Large-Scale Mini-Magnetosphere Plasma Propulsion (M2P2) Experiments

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Abstract Mini-Magnetosphere Plasma Propulsion (M2P2) is an innovative plasma propulsion system that has the potential to propel spacecraft at unprecedented speeds of 50 to 80 km•s^{-1}, with a low-power requirement of ~1 kW per 100 kg of payload and ~1 kg of neutral gas [fuel] consumption per day of acceleration. Acceleration periods from several days to a few months are envisioned. High specific impulse and efficiency are achieved through coupling of the spacecraft to the 400 km•s^{-1} solar wind through an artificial magnetosphere. The mini-magnetosphere or inflated magnetic bubble is produced by the injection of cold dense plasma into a spacecraft-generated magnetic field envelope. Magnetic bubble inflation is driven by electromagnetic processes thereby avoiding the material and deployment problems faced by mechanical solar sail designs.

Here, we present the theoretical design of M2P2 as well as initial results from experimental testing of an M2P2 prototype demonstrating: 1) inflation of the dipole magnetic field geometry through the internal injection of cold plasma; and 2) deflection of and artificial solar wind by the prototype M2P2 system. In addition, we present plans for direct laboratory measurement of thrust imparted to a prototype M2P2 by an artificial solar wind during the summer of 2001.

1. Introduction

The goal of NASA's Advanced Space Transportation (AST) initiative is to, *"Create a safe, affordable highway through the air into space."* One of the objectives of AST is extend exploration's reach in space through reduced travel times. Specifically, the AST planning roadmap defines: (1) a near-term plan through 2005 which calls for the development of advanced transportation concepts and the initiation of the necessary enabling technology programs; (2) a mid-term plan through 2011 which realizes a reduction in propulsion system mass in concert with a factor of 2 reduction in interplanetary mission travel; and (3) and a long-term plan through 2025 which oversees the development of outer-planetary and edge-of-planetary missions possessing mission travel times which have been reduced by a factor of 10 in comparison to mission scenarios attainable through current technology.

The reasoning behind this initiative becomes clear when one considers Voyager 1, which was launched in 1977. Through the use of chemical propulsion combined with planetary gravitational boosts, Voyager 1 is located (as of 20 April 2001) at 80.84 AU (1 AU = 1.5×10^8 km) with a current speed of ~17 km•s^{-1}. Despite traveling at twice the speed attainable by the Space Shuttle, the expectation is that Voyager 1 will not encounter the termination shock of the heliopause (80 ± 10 AU) for several more years, to be followed by an encounter with the heliopause (~140 ± 20 AU) itself after an additional 20 years. In order to meet AST's mid-term goal of a factor of 2 reduction in interplanetary mission times, a spacecraft must traverse 10 AU•yr^{-1}, or travel at velocities in excess of ~50 km•s^{-1}. Clearly, this is a goal beyond the capabilities of conventional chemical propellants.

Hence, the mandate of AST has forced a major paradigm shift toward more innovative propulsion concepts. One innovative area of propulsion research has been the solar sail. The solar sail concept involves the transfer of solar photon momentum through a thin opaque/ reflective foil attached to a mechanical support structure, which is itself attached to a spacecraft. Theoretical evaluation of the solar sail coupling to solar photons is highly efficient and capable of producing the necessary velocities through the deployment of large surface-area (~10's km^2) sails. However, the deployment of such large-area sails has the technological disadvantages of requiring low aerial density foils and extensive support structures with which to expand to the necessary surface area. Fortunately, however, there is another propulsion concept capable of extracting momentum from the solar wind; a concept that offers the potential of attaining the necessary spacecraft velocities in excess of 50 km•s^{-1}; a concept that relies solely on current, off-the-shelf technology. That concept is the Mini-Magnetosphere Plasma Propulsion (M2P2) system.

2. The M2P2 Concept

The solar wind primarily expands outward from the solar surface with an average speed between 350 to 800 km•s^{-1}, and occasionally exceeds 10^3 km•s^{-1} [*McComas et al.*, 1998]. The objective of the M2P2 propulsion concept is the deflection of charged solar wind particles through the use of a large magnetic bubble whose field lines intercept the deploying spacecraft body. As the trajectories of these charged solar particles are diverted by the magnetic field, momentum [force] is transmitted through the magnetic field lines to the spacecraft producing acceleration. However, the production of a magnetic [field] bubble alone, in space, is incapable of efficiently coupling a spacecraft to the solar wind.

Consider the scenario of a simple current loop of radius R in the solar wind. In such a scenario, the external magnetic field generated by the current loop, assuming a fixed driving current, decreases as a function of R^3. Consequently, the external magnetic field is essentially zero at distances $\geq 10R$, severely limiting the effective coupling or interaction cross-section of the field. If the magnetic field were dipolar-like, produced using a solenoid (coil of current loops), the R^3 decrease in external field strength would remain applicable and is illustrated in the numerical simulation of the interaction presented in the left-hand panel of Figure 1. This coupling-dimension limitation may be overcome by increasing the radius of the coil, but at the cost of an increased the mass budget. Fortunately, there is another means of overcoming this limitation.

Injecting dense, cold plasma into a dipolar magnetic field causes the field to inflate into a magnetic bubble until equilibrium between the thermal pressure of the plasma and the magnetic pressure of the [dipolar] field is achieved. In this configuration, the external field strength of the inflated magnetic bubble decreases as a function of R^1. This R^1 dependence of a plasma-inflated dipole magnetic field in the solar wind is illustrated in the right-hand panel of Figure 1. As a result, the inflated magnetic bubble provides a greater cross-section resulting in a greater force being imparted to the system by the solar wind.
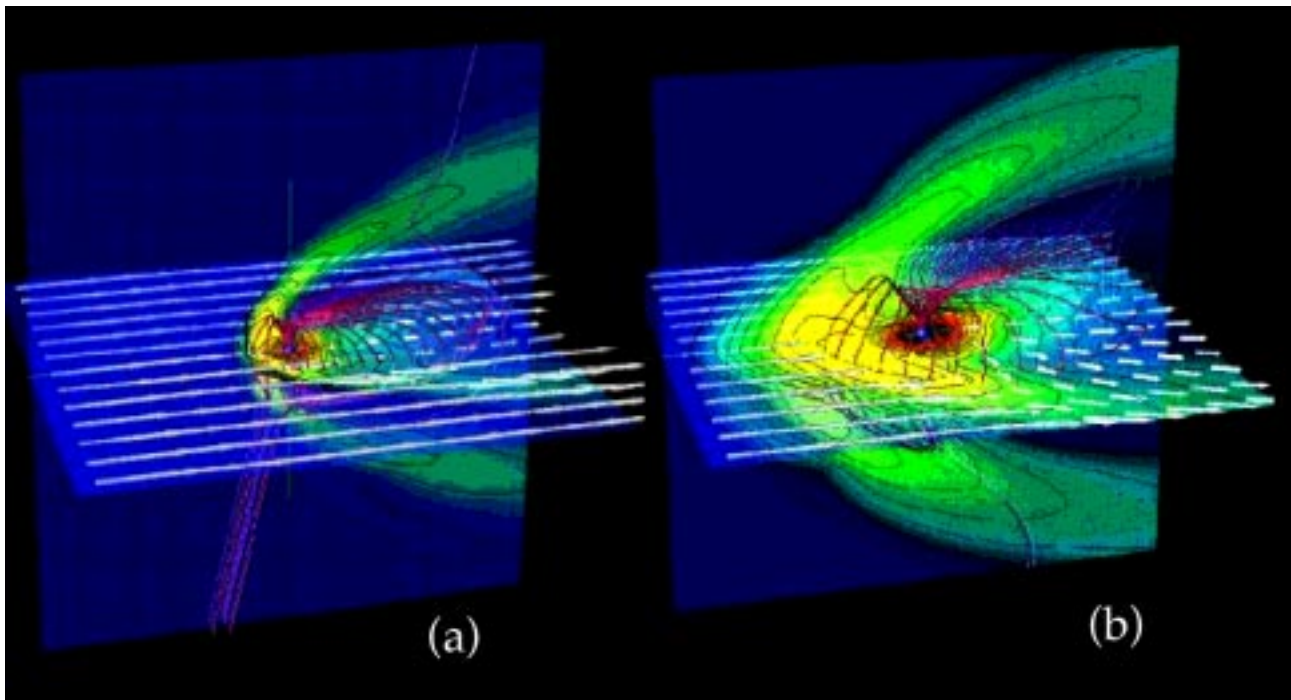
Figure 1. Numerical simulation of (a) dipole magnetic field and (b) plasma inflated dipole magnetic field in the solar wind.

Creating this coupling between the ambient solar wind and the spacecraft mandates the M2P2 to possess three components: (1) a strong magnetic field with a base strength of ~700 G; (2) provide a mechanism capable of injecting copious amounts of cold (~2-5 eV) plasma into the magnetic bubble for [bubble] inflation; and (3) a sufficient power source to handle the generation of both the magnetic field and injected plasma.

2.1. Theoretical Development and Simulation

A full theoretical development of the M2P2 concept, including numerical simulation, has previously been presented by *Winglee et al.* [2000]. The results of this development show that a typical helicon operating with argon (Ar), consuming 600 W to 1 kW of RF power, and producing typical output densities and

temperatures, would: (1) inflate an ~1 kG magnetic field into a magnetic bubble with a coupling cross-section of 15–20 km; (2) would intercept ~40 mN of force from the solar wind; (3) the helicon source would develop ~120 W of plasma power [considering a bulk argon ion (Ar+) speed of ~3 km•s^{-1}]; while (4) consuming 0.6 kg•day^{-1} of [neutral] propellant. Lighter propellants would allow for reduced input mass fluxes of ~0.25 kg•day^{-1} but with an increased power requirement of ~1 kW.

Of course, the final velocity attained by a spacecraft is dependent upon the chosen M2P2 power configuration, the propellant, and its atomic/molecular mass. *Winglee et al.* [2000] simulated the acceleration period and speeds of two specific spacecraft scenarios: a 100 kg vehicle (70 kg payload with 30 kg of propellant); and a 200 kg vehicle (170 kg payload with 30 kg of propellant). The simulation assumed an available power reservoir from solar cells/panels of 2.5 kW at 1 AU (comparable to that of Deep Space 1) and an R^2 decrease in power with an M2P2 cutoff distance (where available power fell below M2P2 requirements) of R_{cutoff} = 1.4 AU. Beyond R_{cutoff} the simulation operated M2P2 in a pulsed-mode with duty cycle $(R_{cutoff}/R)^2$. The simulation also assumed the use of a light propellant and assumed that M2P2 extracted 1 N of force from the solar wind. Results of these simulations showed that spacecraft velocities after 365 days of flight had attained 50 and 75 km•s^{-1}, respectively.

Clearly, a major limitation on the effectiveness of M2P2 is the availability of power. If solar cell power were supplemented using some form of radioisotope source, such as a radioisotope thermal generator (RTG), the M2P2 could be operated in a pulsed-mode for several tens of AU resulting in spacecraft velocities of ~100 km•s^{-1}.

Additionally, it should be pointed out that an M2P2-generated magnetic bubble is a constant force surface. This means that as the M2P2 magnetic bubble travels away from the sun into the solar system, the bubble expands in response to the decreasing solar wind pressure.

2.2. Prototype Characteristics

A prototype M2P2 has been assembled at the University of Washington. The prototype M2P2 system consists of a solenoid to produce the dipolar magnetic field and a helicon plasma source. Figure 2 shows a photograph of the prototype M2P2 system. The solenoid consists of ~2 km of 6-gauge copper wire wrapped around a ~30-cm radius × 20-cm high stainless steel tube. The solenoid is encased inside a stainless steel annular housing to shield the solenoid from direct exposure to plasma. The helicon plasma source [*Chen,* 1994] is capable of producing plasma densities of 10^{13}–10^{14} cm^{-3} and temperatures of 2–5 eV with an input power requirement of ~1 kW. The

M2P2 helicon consists of a 3′-turn 2.5-cm radius helical antenna formed from 6-mm diameter copper tubing allowing the antenna to serve as the delivery system for the fuel [neutral gas]. An aperture located in the vicinity of the cylindrical axis of the antenna allows for the release of fuel near the region of optimal ionization. To ensure sufficient trapping of the helicon-produced plasma by the solenoid generated dipole field the cylindrical axis of the helical antenna is radially offset from the cylindrical axis of the solenoid.
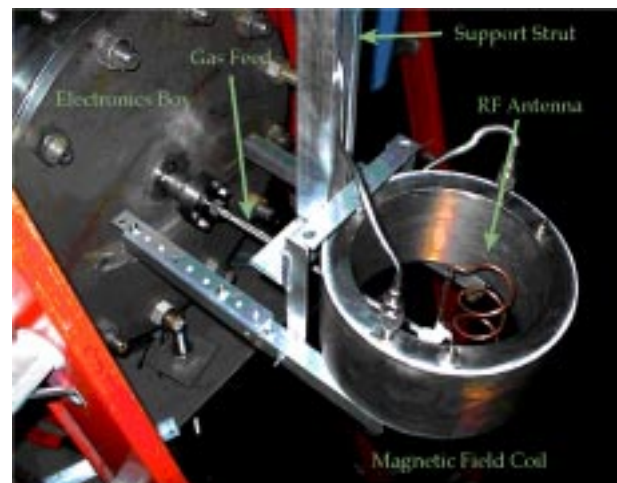
Figure 2. Photograph of the prototype Mini-Magnetosphere Plasma Propulsion (M2P2) system.

3. Large-Scale Testing

Initial large-scale testing of the prototype M2P2 system was conducted at Test Area 300 of NASA/Marshall Space Flight Center (MSFC) from August–September 2000. The testing was performed in a 6-m diameter × 9-m high cylindrical vacuum chamber supported by two (2) 1-m diameter diffusion pumps capable of a pumping rate of 9×10^4 litres•m^{-1}. Laboratory testing of M2P2 utilized helium (He), argon (Ar), and molecular nitrogen (N_2) as helicon fuel and xenon (Xe) in the SEPAC -PC. The goals of the initial large-scale testing of the M2P2 concept were: (1) demonstrate inflation of the magnetic bubble as a function of solenoid current and neutral [fuel] pressure; and (2) demonstrate the deflection capabilities of an inflated magnetic bubble. 2 off-the-shelf video cameras, 1 personal computer "QuickCam", a high-gain CCD-camera, and a double probe that could be translated radially outward along the equatorial plane of the dipole magnetic field provided diagnostics for the initial testing.
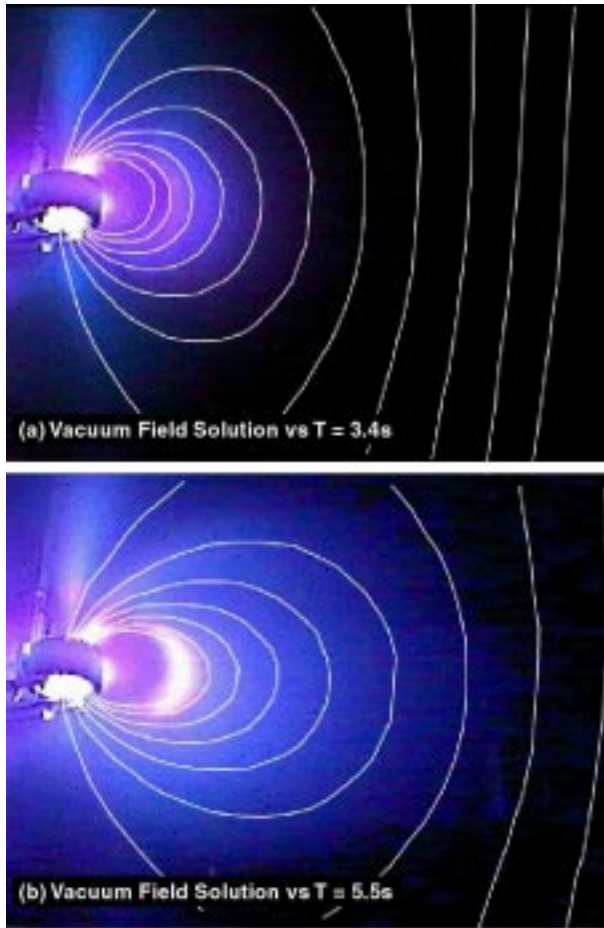
3.1. Inflation

Inflation of the magnetic field [bubble] geometry is illustrated in Figure 3, which presents optical emission from the helicon-generated He+ plasma in a ~350 G dipole magnetic field and requiring 20-dbm of power. Panel (a) shows the configuration of the M2P2-generated magnetic bubble shortly after ignition (T = 3.4 s) in comparison to a vacuum field model of the solenoid-driven dipole field geometry. Notice that the plasma emission closely matches the vacuum field solution and that the vacuum field solution indicates that no closed field lines exists beyond ~ 1-m. Panel (b) shows an inflated M2P2-generated magnetic bubble at T = 5.5 s where β ~ 0.5 is the estimated plasma beta. The vacuum field solution for panel (b) indicates expansion of closed field line geometry beyond ~1.5-m. Expansion of the magnetic bubble continues as $\beta \rightarrow 1$. Optical plasma emission demonstrates that as $\beta \rightarrow 1$ the expansion of the magnetic bubble exceeds ~30 R_{M2P2}, and that the primary limitation to the expansion in the testing facility is recombination with chamber neutrals and the chamber walls themselves.
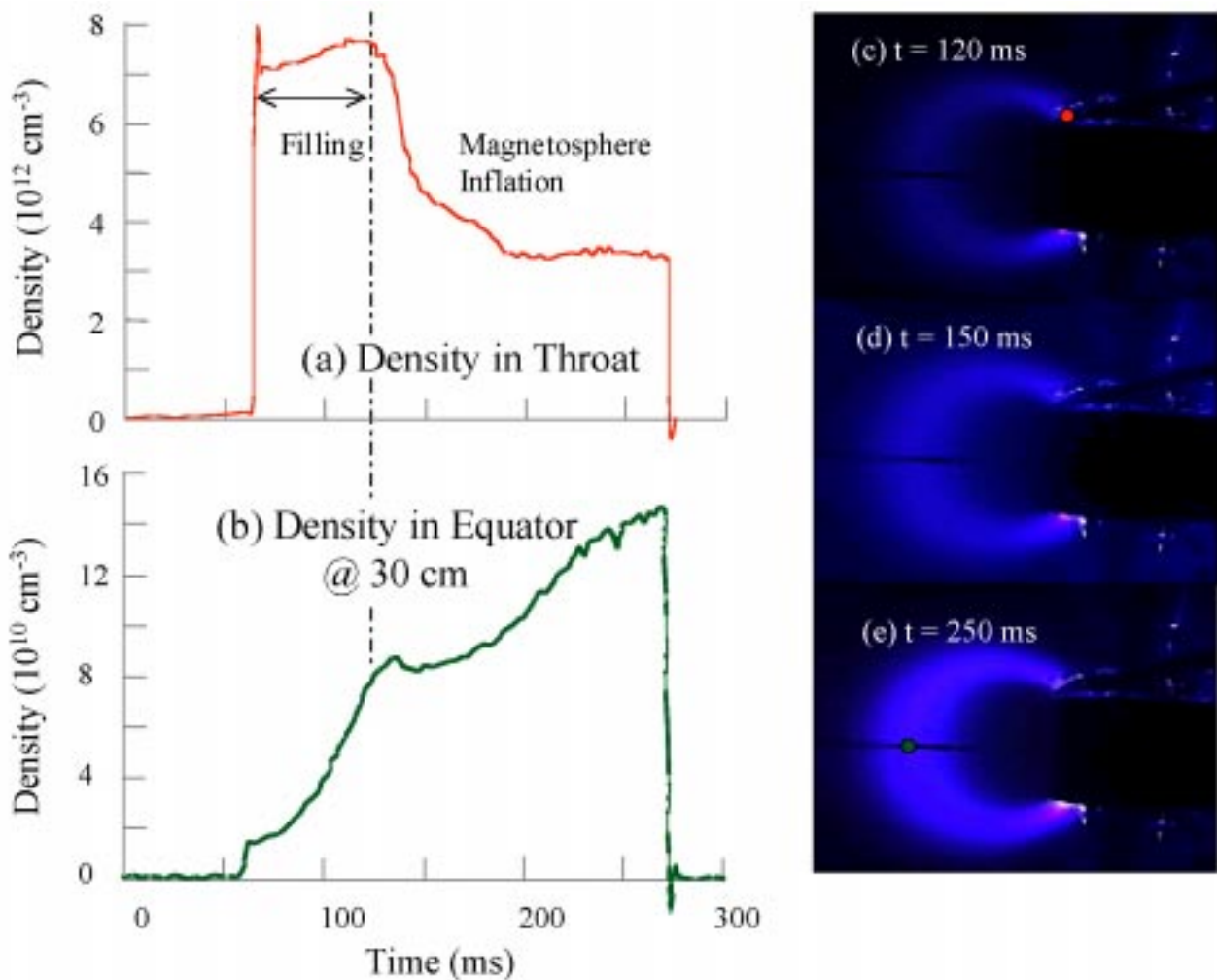
Figure 4 presents ambient electron density profiles acquired by double probe during magnetic bubble expansion. Figure 4(a) shows the temporal density profile in the throat of M2P2 as indicated by the red dot in Figure 4(c). The profile shows that as the magnetic bubble is initially filled with plasma, the throat density holds relatively constant at 7×10^{13} cm^{-3}, and then decreases exponentially once expansion of the magnetosphere [bubble] begins at ~150-ms. Figure 4(b) presents the temporal density profile measured at an equatorial distance of ~30-cm away from the outer surface of M2P2, as indicated by the green dot in Figure 4(e). The equatorial density profile is seen to increase at a near linear rate of ~6×10^{11} cm$^{-3} \cdot$ s^{-1}, after T = 60-ms, due to expansion of the mini-magnetosphere [bubble].

Figure 3. Demonstration of inflation of an artificial magnetosphere [magnetic bubble] as a function of the injection of cold plasma into a 350 G dipole field at (a) T = 3.4 s and (b) T = 5.5 s after ignition of the plasma.

3.2. Deflection

Having established the inflation characteristics of the prototype M2P2 system, focus of the testing shifted to demonstrating the ability of the M2P2-generated magnetic bubble to deflect a *"surrogate"* solar wind. The surrogate solar wind plasma stream was produced on the opposite side of the test chamber (~4.25-m separation) using the Xenon Plasma Contactor (PC) from the Space Experiments with Particle Accelerators (SEPAC) experiment [*Burch et al.* (1994)], which flew on the Atlas-1 mission. The PC is a hollow-cathode ion contactor capable of delivering an ion-electron production rate of 1.6 A during continuous operation. The expectation thermal energy of the PC-emitted plasma stream is ~2–5 eV. In each case, SEPAC is ignited and allowed to attain a steady-state condition prior to ignition of M2P2.

Figure 5 presents results of the interaction of the M2P2 magnetic bubble and a SEPAC-generated plasma stream. During this sequence of testing, M2P2 was supplied with argon (Ar) fuel and operated at 400 W of RF-power, while SEPAC was operated at 4 A and 800 W of power. A barrier [magnetopause] between the M2P2-generated Ar+–filled magnetic bubble (400 G) on the left and the SEPAC-generated Xe+–e⁻ stream on the right appears as the slightly curved transition from blue-to-black located ~0.55 of the way across the image (referenced from the left) of Figure 5(a). Note that the field-of-view of the image only encompasses ~2 m. This barrier is observed to move toward SEPAC (toward the right) as the magnetic bubble inflates with plasma. The barrier also translates across the field-of-view as a function of M2P2 base magnetic field strength. This is demonstrated in Figure 5(b) where the operational parameters of both M2P2 and SEPAC are identical to those of Figure 5(a) with the exception of an increase in M2P2 magnetic field to 800 G. Consequently, the barrier [magnetopause] in Figure 5(b) is located ~0.75 of the way across the image.

Figure 4. Double probe measurement of the ambient electron density (a) at the throat of the magnetic field coil and (b) at an equatorial position ~30 cm from the outer radius of the field coil. Panels (c)–(e) show a time series of images showing the expansion of the artificial magnetosphere and location of the density measurements.

4. Future Testing

Follow-on testing of the M2P2 system will commence at Test Area 300 of NASA/Marshall Space Flight Center in August 2001. This sequence of tests will focus on three major areas: (1) quantification of the plasma parameters of the artificial magnetic bubble; (2) obtaining a reliable and reproducible measure of the thrust developed in response to the deflection of a surrogate solar wind; and (3) optimization of M2P2 operational parameters.

Quantifying the ambient plasma parameters of M2P2 will be accomplished through the use of a number of techniques [e.g., *Huddlestone and Leonard*, 1965] including: spectroscopic techniques, a translational double-probe, an array of Hall probes, an array of [standard] Langmuir probes, and an array of RF-compensated probes [*Sudit and Chen*, 1994]. Measurement of the thrust likely to be imparted to the M2P2 system from a surrogate solar wind (≥ 10 mN) is not trivial. Consequently, two separate and distinct measurements of M2P2-intercepted thrust are planned. In July 2001, collaboration with researchers at NASA/Glenn Research Center (GRC) is planned. During this testing the prototype M2P2 will be mounted to a GRC thrust stand and then the inflated magnetic bubble will be subjected to the plasma flow from either a Hall or ion thruster. Then, in August 2001, thrust measurements will be made at MSFC with the prototype M2P2 mounted to a simpler thrust stand and subjecting the inflated magnetic bubble to a Vasimir flow from a University of Washington ion source. The thrust measurements acquired at MSFC will be supported by the in-situ plasma diagnostics described previously.

With these measurements in hand the M2P2 Technical Working Group (TWG) will be better able gain a sense of the potential coupling efficiency of the system as well as allow for the optimization of the

system's operational parameters. The data will also allow for a theoretical evaluation of the stability of an artificially generated magnetic bubble subjected to the solar wind as well as the probable velocities attainable by an M2P2-based spacecraft.

5. Conclusions

Man's desire to explore the outer reaches of the solar system imposes a requirement that future spacecraft possess the ability to travel at speeds in excess of 50 km•s^{-1}. While solar sails offer the potential of obtaining such velocities through a highly efficient coupling between solar photons and an opaque/reflective sail, the concept is [currently] technologically limited by the need for robust ultra-thin foils and extensive light-weight support structures. Consequently, an alternative approach for coupling to the solar environment is required. Such an alternative is the Mini-Magnetosphere Plasma Propulsion (M2P2) system which seeks to use current off-the-shelf technology to inflate a large magnetic bubble around a spacecraft in order to deflect the charged 300–800 km•s^{-1} solar wind particles thereby transferring particle momentum to the spacecraft. The overview of theoretical and numerical simulation of the M2P2 presented in this paper clearly demonstrates the potential of this system to develop the required spacecraft velocities. These velocities are attainable at a modest cost of ~1 kW per 100 kg of payload power requirement and ~1 kg of neutral gas [fuel] consumption per day of acceleration.

Large-scale testing of the Mini-Magnetosphere Plasma Propulsion (M2P2) concept at Test Area 300 of NASA/Marshall Space Flight Center has demonstrated the ability of the M2P2 to produce and inflate an artificial magnetosphere or magnetic bubble using commercially available off-the-shelf technology. Theoretical and laboratory estimates of inflation indicate that the prototype M2P2 tested has the capability to inflate to an operational cross-section of ~15–20 km. Large-scale testing of a prototype M2P2 has also demonstrated the ability of an M2P2-generated magnetic bubble to deflect a surrogate solar wind. Future testing of the prototype M2P2 system seeks to quantify the ambient parameters of the trapped plasma used to inflate the magnetic bubble, as well as measure the thrust imparted to the system through interaction with a surrogate solar wind. This information will then be used as a simulation input to optimize the M2P2 system and obtain definitive estimates for the expectation thrust and spacecraft velocities extracted from the solar wind in a space-borne application, leading to the production of an engineering model for flight on a proof-of-concept mission.

Figure 5. Interaction of an artificial magnetosphere and a surrogate solar wind showing the presence of a magnetopause (dark slightly curved vertical region) separating the opposing plasmas. Note the translation of the magnetopause location from (a) ~0.55 the width of the image to (b) ~0.75 the width.

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