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The Dipole Drive: A New Concept in Propellantless Propulsion

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Abstract

The dipole drive is a new propulsion system which uses ambient space plasma as propellant, thereby avoiding the need to carry any of its own. The dipole drive remedies two shortcomings of the classic electric sail in that it can generate thrust within planetary magnetospheres and it can generate thrust in any direction in interplanetary space. In contrast to the single positively charged screen employed by the electric sail, the dipole drive is constructed from two parallel screens, one charged positive, the other negative, creating an electric field between them with no significant field outside. Ambient solar wind protons entering the dipole drive field from the negative screen side are reflected out, with the angle of incidence equalling the angle of reflection, thereby providing lift if the screen is placed at an angle to the plasma wind. If the screen is perpendicular to the solar wind, only drag is generated but the amount is double that of electric sail of the same area. To accelerate within a magnetosphere, the positive screen is positioned forward in the direction of orbital motion. Ions entering are then propelled from the positive to the negative screen and then out beyond, while electrons are reflected. There are thus two exhausts, but because the protons are much more massive than the electrons, the thrust of the ion current is more than 43 times greater than the opposing electron thrust, providing net thrust. The dipole drive in thrust mode can achieve more than 6 mN/kWe in interplanetary space and better than 20 mN/kWe in Earth, Venus, Mars, or Jupiter orbit. To deorbit, the negative screen is positioned forward, turning the screen into an ion reflector. No power is required to produce lift or drag. In contrast to the electric sail, the ultimate velocity of the dipole drive is not limited by the speed of the solar wind. It therefore offers potential as a means of achieving ultra-high velocities necessary for interstellar flight.

Keywords: (Advanced propulsion, electric propulsion, plasma, propellantless propulsion)

I. Introduction

The performance of rockets as propulsion systems is greatly limited by their need to carry onboard propellant, which adds to the mass which must be propelled exponentially as the extent of propulsive maneuvers is increased. For this reason, engineers have long been interested in propulsion systems that require no propellant.

The best known propellantless system is the solar sail, which derives its thrust by reflecting light emitted by the Sun. Solar sails are limited in their performance however, by their dependence upon sunlight, which decreases in strength with the square of the distance, and the laws of reflection, which dictate that the direction of thrust can only lie within 90 degrees of the vector of sunlight. Moreover, because photons move so swiftly, the amount of thrust that can be derived be reflecting light is at best 0.0067 mN/kW (at 100% reflectance, full normal incidence), which means that very large sails, which necessarily must have significant mass and be difficult to deploy, must be used to generate appreciable thrust. As a result, while solar sails have been studied since the time of Tsiolokovsky[1], they have only been used once in space.

An alternative to the solar sail is the magnetic sail, or magsail, which was first proposed by Zubrin and Andrews in 1988, and subsequently analyzed extensively by them in a variety of further papers[2,3] in the 1990s. The magnetic sail uses a loop of superconducting wire to generate a magnetosphere to deflect the solar wind. Assuming the development of high temperature superconducting wire with the same current density as existing low temperature superconductors, a magsail should be able to generate significantly higher thrust to weight than is possible with solar sails. However such wire still under development.

Another propellantless propulsion system of interest is the electric sail[4], which like the magsail operates by deflecting the solar wind, in its case by using an electrostatic charge. As a result, like the magsail, the classic electric sail (electric sail) cannot operate inside of a planetary magnetosphere other than as a drag device, has its thrust decrease with distance from the Sun, and is limited in the potential direction of its thrust. Because of the low momentum density of the solar wind, electric sails must be even bigger than solar sails. However, because only sparsely spaced thin wires are needed to create sail area, higher thrust to mass ratios can be achieved than are possible using solar sails which require solid sheets of aluminized plastic.

Electrodynamic tethers[5] have also been proposed, which use the interaction of a current in a tether with the Earth's geomagnetic field to produce thrust. In addition to facing a variety of engineering and operational issues, however, such systems can only operate in a planetary magnetic field and can only thrust in a direction normal to the field lines, a consideration which limits their applicability.

Finally, we note recent claims for a system called the EM Drive[6], which according to its proponents can generate about 1 mN/kWe, in any direction, without the use of propellant, an external light source or plasma wind, or magnetic field. Such performance would be of considerable interest. However, as it appears to contradict the laws of physics, there is reason to suspect that the measurements supporting it may be erroneous.

As a result, there clearly remains a need for a new type of propellantless propulsion system, which can operate both inside and outside of a planetary magnetosphere, can thrust in a multitude of directions, and which is not dependent upon sunlight or the solar wind as a momentum source. The dipole drive is such a system.

II. The Dipole Drive

In what follows, we will discuss the principles of operation of the dipole drive first using the ideal approximation of an infinite screen operating in a perfect vacuum, and then modify the results to the case of a finite dipole drive screen operating in a space containing conductive plasma.

II.1 Ideal infinite dipole drive in vacuum.

The principle of operation of the dipole drive while accelerating a spacecraft within a planetary magnetosphere is illustrated in Fig. 1 below.

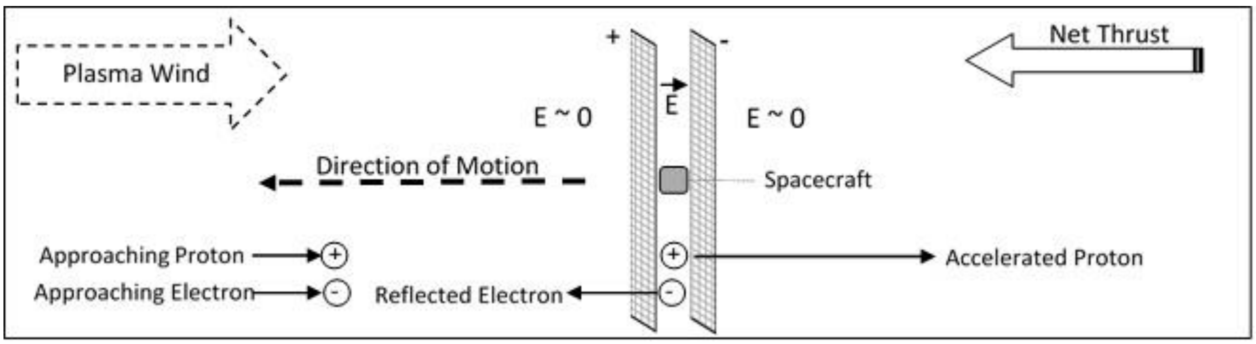

Fig. 1. The Dipole Drive Accelerating within a Magnetosphere. Power is required to fire electrons to match the accelerated proton jet.

In Fig. 1 we see two parallel screens, with the one on the left charged positive and the one on the right charged negative. There is thus an electric field between them, and almost no field outside of them, (zero field outside the screens in the infinite case) as on the outside the field of each screen negates the other. There is also a voltage drop between the two, which for purposes of this example we will take to be 64 volts.

Protons entering the field region from the left are accelerated towards the right and then outward through the right-hand screen, after which they escape the field and experience no further force. Protons entering from the right are reflected towards the right, adding their momentum to that generated by the protons accelerated from left to right. There is thus a net proton current from left to right, and a net proton thrust towards the left.

In the case of electrons, the situation is exactly the opposite, with a net electron current from right to left, and a net electron thrust towards the right. Note that while electrons entering from the right will be greatly accelerated by the field, reflected electrons will only be reflected with their initial velocity. As they are only moving with low velocity, many of these will be attracted to the positive screen. Power will therefore be necessary to lift them from the positive screen to the negative screen and fire them rearward. This could be done either by having a high voltage electronic gun on the positive screen or a low voltage one on the negative screen. In either case the amount of power required will be equal to the proton current times the voltage.

Because space plasmas are electrically neutral, the number density of both electrons and ions (which for the moment we will consider to be protons, but may which –advantageously - be heavier species, as we shall discuss later.) will be the same, so the proton and electron electrical currents will be equal, as will the power associated with each of them. However because the mass of a proton is about 1842 times as great as the mass of an electron, the thrust of the proton current will be about 43 times greater than the opposing electron current thrust (because the momentum of particles of equal energy will scale as the square root of their mass, sqrt(1842)=43) and the system will generate a net thrust. The acceleration of the electrons is a form of drag, which is provided for by loss of spacecraft kinetic energy. It therefore could, in principle be used to generate electric power, partially compensating for the power consumed to accelerate the protons. In the following examples, however, we will assume that there is no provision for doing this, i.e. that the efficiency of any such energy recovery is zero.

To see what the performance of a dipole drive might be, let us work an example, assuming a 500 W power source to drive the system. The electron current negates about 2% of the thrust (1/43rd) produced by the proton current. The maximum possible jet power is thus about 490 Wj. Assuming additional inefficiencies, we will round this down to 400 Wj, for a total system electrical to jet power efficiency of 0.8.

A Coulomb of protons has a mass of 0.011 milligrams. If the jet power is 400 W, and the potential difference is 64 V, so the proton current will be 6.25 A, and have a mass flow of 0.0652 mg/s.

The relationship of jet power (P) to mass flow ($\underline{m}$) and exhaust velocity (c) is given by:

$$P = \underline{m}c^2/2 \quad (1)$$

Taking P = 400 W and $\underline{m}$ = 0.0652 mg/s, we find that c= 110,780 m/s. Since thrust (T) is given by T=$\underline{m}$c, we find:

$$T = \underline{m}c = 7.2 \text{ mN}. \quad (2)$$

This is a rather striking result. It will be recalled that the electrical power driving this system is 500 W. So what we are seeing here is thrust to power ratio of 14.4 mN/kWe, *more than ten times better than that claimed for the EM Drive*, but done entirely within the known laws of physics!

If it is desired to deorbit (decelerate) a spacecraft, the direction of the screens would be reversed, with the negative screen leading in the direction of orbital motion. In this case, the screens would become a proton reflector. An electric sail could also be used as a drag device to serve the same purpose. However, because the dipole drive doesn't merely create drag against passing protons, but reflects them, it would create twice the drag of an electric sail of the same area. If the dipole drive is positioned obliquely to the wind angle, it can reflect protons, with the angle of incidence equaling the angle of reflection. For example, if it is tilted 45 degrees to the wind, a force will be generated perpendicular to the wind, that is "lift" will be created. Such maneuvers could also be done with the dipole drive in acceleration mode, deflecting protons to combine lift with thrust. Using this capability, a dipole drive propelled spacecraft in orbit around a planet could execute inclination changes.

II.2 Finite dipole drive operating in a conducting medium

No actual dipole drive will be of infinite dimensions. Consequently there will be a weak electric field outside the screens in the exact opposite direction to the strong field between the screens. If the dipole drive were operating in a vacuum, this weak field would extend to infinity, and a proton approaching the screen from the left in Fig. 1 would have to climb a potential hill equal to half the drop between the screens before it entered the gap, and then lose the other half of what it gained falling down the potential gap between the screens when it pulled away on the other side. If this were the case the dipole drive would not accelerate the proton at all and consequently exert no thrust.

However the field at infinity does not exist. In space, electric fields don't go as $1/r^2$. There is Debye shielding caused by free charges moving to mask out any field, with an-e folding drop every Debye length. In LEO, the Debye length is order of centimeters. In interplanetary space it is of order of 30 meters. So there is no integration of weak potential gradients to infinity. Provided that the dimensions of the screens are significantly larger than the Debye Length (as they generally will be) effectively no field is seen by oncoming particles until they are very close to the screens, where both appear to the particle as infinite planes of equal charge and field. Once between the screens there is a strong field, because the charges are constantly accelerated each way through the screens and then outside at velocities greater than their thermal velocities.

So the bottom line is that if both finite screen size and surrounding conductive plasma are taken into account, the performance of the dipole drive in thrust mode is about the same in both the infinite screen ion vacuum and the finite screen in plasma cases.

This, however, is not the case for the dipole drive operating in drag or lift mode where it seeks to accelerate the spacecraft by reflecting an ambient plasma wind. In this case, the protons outside the screen are accelerated slightly towards the screens by the weak exterior field, before they enter the strong field region between the screens which reflects them outward at their incident velocity with the angle of incidence equal the angle of reflection. One might think that the electrons would be accelerated past the screens, acting the role the protons play in Fig 1. But this requires that the electrons can climb through the weak repulsive potential gradient they face while approaching the finite screens. They probably can't, however, because the lightweight electrons moving at the velocity of a spacecraft have very little incident kinetic energy. While proton approaching a spacecraft at 8 km/s has the ability to climb an exterior potential hill of 0.32 volts, an electron could only climb a potential hill of 0.00018 volts. Even a solar wind electron approaching a dipole drive in interplanetary space at 500 km/s would only have enough kinetic energy to climb a potential of about 0.7 volts. So, weak as it is, the damped exterior field of a dipole drive in drag/lift mode will generally be enough to repel electrons before they ever make it to the strong accelerating region between the screens. Consequently, *both* the electrons and the protons will be reflected by the dipole drive with the angle of incidence equal to the angle of reflection, and almost no power will be required to run the drive, which will actually operate as a one fluid plasma *sail*. (A small amount of power will be needed to maintain charge against neutralization by occasional incident electrons).

To summarize, in contrast to the electric sail which can only create drag against the wind to lower its orbit, the dipole drive can thrust in any direction, raising or lowering its orbit or changing its orbital inclination. In addition, when used as a drag device, the dipole drive can create twice the drag per unit area as the electric sail.

III. The Dipole Drive in Earth Orbit

Let us therefore analyze the system further. The dipole drive exerts no field outside of its screens, so the only plasma it collects is the result of its own motion through the surrounding medium. So how big does its screen need to be?

We consider first the case of the above described dipole drive system operating in LEO at an altitude of 400 km, being used to thrust in the direction of orbital motion. It is moving forward at an orbital velocity of 7760 m/s. The average density of ions at this altitude is about 1,000,000 per cc. Assuming (conservatively) that all the ions are protons, the required ion mass flow of 0.0652 mg/s would be swept up by a screen with a radius of 127 m.

It may be noted however, that at 400 km altitude there are also O+ ions, each with a mass 16 times that of a proton, with a numerical density of about 100,000/cc. These therefore more than double the ion mass density provided by the protons alone. If these are taken into account, the required scoop radius would drop to about 80 m.

Another way to reduce the scoop size would be by going to higher voltage, so that more power can be delivered to a smaller number of ions. If, for example, we quadrupled the voltage to 256 volts, the exhaust velocity would double, to 222 km/s, allowing us to cut the mass flow by a factor of four, and the scoop radius by a factor of two, to just 40 m. The thrust, however, would be cut in half, giving us 3.6 mN/kWe.

As we go up in altitude, the plasma density decreases, as does the orbital velocity, requiring us to go to larger scoops. Examples of 500 W dipole drive systems operating at a variety of altitudes are provided in Table 1. In Table 1, Vo and C are orbital velocity and exhaust velocity, in km/s.

Table 1. Dipole Drive Systems Operating in Earth Orbit (Power=500 W)

Altitude (km)	*ion density/cc*	*Volts*	*Vo*	*C*	*Thrust (mN)*	*Screen Radius (m)*
400	1.000,000	1	7.8	14	57.6	640
400	1,000,000	4	7.8	28	28.8	320
400	1,000,000	16	7.8	56	14.4	160
400	1,000,000	64	7.8	111	7.2	80
400	1,000,000	256	7.8	222	3.6	40
400	1,000,000	1024	7.8	444	1.8	20
700	100,000	64	7.5	111	7.2	288
700	100,000	256	7.5	222	3.6	144
700	100,000	1024	7.5	444	1.8	72
1000	50,000	64	7.35	111	7.2	410
1000	50,000	256	7.35	222	3.6	205
1000	50,000	1024	7.35	444	1.8	103

It can be seen that the dipole drive is a very attractive system for maneuvering around from LEO to MEO orbits, as the high ion density makes the required scoop size quite modest. It should be emphasized that the above numbers are for a 500 W system. If a 5 W dipole drive thruster were employed by a microsatellite, the required scoop areas would be reduced by a factor of 100, and the radius by a factor of 10.

It may be noted that Mars, Venus and Jupiter all have ion densities in low orbit comparable to those above. For example, Mars has 500,000/cc at 300 km, Venus has 300,000/cc at 150 km, and Jupiter has 100,000/cc at 200 km, making the dipole drive attractive for use around such planets as well. Many of the moons of the outer planets also have ionospheres, and the dipole drive should work very well in such environments.

As one ascends to higher orbits, the density of ions decreases dramatically, while the orbital speed decreases as well. For example, in GEO, the ion density is only about 20/cc, while the orbital velocity is 3 km/s. These two factors combine to make much larger scoops necessary. So, for example, in GEO, a 500 W dipole drive operating at 1024 volts would need a scoop 3.6 km in radius.

Because the effectiveness of the dipole drive decreases at higher altitudes while operating within the magnetosphere, the best way for a dipole drive propelled spacecraft to escape the Earth is not to continually thrust, as this would cause it to spiral out to trans GEO regions where it would become ineffective. Rather, what should be done is to only employ it on thrust arcs of perhaps 30 degrees around its perigee, delivering a series of perigee kicks that would raise its apogee on the other side of its orbit higher and higher until it escaped the magnetosphere and became able to access the solar wind.

IV. The Dipole Drive in Interplanetary Space

The dipole drive can also operate in interplanetary space. Compared to planetary orbit, the ion densities are lower, but this is partially compensated for by much higher spacecraft velocities relative to the plasma wind. As a result, the required scoop sizes are increased compared to planetary orbital applications, but not by as much as considerations of ion density alone might imply.

Let us consider the case of a dipole drive traveling in heliocentric space at 1 AU, positioned at an angle of 45 degrees to the wind, with its negative screen on the sunward side. It would thus reflect solar wind protons 90 degrees, thereby accelerating itself forward in the direction of orbital motion. A diagram showing the dipole drive operating as a sail in interplanetary space is shown in Fig. 2.

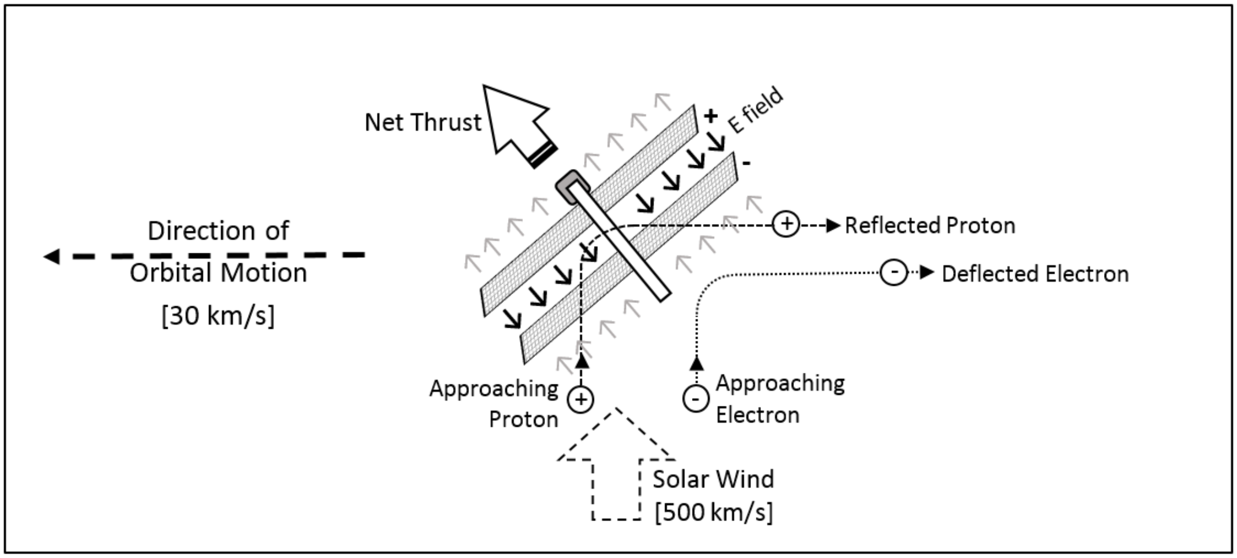

Fig. 2 The Dipole Drive Operating as a Sail in Interplanetary Space. The protons are reflected by the strong positive field between the screens, while the electrons are reflected before they can reach this region by the weak electrical field outside the screens. The drive thus acts as a sail reflecting a one-fluid plasma. No power is required.

The solar wind has a velocity of 500 km/s, so to insure reflection, we employ a voltage of 2028 volts, sufficient to reverse the motion of a proton moving as fast as 630 km/s. With a density of 6 million protons per cubic meter, the wind has a dynamic pressure of 1.25 nN/m^2. This will be doubled because the wind is reflected. As the sail is positioned 45 degrees obliquely to the wind, its effective area will be reduced by a factor of 0.707, with the force generated reduced to 1.8 nN/m^2. In this case, virtually all of the protons hitting the sail will be coming from the sunward side, and since they are reflected without adding any kinetic energy, no power is required to drive them. However electrons approaching even at a velocity of 630 km/s will only be able to climb a potential of about 1.1 volts, so they will be reflected by the weak reverse field outside of the screens before they make it into the region between the screens that would otherwise accelerate them. So both protons and electrons will be reflected, with the angle of incidence equal to the angle of reflection, and both lift and drag can be generated with no power required.

However, if we wish to thrust upwind, we will require power. With 500 W, total radial thrust would be 1.27 mN, with 1.27 mN also delivered in the direction of orbital motion. The total effective screen area would therefore need to be 1,414,000 m^2, with an actual area of 2,000,000 m^2, requiring a radius of 798 m. Total thrust to power would be 3.6 mN/kWe.

If instead we had not concerned ourselves with obtaining high acceleration of each particle, we could have used a lower voltage. This would increase the thrust per unit power, but increase the required sail area for a given amount of thrust. So, for example, if we chose 512 volts, we would have a total thrust of 3.6 mN, for a thrust/power ratio of 7.2mN/kWe, but need a sail radius of 1127 m.

It may be noted that all of these results are for a 500 W dipole drive. A microsatellite might employ a 5 W dipole drive, in which case the required scoop radii would drop by a factor of 10.

The thrust and diameter of a 1 kWe dipole drive system operating as a thruster in interplanetary space at 1 AU is shown in fig. 3.

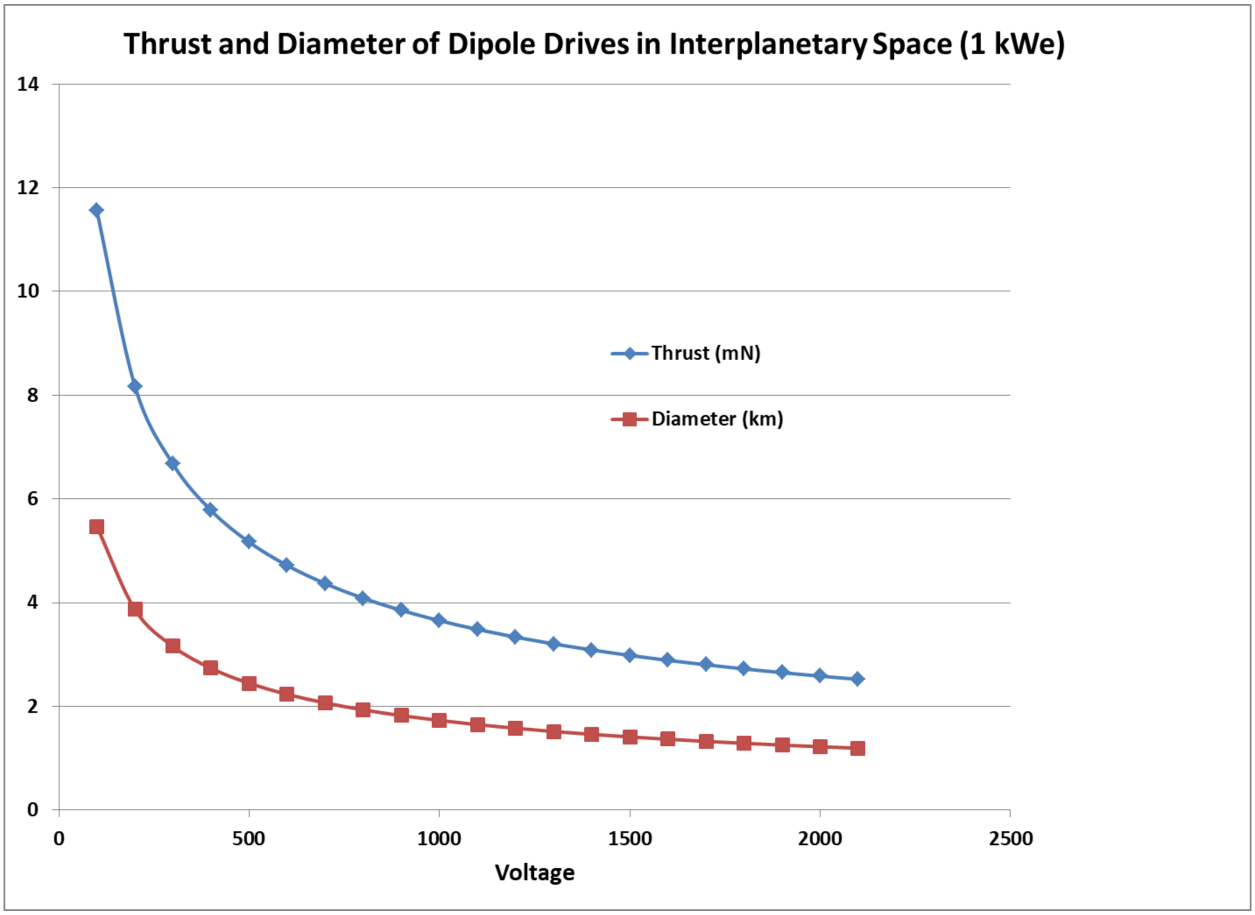

Fig. 3. Thrust and Diameter of a 1 kWe dipole drive system operatingas a thruster in interplanetary space. For comparison, a 2 kilovolt dipole drive acting as a solar wind sail with a diameter of 1 km would use no power and generate drag/lift force of about 2 mN at 1 AU.

V. Use of the Dipole Drive for Interstellar Flight

In contrast to the electric sail, the dipole drive can be used to accelerate a spacecraft at velocities greater than that of the solar wind. For example, consider a spacecraft moving away from the Sun at a velocity of 1000 km/s. The solar wind is following it at a velocity of 500 km/s, so relative to the spacecraft there is a wind moving inward towards the sun at a velocity of 500 km/s. In this case, to accelerate the spacecraft would direct its positive screen away from the sun. This would cause it to accelerate protons sunward, while reflecting electrons outward, for a net outward thrust. At 500 km/s the protons are approaching the spacecraft with a kinetic energy equal to 1300 volts. It can be shown that employing a screen voltage difference that is about triple the kinetic voltage produces an optimal design for an accelerating system, while one using a voltage difference equal to the kinetic voltage is optimal for deceleration. This is illustrated in figs 4 and 5 which respectively show the kinetic voltage as a function of velocity, and the relative power/ thrust and area/thrust ratios of the spacecraft as a function of the dimensionless parameter Z, where Z=(engine voltage)/(kinetic voltage.)

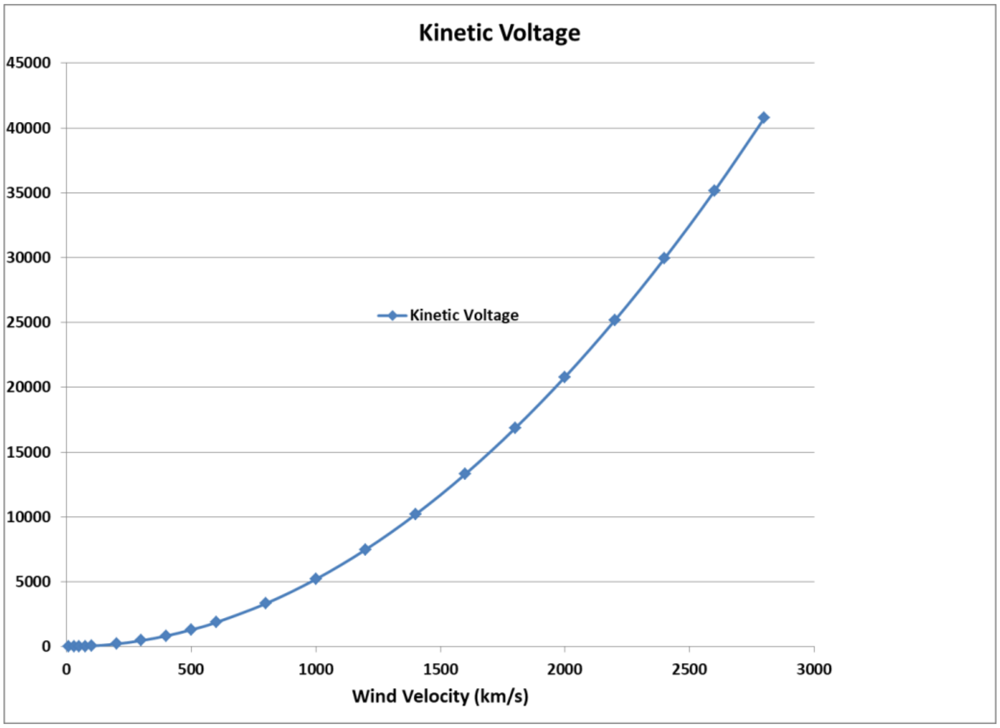

Fig 4. Kinetic voltage of protons as a function of spacecraft velocity.

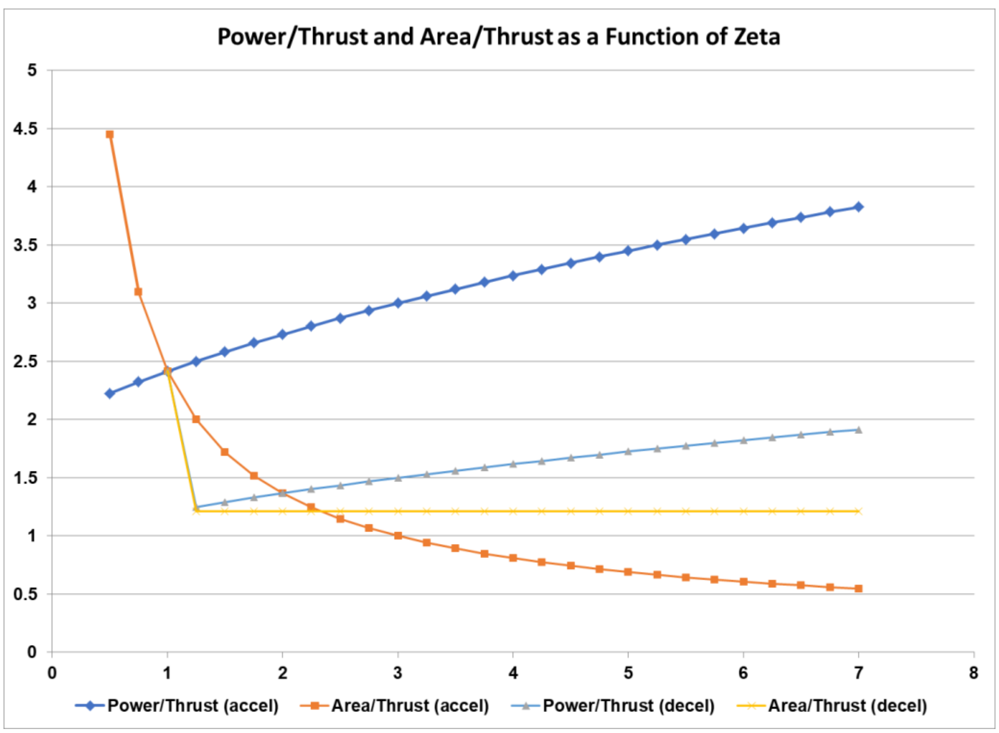

Fig 5. Relative Power/Thrust and Area/Thrust as a function of Z=(engine voltage)/(kinetic voltage.) There is a step factor of 2 increase in thrust during deceleration when Z reaches 1, because protons are reflected. For acceleration, Power/Thrust ~ 1 + sqrt(1+Z), while Area/Thrust ~ 1/(-1 + sqrt(1+Z)).

If we add 3900 volts to the incoming protons, quadrupling their energy, we will double their velocity relative to the spacecraft, thereby providing an effective exhaust velocity of 500 km/s. The solar wind has a density of 6 million protons/m^3 at 1 AU, with ambient density decreasing to 1 million/m^3 in interstellar space. If we take the former value, we get a thrust of (1.67e-27 kg/proton)(500,000m/s)^2(6,000,000/m^3) = 2.5 nN/m^2. If we take the latter value, it would be 0.42 nN/m^2. The proton current at the smaller value would be 80 nA/m^2, which at 3900 volts works out to 0.312 mW/m^2. The thrust to power ratio would therefore be 1.35 mN/kW. (This ratio would also hold true at the 1 AU value, but the magnitudes of both the thrust and power per unit area would be six times greater.)

If dipole drive powered spacecraft were receding 500 km/s directly away from the Sun, it would see no relative wind and thus produce no thrust. However, like a modern sailboat that can sail faster crosswind than downwind, because it can generate lift, the dipole drive can get to speeds above 500 km/s by sailing across the wind. As the spacecraft's crosswind speed increases, it becomes advisable to turn the sail to ever greater angles to the solar wind and increasingly normal to the crosswind. As this occurs, the L/D resulting from solar wind reflection increases while the total solar wind thrust decreases. At the same time, however, thrust resulting from the acceleration through the screens of crosswind protons increases, maintaining total thrust constant at ever higher L/D (relative to the solar wind) levels. Once the crosswind velocity exceeds the solar wind velocity the solar wind becomes increasingly irrelevant and the dipole drive becomes a pure acceleration system, driving the incoming crosswind plasma behind it to produce thrust,

As the speed of the spacecraft increases relative to the wind, it is necessary to increase the voltage in order maintain thrust/power ratio efficiency. For example, let's say we want to achieve 3000 km/s, or 0.01c. Then the kinetic energy equivalent voltage of the approaching protons would be 47 kV. So, to double this velocity we need to quadruple the total voltage, or add a sail voltage drop of 141 kV. The proton current would have a value of 480 nA/m^2, with a power of 68 mW/m^2. The thrust would be 15.1 nN/m^2, for a thrust to power ratio of 0.22 mN/kW.

It may be observed that since the necessary voltage increases as the square of the velocity, with power increasing with voltage but thrust increasing with velocity, the thrust to power ratio of the dipole drive decreases linearly with velocity. This puts limitations on the ultimate velocity achievable. For example, the most optimistic projections for advanced large space nuclear power system project a mass to power ratio of 1 kg/kW. If we accept this number, then, neglecting the mass of any payload or the dipole drive system itself, then the system described in the previous paragraph performing with a thrust to power ratio of 0.22mN/kilowatt at 3000 km/s would have an acceleration of 0.00022m/s^2, or 7 km/s per year. The average acceleration getting up to 3000 km/s would be twice this, so the spacecraft would take 214 years to reach this speed. During this time it would travel 1.07 light years. To reach 6000 km/s (0.02 c) starting from negligible velocity would require 857 years, during which time the spacecraft would travel 8.57 light years. The performance of such a system is shown in Table 2. Note 63,000 AU = 1 light year. The performance shown assumes an advanced 1 kg/kWe power supply. If a more near-term power system with a higher mass/power is assumed, the time to reach any given distance increases as the square root of the mass/power ratio. So for example, if we assume a conservative near-term space nuclear power reactor with a mass/power ratio of 25 kg/kW, the time required to reach any given distance would increase by a factor of 5.

Table 2. Advanced Dipole Drive Performance for Ultra High-Speed Missions (1 kg/kW power)

Final Speed	Final Voltage	Final Acceleration	Average Acceleration	Time	Distance
250 km/s	0.975 kilovolts	84 km/s-yr	164 km/s-yr	1.52 yrs	39.9 AU
500	3.9	42	84	5.95	319
1000	15.6	21	42	23.8	2554
2000	62.4	10.5	21	95.2	20,432
3000	141	7	14	214	68,958
4000	250	5.25	10.5	381	163,458
5000	390	4.2	8.1	617	319,250
6000	564	3.5	7	857	551,664

It can be seen that advanced dipole drive spacecraft could be quite promising as a method of propulsion for missions to near interstellar space, for example voyages the Sun's gravitational focus at 550 AU. Unless much lighter power systems can be devised than currently anticipated however, they would still require centuries to reach the nearest stars. Power beaming may provide an answer. However such technologies are outside the scope of this paper.

If a spacecraft has been accelerated to interstellar class velocities, whether by means of the dipole drive or any alternative technology, the dipole drive provides a means of deceleration with little or no power (it could actually generate power, in principle) by creating drag against the relative plasma wind. Such propellantless deceleration can also be done by a magnetic sail or an electric sail. However because it can also create lift as well as drag, the dipole drive offers much greater maneuverability during deceleration as well as a means to freely maneuver within the destination solar system after arrival.

VI. Dipole Drive Design Issues

Let us consider the case of a 2 kg microsatellite operating in LEO, with 5 W of available power to drive a dipole drive. (Note, a typical CubeSat has a mass of 1.3 kg. At 20 kg/kWe, a 5 W solar array should have a mass of about 0.1 kg.) If we operate it with a voltage of 16 Volts, it will produce 28.8 mN/kWe, or 0.144 mN thrust over all. It would have an acceleration of 0.000072 m/s^2. This would allow it to generate a ΔV of 2288 m/s in a year, sufficient to provide extensive station keeping propulsion, substantially change its inclination, or to raise it from a 400 km altitude orbit to a 700 km orbit in 1.6 months. To generate this much thrust at 400 km would require a scoop with a radius of 16 m, while doing so at 700 km would require a scoop with a radius of 58 m. Let us assume that the scoop is made of aluminum wire mesh, using wires 0.1 mm in diameter separated by distances of 2 m. Each square meter of mesh would thus have about 1 m length of wire. This needs to be doubled as there are two meshes, one positive and one negative. Therefore, a scoop with a radius of 16 m would have a mass of 32 grams. If the propulsion system were used simply for station keeping, inclination change, or deorbit functions at the 400 km altitude, that's all that would be needed. To operate at 700 km, a 116 gram scoop would be required. From these examples we can see that the use of the dipole drive to provide propulsion for microsatellites in LEO could potentially be quite attractive, as the modest scoop sizes required do not pose major deployment challenges.

Now let us consider a 100 kg interplanetary spacecraft in interplanetary space, operating with 500 W at a voltage of 2028 volts. From the discussion above it can be seen that this would generate about 2.54 mN of thrust in the direction of orbital motion. The scoop would need to have a radius of about 800 m. In interplanetary space, the Debye shielding length is ~60 m, and so a screen with a 20 m mesh would suffice. Such a screen would have a mass of about 8.5 kg, which would be well within the spacecraft mass budget. The 2.54 mN thrust would accelerate the spacecraft at 0.000025 m/s^2. It could thus impart a ΔV to the spacecraft of about 804 m/s per year. Higher accelerations could be provided by increasing the spacecraft power to mass ratio. If instead of attempting thrust against the solar wind, the dipole drive were used to sail on the wind, the spacecraft would also generate about 2.5 mN of combined drag/lift force, but require almost no power.

The deployment of large scoops composed of two parallel, oppositely charged meshes poses operational and design issues. Prominent among these is the fact that the two opposite charged screens will attract each other. However the total force involved is not that large. For example, let us consider a configuration consisting to two sails of 500 m radius separated by 500 m with a 2 kV potential difference. Then the electric field between them will be 4 volts/m. The area of each screen will be 785,400 m^2. From basic electrostatics we have EA = Q/ε, so Q, the charge of each screen will be given by Q=(4)(785,400)(8.85 e-12) = 0.000028 coulombs. The electrostatic force on each sail is given by F=QE, so the total electrostatic force of each sail will be 0.1 mN. This is about a tenth the thrust force exerted by the screens themselves. Nevertheless, as small as they are, both of these forces will need to be negated. This can be done either with structural supports or by rotating the spacecraft and using artificial gravity to hold the sails out perpendicular to the axis of rotation. An alternative is to use the self-repulsion of the charge of each sail to help hold it out flat. In such a configuration two sails held separate from each other by a boom attached to their centers could be expected to curve towards each other at their edges until the stiffening self-repulsive force on each sail from its own charge balanced the bending forces exerted by the spacecraft's acceleration, the push of the wind, and the attractive force of the opposite sail.

A critical issue is the material to be used to create the dipole drive. In his original paper on the classic electric sail[4], Pekka Janhunen suggested using copper wires with diameters between 2.5 and 10 microns. This is not an optimal choice, as copper has a much lower strength to mass ratio than aluminum, and such thin strands would be quite delicate. For this reason, in the above examples we specified aluminum wire with 100-micron diameters. A potentially much better option, however, might be to use aluminized Spectra, as Spectra has about 10 times the yield strength of aluminum, and roughly 1/3 the density (Aluminum 40,000 psi, 2700 kg/m^3, compared to Spectra 400,000 psi, 970 kg/m^3.). Spectra strands with 100-micron diameters and a coating of 1 micron of aluminum could thus be a far superior material for dipole drive system, and classic electric sails as well. An issue however is Spectra's low melting point of 147 C. Kevlar, however, with a yield strength of 200,000 psi, a density of 1230 kg/m^3, and a melting point of 500 C could provide a good compromise. Still another promising option might be aluminized strands made of high strength carbon fiber, such as the T1000G (924,000 psi, 1800 kg/m^3) produced by Toray Carbon Fibers America.

Some options for dipole drive spacecraft configurations are show in in Fig. 6. As can be seen, small dipole drive systems can be used for spacecraft control, for example as an empennage. Such small dipole drive units could also be used for attitude control on non-dipole drive spacecraft, such as solar sails or space telescopes positioned in heliocentric space.

As with the electric sail, the dipole drive must deal with the issue of sail charge neutralization caused by the attraction of ambient electrons to the sail's positive screen. In reference 4, P. Janhunen showed that the total such current that an electric sail would need to dispose of would be modest, entailing small power requirements if ejected from the spacecraft by a high voltage electron gun. In the case of the dipole drive, the current would be still smaller because the spacecraft has no net charge. Electrons acquired by the positive screen could be also disposed of by using the power source to transport them to the negative screen, and then ejected into space with a low voltage electron gun. Alternatively, if an electron gun were used, its required voltage would be less than that needed by an electric sail because external to the screens, the dipole drive's field is much weaker and falls off much more quickly. For these reasons, the issue of sail charge neutralization on the dipole drive should be quite manageable.

Because the dipole drive does not interact with plasma outside of the zone between its screens, the issue of Debye shielding of its screen system to outside charges is not a major concern. Debye shielding of its individual wires within screens can be dealt with by means of adequately tight wire spacing. As shown by Janhunen[4] such spacing may be quite liberal (~30 m in near Earth interplanetary space), enabling sails with very low mass to area ratios.[7]

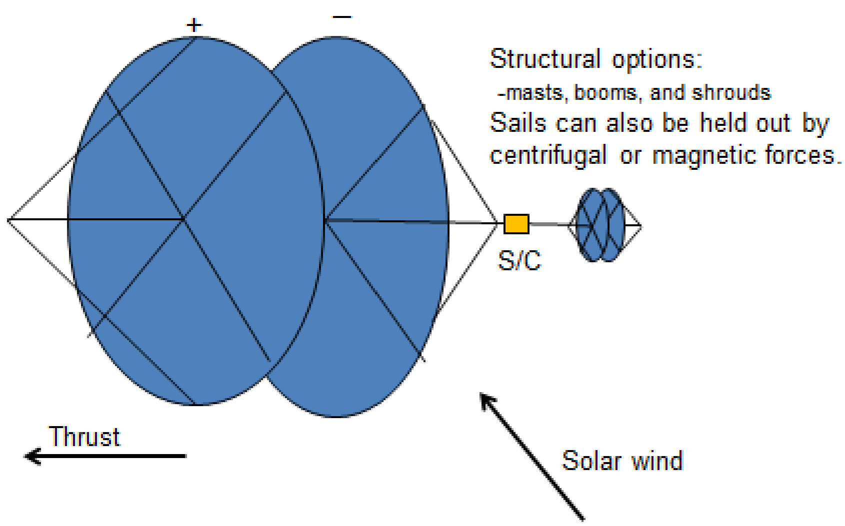

Fig. 6. Options for dipole drive spacecraft configuration. Small dipole drive systems can be used for attitude control.

VII. Answers to Critics

Since the dipole drive was first published, some critics have claimed that the dipole drive will not work for a variety of reasons. For example, it is argued that while the field between the parallel screens is clearly strong from the positive screen A to the negative screen B, and while these nearly balance outside of the screens, there is a very weak field above, below, and outside the borders of the screens caused by the finite difference in distance between them, which when integrated to infinity, means there is no net energy imparted by a proton traveling from the region above A to the region below B.

Very weak field pointing up

A________________________________+

Very strong field pointing down.

B________________________________ -

Very weak field pointing up

1. This argument is false because the field at infinity does not exist. In space, electric fields don't go as $1/r^2$. There is Debye shielding caused by free charges moving to mask out any field, with an-e folding drop every Debye length. In LEO, the Debye length is order of centimeters. In interplanetary space it is of order of 30 to 60 meters. So there is no integration to infinity. Provided that the dimensions of the screens are significantly larger than the Debye Length (as they generally will be) effectively no field is seen by oncoming particles until they are very close to the screens, where both appear to the particle as infinite planes of equal charge and field. Once between the screens there is a strong field, because the charges are constantly accelerated each way through the screens and then outside at velocities greater than their thermal velocities.
2. The dipole drive is not a passive system. In thrust mode power is expended to fire electrons to travel along with the protons. In sail mode electrons and protons travel together as well supplying momentum as a wind. So that in either case what really is being accelerated is a one-fluid plasma, consisting of both electrons and protons.
3. It has been argued there is counterflow that exactly matches and reverses the dipole drive thrust outside of the screens. This can be seen to be wrong by considering a dipole drive, with screens 10 m in diameter separated from each other by 10 m. Then there will be a weak counter field above, below and to the sides of the screens, which according to the critics, if integrated everywhere, will generate drag exactly balancing the thrust produced by the potential drop between the screens. Let's for the moment stipulate that is true for this configuration. But now let us bring the screens closer together, so that instead of being separated by 10 m, they are separated by 1 cm. In that case the counter field outside of the screens will decrease by two orders of magnitude, and the balance in numbers between those particles that are accelerated and those decelerated will change radically. So the drag it generates can no longer balance the thrust, which remains the same given that the potential drop between screens remains unaltered.
4. 4. The argument that the dipole drive creates a counterflow equal to its thrust is equivalent to the argument that a propeller can't impart forward thrust to an airplane, because while it drives air backwards creating thrust, some other air elsewhere must more forward to take the place of the backward moving air, creating equivalent drag. This is simply false.
5. 5. The argument that the potentials are equal on either side of the screens means that the drive can't do anything can also be seen to be wrong, from the following thought experiment:

Consider a proton approaching the dipole drive A+/B- shown from below, with a velocity of 8 km/s. This gives it a kinetic energy equal to about 0.33 volts. Let us say the potential difference between the screens is 1 volt. In this case the proton will clearly be reflected, as it does not have enough energy the climb the potential well. In fact, it will climb only 1/3 of the way from B to A and then be reflected, and be fired back out of screen B with the same velocity that it entered. That should be evident. In this case, the dipole drive is acting as a sail, reflecting protons to gain momentum.

So now let's say the proton approached with a velocity of 16 km/s, or 1.33 volts. Then it would have enough energy to climb from B to A, and still have 0.33 volts left over to keep going after A at 8 km/s. So the screens slowed it down but didn't stop it. In the process of going through the screens and getting slowed down, the proton gave the dipole drive screens a shove.

But now let us reverse the maneuver above in time. Instead of leaving screen A going up at 8 km/s, the proton is now approaching screen A going down at 8 km/s, and instead of approaching B coming up from below at 16 km/s it leaves screen B going down at 16 km/s. QED.

So the dipole drive has accelerated the proton from 8 km/s to 16 km/s, thereby creating jet thrust to move itself forward (upward in this case). The required energy comes from moving an electric current through a potential drop, and then discharging the electrons to join the proton exhaust, thereby balancing charge. The power to do this is provided by an onboard power source. Momentum is conserved because the acceleration of the proton one way is balanced by the acceleration of the dipole drive screens the other way.

6. Now consider the arrangement shown in Fig 2. It is clear that the proton will be reflected, and furthermore deflected to create a force perpendicular to the wind (i.e. lift)? Yet the potentials at infinity are equal. So the "equal potentials at infinity means there can be no effect" argument is clearly untrue.

7. Finally, let us note, there is a device, known as a fusor, invented by Philo Farnsworth (the inventor of television) that has been used for decades to accelerate either electrons of protons to very high velocities. The fusor consists of concentric electrostatic grids. If it is desired to accelerate protons inward, the positive is on the outside and negative on the inside. If deuterons are used, fusion reactions can be made to occur. (Unfortunately not enough for breakeven, but more than enough to produce neutrons for diagnostic instrumentation purposes.) Fusors have been built with both spherical and cylindrical geometries. The dipole drive is just the infinite plane (flat Earth) version of the fusor.[8]

So, there is no question that the dipole drive will work. It has worked. Have a look.

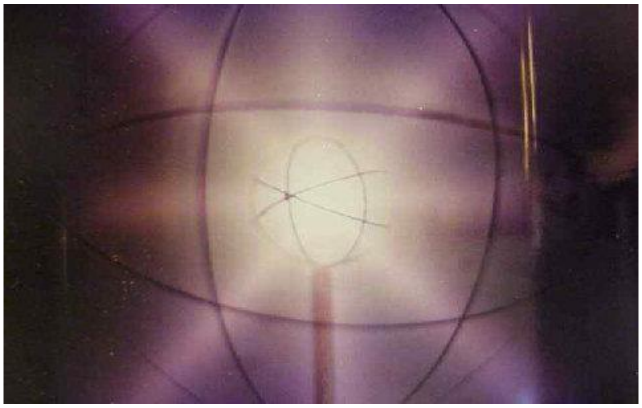

Fig. 7 Photograph of a fusor in operation.

VIII. Conclusion

The dipole drive is a promising new technological concept that offers unique advantages for space propulsion. Requiring no propellant, it can be used to thrust in any direction, and both accelerate and decelerate spacecraft operating within planetary magnetospheres, in interplanetary space, and interstellar space. Unlike magnetic sails and electric sails, it can generate both lift and drag, and its maximum velocity is not limited by the speed of the solar wind. Near-term dipole drives could be used to provide a reliable, low cost, low mass technology to enable propellantless movement of spacecraft from one orbit to another, to provide station keeping propulsion, or to deorbit satellites, as required. Then dipole drive could also be used as a method of capturing interplanetary spacecraft into orbit around destination planets, or of lowering the orbits of spacecraft captured into initial elliptical orbits using high thrust propulsion. The latter application is particularly interesting, because it requires no power and could enable a small lightweight lunar ascent vehicle to carry astronauts home from the Moon by launching directly from the lunar surface to trans-Earth injection and then subsequently lower itself to LEO to rendezvous with a space station or reentry capsule spacecraft without further use of propellant. Such an approach could potentially reduce the mass of a manned lunar mission to within the launch capacity of a single Falcon Heavy. Because it needs no propellant, the dipole drive offers the unique advantage of being able to provide its propulsion service to any spacecraft indefinitely. While the dipole drive is most attractive in low orbital space whether ambient plasma is thickest, it can be used in interplanetary space and even enable interstellar missions as well, becoming more attractive for such applications as ancillary technologies, such as power generation evolve.

There are many technical issues that need to be resolved before practical dipole drive spacecraft can become a reality. However both the theory of dipole drive operation and it potential benefits are clear. Work should therefore begin to advance it to flight status. The stars are worth the effort.

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