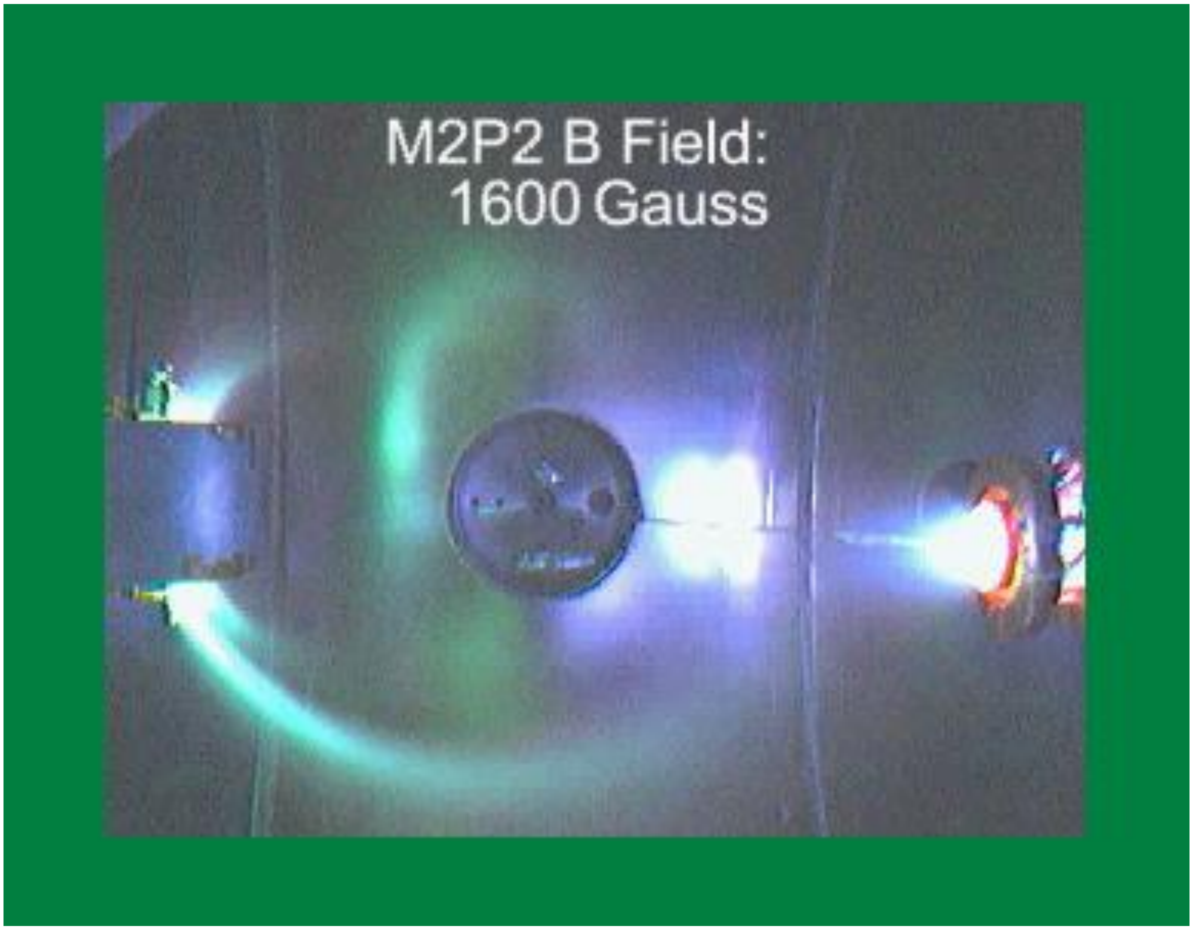

Figure 5: Successful test deflection of 1 N plasma using less than 1 kW of power (figure courtesy of official M2P2 website).

4. Advantages of M2P2

One of the main advantages of the M2P2 design is that it maintains its thrust at increasing distances from the Sun. While efficiencies of normal magnetic and solar sails decrease with the square of the spacecraft's distance from the Sun, the M2P2 field expands as the solar wind density decreases. The magnetic "bubble" self-adjusts to fluctuations in the solar wind in a dynamic balance of pressures, keeping the total force imparted on the spacecraft constant. For long-distance space flights, this is a very attractive feature.

There is also great mass savings with the expanded magnetic field concept. For typical solar sail missions, sails are large and unwieldy and add a significant amount of mass to the spacecraft. The expanded M2P2 magnetic field would be created by electromagnetic processes, adding only the small mass (~70 kg) of the solenoid and plasma injection system. Furthermore, the practice of deploying solar sails adds an additional element of risk to a mission, as any moveable parts are subject to failure. With mini-magnetospheric propulsion, the expansive magnetic field would form almost instantaneously and lay independently outside the spacecraft.

Power is also saved using the system, further making it an attractive candidate for long-distance space flight. The solenoid could be run using an estimated 3 kW of electricity, which could very feasibly come from solar cells; 3 kg of helium could be maintained for 3 months. In contrast, plasma rockets require much larger amounts of electric power. Because power is limited in space, this factor is an important one to consider when planning long-duration space flights.

Another feature of the M2P2 design is that it involves no erosion of system components by the plasma. While plasma rocket components (specifically the nozzle) come into contact with hot plasma and degrade with use, plasma in the M2P2 system would be confined by a magnetic field and therefore wouldn't have this drawback. This feature would lead to a longer lifetime of the system, reducing risk and cost.

As a candidate for propelling manned spacecraft, M2P2 would have the additional advantage of protecting the crew from much of the particle radiation that would otherwise penetrate into the spacecraft. The magnetic field would deflect this radiation, much like the way the Earth's magnetosphere currently shields people on the ground.

M2P2 would also exhibit the benefit of greater schedule flexibility. While conventional nuclear-propelled systems have launch windows on the order of once every 26 months, M2P2 would have multiple launch windows per year. A system with more launch (and landing) opportunities would further allow many more choices for mission duration. Mission duration is an important factor when calculating the mass budget, power budget, etc, and the ability to ease this constraint is very desirable.

5. Application to Outer-Planet Missions

For the reasons mentioned above, M2P2 is a strong candidate for future missions to the outer planets and beyond. To make some comparisons, the M2P2 system would be capable of speeds 100 times faster than the space shuttle, traveling as far as an estimated 4.3 million miles per day (vs. 430,000 miles per day for the shuttle). The specific impulse would be 200 times better than that of the space shuttle's main engine, and the system could potentially overtake Pioneers 10 & 11 and Voyagers 1 & 2 to become the first manmade object to ever leave the solar system.

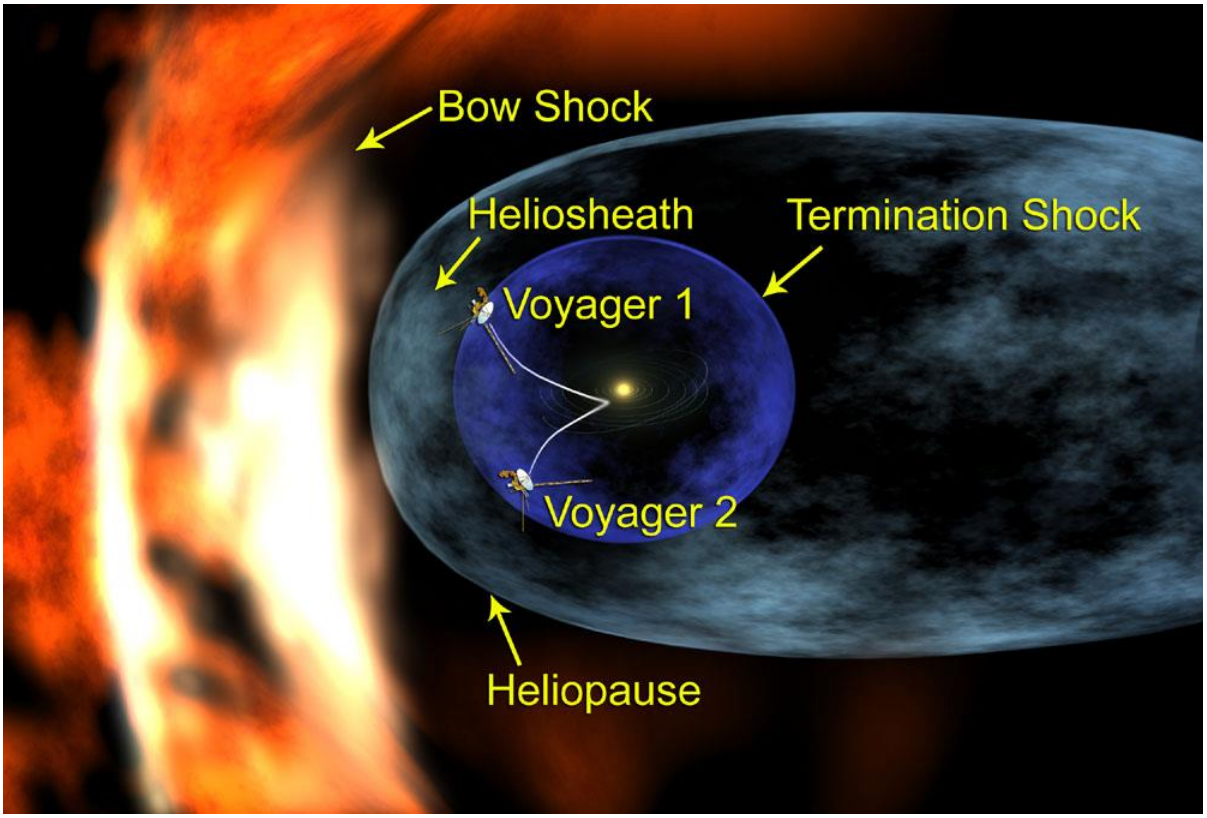

Figure 6: Voyagers 1 and 2, on their way out of the solar system (figure courtesy of http://astronet.ru).

For an initial spacecraft mass of 1000 kg, the M2P2 design could achieve an estimated thrust/power ratio of 1N/4kW, with a propellant flow rate of 0.5 kg/day/kW. The thrust would be higher than that of typical low-thrust (electric) propulsion systems, and when combined with a specific impulse of 3–8 x 10^4 s, M2P2 would be able to achieve the required acceleration for planetary transfer very quickly (possibly avoiding the use of a planetary gravity assist).

A 70–140 kg payload could be propelled to speeds of 50-80 km/s, making destinations beyond the heliopause reachable in under 10 years. As a comparison, the propellant temperature and exit velocity required to reach a speed of 50-80 km/s is not even economically attainable for chemical thrusters. The temperature requirement would constrain the system to using plasma, but the energy requirements for maintaining enough plasma to reach that speed would be too large to be handled by solar cells alone. Nuclear power might solve this problem, except its use would greatly increase the mass and overall cost. Clearly, using the ambient energy in space is the best solution. Since solar sails can bring on significant impacts on mass, cost and risk, magnetic propulsion seems like the best option for high-speed, long-distance space flight. The plasma-expanded field (or "plasma sail") created by M2P2 would be large enough to achieve the desired 50-80 km/s for a 10-year voyage out of the solar system with low mass, low power and reduced cost.

6. Prototypes and Testing

While not yet flown in space, a small-scale prototype of the M2P2 design has been tested in a 4000 L test chamber at the University of Washington in Seattle, WA, and at the large vacuum chamber at NASA Marshall Space Flight Center. Clearly, Earth-based testing of a system that spans tens of kilometers and relies on the specific environmental properties of space is difficult, if not impossible. Instead, computer simulations have been run to predict the performance of M2P2, and supplementary small-scale prototype tests have been conducted to support these predictions. So far during this testing, plasma with a density on the order of $10^{11} – 10^{12}$ cm^{-3} has been produced and its pressure has been sufficient to demonstrate outward expansion of the system's mini-magnetosphere. Inflation to several feet away from the coil has been achieved which, for a life-sized model of similar configuration in space, would translate to 15-20 km. At this field size, a ~100 kg payload could be accelerated to 50-80 km/s over the course of three months, which is the speed calculated to be necessary for a spacecraft to reach the heliopause in under 10 years.

It is hoped that Earth-based methods for physically demonstrating momentum gains from solar wind will be possible in the near future, although current computer simulations of this are already being supplemented by fluid experiments.

Figure 7: 4000 L prototype test chamber at the University of Washington (figure courtesy of official M2P2 website).

7. Summary

In order to reach farther distances into space within a reasonable amount of time, a spacecraft propulsion system is desired that can achieve high speeds with mass, power, cost and risk at the lowest values possible. The M2P2 design provides increased mission flexibility in the context of launch opportunities and choices for mission duration, and provides significant mass savings over conventional methods. Its ability to reach high speeds would enable the system to perform missions in greatly reduced amounts of time and with relatively little power consumption. Furthermore, the design of M2P2 is low risk, containing no physically deployable sails and involving no corrosion of components by propellants. Needing only to demonstrate a successful test flight in space, M2P2 is a strong candidate for satisfying the propulsion needs of future long-distance missions – a topic that will become more and more relevant in the near futures of both manned and unmanned space flight.

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