# M2P2 - USING VARIABLE POWER RADIAL THRUST FOR INTERPLANETARY AND INTERSTELLAR TRAVEL

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***Mini-Magnetospheric Plasma Propulsion, or M2P2 inflates a magnetized plasma to capture the momentum of the solar wind. M2P2 systems are capable of reaching speeds of over 80 km/s making travel to the edge of the solar system and beyond possible. The size of the magnetic "bubble," or sail, is largely dependent on the power input. This leads to very fine control over the force on the spacecraft throughout the flight time. Because of this, launch windows can be extended, and a wide range of planetary approach vectors are available.***

## Introduction

Exploration beyond our own solar system is an enticing goal, but is as of yet, difficult to achieve. Voyager 1, launched in 1977, has a speed of approximately 20 km $s^{-1}$.[1] It has been traveling for 26 years and is only now reaching the termination shock of the solar system. Designing any space system is a complicated process, a system which must function for 26 years just to begin its primary mission to explore beyond the solar system is not practical. Exploring deep space requires faster spacecraft to allow for shorter, more practical, mission times.

Exploration within the solar system is not without difficulties of its own. Current methods of electric propulsion generate very low thrusts making massive spacecraft for interplanetary missions difficult. High thrust options, such as chemical rockets, are so massive that the launch costs become prohibitive. As Earth's space presence increases, more massive spacecraft will be required to go further distances and current propulsion methods do not easily allow for this.

Another problem holding back more ambitious space missions, such as bases on other planets, is that of the launch window. Most current propulsion methods have thrust levels that are not easily altered. This means that the spacecraft will reach its destination in a specific amount of time. If a problem appears and the launch must be delayed even for a few days, the mission must often be put off until the planets line up in that same configuration again, which could be years. Launch windows will need to be extended to ensure that space missions can continue even if they need to be delayed for a time.

Mini-Magnetospheric Plasma Propulsion, or M2P2 is a method of propulsion that uses the solar wind pressure to propel a spacecraft. A magnetic field is generated to produce a "sail" that deflects the solar wind causing a transfer of momentum to the spacecraft. Ordinarily, the magnetic field that would be able to be generated by standard spacecraft power systems would only be a few meters. M2P2 proposes the idea of injecting a plasma into the magnetic field, which would stretch the field to tens of kilometers, hence the name plasma sail. This system avoids the complications commonly associated with solar and other mechanical sails. Since there is no physical sail the mass is greatly reduced and there is no need for a deployment mechanism. Because M2P2 uses the ambient medium for momentum transfer and has such a large sail, thrusts of several Newtons can be achieved. Many other means of electric propulsion have thrusts in the milli-Newton range. Under ideal circumstances, an M2P2 system could produce thrusts of over 120 N[2] with a mass of only 130 kg and a power requirement of 1.8 kW.

Because of the large thrust, M2P2 is able to reach speeds approaching 100 km $s^{-1}$. This makes interstellar travel more reachable due to the shorter mission times. The thrust generated is a function of distance from the Sun and power. By adjusting the power, very fine control over the thrust is available. This allows for variable travel times to a destination allowing for a longer launch window. Since all thrust from solar wind is in the radial direction, there is no increase in angular momentum. This allows for any travel time to result in the same velocity when the craft arrives at its destination assuming a tangential arrival. This can allow for a launch window extension of several weeks.

## Performance Modeling

The performance of an M2P2 system is dependent on the size of the sail and the solar wind pressure. The solar wind pressure is a function of distance and, obviously, cannot be modified. The regulation of the systems performance is therefore dictated by the sail size. The 'sail' is simply the portion of the generated magnetic field strong enough to deflect the solar wind particles. Once the sail size has been determined a force and orbit transfer calculation can be done.

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### Magnetic Field Modeling

The magnetic field is largely dependent on the properties of the solenoid used. The following coil parameters were used for calculations in this discussion:

**Table 1 Coil Parameters**

| Variable | Description | Value |
|---|---|---|
| $R_c$ | Coil Radius | $0.1m$ |
| $L_c$ | Coil Length | $0.2m$ |
| $R_{plas}$ | Plasma Source Radius | $0.025m$ |
| $r_w$ | Wire Resistance[3] | $0.0053\Omega m^{-1}$ |
| $L_w$ | Wire Length | $7000m$ |
| $B_{MP}$ | Required Field Strength | $50 * 10^{-9}T$ |
| $\frac{V_A}{V_{plas}}$ | Ratio of Alfven Velocity[4] to Plasma Velocity | 50 |

The sail radius is limited by the boundary where the magnetic pressure of the sail matches the pressure of the solar wind. The falloff of the magnetic field strength is governed by the equation

$$B(R) = B_0 \left( \frac{R_c}{R} \right)^n \tag{1}$$

with $R$ equalling the radial coordinate and $n$ equalling the magnetic field profile parameter.[5] For a standard magnetic field, $n$ is approximately equal to 3. Simulations done by Robert Winglee show that the injected plasma reduces $n$ to near 1, slowing the drop in the magnetic field to $R^{-1}$, allowing for much larger sail sizes.[4] This paper will use a value of 1.05 for $n$ allowing for some variation from the ideal case of $n = 1$.

The magnetic field generated by a solenoid is given by

$$B_0 = \frac{\mu_0 N I}{L_c} \tag{2}$$

where $N$ is the number of turns, $I$ is the current, and $\mu_0$ is the permeability of free space. Combining this with the required electrical power

$$P = r_w L_w I^2 \tag{3}$$

leads to the final result for coil field strength as a function of power:

$$B_0 = \sqrt{\frac{P}{L_w r_w}} \frac{\mu_0}{2\pi L_c R_c} \tag{4}$$

where the power is modeled as a squared falloff shown by

$$P = P_0 \left( \frac{R_0}{R} \right)^2 \tag{5}$$

with $P_0$ equalling the initial available power and $R_0$ representing the initial orbital radius. By combining equations 1 and 4, the sail size can then be determined from

$$R_{sail} = \frac{R_c}{\frac{B_{MP}}{B_0}^{\frac{1}{n}}} \tag{6}$$

### Force Modeling

Several force measurements were obtained empirically by Dr. Joseph Wang for different coil strengths and orbital radii.[2] The force on the spacecraft for a constant power is linearly proportional to radius as:

$$F(R) = m_F R + F_0 \tag{7}$$

where $m_F$ and $F_0$ are functions of power following

$$F_0 = 73260 B_0^{3.6353} \tag{8}$$

$$m_F = -1 \times 10^{-9} B_0^2 + 5 \times 10^{-11} B_0 - 3 \times 10^{-13} \tag{9}$$

Equation 9 becomes closer to the exponential function

$$m_F = -6 \times 10^{-8} B_0^{3.6918} \tag{10}$$

for very low force values such as those experienced near the edge of the solar system.

The equations of motion

$$F(R) - M \frac{G M_S}{R^2} = M \left( \frac{d^2 R}{dt^2} - R \left( \frac{d\theta}{dt} \right)^2 \right) \tag{11}$$

$$0 = M \left( R \frac{d^2\theta}{dt^2} + 2 \frac{dr}{dt} \frac{d\theta}{dt} \right) \tag{12}$$

where $M$ is the spacecraft mass and $M_S$ is the mass of the Sun, can then be numerically integrated to obtain an orbit transfer track and velocity profile.

## Interstellar Travel

The primary focus of M2P2 systems to this point has been for interstellar travel. In order for a mission to the edge of the solar system to be practical it must have a relatively short time frame of about 10 years.[4] Beyond this it is difficult to maintain functionality on a spacecraft. It is also difficult to coordinate scientific missions that will span such a long time. In order to achieve this sort of time frame, speeds of 50 km s$^{-1}$ are required.

M2P2 systems are potentially capable of speeds approaching 100 km s$^{-1}$. Using the squared power falloff model which represents a solar cell array, the M2P2 has a relatively short acceleration time. For interstellar missions a secondary power source may be required to keep the system operating beyond a couple of AU.

Below is an example of a 200 kg spacecraft with an initial power of 1 kW. If the power is limited strictly to the solar cell falloff rate, the system settles at around 42 km s$^{-1}$. If the power is kept at a minimum of 400 W, however, the spacecraft reaches speeds close to 80 km s$^{-1}$. One method to maintain this power could be a radioisotope thermal generator, or RTG system.[6] A second option would be to run the system in pulsed mode. In this mode the system turns off long enough to charge a battery and then turns back on for a short pulse.[4]

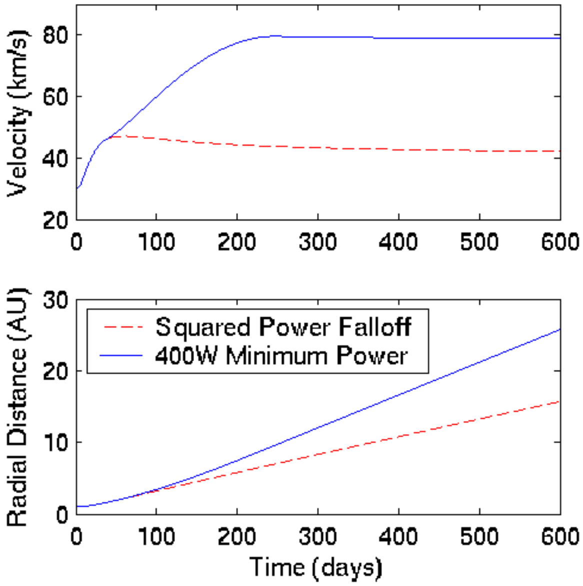

**Fig. 1 Sample escape trajectory for 200 kg spacecraft with 1 kW initial power.**

Figure 1 shows how an M2P2 system would be able to reach the speeds required for interstellar exploration assuming a reserve source of power can be found. The figure shows velocity and distance profiles for the 200 kg spacecraft for a period of 600 days. In both cases the spacecraft reaches a relatively constant velocity in under a year. Even with no backup power system, the spacecraft still achieves speeds over 40 km $s^{-1}$; twice as fast as Voyager 1.

## Interplanetary Travel

Because of M2P2's control over thrust and the fact that the thrust is in the radial direction, it makes a good interplanetary propulsion system as well. The thrust exerted on an M2P2 system is entirely in the radial direction. This means that no angular momentum is added to the system throughout the orbit transfer. Because of this, when the orbit transfer is tangent to a circular orbit, such as in arrival at a planet, the velocity can be predicted since there is no radial velocity at this point. This can be extended to say that regardless of how quickly, or what path is taken, when the spacecraft arrives at a planet tangentially it will have the same velocity. This allows for the same capture and landing procedures to be used for a variety of transfer orbits.

Since M2P2's thrust is dependent on power, a spacecraft with excess power can greatly alter its orbit when using an M2P2 system. By engaging the engine at hight thrust, escape orbits, or high energy orbits that do not escape can be easily achieved. By engaging the engine at low thrust the same spacecraft could approach a planet and achieve a tangential arrival. By starting the engine at a high thrust and then switching it off once sufficient energy has been built up, the spacecraft can coast into a tangential planetary capture, but in a much shorter amount of time than the low thrust alternative.

These orbit transfer types are shown in Figure 2 for a 450 kg spacecraft with an initial power availability of 1 kW.

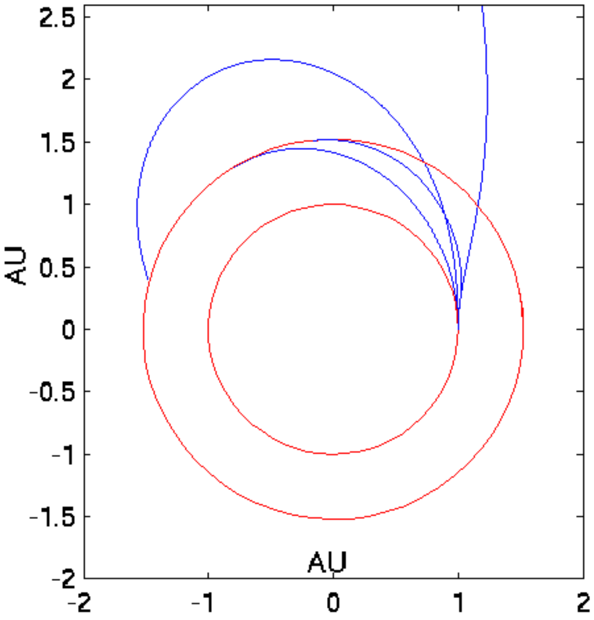

**Fig. 2 Sample Mars orbit transfers. Two have tangential arrivals, one high energy, and one escape velocity.**

The escape orbit is easily achieved by thrusting at the full 1 kW. The other high energy orbit is attained by running the system at 750 W. These orbits may be useful for a fly-by of Mars, but are not especially useful for planetary capture since the relative velocity will be prohibitively high. The other two orbits are of more interest. Both of these orbits arrive at Mars tangentially, but in different amounts of time. The longer orbit uses 500 W of initial power and is run the entire time. The second orbit starts at the full 1 kW of power and is turned off when sufficient energy is added to reach Mars.

With a variable radial thrust system, such as M2P2, a wide range of orbital trajectories are available for a single spacecraft. Not only does this allow for a more standardized spacecraft to do a variety of missions, it also allows for an increased launch window. Figure 3 shows the time of flight difference for four different spacecraft masses. All orbits arrive at Mars tangentially with a velocity of 19.5 km $s^{-1}$.

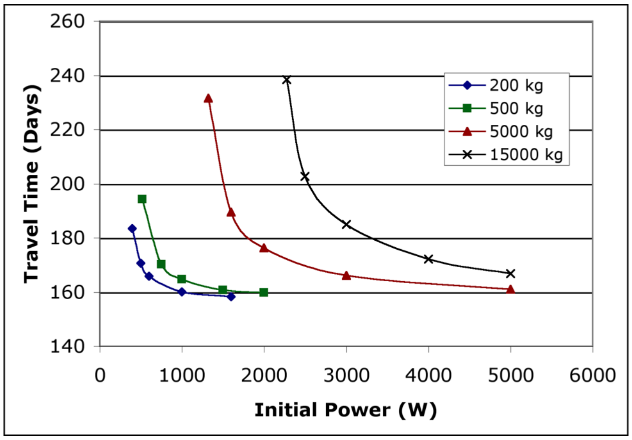

**Fig. 3 Transfer times for Mars transfer as a function of initial available power. Four different spacecraft masses are represented**

In all cases a small increase in power can lead to a large decrease in travel time. A large increase in power, however, will not necessarily translate to a larger decrease in travel time as diminished results are experienced after substantial increases in power. Since all of the orbits end up with the same velocity relative to Mars, they all can use the same landing system. Since the orbit is a function of power, the launch window can be greatly extended for a given spacecraft.

## Removal of Mass Dependancy

Figure 3 shows time of flight for four different spacecraft masses as a function of initial power. By dividing the available power by the square root of the spacecraft mass, the plot becomes independent of mass. This is shown below in Figure 4.

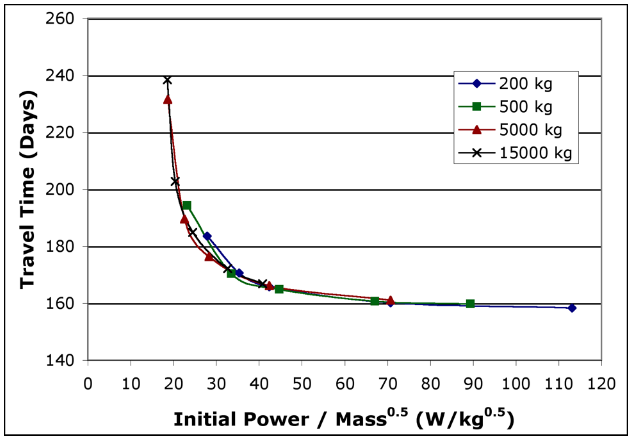

**Fig. 4 Transfer times for Mars transfer orbits. The square root of the mass has been divided into the power to converge all masses onto one line.**

Figure 4 expresses a convenient way to estimate the time of flight to Mars as a function of the two driving factors, initial power and mass. It make sense to define a variable, $\alpha$ for this term:

$$\alpha = \frac{P_0}{\sqrt{M}} \tag{13}$$

Increasing $\alpha$ generally lowers your transfer time at the expense of increased power requirements. This relationship experiences diminished results and becomes asymptotic at a time of flight around 158 days implying that it would be difficult to attain a tangential arrival in under 158 days. This is not to say that a non-tangential arrival could not take place in under 158 days, however, such as those shown in Figure 2. Conversely, there is also a minimum $\alpha$ of around 16, implying that raising your travel time much above 200 days does not save any appreciable amount of power.

## Approximation of Minimum Power

While the curve in Figure 4 theoretically extends forever asymptotically, that is not to say that any spacecraft can be placed at any point on that curve. Every spacecraft has a minimum initial power, based on mass, that is required for the spacecraft to reach its destination. A plot of minimum power to reach Mars is shown below.

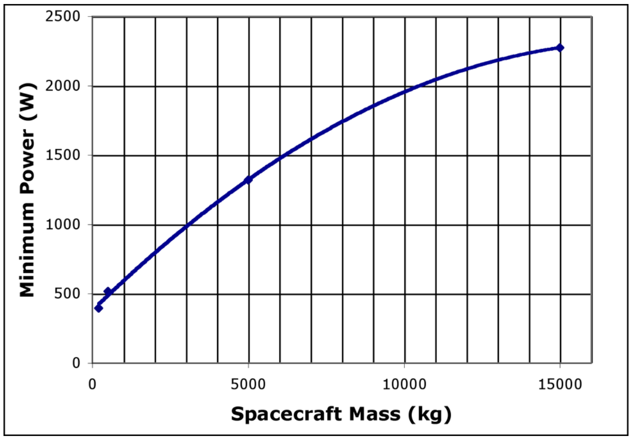

**Fig. 5 Minimum initial power required for Mars transfer based on spacecraft mass.**

This leads to larger spacecraft having lower minimum $\alpha$ values and therefore higher maximum travel times. This minimum $\alpha$ can be plugged into Figure 4 to get the transfer time for the lowest power scenario.

Figure 6, below, shows a plot of $\alpha$ vs $\delta$ for five different planets. In this case $\delta$ is a temporary variable used for comparison purposes. Plugging in two different $\alpha$ values will result in two different $\delta$ values, measured in days. The difference between these two values is the difference in flight time for the two $\alpha$ values.

For example, take the same 450 kg, 1 kW spacecraft on a mission to Mars. By plugging 450 kg into Figure 5 it is shown that the minimum power to reach Mars is about 500 W. This corresponds to an $\alpha$ of about 24 W

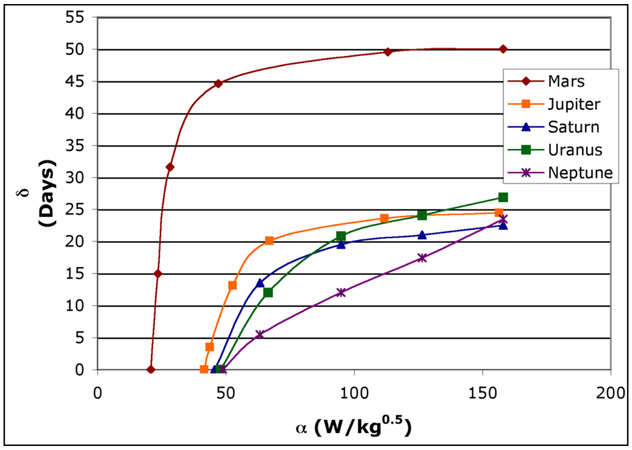

**Fig. 6 Used to calculate difference in flight time for five different planets. $\delta_{\alpha min} - \delta_{\alpha_0}$ is the difference in flight time for the two power levels**

kg$^{-0.5}$. The maximum initial power, 1 kW, translates to an $\alpha$ of about 47 W kg$^{-0.5}$. Using Figure 6, these correspond to $\delta$ values of 15 and 44.6 days, for a savings of 29.6 days.

Figure 6 only shows a small segment of this graph. All of the lines, theoretically approach asymptotic values in both directions. This region, however, includes most spacecraft arrangements that are currently in use.

Although the plot for Mars is above all of the other planets, this does not mean that Mars necessarily has a larger difference in flight times, since this plot only measures a difference between two values, not an absolute value. Mars does, however, have a much sharper curve than the other planets. As the distance increases, the curvature of the plot decreases. This implies that for a closer planet, such as Mars, a small amount of power will result in a large savings in time, but larger amounts of power will not extend the time difference much further. A far planet, such as Neptune, on the other hand, will take a larger amount of power for the same time savings, but will be able to be extended much further with reasonable power requirements. In fact, for this region where most spacecraft lie, Neptune has an almost linear relationship between $\delta$ and $\alpha$.

### Launch Window Extension

Launch windows for space missions have always been a problem. If the window is missed it may be years before another alignment takes place and most current space missions have a launch window of only a day or two. M2P2 presents an extended launch window by varying the power. The launch window can be calculated according to

$$LW = \frac{\Delta\nu - \Delta TOF \dot{\theta}_{rel}}{\dot{\theta}_{rel}} \tag{14}$$

where $\Delta\nu$ is the difference in true anomaly of the two orbits and $\dot{\theta}$ is the relative motion of the target planet to Earth. This equation accounts for the difference in flight times as well as the different arrival positions in the planet's orbit and the synodic rates of the two planets.

The true anomaly, or angular position, of the spacecraft upon arrival is important when calculating the launch window. Figure 7, below, shows the true anomaly of the spacecraft for an arrival at Mars.

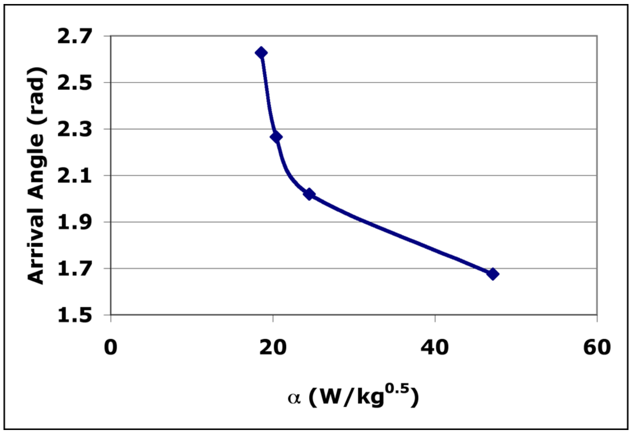

**Fig. 7 The relative angle, or true anomaly, of a spacecraft arriving at Mars.**

Combining this with Figure 6 and Equation 14, leads to a plot of the launch window as a function of $\alpha$ shown below in figure 8.

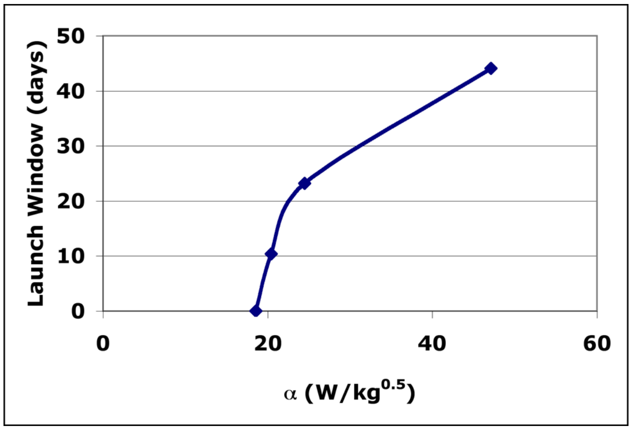

**Fig. 8 Launch window for a spacecraft mission to Mars.**

Figure 8 shows that the launch window for a mission to Mars can be extended to 45 days and beyond by increasing the power. This would allow for delays in launch due to bad weather, equipment problems, etc. With 45 days available there may even be time for a second launch attempt if the first fails.

## Potential Limitations

The most critical limitation of this study is fuel consumption. The rate at which plasma will need to be used is not entirely known and is not constant. This study, therefore does not account for mass loss due to propellant. It is estimated that plasma usage will be on the order of 0.25-0.5 kg day$^{-1}$, but this is speculative and is dependent on power.[4]

The direction of the force on the spacecraft is always in the radial direction. This may lead to a secondary method of propulsion being required for slowing down or changing direction. This paper does not take into account course corrections, or planetary capture once the destination is reached.

The preceding calculations were based on empirical data. The curve fits are not perfect and may result in slight errors in calculations. Additionally, the orbit integrations could be made more accurate by using a smaller time-step.

M2P2 systems will not work inside of Earth, or any other planet's own magnetic field. A planet's magnetic field acts in the same way the spacecraft's field acts to stop the solar wind. This means that any spacecraft to use an M2P2 system must have a method of traveling outside of Earth's magnetic field and a method of operating once it enters another planet's magnetic field. The radius of Earth's magnetic field is estimated at 60,000 km although this number has a large amount of uncertainty.

The problem of variations in the solar wind is not of major importance. Since the plasma sail is based on a pressure balance, any increase in pressure will shrink the sail and a decrease in pressure will stretch the sail, resulting in approximately the same force. This is a major advantage over structural sail systems which have a fixed cross section regardless of pressure.

## Further Research

If extended for long periods of time, radial force orbits such as M2P2 produce cyclical orbits such as the one shown below in Figure 9. This type of orbit could potentially prove useful for recurring missions such as resupply or repair of an object in space. If a manned presence is ever placed on Mars, for instance, cycler orbits such as this will be very useful for supply missions. While the orbit shown in figure 9 lines up with Jupiter and Earth, that is not to say that it matches the synodic period of the two planets. A more detailed study would have to be done to design an orbit that lined up with the orbits at the correct times.

Further research must be done on the solar wind pressure and its interaction with the plasma sail. This would allow for more accurate force measurements as well as a better understanding of how much plasma will be required to keep the system operational.

It is possible to use an attitude control system to rotate the spacecraft allowing the solar wind to hit the magnetic plasma bubble from a different angle. This method may be used to change the direction of the force vector. This would, however, require a relatively strong attitude control system to counteract the torque put on the spacecraft by the solar wind pressure.

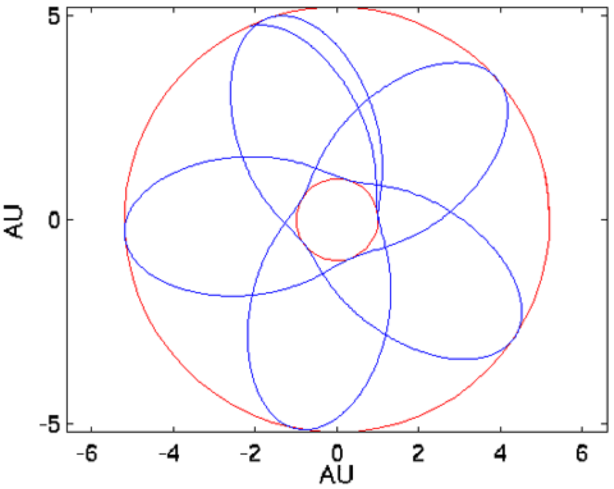

**Fig. 9 Cyclical orbit between Earth and Jupiter generated with radial thrust M2P2 system.**

## Conclusion

In order to practically explore beyond the solar system, spacecraft will need to travel at speeds of 50-80 km s$^{-1}$. The would be too high to use chemical propulsion and the power requirements too great to use most electric propulsion methods. Mini-Magnetospheric Plasma Propulsion, or M2P2 uses an energized plasma to inflate a magnetic field bubble to a radius of tens of kilometers. This bubble, or plasma sail, can then gain momentum from the incoming solar wind. Because the spacecraft uses the momentum of the ambient medium, the system can generate moderate thrusts with far lower power requirements than current electric propulsion methods. M2P2 offers a method of achieveing speeds of 50-80 km s$^{-1}$ with modest power and mass requirements on the order of 1 kW and .25-.5 kg day$^{-1}$ making exploration of distant space possible.

The M2P2 system can also be used effectively for interplanetary travel. Because the force is dependent on power input, the thrust can be altered dramatically throughout flight. All thrust is radial, meaning that no angular momentum is added to the system. Because of this any tangential approach to a planet, regardless of time or path taken, will have the same velocity on arrival. By operating at different power levels, an M2P2 powered spacecraft can therefore have a launch window of several weeks and if need be, arrive in a very short time. Radial thrust orbits, such as M2P2, also produce cyclic orbital tracks and may be used for recurring missions such as resupply or repair missions.

M2P2 is in very early development, however, and any calculations done are rudimentary. Many of the interactions between the solar wind and the plasma sail are not yet fully modeled and there is a large amount of uncertainty in the performance of the sail.

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