USE OF MAGNETIC SAILS FOR ADVANCED EXPLORATION MISSIONS

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ABSTRACT

The magnetic sail, or magsail, is a field effect device which interacts with the ambient solar wind or interstellar medium over a considerable volume of space to generate drag and lift forces. Two theories describing the method of thrust generation are analyzed and data results presented. The techniques for maintaining superconductor temperatures in interplanetary space are analyzed and low risk options presented. Comparisons are presented showing mission performance differences between currently proposed spacecraft utilizing conventional chemical and electric propulsion systems, and a Magsail propelled Spacecraft capable of generating an average thrust of 250 Newtons at a radius of one A.U. The magsail also provides unique capabilities for interstellar missions, in that at relativistic speeds the magnetic field would ionize and deflect the interstellar medium producing a large drag force. This would make it an ideal brake for decelerating a spacecraft from relativistic speeds and then maneuvering within the target star system.

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. Its principle of operation is as follows: A loop of superconducting cable hundreds 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 into space 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 10^{-6} Tesla, so little structural strengthening is required.Two different configurations were examined as shown in figure 1. In the axial configuration (fig. 1a), the axis of the dipole is somewhat aligned with the direction of flight. In the normal configuration (fig. 1b) the axis of the dipole is normal (or perpendicular) to the direction of flight. Three previous papers by the same authors (references 1,2 &3) have discussed the Magsail's principles of operation and its applications for interstellar and planetary missions. This paper will show additional data generated this year and incorporate various technology advancements made since the last paper. A general description of the principles of operation follows:

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 degrees Kelvin where current low temperaturesuperconductors NbTi and Nb_3Sn have critical currents of about 1.0×10^{10} and 2.0×10^{10} Amps/m^2 respectively. In interplanetary space, where ambient temperatures are above the critical temperatures of low temperature superconductors, these materials would require expensive refrigeration. However, the new high temperature ceramic suporconductors such as $YBa_2Cu_3O_7$ have demonstrated enormous critical currents in samples at temperatures maintainable in interplanetary space using simple radiative thermal control concepts (ie. 70-90 degrees K). Assuming this performance will someday be available in bulk cable we have chosen to parameterize the problem by assuming a near term high temperature superconductor with a critical current of 10^{10} amp/m^2, and an advanced technology superconductor with a critical current of 10^{11} amps/m^2. Because the magnets are only 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 magnets have current to mass density ratios (i/ρ) of 2×10^6 and 2×10^7 amp-m/kg for the near term and advanced cases, respectively.

The equation for superconductor mass as a function of radius, peak field strength, and current density ratio was found to be:

$$M_{sc}=4(\pi/\mu o)\, B_m R_m^2/(\, J/\rho\,) \qquad (1)$$

where μo is the permitivity of free space, B_m = maximum field strength in center of loop, R_m = loop radius and J/ρ = maximum allowable current density to mass ratio.

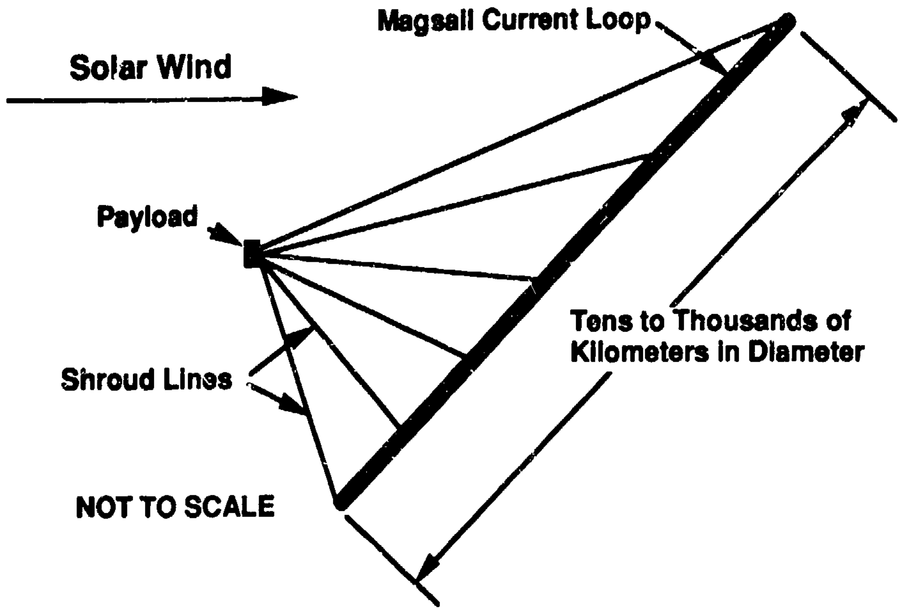


Figure 1a Axial Magsail Configuration

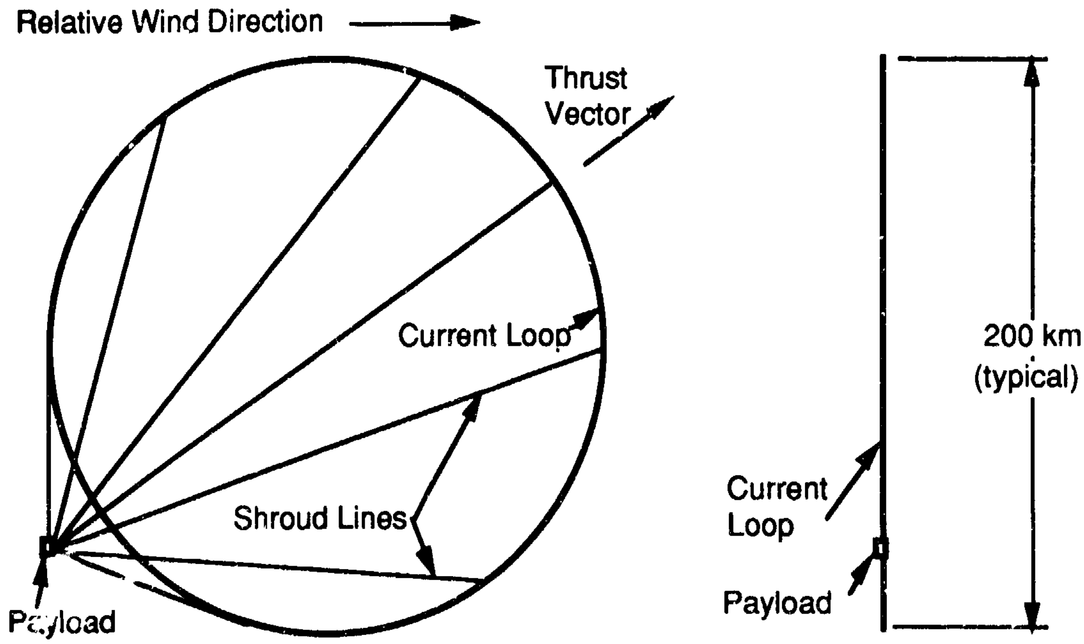


Figure 1b. Normal Magsail Configuration

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, exsists 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 earth is a flux of several million protons and electrons per cubic meter at a velocity of 300 to 600 km/sec. This can be used to accelerate a spacecraft radially away from the sun and the maximum speed available would approximate that of the solar wind itself. While inadequate for interstellar missions these velocities are certainly more than adequate for interplanetary missions.

When the dipole field is inclined to the wind vector the magsail also generates a force perpendicular to the wind (i.e. lift). While not crucial for interstellar applications, lift greatly enhances the usefulness of the Magsail for interplanetary operations. Additional interplanetary maneuvering capability could be attained by using gravitational swingbys of the major planets. The second application, and the one which will receive the majority of our attention in this paper, is as a brake for an interstellar spacecraft travelling at fractions of the speed of light. The rapidly moving magnetic field of the Magsail ionizes the interstellar medium and then deflects the resulting plasma, creating drag which decelerates the spacecraft. The ability to slow down spacecraft from interstellar to interplanetary velocities without the expenditure of rocket propellant results in a dramatic lowering of the total mission mass, as we shall show in the detailed systems performance trades presented below.

There are two ways in which the Magsail physically interacts with the surrounding plasma. At very low particle densities we would expect a particle interaction, where each particle interacts separately with the field of the magnetic dipole. In this case, we calculate the lift and drag generated by the current loop by summing the momentum changes over all incoming particles.

For the particle flows characteristic of the solar wind in Earth's vicinity and for the large current loops where the dipole magnetic field dominates the local magnetic field beyond several proton gyration radii, we would expect a fluid interaction, where the solar wind interacts with the Magsail field as a magnetohydrodynamic fluid, in the same manner as it interacts with the earths' magnetic field. In this case, we can calculate Magsail lift and drag using aerodynamic approximations developed to explain the shape of earth's magnetosphere. We will discuss the mechanism for thrust generation and its impact on interplanetary orbital mechanics only briefly in this paper. For details on the orbital trajectories of a Magsail propelled vehicle using with the solar wind, see references 2 &3.

Particle Interaction

For the particle interaction, a computer code, TRACE, was written which follows the trajectory of individual charged particles as they interact with the magnetic field generated by the current loop, and a series of computer experiments were conducted testing 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. Summing the momentum changes of individual protons as they traversed various regions of the magnetic field allows the total impact of the field on the oncoming solar wind to be calculated. The total changes in momentum would be experienced as drag and lift on the current loop.

As a test case, we have integrated the change in proton momentums in the radial and orbital directions for a example magsail loop in the normal configuration (fig. 1b) with a Magnetic Dipole Moment (M_{DM}) of 1.63×10^{15} amp-turns-m^2. The initial integration was over a square intercept area 40 loop radii on a side using the TRACE program. This was then extended to an area more than 200 loop radii on a side using statistical sampling and emperical equations derived through curve fitting, and showed that the average change in radial momentum summed over the entire area, A_o, ($A_o = 10^{14}$m^2) was:

$$A_o \frac{\Delta V_r}{V_{ro}} = -0.00237 \, A_o \qquad (2)$$

Therefore the radial force, F_r, can be represented as:

$$F_r = \rho_o V_{ro}^2 A_o \frac{\Delta V_r}{V_{ro}} \qquad (3)$$

Which becomes $F_r = 2q\,A_0 \frac{\Delta V_r}{V_{ro}} = 264.5$ Newtons for a quiet sun solar wind at one AU. For this study, we have assumed that a quiet sun solar wind at one AU has $q = 5\times10^{-10}$ N/m^2($q = \frac{1}{2}\rho_o V_{ro}^2$), that an average solar wind has $q = 1.0\times10^{-9}$ N/m^2, and that a high solar wind has $q = 2.0\times10^{-9}$ N/m^2. These are approximations based on published Mariner 2 data.

The average change in velocity in the orbital plane(zero average particle velocity before encountering the magnetic field) summed over the same area is:

$$A_0 \frac{\Delta V_z}{V_{ro}} = +72.4\ R_m^2 \tag{4}$$

Therefore, the minimum tangential force ,F_t, can represented as:

$$F_t = 2q\,A_0 \frac{\Delta V_z}{V_{ro}} = 74.1 \text{ Newtons} \tag{5}$$

and the Magsail produces a lift to drag ratio of 0.28. The generation of significant lift is an important result, and as we show below , is in contrast to the fluid interaction case.

Fluid Interaction

In the fluid interaction case, the forces on the current loop are modeled from the measured interaction of the solar wind with the earth's magnetic field, with corrections for scale based on known physical principles.

The solar wind is a continuous hydrodynamic expansion of the solar corona out through the solar system. The nature of this expansion is such that the plasma achieves very high velocities ($V_0 \sim 500$ km/sec) within the first one tenth astronomical unit and then the velocity increases very slowly with radius (ie. $V \sim V_0(\ln R)^{1/2}$), where R is the radius from the center of the sun (reference 4). The hot coronal plasma had very high electrical conductivity and, as such a fluid expands, the magnetic field lines are "frozen-in". This "frozen-in" magnetic field causes the solar wind to behave as a fluid even when its density is so low that the mean free length between collisions is several Astronomical Units!

The fluid interaction process between the solar wind and Earths magnetic field is shown schematically in figure 2 from reference 5.

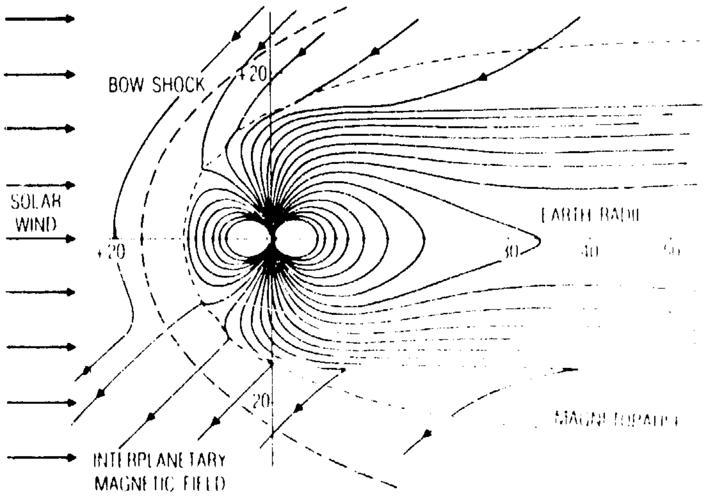


Figure 2 Schematic of the Earth's Magnetosphere

The magnetosphere represents the boundary between the perfectly conducting plasma in the solar wind and the compressed dipole magnetic field. The pressure, p, on a unit surface area of the magnetosphere is determined by the balance between the dynamic pressure from Newtonian flow aerodynamics, and the magnetic pressure from the magnetic field. This can be repesented as:

$$2\left(\frac{1}{2}\rho_o V_o^2 \cos^2\theta\right) = \frac{B^2}{2\mu_o} \qquad (6)$$

where θ is the angle between the solar wind vector and the normal to the unit surface area of the magnetosphere. Note that μ_o is the vacuum magnetic permitivity described earlier ($\mu_o = 1.26\times10^{-6}$ henry/meter). At this point the solar wind has lost its velocity normal to the field lines and only flows tangentially. In front of this region a bow shock forms similar to the shock wave in front of a blunt body in hypersonic flow. The region between the bow shock and the magnetosphere is called the magnetosheath. The magnetosheath is made up of higher density, thermalized solar wind, which is deflected and accelerated as it flows around the magnetopause region (again very similar to hypersonic flow). Assuming the solar wind excludes the magnetic field by generating surface currents to create an equal and opposite magnetic field at the boundary, we get a doubling of the magnetic field inside the boundary from symmetry (reference 2). The magnetic field at any point for a dipole in a vacuum can be written as:

$$B = \frac{\mu_o M_{DM}}{4\pi r^3}\left(2\cos\phi\,\mathbf{r} + \sin\phi\,\boldsymbol{\phi}\right) \qquad (7)$$

where M_{DM}, the magnetic dipole moment, is equal to the number of amp-turns of current times the area of the current loop, r is the radius from the center of the current loop to the point in question, ϕ is the angle between r and the dipole axis. $\mathbf{r}$ and $\boldsymbol{\phi}$ are the corresponding spherical coordinate vectors. Since the field strength at the magnetosphere boundary is twice that at the same point in a vacuum, we can write an equality for the pressure at any point on the boundary surface:

$$2q\cos^2\theta = \frac{B^2}{2\mu_o} = \frac{(2\mu_o M_{DM})^2}{(4\pi)^2}\,\frac{1}{2\mu_o}\,\frac{1}{r^6}(1+3\cos^2\phi) \qquad (8)$$

which can be written:

$$\cos\theta = \left(\frac{M}{Q}\,\frac{G}{r^6}\right)^{0.5} \qquad (9)$$

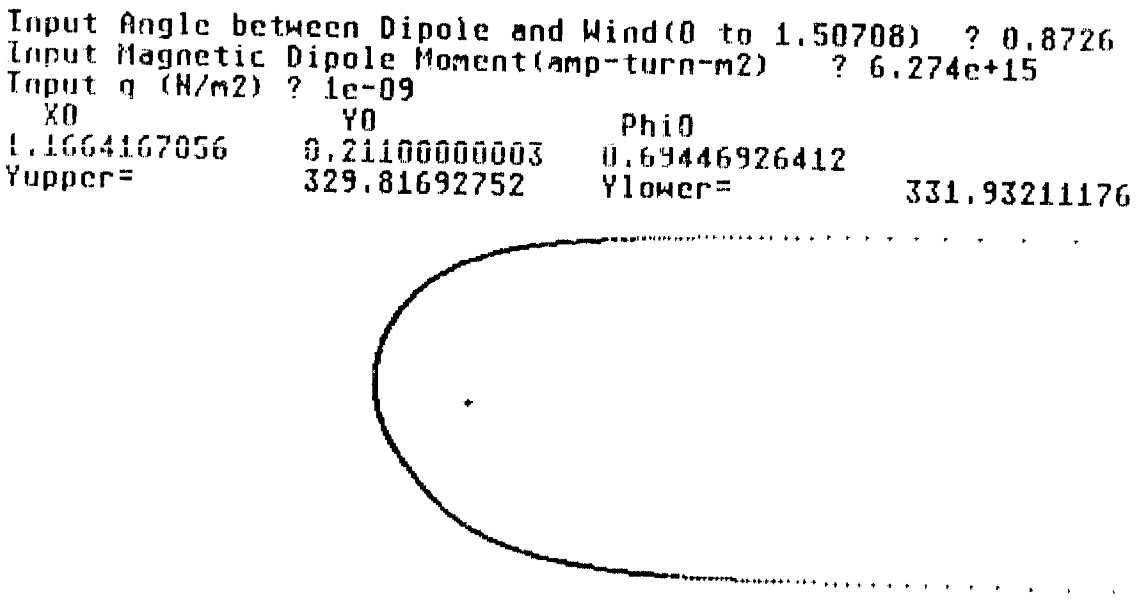
where $M = \frac{\mu_o M_{DM}^2}{16\pi^2}$ and, $G = 1+3\cos^2\phi$

For calculating purposes, we define a new variable: $R_{MQ} = \left(\frac{M}{Q}\right)^{0.16667}$, so that:

$$r = R_{MQ}\left(G\cos^2\theta\right)^{0.16667} \qquad (10)$$

Note, that R_{MQ} is the characteristic standoff distance between the loop center and the front surface of the magnetosphere when $\phi = 90$ degrees (dipole axis is normal to the flow).

A computer program , MAGSHAPE, has been written to numerically integrate Equation (10) in order to determine the shape of the magnetosphere. A typical result is shown in figure 3. A variant of MAGSHAPE, called MAGFORCE, which integrates the pressures over the entire magnetosphere body of revolution has recently been completed. This enabled us to calculate the magsail drag, lift, and moment coefficients based on equivalent Newtonian flow aerodynamics. The results, sumarized in figure 4, are somewhat disappointing because the maximum magsail L/D is so low (about 0.05), but this L/D is more than adequate for interstellar applications, and precludes very few interplanetary applications. The only effect seen in Mars mission simulations using the reduced L/D was an increase in flight times of around ten percent. The full impact of magsail aerodynamics on interplanetary missions will be explored in a future paper (AIAA Paper 90-2367 "Progress in Magnetic Sails").



```
Input Angle between Dipole and Wind(0 to 1.50708)  ? 0.8726
Input Magnetic Dipole Moment(amp-turn-m2)   ? 6.274e+15
Input q (N/m2) ? 1e-09
  X0               Y0              Phi0
1.1664167056     0.21100000003    0.69446926412
Yupper=          329.81692752    Ylower=          331.93211176
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Figure 3. Integrated Magnetosphere Shape

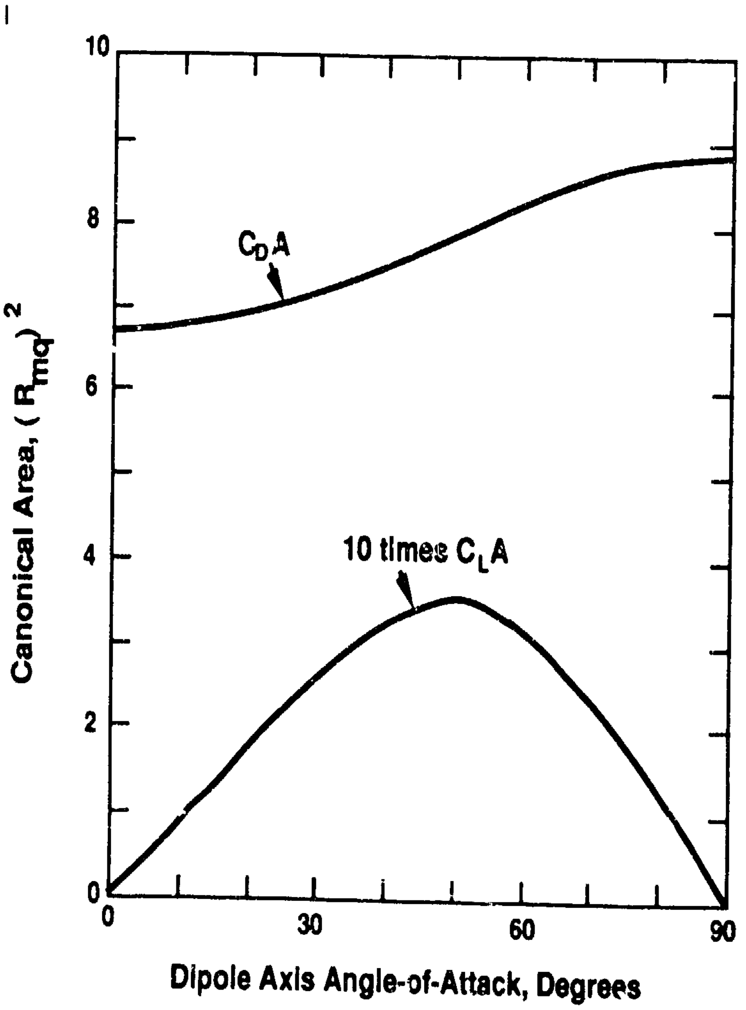

Figure 4. Magsail Aerodynamics

The aerodynamic data was used to generate parametric "bare magsail" performance at one AU solar radius with a "average" solar wind ,($q = 1.0x10^{-9}$ N/m^2). This data, included as figure 5, shows that the magsail scales favorably with size. In effect, the drag is increasing with current loop area while the mass increases with loop perimeter. The "bare" magsail for each dipole moment was sized for minimum mass including the superconductor, structural reinforcement (if required), and the Thermal Protection System (TPS). When this data was crossplotted it was discovered that every minimum mass loop had 57,700 amps of current circulating and all had a hoop force of 720 Newtons. These optimums are determined by the j/ρ and lineal TPS masses assumed. Improvements in technology, or limits on hoop force to meet acceleration requirements, will shift the optimums, but a minimum mass magsail will have the same current and same hoop force regardless of size (dipole moment). This means only one type of magsail cable must be developed and different lengths are used for different applications. This should provide significant cost savings, design flexibility, and mission safety.

Note: j/ρ = 2,000,000 amp-m/kg & Lineal Mass of TPS = 0.0288 kg/m

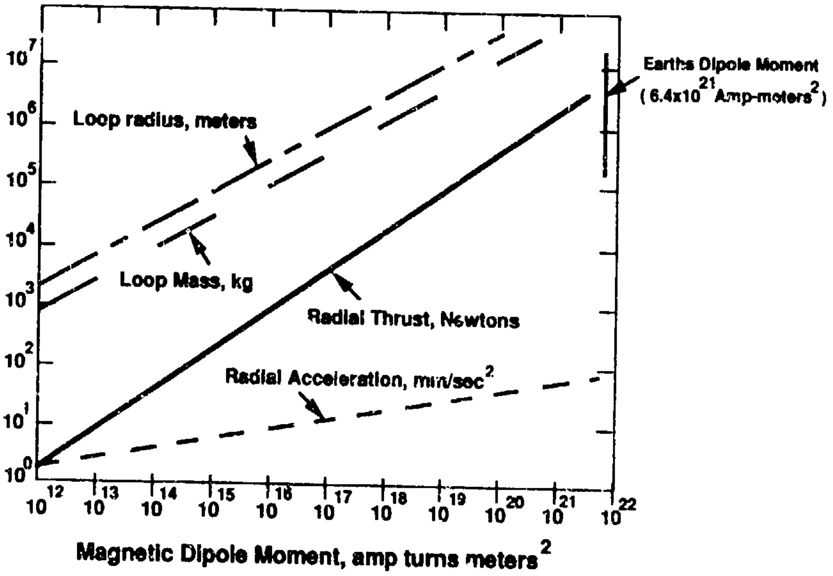

Figure 5. Bare Magsail Performance

Interstellar Magsail Missions

This paper was aimed at the interstellar applications of magsails, which are further in the future, but a better "fit" with magsail capabilities.The use of magsails to slow a laser lightsail propelled interstellar exploration vehicle was introduced in reference 1. In that paper, the limits to laser lightsails were discussed and some example missions were presented. As a point of reference, the trip time for a one-way 1000 ton manned exploration mission to a star ten lightyears away was 107 years assuming a 1000 Terawatt laser with a beam divergence angle of $1.0x10^{-10}$ radians. The vehicle dry mass was 3035 tons, of which 1000 tons is payload, 1156 tons is a metalized kapton lightsail, 687 tons is magsail, and 193 tons is a fusion pulse rocket and propellant to reduce the time spent in the doldrums. (The doldrums are the regions outside the boundary which separates the target star's solar wind from the interstellar medium.) The magsail is travelling between 3000 and 500 km/sec in this region and because the mass flow is so small, it takes several years elapsed time and almost a light year of distance to decelerate between these velocities. Adding a small rocket reduces the total deceleration period by four to five years.

The relatively long trip times are due to low acceleration and deceleration rates caused by a variety of physical limitations. Initial lightsail acceleration is limited by temperature constraints on the metal lightsail material, and the duration of acceleration is limited by the focusing capability of the laser optics (at distances approaching one lightyear the diameter of the image of the laser power-limited aperture greatly exceeds the diameter of the lightsail). Initial deceleration of the magsail was excellent, but a disportionately long time was spent decelerating between 3000 and 500 km/sec.

Solutions to these problems seem to be at hand. The acceleration issues have been solved by Geoffrey Landis who introduced the subject of dielectric lightsail materials in reference 6 (with help from Robert Forward). A laser lightsail made from pure dielectric materials, operating at the proper wavelength, will absorb very little laser light and can operate at intensities many orders of magnitude above metal reflectors. This means laser power can be increased, acceleration raised, and acceleration distance shortened. Shortening the acceleration distance means laser beam imaging and pointing accuracy can cease to be a problem. The principal remaining acceleration problem becomes where to build a multi-thousand Terawatt laser. A candidate laser power station is shown in figure6. It uses a small asteroid to stabilize the focusing mirror during operation.

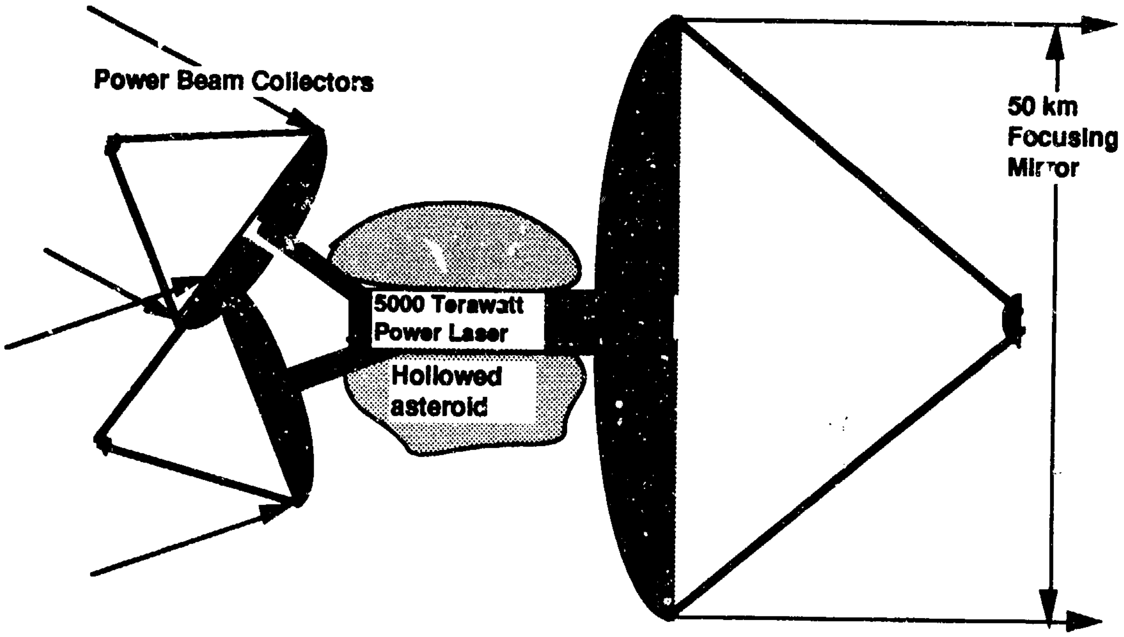

Figure 6. Possible Solar System Laser Power Station

The deceleration issues were the low drag to mass ratios of the initial magsail designs and the slow trip through the"doldrums". The current magsail designs have much better drag to mass ratios because they have bigger radii. This is the area-to-perimeter issue discussed earlier. By minimizing the design loop current to just barely sustain the hoop force required to counter the deceleration forces fed through the shrouds, a very large but very light magsail, is possible. The magsail proposed now is 3100 km in diameter versus 1000 km in the 1988 study and masses about 1000 tons. However, it provides deceleration times roughly half of those in the 1988 study. This magsail has a Magnetic Dipole Moment of 1.0×10^{19} amp-m^2 , with a current of 1,350,000 amps, and a hoop force of 390,000 newtons.

Predicted Performance (1990 Edition)

One-way trip time for the same 1000 ton manned exploration mission descibed in reference 1 is now 37 years, of which 0.8 years is spent accelerating, 17.4 years is spent coasting at half the speed of light, and 18.8 years is spent decelerating. The initial vehicle masses 2344 tons, of which 1000 tons is payload, 950 tons is magsail, and 394 tons is lightsail. The vehicle is propelled by a 5000 Terawatt laser and reaches half the speed of light in 0.21 lightyears. The laser focusing mirror has a 50 km aperture and the lighsail is 50 km in diameter.

An alternative design carries a 201 ton fusion rocket and 159 tons of propellant. It has an initial mass of 2780 tons, requires a slightly heavier magsail (1028 tons) because it has to decelerate the fusion rocket also, but uses the same lightsail. Because of the higher initial mass it takes 0.32 years to accelerate,. It coasts for 17.8 years , and then decelerates for 14.5 years. The net result is a total savings of 4.4 years. Provided advanced fusion rocket technology is available, the time savings is probably worth the additional cost.

CONCLUSIONS

Advancements in technology have increased the probability and the usefulness of the magsail. Using current technology, it can compete with advanced rocket systems to deliver people and cargo to Mars. Using straightforward extrapolations of todays technolgies, it can deliver manned vehicles to nearby stars within the time constraints of a single human lifetime.

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