Magnetic Sails and Interplanetary Travel

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A new concept, the magnetic sail, or "magsail," which propels spacecraft by using the magnetic field generated by a loop of superconducting cable to deflect interplanetary or interstellar plasma winds, is proposed. The performance of such a device is evaluated using both a plasma particle model and a fluid model, and the results of a series of investigations are presented. It is found that a magsail sailing on the solar wind at a radius of one astronautical unit can attain accelerations on the order of 0.01 m/s^2, much greater than that available from a conventional solar lightsail, and also greater than the acceleration due to the sun's gravitational attraction. A net tangential force, or "lift," can also be generated. Lift-to-drag ratios of about 0.3 appear attainable. Equations are derived whereby orbital transfers using magsail propulsion can be calculated analytically. It is found that a magsail can transfer payloads to and from any two circular orbits in the solar system in a flight time slightly larger than the Hohmann ballistic transfer time. The magsail can accomplish these missions at any time, unrestricted by the usual ballistic transfer launch window. The necessary magsail/payload mass ratios are less than 0.15.

Nomenclature

A = cross-sectional area of magsail wire, m^2
a = semimajor axis of magsail orbit, a.u.
B_m = magnetic field at the magsail center, T
B_0 = ambient interplanetary magnetic field, T
C = characteristic radius of magsail action, m
D = drag force exerted by plasma wind on magsail, N
d = diameter of magsail wire
E = canonical energy of magsail orbit
e = eccentricity of magsail orbit
h = canonical angular momentum of magsail orbit
I = magsail loop current, A
J = magsail loop current density, A/m^2
L = lift force exerted by plasma wind on magsail, N
M = mass of magsail, kg
P = Semilatus rectum of the magsail orbit, a.u.
P_m = magnetic pressure of the magsail field, Pa
P_{mb} = magnetic pressure at the magnetosphere boundary, Pa
R_c = collection radius of the magsail, m
R_m = radius of the magsail loop, m
R_s = radius of spacecraft from sun, a.u.
R_0 = initial diplacement of proton off magsail axis, m
t = time of flight of magsail orbit, $1/2\pi$ yr
V = velocity of the plasma wind, m/s
V_x = velocity of proton parallel to magsail loop axis, m/s
V_y = velocity of proton perpendicular to magsail loop axis, m/s
V_{sc} = velocity of magsail spacecraft, 2π a.u./yr
W = magsail spacecraft weight ratio
α = fraction of sun's gravitational attraction felt by magsail spacecraft
ϕ = polar angle off dipole axis
Ω = true anomaly of magsail spacecraft within its orbit
ρ = density of the plasma wind, kg/m^3
ρ_m = magsail loop mass density, kg/m^3
θ = angle between plasma freestream and the normal to the magnetospheric boundary

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I. Introduction

THE magnetic sail, or magsail, is a device which can be used to accelerate or decelerate a spacecraft by using a magnetic field to accelerate/deflect the plasma naturally found in the solar wind and interstellar medium. The principle of operation is as follows.

A loop of superconducting cable tens of kilometers in diameter is stored on a drum attached to a payload spacecraft. When the time comes for operation, the cable is played out and a current is initiated in the loop. This current, once initiated, will be maintained indefinitely in the superconductor without further power. The magnetic field created by the current will impart a hoop stress to the loop aiding the deployment and eventually forcing it to a rigid circular shape. The loop operates at low field strengths, typically 0.00001 T, so little structural strengthening is required. The loop can be positioned with its dipole axis at any angle with respect to the plasma wind; two extreme cases examined for analytical purposes are the axial configuration, in which the dipole axis is parallel to the wind, and the normal configuration, in which the dipole axis is perpendicular to the wind. A magsail with payload is depicted in Fig. 1.

In operation, charged particles entering the field are deflected according to the *B*-field they experience, thus, imparting momentum to the loop. If a net plasma wind, such as the solar wind, exists relative to the spacecraft, the magsail loop will always create drag and thus accelerate the spacecraft in the direction of the relative wind. The solar wind in the vicinity of the Earth is a flux of several million protons and electrons per cubic meter at a velocity of 400–600 km/s. This can be used to accelerate a spacecraft radially away from the sun, and the maximum speed available would be that of the solar wind itself. Although inadequate for interstellar missions, these velocities are certainly more than adequate for interplanetary missions.

However, if the magsail spacecraft has somehow been accelerated to a relevant interstellar velocity, for example, by a fu-

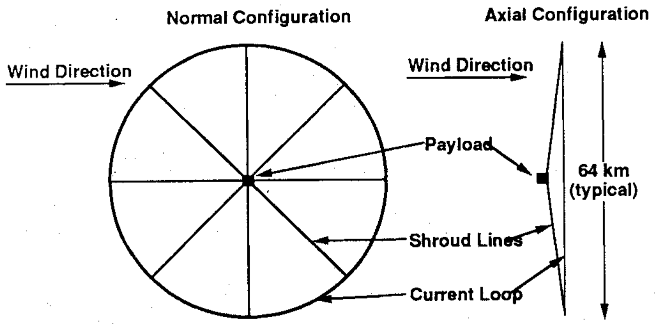

Fig. 1 Magsail deployed with payload.

sion rocket or a laser-pushed lightsail, the magsail can be used to create drag against the static interstellar medium and thus act as an effective braking device.[1] The ability to slow spacecraft from relativistic to interplanetary velocities without the use of rocket propellant results in a dramatic lowering of both rocket mass ratio and the total mission time.

If the magsail is utilized in a nonaxial configuration, symmetry is destroyed, and it becomes possible for the magsail to generate a force perpendicular to the wind, i.e., lift. Lift can be used to alter the magsail spacecraft's angular momentum about the sun, thus greatly increasing the repertoire of possible maneuvers. In addition, lift can be used to provide steering ability to a decelerating relativistic interstellar spacecraft.

The magsail as currently conceived depends on operating the superconducting loop at high current densities at ambient temperatures. In interstellar space, ambient is 2.7 K, where current low temperature superconductors NbTi and Nb_3Sn have critical currents of 1.0×10^{10} and 2.0×10^{10} A/m^2, respectively. In interplanetary space, where ambient temperatures are above the critical temperatures of low temperature superconductors, these materials would require expensive and heavy refrigeration systems. However the new high temperature superconductors such as $YBa_2Cu_3O_7$ have demonstrated comparable critical currents in microscopic samples at temperatures of 77 K or more,[2] which would make the superconductors maintainable in interplanetary space using simple multilayer insulation and highly reflective coatings. Such passive thermal control systems[3] add bulk and mass to the magsail, thus degrading the performance of the magsail and potentially complicating its deployment somewhat, but also can be used to provide protection to the cable from micrometeorite impacts. Assuming that critical temperatures of 77 K will someday be realizable in practical bulk cable, we have chosen to parameterize the problem by assuming the availability of a high temperature superconducting cable with a critical current of 10^{10} A/m^2, i.e., equal to that of NbTi. Because the magnets are operating in an ambient environment below their critical temperature, no substrate material beyond that required for mechanical support was assumed. Assuming a fixed magnet density of 5000 kg/m^3 (copper oxide), our magnet has a current to mass density (j/ρ_m) of 2.0×10^6 A-m/kg.

II. Method of Analysis

Two alternative methods were adopted to analyze the performance of the magsail. In the first, the particle method, the solar wind was viewed as an aggregation of particles, each interacting individually with the vacuum magnetic field of the magsail. In the second model, whose investigation was suggested to the authors by J. Sercel,[4] the solar wind is viewed as a plasma fluid creating a supersonic shock as it impinges upon the magnetosphere of the magsail, much as occurs in the case of the interaction between the Earth's geomagnetic field and the solar wind. This second, plasma, model is probably a closer reflection of the actual behavior of the magsail. However, because the ion cyclotron radius in the outer region of the magsail's magnetosphere (about 100 km) is comparable to the overall dimensions of that magnetosphere, the particle model has a certain amount of validity as well. The truth, no doubt, will be found somewhere between the two. The results of both investigations will therefore be reported here.

III. Particle Model

To analyze the performance of the magsail using the particle model, a computer code that follows the trajectory of individual charged particles as they interact with the magnetic field generated by the current loop was written. Beyond one loop radius, the field is modeled as a simple dipole to economize on computer time, while inside one loop radius the exact Biot-Savart law[5] was used. The forces on a moving proton are accurately modeled, and the proton's velocity and position are advanced in time in accordance with a simple Euler numerical scheme. Because the proton's gyro radius can be much larger than $B/\mathrm{grad}(B)$, no a priori assumption was made that magnetic moment would be conserved.

A series of computer experiments were conducted to test the final disposition of particles fired into the magnetic field with various wind velocities and starting positions. A random thermal velocity perpendicular to the wind velocity was included to accurately model proton reflection characteristics, and an ambient magnetic field B_0, was also included.

Axial Configuration Results

In the axial configuration, protons are coming in parallel to the loop axis. Results show that protons starting from points displaced off the loop axis less than a certain critical radius, the collection radius R_c, are reflected almost completely, e.g., $\Delta V_x/V = -2$, where V_x is the component of the initial proton velocity, which is parallel to the loop axis. Beyond R_c the deflection falls off rapidly, so that at $2R_c$, $\Delta V/V$ might equal -0.4, and at $3R_c$, $\Delta V/V$ would equal -0.06 (see Fig. 2). Based on statistical data, the equation describing R_c is

$$R_c/R_m = 49{,}810\, V^{-0.43} B_m^{0.5} \exp(-1.07\times 10^8 B_0) \quad (1)$$

and an equation describing $\Delta V_x/V$ is

$$\Delta V_x/V = -3.76 \times 10^{13} B_m{}^{1.165} V^{-1} (R_m/R_0)^{2.33} \times \exp(-2.5 \times 10^8 B_0) \quad (2)$$

For wind velocities typical of interplanetary conditions and B_m of 10^{-5} T, R_c is about five times the loop radius. Although the deflection per particle outside of R_c is small, the total area

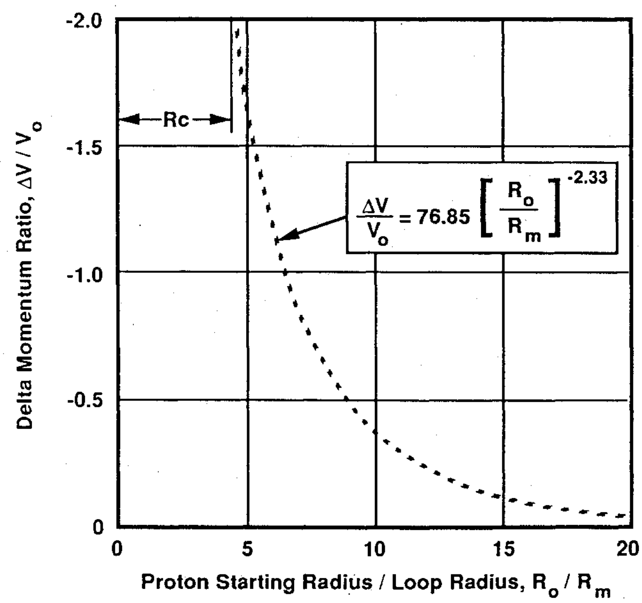

Fig. 2 Particle momentum variation for an axial magsail.

affected is huge, so that after integrating all particles coming in at all radii, the total momentum generated in the area outside of R_c tends to be about twice that generated inside of R_c.

The equation for thrust, obtained by integrating Eq. (2) over the limits described in Eq. (1) is

$$F = 2\pi R_m{}^2 \rho V^2 (1.05 \times 10^{13} B_m V^{-0.86}) \times \exp(-2.15 \times 10^8 B_0) \tag{3}$$

Thus for our typical case, which is based upon a 10-km radius loop operating in a 1 a.u. interplanetary medium with a centerline field strength of 10^{-5} T, the area of effective total reflection is equal to about 75 times the area actually enclosed by the loop. The scaling of thrust going as $B_m R_m^2$ is quite significant, since if the loop is already at its critical current, its cross-sectional area and thus its mass must be increased in direct proportion to B_m if B_m is to be increased. Similarly, if we attempt to increase thrust by increasing R_m while holding B_m constant, we will find it necessary to increase the mass of the magsail in proportion to R_m^2 (since as R_m increases, the magsail current and thus its cross-sectional area must be increased in proportion if B_m is to be held constant). The bottom line is that in the particle model, there is nothing to be gained by either increasing or decreasing either the magnetic field or the coil radius; to first order the magsail performance is a function of J/ρ_m only. If we adopt a typical 1 a.u. solar wind proton density of $5 \times 10^6/\text{m}^3$, a wind velocity of 500 km/s, and a J/ρ_m of 2×10^6 A-m/kg, we find our base case magsail described above has a mass of 5 tons and generates a thrust of 19.8 N. This provides a self-acceleration for the sail alone of 0.004 m/s^2 or 123 km/s per yr. In an actual spacecraft, this performance would be degraded by the "weight factor" W, where W equals the mass of the magsail plus payload and auxiliary systems and structure divided by the mass of the magsail itself.

Normal Configuration Results

The normal configuration with the protons approaching perpendicularly to the loop axis is more difficult to analyze as the behavior of particles whose point of origin is displaced from the loop center is not symmetric in X or Z directions (the loop axis is assumed to lie on the X axis and protons approach along the Y axis). It is found that, for a given R_m, B_m, and wind velocity, there is a certain elliptical region in the X-Z plane with an average radius of R_{cn} within which the typical proton deflection is greater than that represented by a $\Delta V_y/V$ of -1. This radius R_{cn} is about 2 times larger than the R_c that would be obtained for the same magsail in the axial configuration. Beyond R_{cn}, the $\Delta V/V$ is found to fall off as $(R/R_{cn})^{-2.33}$, as in the axial configuration. The total thrust is found to be about 3 times that available from the axial configuration, thus giving our base case magsail a self acceleration of 0.012 m/s^2. In addition, a net tangential force, equal to about 0.3 times the thrust (i.e., $L/D = 0.3$) is found to exist, due to a preferential sideways deflection by the "vertical" dipole field.

IV. Plasma Fluid Model

In the plasma fluid model, the magsail is approximated by a dipole field (or a collection of dipoles) compressed within a boundary created by a perfectly conducting plasma wind. Within the boundary, there is a magnetic field but no significant plasma pressure; outside the boundary there is a plasma stream with significant dynamic pressure ($q = \rho V^2/2$) but no magnetic field. The boundary is taken to be the surface in space at which the magnetic pressure $B^2/2\mu = q\cos^2\theta$, where θ is the angle between the freestream solar wind direction and the normal to the boundary surface.[6]

The magnetic field at the boundary surface is not the same as the magnetic field would be at that location in the absence of a plasma wind, as it is augmented by magnetic flux that has been compressed inward by the plasma flow. An estimate of the field augmentation can be obtained by considering the boundary as layer of zero thickness containing a surface current. Since the radius of curvature of the boundary is quite large, it can be viewed as locally planar. Now there is no magnetic field just outside of the boundary, which means that the surface current must be creating a magnetic field at that location, which precisely negates the magnetic field created by the dipole. By the law of symmetry then, the surface current must be creating a magnetic field just on the interior of the boundary which is equal to the dipole field but adds to it. Thus the magnetic field at the boundary in the presence of plasma is equal to precisely double what it would be in a vacuum. Since the dipole field decreases with distance cubed, this means that the radius from the dipole center at which the boundary occurs will be enlarged by a factor of $2^{1/3}$ (about 1.26) over what would be obtained if we calculated the radius on the basis of the vacuum dipole field.

This entire model may seem highly idealized, but actually it shows remarkable agreement with experimental evidence[6] gained from spacecraft measurements of the Earth's magnetosphere (shown schematically in Fig. 3). This is true even to the detail of the factor of the $2^{1/3}$ increase in magnetospheric radius due to flux compression. That is, if we calculated the location of the leading-edge stagnation point of the Earth's magnetosphere on the basis of its vacuum dipole field, we would conclude that the point rests at 8.5 Earth radii sunward from the Earth; in reality the point is found at 11 Earth radii, i.e., within 3% of agreement with our idealized result.

The magnetic field of a dipole can be written

$$B = B_m (R_m/R)^3 (\cos\phi \boldsymbol{r} + \sin\phi \boldsymbol{\phi}/2) \tag{4}$$

where $\boldsymbol{r}$ is the radial unit vector to a point at distance R from the dipole center, and ϕ is the angle that the line joining the point with the dipole center makes with the dipole axis.

The magnetic pressure exerted by such a dipole is

$$P_m = B^2/2\mu = B_m^2/8\mu (Rm/R)^6 (1 + 3\cos^2\phi) \tag{5}$$

Now since the magnetic field at the boundary of the magsail's magnetosphere is doubled by plasma compression, the magnetic pressure of the magsail at the boundary P_{mb}, is four times that given by Eq. (5). We set P_{mb} equal to $(\rho V^2/2)\cos^2\theta$ and obtain

$$\cos\theta = [B_m/(V\sqrt{(\rho\mu)})](R_m/R)^3\sqrt{f} \tag{6}$$

where $f = (1 + 3\cos^2\phi)$. We define $C = R_m[B_m/(V\sqrt{(\rho\mu)})]^{1/3}$. Then the position of the leading-edge stagnation point of the magsail boundary is at a distance $C(f^{1/6})$ sunward of the mag-

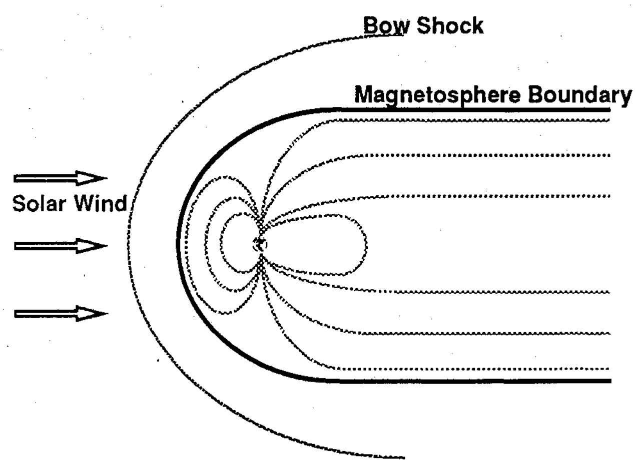

Fig. 3 Earth's magnetosphere.

sail center. Furthermore, after some algebra, we can rework Eq. (6) into the form

$$dx/dy = [(R^6 - C^6 f)/C^6 f]^{0.5} \tag{7}$$

where x is the distance traveled by the boundary in the direction of the solar wind, and y is the distance traveled in the direction perpendicular to the solar wind.

This equation can be integrated numerically, and a program was written to do so. If we chose to integrate Eq. (7) a distance $3C$ downstream of the magsail center, we find that a magsail in the axial configuration creates a circular cross section (in the plane normal to the solar wind) with a radius of $1.89C$, while a magsail in the normal configuration creates an elliptical cross section with a semimajor axis of $2.13C$ and a semiminor axis of $1.75C$.

If we plug in our standard numbers of $B_m = 10^{-5}$ T, $\rho = 8 \times 10^{-21}$ kg/m³ (a proton number density of 5×10^6/m³), and a wind velocity of 500 km/s, we find that $C = 5.847R_m$. Using these numbers together with the results above, we find a magsail in the axial configuration creates drag across a cross-sectional area equal to 122 times the area enclosed by the loop itself, whereas a magsail in the normal configuration creates drag across an area 127 times that enclosed by the loop. Assuming a drag coefficient of unity, these results yield a performance roughly equivalent to those found in the particle model.

However, in the case of the fluid model, the scaling of performance is different than in the particle model, as we shall now show. Using the fact that $B_m = \mu I/2R_m$, where I is the current in the magsail loop, we can rewrite our expression for C, and then, using our results for the magnetosphere boundary above, we find the magsail drag (thrust) D is given by

$$D = (2.13)(1.79)q\pi C^2 = 1.175\pi(\rho\mu^{1/2} IR_m^2 V^2)^{2/3} \tag{8}$$

The mass of the magsail M is

$$M = 2\pi R_m A d = 2\pi R_m I/(J/\rho_m) \tag{9}$$

Taking the quotient of these two expressions, we find that the self-acceleration of the magsail D/M is given by

$$D/M = 0.59(\mu\rho^2 V^4 R_m/I)^{1/3}(J/\rho_m) \tag{10}$$

If we substitute into this expression typical solar wind values of $V = 5 \times 10^5$ m/s, $\rho = (8.35 \times 10^{-21}$ kg/m³$)/R_s^2$, where R_s is the distance of the magsail from the sun in astronomical units, $J/\rho_m = 2 \times 10^6$ A-m/kg, and $\mu = 4\pi \times 10^{-7}$ N/A², Eq. (10) reduces to

$$D/M = 0.02[R_m/(IR_s^4)]^{1/3} \text{ m/s}^2 \tag{11}$$

From Eqs. (10) or (11), it can clearly be seen that in the fluid model it is advantageous to construct the magsail with a small current (i.e., thin wire) but a large radius. Thus using Eq. (11) we find our previous sample magsail ($B_m = 10^{-5}$ T, $R_m = 10$ km, $I = 159$ kA, wire diameter, $d = 4.5$ mm) sailing at 1 a.u. has a self-acceleration of 0.00795 m/s². But if we change the design so that $R_m = 100$ km, $I = 15.9$ kA, $d = 1.42$ mm, $B_m = 10^{-7}$ T, we find that the self-acceleration is now 0.037 m/s². Since $B_m > 5.12 \times 10^{-8}$ T is the minimum requirement to create a magnetosphere boundary at all [i.e., make a solution to Eq. (6) possible], this is about as far as we can go in maximizing the performance of the magsail by thinning the wire and expanding the radius. To be safe, we shall back away from this limit and choose $R_m = 31.6$ km, $I = 50$ kA, $d = 2.52$ mm, $B_m = 10^{-6}$ T as our standard magsail from now on. Such a sail has a mass of 5 metric tons and a self-acceleration of 0.0172 m/s² at 1 a.u., which performance would be degraded on an actual spacecraft in proportion to the weight factor W. The total magnetic energy contained in this sail is about 80 MJ, and the hoop stress is 11,760 psi. Thus this magsail can be "inflated" (i.e., have its current built up) by a 10 kW$_e$ solar panel power array in about 2.2 hr, and the magsail material can probably react the hoop stress without additional mechanical support. However, even if the ceramic superconductor had a tensile strength of zero, this hoop stress could be reacted by a reinforcement of high strength aluminum that would only add about 10% to the sail mass. Adopting this worst-case assumption, the reinforced magsail self-acceleration is found to be 0.015 m/s². A 10 kW$_e$ (at 1 a.u.) power source can be built for a mass as low as 200 kg and so could easily travel with the magsail, which would allow the magsail to be recharged if for any reason it is shut off during the mission. For missions to the outer solar system, a dynamic isotope power system (DIPS) would be more appropriate. Such systems, massing 800 kg and generating 6 kW$_e$, are currently under development by the U.S. Department of Energy.

In the plasma fluid model, lift can also be generated if the dipole is situated with its axis at some orientation intermediate between the axial and normal configurations. Using a hypersonic aerodynamics code, we have found simple dipole configurations with L/D as high as 0.14. If compound magsails were adopted, consisting of two or more loops connected by a spar along their axes, more desirable magnetospheric boundary shapes could be obtained yielding a much higher L/D. The analysis of such compound magsails will be a subject of a future paper.

V. Magsail Orbits

Magsail Orbits Without Lift

To calculate the orbit of a magsail spacecraft, we choose to parameterize the drag (thrust) generated by the magsail as a fraction of the sun's gravitational attraction on the spacecraft. The sun's gravitational acceleration $g_s = 0.006/R_s^2$, and the maximum magsail spacecraft acceleration $D/M = 0.015/(WR_s^{4/3})$, where W, the weight ratio, equals the mass of the total magsail spacecraft (including payload) divided by the mass of the active magsail cable. The apparent fraction α of the sun's gravity operating on the spacecraft with its magsail operating at full current is then given by

$$\alpha = [1 - D/(Mg_s)] = (1 - 2.5R_s^{2/3}/W) \tag{12}$$

If $\alpha = 1$, the magsail is not operating. If α is between 1 and zero, the spacecraft acts as a body moving about a star whose mass is the fraction of the sun's mass represented by α. If $\alpha = 0$, the spacecraft feels no solar force and moves in a straight line, whereas if $\alpha < 0$, the spacecraft feels a net repulsion from the sun and moves away in a hyperbolic orbit.

Let us say our 5-ton magsail requires 3 tons of micrometeorite shielding and insulation plus an additional mass of 1 ton for shrouds, solar panels, avionics, etc., and we wish to use it to transfer a 38.5 ton payload ($W = 9.5$) from Earth to Mars. Assume that the magsail is co-orbiting with the Earth but outside of its gravitational well. Using canonical units[7] such that $R_{\text{Earth}} = V_{\text{Earth}} = GM_{\text{sun}} = 1$, we can write

$$E = V_{sc}^2/2 - \alpha/R_s = -\alpha/2a \tag{13}$$

Since for a Hohmann transfer to Mars, $2a = 2.52$, we can solve Eq. (13) for the required value of α(V_{sc} initially = 1) to send the spacecraft onto such an orbit. The result is $\alpha = 0.8289$. Checking Eq. (12) we find our spacecraft with $W = 9.5$ can attain an α at 1 a.u. as low as 0.7368, so the spacecraft is capable of doing this maneuver. Since in this zero-lift trajectory, angular momentum about the sun is conserved, upon reaching Mars orbit, the ship will be moving with a velocity of V_{sc} (Mars arrival) = 1/1.52 = 0.6579. If we now wish to circularize the orbit, we use this value of V_{sc} together with $2a = 3.04$ in Eq. (13) and find that the required value of α to circularize at Mars is 0.6579. Checking Eq. (12), we see that our spacecraft at 1.52 a.u. is capable of generating α as low as 0.652, and so it can circularize at Mars.

Our spacecraft is now moving in Mars' orbit about the sun, but at a different speed than Mars. Mars is overtaking the spacecraft with a relative velocity of 4.564 km/s. This odd situation gives the magsail craft a very interesting capability. What it means is that the spacecraft can leave Earth for a Hohmann transfer to Mars' orbit, circularize, and then loiter at will in Mars' orbit until the Red Planet catches up to it. Thus a magsail interplanetary transfer can be done at any time, unlike ballistic interplanetary transfer orbits, there are no limited launch windows.

When Mars approaches, the magsail can release its payload, consisting of cargo plus an aerobrake, allowing the payload to aerobrake (entry velocity is 6.77 km/s) into Mars' orbit or land. Simultaneously, the magsail reduces its current partially so as to increase α back to 0.8289, which sends the magsail on a Hohmann transfer orbit back to Earth. Upon reaching Earth orbit, the magsail is turned off, and the spacecraft will circularize at 1 a.u. If the timing of this maneuver is incorrect for Earth rendezvous, all the magsail has to do is make its initial Hohmann transfer back from Mars not to Earth, but to a circular orbit intermediate between Earth and Mars. The magsail can then waste as much time as required in that orbit to allow the Earth to attain the correct position for the final Hohmann transfer home. Since the intermediate orbit can be chosen at will, such return flights can be scheduled with great flexibility.

The time of flight of such magsail Hohmann transfers is given by

$$t = \pi(a^3/\alpha)^{1/2} \tag{14}$$

For our Earth-Mars Hohmann transfer, $a = 1.26$, $\alpha = 0.8289$, and thus $t = 4.88$ canonical units = 283 days, a time slightly longer than the usual Hohmann transfer ballistic flight time.

In Table 1 we show magsail requirements and capabilities for moving payloads to different planetary destinations in the outer solar system, assuming no magsail lift.

In Table 1, α_{trans} is the value of α required to initiate the transfer ellipse to the given destination, α_{circ} is the value of α required at that destination to circularize the orbit, α_{circ0} is the value that α would have to have been at 1 a.u. to allow the spacecraft to attain α_{circ} at the destination, W_{trans} is the weight ratio (the mass of the magsail plus payload divided by the mass of the magsail) allowable to permit the attainment of α_{trans}, and W_{circ} is the weight ratio allowable to permit the attainment of α_{circ0}. The weight ratio actually attainable for any given destination is simply the lesser of W_{trans} and W_{circ}. We can see that a magsail without lift can move a payload amounting to four times the sail weight to any destination in the outer solar system.

Finally, if we do not desire to go anywhere in particular, but only wish to rapidly accelerate out of the solar system (as is required for the proposed thousand astronomical unit[8] probe, for example), we can set $W = 1.25$ and thus $\alpha = -1$ at 1 a.u. and become more negative as we move out. Integrating the equations of motion, we find that the probe will be hurled out of the solar system with a terminal velocity of 95 km/s and will reach 1000 a.u. in about 50 yr.

Magsail Orbits Utilizing Lift

If lift can be generated, the magsail becomes capable of changing its angular momentum about the sun, which gives the magsail both greater maneuverability and payload hauling capability.

If h is the angular momentum in canonical units, it follows from the laws of physics that

$$dh/dt = (L/D)(1 - \alpha)/R_s \tag{15}$$

Table 1 Zero lift magsail payload capability

Destination	α_{trans}	α_{circ}	α_{circ0}	W_{trans}	W_{circ}
Mars	0.8289	0.657	0.741	14.60	9.66
Jupiter	0.5906	0.192	0.711	6.11	8.64
Saturn	0.5525	0.105	0.801	5.58	12.55
Uranus	0.5259	0.052	0.868	5.27	18.96
Neptune	0.5165	0.033	0.900	5.17	25.06
Pluto	0.5125	0.025	0.916	5.12	29.87
Escape	0.5000	0.000	1.000	5.00	infinite

We wish to follow an elliptical trajectory given by

$$R_s = P/[1 + (e)\cos\Omega] \tag{16}$$

where

$$P = h^2/\alpha \tag{17}$$

is the semilatus rectum of the ellipse, e is the eccentricity, and Ω is the true anomaly. To keep P a constant of the motion, as h increases in accordance with Eq. (15), we shall increase α in accordance with Eq. (17). We also have

$$h = \text{angular momentum} = R_s^2(d\Omega/dt) \tag{18}$$

Substituting Eqs. (16–18) into Eq. (15) we obtain

$$dh/d\Omega = (L/D)(1 - h^2/P)(1/h)\{P/[1 + (e)\cos\Omega]\} \tag{19}$$

This can be separated and integrated, and its solution is

$$P - h^2 = (P - h_0^2)\exp(Z) \tag{20}$$

where h_0 is the angular momentum at the start of the trajectory, and Z is given by

$$Z = -4(L/D)(1 - e^2)^{-1/2} \times \tan^{-1}\{[(1 - e)/(1 + e)]^{1/2} \tan\Omega/2\} \tag{21}$$

For the trans-Mars ellipse orbit, $e = 0.20635$, $P = 1.20635$, we let Ω go to π and we obtain

$$1.20635 - h^2 = (0.20635)\exp(-2.044\pi L/D) \tag{22}$$

If $L/D = 0.14$, we obtain $h = 1.0594$, which means that V_{sc}(Mars arrival) = 0.697 units = 20.73 km/s for a velocity difference with Mars of 3.39 km/s. The flight time is slightly faster than for the zero-lift case because of the higher average value of α. At arrival, $\alpha = 0.93$. To circularize the orbit, we now require $\alpha = 0.738$ (instead of the 0.657 required in the no-lift case). This increases the attainable payload weight ratio from $W = 9.66$ in the no-lift case to 12.61 in the present case. This is a significant gain, but equally valuable is the increased flexibility of flight plan such lift makes possible.

For example, let us say we send the spacecraft on a zero-lift trajectory toward Mars. We arrive in Mars orbit and dally until Mars shows up, at which point we release the payload (which aerocaptures with a hyperbolic excess velocity of 4.564 km/s and an atmospheric entry velocity of 6.77 km/s) and then return the magsail on a transfer orbit toward Earth, all as described in the section on zero-lift maneuvers. Now, however, we apply negative lift to decrease the spacecraft's angular momentum about the sun. In this case, when we arrive at Earth orbit, we need a value of $\alpha < 1$ to circularize, which means that we can now circularize in Earth orbit with a different orbital velocity than the Earth and loiter until the Earth catches up to us. We thus have the ability to move large payloads back and forth between the Earth and Mars with the knowledge that rendezvous can be achieved at each end of the orbit without regard to when the spacecraft sets forth. This improves the potential performance of the concept of cycling interplanetary "castles,"[9] i.e., by enabling these large manned habitats following ballistic interplanetary orbits to obtain a greater number of planetary encounters in their lifetime. In effect the magsail allows the castle to "cheat" against the laws of orbital mechanics by giving it the ability to adjust the effective mass of the sun to that required to assure orbital rendezvous with the target planet at each end of the castle's commute. In addition, the use of negative lift allows the magsail to drop below Earth orbit to visit Mercury and Venus.

The use of lift also allows the magsail to perform interesting nonelliptical orbits, whose trajectories can be plotted numerically. For example, if we allow P to vary, we can use the expressions

$$e = (1 + 2Eh^2/\alpha^2)^{1/2} \tag{23}$$

$$r_a = a(1 + e) \tag{24}$$

where r_a is the instantaneous orbit apogee, together with Eq. (13) to obtain

$$a = 0.5R(r_a^2 V_{sc}^2 - h^2)/(r_a^2 - r_a R) \tag{25}$$

Equation (25) can be used as a guidance algorithm in a computer program in which a magsail spacecraft using lift can start with a very high α (large payload) and increase h and r_a until the desired r_a is obtained, and then hold r_a constant until the destination is reached. Using this strategy, the payload hauling capability of the magsail can be significantly expanded.[10]

If lift is to be utilized, it becomes necessary to be able to control the orientation of the magsail. One way to accomplish this would be to connect the payload to the magsail loop with a set of tethers that can be either reeled in or out on a windlass. This would allow the magsail to shift its center of mass in either of the two dimensions within the plane of the loop. By moving the center of mass relative to the sail's center of pressure, a torque can be induced, which would allow the magsail to be swung into the desired attitude.

Above and beyond its propulsive capability, the magsail has an additional advantage as a system for manned interplanetary spacecraft, in that it shields the crew from a large portion of the radiation dose they would otherwise receive from the solar wind and solar flares. Without such shielding, these hazards may well place a severe constraint on long distance manned spaceflight.

VI. Mars Cargo Mission Analysis

The utility of the magsail can be demonstrated by an analysis of a simple Mars cargo mission. Let us say we wish to deliver a series of 30-ton payloads from low Earth orbit (LEO) to low Mars orbit (LMO). We consider three alternatives.

1) Cryogenic chemical propulsion with a specific impulse of 460 s is used to drive the payload onto a minimum energy orbit from Earth to Mars, where the payload is aerocaptured into LMO. An aerobrake mass equal to 15% of the payload mass is assumed, the chemical engines are assumed to mass 1 metric ton, and tank masses are taken as 10% of the propellant they contain. Delta-V are taken as 3.8 km/s for trans-Mars injection, 0.2 km/s for midcourse corrections, and 0.1 km/s for periapsis raise.

2) Nuclear electric propulsion (NEP) with a specific impulse of 5000 s is used to transfer the payload from LEO to LMO, where it is released. The NEP vehicle then returns to LEO without cargo. The NEP unit was assumed to have a mass of 10 metric tons and generate 625 kW_e, with a jet power of 500 kW_j. As relatively dense argon propellant was assumed, tank masses were taken as 5% of the propellant contained. Delta-V used were derived from the Edelbaum equation and were 7.5 km/s for transit either way between LEO and Earth escape, 5.8 km/s for interplanetary transfer either way, and 3.6 km/s for transfer to and from Mars escape and LMO. A re-entry heat shield of 8% of the payload mass was added to the payload in order to allow it to enter atmosphere of Mars and land.

3) Nuclear electric propulsion with a specific impulse of 5000 s was used to lift the payload from LEO to Earth escape, where the payload was switched to magsail propulsion for the transfer to Mars, while the NEP unit returned to LEO unloaded. The magsail executes a zero-lift transfer to Mars orbit, where the magsail releases the payload to aerocapture at Mars, while the magsail returns to co-orbit with the Earth at the edge of the Earth's gravitational influence. On the first mission, the NEP vehicle lifts the magsail to Earth escape; afterwards the NEP vehicle need only transfer the cargo. The NEP vehicle used in this scenario was identical to that used in scenario 2. The payload was equipped with an aerobrake massing 15% of the payload mass plus a cryogenic chemical engine with a specific impulse of 460 s, a mass of 0.3 metric tons, and enough propellant for a delta-V of 300 m/s to allow for maneuvering away from the magsail and a periapsis raise at Mars. The magsail used was that described in Sec. V, which consisted of a 5-metric-ton active cable, 3 metric tons of micrometeorite shielding and insulation, and 1 metric ton of shrouds, solar panels, and avionics. The results of the analysis are given in Table 2.

In Table 2, all masses are given in metric tons. It can be seen that on the first cargo flight, both pure NEP and the NEP/magsail systems offer similar Earth to orbit (ETO) benefits, with launch requirements reduced about 33% compared to the chemical/aerobrake mission. On the second and succeeding missions, however, both the NEP unit and the magsail can be reused, which strengthens the benefit to an ETO mass reduction of 46% for the pure NEP and 53% for the NEP/magsail. The real benefit of the magsail, however, is shown in the third column, where it can be seen that by using the magsail for the interplanetary leg and only cycling the NEP vehicle between LEO and Earth escape, the number of full power years required by the NEP system for each mission can be reduced by about a factor of 2.4. As both the electric thrusters and the nuclear power generation system on the NEP vehicle are likely to be lifetime limited, this may prove to be an important advantage. For example, if the NEP system is rated for a working lifetime of 4 full power yr, then the pure NEP system can only launch two payloads to Mars during its career, while the NEP system assisted by the magsail can be used to launch five missions. This enhanced reusability further enhances the magsail mass savings. Thus in the above example of a 4-yr working life for the NEP unit, launching a series of 10 cargo payloads to Mars with pure NEP would require five NEP units and a total ETO mass of 635 metric tons (compared to 1030 tons for chemical/aerobrake), while if the missions are done with NEP units assisted by magsails, then two NEP units and two magsails are needed, and the total ETO mass is 524 tons (18% less than pure NEP, 49% less than chemical/aerobrake). The use of the magsail further eases the reliability requirements of the NEP system by reducing the required time of full power operation between checkouts. Finally, the magsail increases the utility of the NEP unit by increasing its duty factor, or the number of payloads the NEP can ship out within a given amount of time. In contrast to the pure NEP system, which sails off to Mars with a payload and is not seen again for over 2 yr, the NEP unit assisted by the magsail can be returned to LEO in less than 1 yr. There it can be used to lift another pay-

Table 2 Mars cargo mission comparison

Propulsion	Earth-to-orbit mass		Engine years/ mission	
	1st flight	2nd flight	1st flight	2nd flight
Chem/Aero	103	103	—	—
NEP	69	58	1.88	1.88
NEP/Magsail	70	48	0.88	0.78

load to Earth escape where it can be shipped by magsail to Mars (taking advantage of the magsail's ability to deliver payloads regardless of launch window, discussed in Sec. V), or other destinations.

VII. Magsail as an Interstellar Brake

In addition to its role as an interplanetary propulsion system, the magsail also offers great potential as the braking device[1] for an interstellar spacecraft that has been previously accelerated to relativistic velocities by some other means, for example, by a fusion rocket or a laser pushed lightsail. In this case, the plasma wind is the apparent wind created by the relative velocity between the spacecraft and the interstellar medium. In Ref. 1, we used the particle model to show that a relativistic magsail could brake itself with an e-folding velocity decay time of 36 yr, if $J/\rho_m = 2 \times 10^6$ A-m/kg. We now derive both a more accurate and a more favorable result utilizing our plasma fluid model. Using Eq. (10) with $V = V_{sc}$, $\rho = 1.67 \times 10^{-22}$ kg/m^3, $R_m = 100$ km, $I = 159$ kA, and $W = 2$ (a 50-ton magsail with a 50-ton payload), we obtain

$$dV/dt = -1.66 \times 10^{-11} V^{4/3} \tag{26}$$

The solution of this equation is

$$V = V_0/(1 + 3.68 \times 10^{-12} V_0^{1/3} t)^3 \tag{27}$$

where V_0 is the velocity of the spacecraft at the beginning of the braking maneuver. If V_0 is 3×10^7 m/s (one-tenth the speed of light) and t is given in years, Eq. (27) becomes

$$V = (3 \times 10^7 \text{ m/s})/(1 + 0.054t)^3 \tag{28}$$

which will reduce V by a factor of 8 in 18.5 yr. In 55.5 years, V will be reduced by a factor of 64 to 468 km/s, a velocity suitable for magsail or fusion rocket braking within the destination solar system. For all purposes, the magnetic sail has eliminated the propellant required for terminal deceleration; the result is a massive reduction in mission mass ratio.

The above calculation (as well as the calculations in Ref. 1) is based on an assumed interstellar hydrogen number density of 10^5/m^3. This is quite conservative. Some astronomers put the estimate ten times higher, which would shorten the time scales given above by a factor of 4.64.

VIII. Conclusions

We find that, provided high temperature superconducting cable becomes available with current densities equal to that of existing low temperature superconductors, magnetic sail devices can be developed with the potential to move very large payloads anywhere in the solar system. Such magsails offer the advantage that they require no propellant and can accomplish orbit transfer maneuvers without regard to the usual ballistic transfer launch windows. The required flight times are slightly greater than the usual Hohmann transfer ballistic flight times. Compared to a conventional solar lightsail, the magsail offers a thrust to weight ratio one to two orders of magnitude greater as well as a system that is far more robust and simpler to deploy. The magsail also offers promise as an enabling technology for interstellar missions by providing a braking device which requires no propellant.

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