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MAGNETIC SAILS AND INTERSTELLAR TRAVEL*

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A new concept, the magnetic sail, or "Magsail", is proposed which propels spacecraft by using the magnetic field generated by a loop of superconducting cable to deflect interplanetary or interstellar plasmas winds. A description is given of the computer code used to model the performance of such a device and 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 (A.U.) can attain accelerations on the order of 0.01 m/s^2, much greater than that available from a conventional solar lightsail. When used as a brake for an interstellar spacecraft, the Magsail can reduce spacecraft velocity by a factor of e every five years. A systems performance code was used to analyze the utility of the Magsail when used in conjunction with either fusion rocket or laser lightsail accelerated interstellar spacecraft. It is found that the Magsail can reduce flight times by forty to fifty years and propellant requirements by thirty percent for fusion rocket propelled ten lightyear missions. The Magsail also provides an efficient method for decelerating laser lightsail propelled missions that are otherwise simply impossible.

1. 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 kilometres 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^{-5} Tesla, so little structural strengthening is required. Two different configurations were examined as shown in fig. 1. In the axial configuration (fig. la), the axis of the dipole is aligned with the direction of flight. In the normal configuration (fig. 1 b) the axis of the dipole is normal (or perpendicular) to the direction of flight.

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 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.

The dipole field of the normal configuration 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 planes. 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 ionises the interstellar medium and then deflects

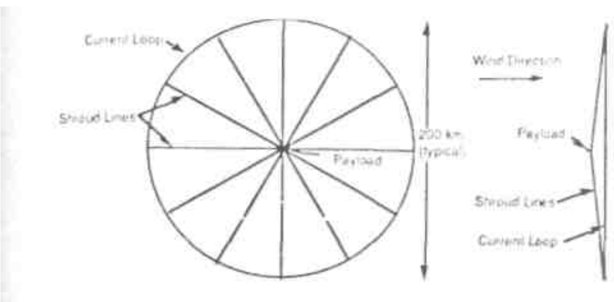

Fig. 1a Axial Magsail Configuration

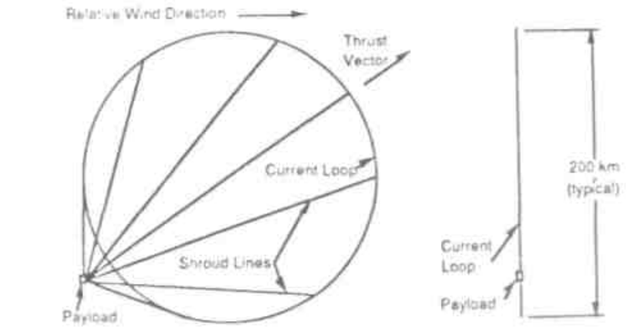

Fig. 1b Normal Magsail Configuration

*This paper was presented at the 39th IAF Congress in Bangalore, October 1988.

the resulting plasma, thus 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 both rocket mass ratio and the total mission mass, as we shall show in the detailed systems performance trades presented below.

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 temperature superconductors NbTi and Nb_3Sn have critical currents of about 1.0 x 10 and 2.0 x 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 superconductors such as $YBa_2Cu_3O_7$ have recently demonstrated similar critical currents at temperatures maintainable in interplanetary space using simple radiative thermal control schemes. Assuming this performance will someday be available in bulk cable we have chosen to parameterise the problem by assuming a near term high temperature superconductor with a critical current of 10^{10} amp/m , and an advanced technology superconductor with a critical current of 10 amps/m . 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 of mass density ratios (j/ρ) of 2 x 10 and 2 x 10 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:

$$M_{sc} = \frac{4\pi}{..} B_m R_m^2 / (j/\rho) \qquad (1)$$

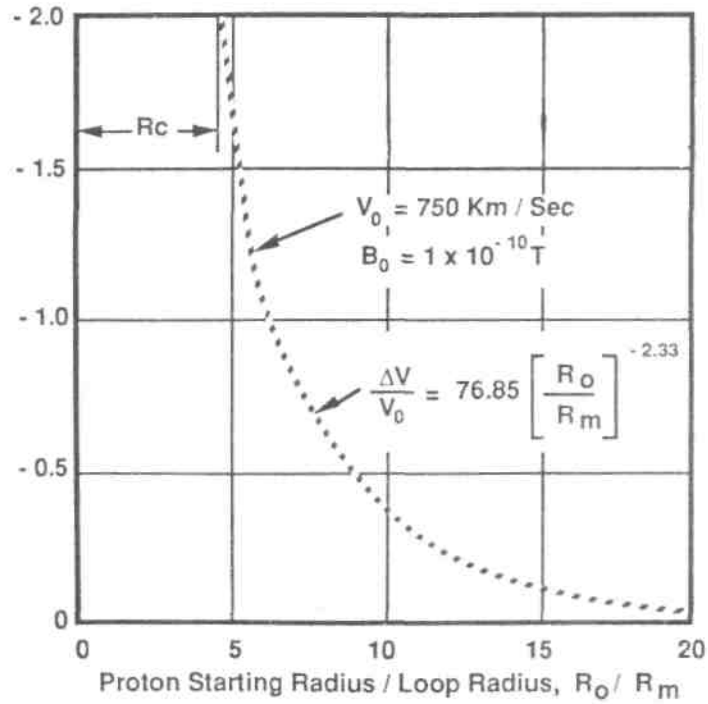

Fig. 2 Momentum Variation for Axial Magsail Configuration

2. METHOD OF ANALYSES

In order to analy the performance of the Magsail, 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. Beyond one loop radius the field is modelled as a simple dipole to economise on computer time while inside one loop radius the exact Biot-Savart law was used, the forces on a moving proton are accurately modelled 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/grad B, no a priori assumption was made that magnetic moment would be con-^ served.

Using TRACE, a series of computer experiments were conduced 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, and an ambient magnetic field, B_0, was also included.

2.1 Axial Configuration Results

In the axial configuraujn 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, Rc, are reflected almost completely; e.g. ΔV/V= -2. Beyond Rc the deflection falls off rapidly, so that at 2Rc, ΔV/V might =-0.4, and at 3Rc ΔV/V would = -0.06 (fig. 2). Based on statistical data the equation defining Re is

$$R_c / R_m = 5 \times 10^5 \, V^{-0.43} \, e^{-1.1 \times 10^8 B_o} \, B_m^{\;0.5} \qquad (2)$$

and the equation defining ΔV/V is:

$$DV/V_o = \frac{3.76x10^{13} \, B_m^{1.165}}{V_o \, e^{\,2.5 \times 10^8} \, B_o} \left(\frac{R}{R_m}\right)^{-2.33} \qquad (3)$$

For relative velocities typical of interplanetary conditions Re is about five times the loop radius. While the deflection per particle outside of Rc is small, the total area affected is huge, so that after integrating all particles coming in at all radii, the total momentum generated in the area outside Rc tends to be about twice that generated inside Rc.

The equation for thrust, obtained by integrating (3) over the limits described in (2) is:

$$F = 2\pi R_m^2 \rho_o \, v_o^2 \left(\frac{1.0474x10^{13} \, B_m}{e^{\,2.15x10^8} \, B_o \, V_o^{\;0.86}} \right) \qquad (4)$$

Thus for our typical case, which is based upon a 100 km radius loop operating in a 1 AU 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. If the loop magnetic field is increased, Re increases approximately as the square root of B_m. the maximum field strength. Now since the collection area increases as Re squared, the thrust generated varies in direct proportion to B_m. Hence, if the loop is already at its critical current, the mass of the loop must also increase in direct proportion to B_m and to a first order approximation there is nothing to be gained by either increasing or decreasing the B field strength. As the wind velocity is increased, Re decreases approximately in proportion to $V^{-0.5}$ Since the total drag (thrust) is proportional pAV^2, this means that the total drag is directly proportional to V. For a spacecraft decelerating through the interstellar medium, this yields an equation of motion of the form $dV/dt=-V/\tau$, whose solution, of course, is $V=V_0e^{-t/\tau}$

where τ = tau, the exponential velocity decay time. Tau is a function of the superconductor current to mass ratio and the ratio of Magsail mass to payload mass.

The ambient magnetic field B_0, has a small but definite effect on drag. A B_0 of 10^{-11} has no measurable effect on drag and as Bo increases, drag decreases proportional to e^{-B_0}. The bottom line result for the axial configuration is as follows: Assume we have a 100 km radius loop operating at 1 AU with a centerline peak B-field, B_m, of 10^{-5}T. The wind velocity is 500 km/sec, and the ambient proton density is 5x10 /m . A loop using near term technology with a current to mass ratio of 2x10 amp-m/kg weighs 500 tons and generates a radial thrust of 1980 Nt. This provides a self acceleration for the loop of 0.004 m/s or 123 km/sec per year. Advanced technology superconductors will have acceleration levels one order of magnitude better. Of course, performance falls off rapidly with radius, as the solar wind density varies with one over solar radius squared. This is only partially offset by the decrease in ambient B-field strength and the slight increase in wind velocity with radius.

Even with this falloff in performance with solar radius the performance of the axial Magsail for interplanetary missions is quite adequate. The performance of the normal Magsail configuration is even more interesting and will be discussed below.

2.2 *Normal Configuration Results*

The normal configuration with the protons approaching perpendicular to the loop axis is more difficult to analyze precisely, as the behaviour of particles whose point of origin is displaced from the loop center is not symmetric in X or Z directions (loop axis is assumed to lie on X axis and^rotons approaching along the Y axis). Since we don't have the simplicity of symmetry as we did

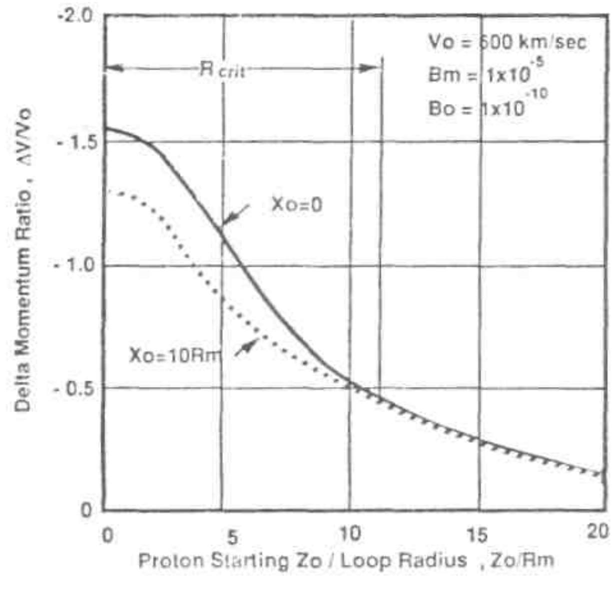

Fig. 3 Momentum Variation for Normal Magsail Configuration.

with the axial configuration, we have to rely on statistical processes and physics intuition to obtain the characteristic equations for the normal configuration. The following results and relationships were generally found to hold: For a given field strength and proton velocity there is an elliptical region around the Y axis approximated by a circle of radius, Rent, within which protons will be captured by the field and randomly released after several circuits. The average AV/V in this region is conservatively estimated to be -1.0 assuming the mean particle is deflected 90 degrees. Outside the Rcrit, the deflection falls off monotonically but slowly (fig. 3).

The ratio of the radius of capture to the radius of the current loop can be approximated as:

$$R_{crit}/R_m = 398885\ B_m^{0.5}V^{-0.36} \tag{5}$$

using our statistical data base. Using the characteristic cross-sectional shape of the dipole we deduce that:

$$DV/V = f(V,B_o)B_m(\cos^2\theta + 1/4\sin2\ \theta)^{1/2}/(R^2/R_m^2 + 1)^{3/2} \tag{6}$$

where $f(V,B_0)=1.25 \times 10^{12}/(B_0^{0.5}V^{1.5})$

Equation (6) was integrated over the limits described in (5) and the following relationship for thrust (drag) obtained:

$$F = (\pi R^2_m e_o V_o^2)\ (1.59 \times 10^{11}\ V_o^{-0.72})B_m \tag{7}$$

$$\left[\frac{11.82\ B_0^{-0.5}\ B_0^{-0.78}}{(1.59 \times 10^{11}\ B_m\ V_0^{-0.72} + 1}\ 0.5 + 1\right]$$

where the first parenthesis gives the reference drag independent of the magnetic field strength, the second, the multiplying effect of the magnetic field, and the last, the correct factor for ambient field strength.

The total effective (100%) reflection area for the normal configuration is about 5.5 times the area for the normal configuration is about 5.5 times the area available with the axial configuration. As a result, with the normal configuration our example interplanetary magsail can achieve accelerations of 0.0218 m/sec^2 with the near tem technology superconductor and ten times better with an advanced technology superconductor. Used as an interstellar brake the normal configuration provides a self braking tau of 36 and 3.6 years respectively. Such results open up exciting interstellar mission possibilities.

3. FUSION ROCKET PERFORMANCE

The idea of utilising thermonuclear fusion reactions to generate rocket thrust has been analyzed by many authors and is one of very few options available that offers serious hope for interstellar travel [1,2]. The fusion reactions of interest are:

$$D+T \rightarrow {}^4He + n + 17.6\ MeV \tag{8}$$

$$D+D \rightarrow {}^3He + n + 3.27\ MeV \tag{9}$$

$$D+D \rightarrow T + {}^1H + 4.03\ MeV \qquad (10)$$

$$D+{}^3He \rightarrow {}^4He + {}^1H + 18.3\ MeV \qquad (11)$$

$${}^1H+{}^6Li \rightarrow {}^3He+{}^4He+4.0\ MeV \qquad (12)$$

$${}^1H+{}^{11}B \rightarrow {}^4He + 2{}^1H + 12.9\ MeV \qquad (13)$$

[*так в тексте – im.*]

$$3He + {}^3He \rightarrow\text{-»}\ {*}He + 2\ {}^JH + 12.9\ MeV \qquad (14)$$

Reaction (8) is the easiest to ignite, and is currently the prime candidate for the worlds first fusion reactor. However, as a rocket engine it suffers from the fact that 80% of its energy yield appears in neutrons which are not effective in heating the rocket exhaust, but are either lost or deposit their energy in the spacecraft structure and payload where it becomes a major heating problem.

Reactions (9) and (10), which occur with about equal frequency, release about 38% of their energy in neutrons, once all side reactions are taken into account. Although this reaction is much more efficient than (8) from a propulsion standpoint 38% energy loss coupled with the need for shielding and radiators to handle the neutron flux makes an interstellar rocket utilising these reactions noncompetitive with one utilising the reactions described below.

Reactions (11) through (14) release practically all of then-energy in the form of charged particles, but only reaction (11) has the potential for ignition using near term fusion technologies. Furthermore, of all the fusion reactions, the D He reaction offers the highest energy per unit of fuel mass, and thus the highest potential specific impulse, and is second only to the DT reaction in ease of ignition. Experiments on the JET Tokamak at Culham Laboratory have already released over 9 kW from D He reactions, and it is expected that this will approach 1 MW when additional heating equipment is installed in the near future [3]. One option of the NET tokamak, currently intended for operation about the year 2000, includes burning a D He plasma for an energy yield of 100 MW. Therefore, there exists an experimental data base and excellent reasons to baseline the D^3He reaction for our study of fusion interstellar rockets.

If all the fusion energy liberated is contained within the fusion products and converted to kinetic energy the D He rocket has an ideal exhaust velocity equal to 8.8% of the speed of light. However, if realistic losses and engineering considerations are included a near term technology fusion rocket would have an exhaust velocity of 3.2% of c, and an advanced technology rocket an exhaust velocity of 5.7% of c Key parameters defining each case are shown in the table below:

TABLE 1 Fusion Rocket Design Parameters

Technology Level	Near Term	Advanced
Specific Power, kw/kg	100	1000
Bum Fraction	0.15	0.60
Radiative Loss Fraction	0.10	0.10
Recirculating Power Losses	0.09	0.04
Thrust Efficiency	0.80	0.85
Neutronic Loss Fraction	0.03	0.03
Exhaust Velocity	0.032c	0.057c

3.1 Fusion Rocket Design

A quick study of magnetic and inertial confinement fusion schemes shows that inertial confinement has the best potential to provide the high specific power (kw/kg) required for an efficient interstellar rocket [1,2]. The need for heavy confinement magnets and the large volume of radiating plasma makes the magnetically confined fusion engine to inefficient to compete. In the inertially confined fusion engine, small D He bomblets are ejected from the spacecraft and detonated with a laser or particle beam driven with recirculating power. Alternatively, in an advanced design, the bomblets could be ignited with small quantities of antimatter, in any case, the bomblet detonates and becomes a high temperature plasma which is directed and expanded using a magnetic nozzle of the type shown in fig. 4. A nozzle is necessary to efficiently convert the kinetic energy of the plasma to directed velocity and thrust, and since no physical material can withstand the plasma temperatures, a magnetic nozzle is an attractive option. Unfortunately, little test data exists to quantify magnetic nozzle performance [6].

While the D He reaction itself produces no neutrons, competing parasitic DD reactions will produce some and they will carry off about 3% of the rockets total thermal power. Assuming that only 10% of the neutrons are intercepted by the spacecraft, these means that a fusion rocket using a 1 Terawatt (10 w) thermal D He reactor will have to dispose of 3 Gigawatts of waste heat. Since this can be done at high temperatures (the neutron thermal energy is not being used in a Carnot cycle) the radiator mass penalty is not excessive.

The equation for exhaust velocity is:

$$V_E^2 = 2\,\eta T \alpha \eta B c^2\,(1-\eta NL)\,(1-\eta RL)\,(1-\tau)/(1-\eta B \eta NR) \qquad (15)$$

where η T = Efficiency of converting energy to thrust,
α = Mass of burned fuel converted to energy.
ηB = Fraction of fuel pellet actually burned.
η NL = Fraction of energy lost to neutrons.
η RL = Fraction of energy lost through radiation.
τ = Fraction of energy lost in sustainer.
η NR = Fraction of reaction mass lost to neutrons.

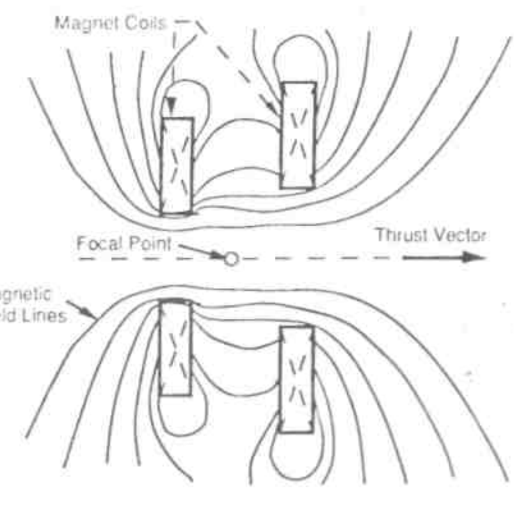

Fig. 4 Example Magnetic Nozzle.

Before delving into mission performance studies in a latter section, let's spend a minute examining the utility of the Magsail to a society possessing fusion rockets. Suppose a fusion rocket with a dry mass of 1000 tons is sent on a one way interstellar mission during which it will be accelerated to a maximum velocity of 0.10 c, coast for several light years, and then decelerate to interplanetary velocities. Assuming the performance of our advanced technology fusion rocket, the total mission mass would be 33,407 tons of which 32,407 tons would be very expensive D He fuel.

Now suppose a 1000 ton Magsail is employed to decelerate the spacecraft. The dry mass is now 2000 tons, but since the rocket must do only the acceleration leg, the total mission mass is now 11,560 tons of which 9560 tons is propellant. Propellant mass has been reduced by a factor of 3.39. If the maximum velocity had been 0.2 c, the Magsail would reduce propellant mass by a factor of 17.2!

It is also interesting to note that if an antimatter driver is used for the 0.1 c mission described above, and a driver to fuel energy gain of 100:1 is assumed, about 145 kg of antimatter would be required. One the other hand, if a pure antimatter rocket is employed on the same mission about 150 tons of antimatter would be needed. Even the best possible mix of antimatter, excess hydrogen propellant, and Magsail would still require over 6 tons of antimatter for this mission.

4. LASER-PUSHED LIGHTSAIL PERFORMANCE

The laser-pushed lightsail has received prominence lately because of articles indicating it is capable of providing manned interstellar missions within the human lifetime, something well beyond the fusion rocket [7]. In this section we will explore the physics of the laser-pushed lightsail and show its limitations and its potential when married to the Magsail.

The governing equation for thrust on any lightsail is:

$$F = IA_s(1-T_r)\,(2R_e + A)/c \qquad (16)$$

where; I	=	average intensity on the sail, w/m^2
As	=	sail area, m
T_r	=	transmissivity of sail
Re	=	reflectivity of sail material at wavelength of laser XL)
A	=	absorptivity of sail material at XL)
and c	=	speed of light

The maximum possible light intensity on the sail is determined by the Stefan-Boltzmann equation, namely:

$$I/A_s = 2\,\sigma\,T^4/(A/\varepsilon) \qquad (17)$$

where: σ = Stefan-Boltzmann constant (5.67x10^{18} w/m^2-deg)
and A/ε = absorptivity to emissivity ratio

Several candidate materials including aluminum, beryllium, and aluminised Kapton were investigated and their characteristics shown in Table 2. Notice that aluminum's properties improve significantly at wavelengths over one micron. Unfortunately, while good for the lightsail this increases the size of the laser transmitter.

TABLE 2: *Lightsail Material Properties*

	Re	A	T	A/e	**Io**
Al in visible	0.85	0.14	600	4.0	3674
Al @ 4 microns	0.96	0.03	600	1.2	12247
Be in visible	0.50	0.5	1200	5.0	47030
5 nm Al on kapton	0.96	0.03	600	0.15	95433

Lightsail performance can be determined by combining equations (16) and (17) with the equation for lightsail mass:

$$M_{sail} = A_s(1.1 \times t \times \text{Density}) \qquad (18)$$

where; t	=	sail thickness, m
1.1	=	sail structural support factor
Density	=	density of sail material, kg/m

to generate the range of maximum accelerations shown in fig. 5. Note that these curves have been adjusted for the nonuniform Gaussian illumination found at the focus of a mirror or lens. Sail thicknesses below 50 nanometres (500 atoms thick) were rejected as being too delicate for large scale assembly and long term operation. In the aerospace industry we call this minimum gage. The bare sail acceleration of one third gravity, shown for aluminised kapton 50 nanometres thick is probably very near the ultimate capability for laser pushed lightsails.

The second issue with laser-pushed light-sails is their operating radius from the laser transmitter. The general equation for the divergence half-angle of the transmitted beam from a nearly perfect (L/20) lens/mirror is [8]:

$$\sigma T = ((1.3\,\sigma_o)^2 + (\sigma D^2) + (\lambda L/20/D)^2)^{1/2} \qquad (19)$$

where $\sigma_0 = 1.3\,\lambda/\pi D$ = diffraction-limited half-angle
σD = laser dispersion half-angle = 10^{-8} radians (beam quality, jitter, etc.) and
(λL/20) / D = wave front error

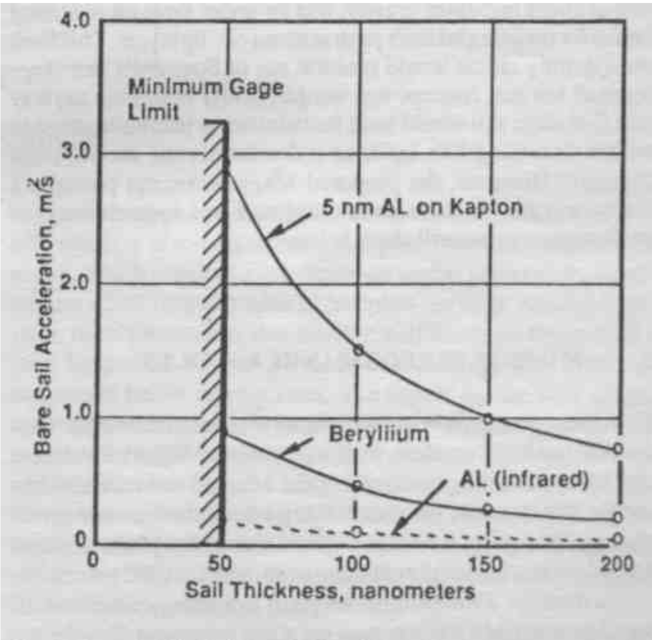

Fig. 5 Intensity Limited Bare Lightsail Acceleration.

The spot size at distance R from the transmitter optics (lens or mirror) is:

$$d_{spot} = 4\sigma_T R \quad (20)$$

to obtain a spot size of 100 km at a radius of one lightyear we see from equation (20) that σ_T must be less than 2.6×10^{-12} radians. Current state of the art in high power laser beam quality is 10^{-8} to 10^{-9} radians. Therefore, as can be see in equation (19), beam quality and not the size of accuracy of the transmitter lens/mirror will determine the operating radius of the laser light-sail, and beam quality must be improved by three to four orders of magnitude to have much laser push left at one lightyear. Note, that beam quality includes items very difficult to eliminate, such as beam jitter and internal finite aperture diffraction.

Better beam quality will require better resonator optics and will begin to affect power efficiency since more of the cavity power must be wasted to use only the highest quality portions. Our best estimate for future beam quality would be to assume that each 100 mm laser mirror could be built and maintained to within one atom thickness of perfect flatness and perfect alignment relative to the reference axis. This gives a beam dispersion half-angle of 1.0×10^{-10} radians independent of laser wave length, and a beam spot size of 3794 km at one lightyear.

What could also be a problem is pointing accuracy. Since the laser rotates around the Sun and since the Sun is moving relative to the target star system, the beam must maintain a prescribed path relative to the fixed star background. Random fluctuations in pointing can instantly move the laser spot sideways several sail diameters rendering the spacecraft helpless to recover. Current state-of-the-art in pointing accuracy is the Hubble Space Telescope with 0.007 arc-seconds (3.4×10^{-8} radians). To maintain a usable beam out to one lightyear we need 10^{-12} radians or four orders of magnitude improvement in pointing accuracy. This is physically realisable if the transmitter lens/mirror is used resolve very distant fixed stars to be used as alignment tools to correct drift. The ability of die Magsail to generate lift could be valuable in chasing a wayward laser beam if pointing accuracy is marginal.

To summarise the result from our investigation of laser-pushed lightsails, we found an upper limit on lightsail acceleration at about one-third gravity, and an upper limit on operating radius for meaningful laser push at about one lightyear. This limit on operating radius would prohibit use of Forward's two-stage lightsail but that concept was not physically realisable anyway (the first stage sail would have to maintain its parabolic shape to within something like $\lambda_L/20$ as it decelerates the second stage lightsail). However, the proposed Magsail concept provides a means to save the laser-pushed lightsail and even enhance its performance as we will show below.

5. MISSION PERFORMANCE RESULTS

Computer programs were written to simulate interstellar missions using fusion rockets with and without Magsail assistance, and laser-pushed lightsails using the Magsail to brake into objective star systems. Three different payload classes were investigated. They were; a 100 ton payload interstellar probe mission, a 1000 ton manned exploration mission, and a 10,000 ton colonisation mission. Two different levels of technology were investigated as described earlier; near term and advanced. Results are given below:

5.1 *Fusion Rocket Performance*

For a hypothetical 10 lightyear mission, the near term fusion rocket is limited to about 350 year shortest trip time even at very high mass ratios, using the Magsail knocks 30 to 50 years off trip time and reduces fusion fuel by about a third. We don't see the large fuel savings postulated earlier because these missions tend to optimise at maximum velocities of only three to four percent of c.

Curves of startburn mass versus total mission time are shown in figs. 6-8 for advanced technology development (near the ultimate in fusion rocket performance). The advanced fusion rocket is limited to about 180 years fastest trip time with a maximum velocity of about 0.07c. Adding the Magsail raises the optimum coast velocity to ten to eleven percent of c for the probe mission and lessor improvements for the larger payloads, again saving thirty to fifty years of mission time. However, there appears to be little savings jn fuel. This is because the missions shown were optimised for minimum time not minimum fuel. The 1000 ton manned exploration mission was reoptimised for better fuel performance resulting a decrease in Magsail diameter from 1200 to 500 km and a decrease in fuel from 14,862 tons to 10,483 tons (assumes one Terawatt fusion powerplant). This reoptimised manned exploration mission had 68 years of acceleration, 70.5 years of coast at 0.094 c, and 39.7 years of deceleration for a total mission time of 178.2 years. The dry weight for the minimum fuel version of this mission was 2367 tons of which 1000 tons was payload, 1000 tons was fusion powerplant, and 367 tons was Magsail. Note, that 97.5 tons of fuel and 84 Gigawatts of fusion reactor were used during the deceleration phase to help slow the spacecraft more quickly between the velocities of 1800 and 600 km/sec. The remainder of the fusion reactor/rocket was discarded during the coast phase.

The comparable fusion rocket without Magsail had a dry weight of2000 tons and carried 16,513 tons of fuel. It accelerated for 81.5 years, coasted for 108.75 years at 0.063 c, and decelerated for 26.8 years for a total mission time of 217 years.

Conclusions from the fusion rocket mission simulations are:

(1) The long mission times will probably preclude any missions using near term technologies since you can get there sooner by waiting for more advanced technologies.

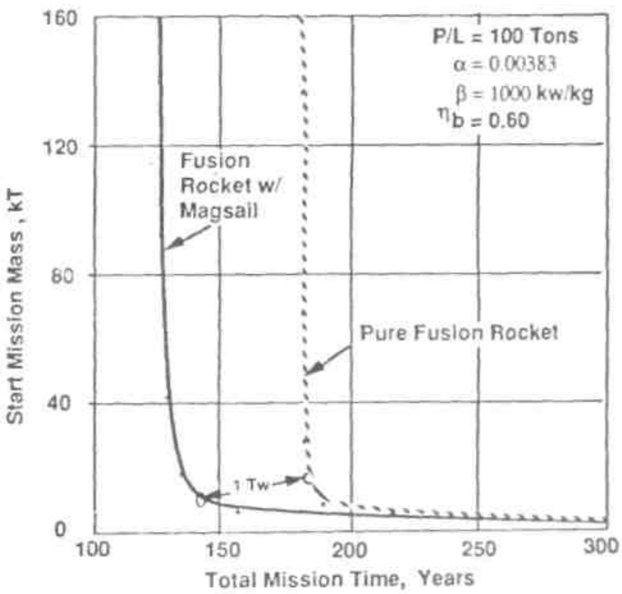

Fig. 6

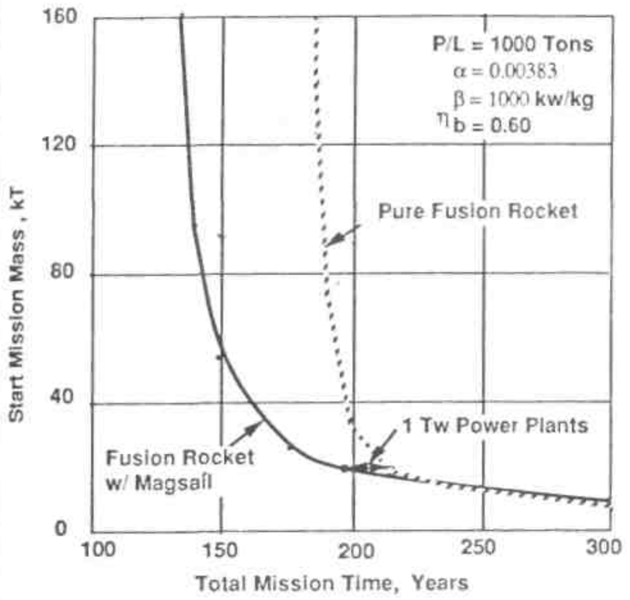

Fig. 7 Fusion Rocket Performance for Ten Lightyear Manned Exploration Mission using Advanced Technologies.

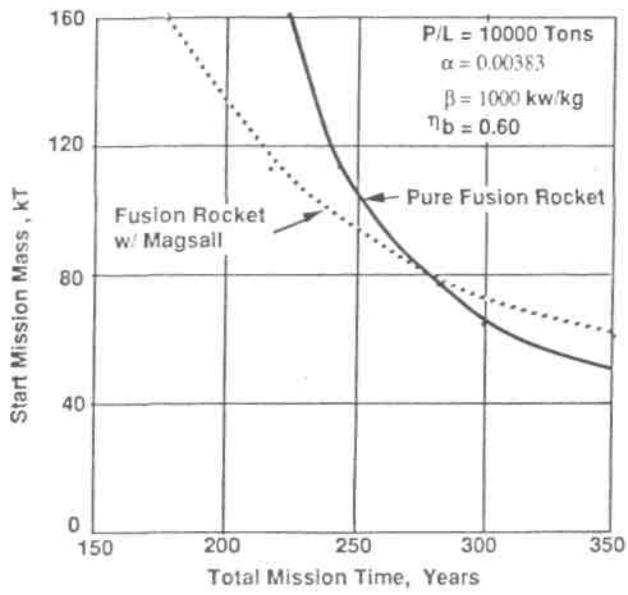

Fig. 8 Fusion Rocket Performance for Ten Lightyear Colonization Missions using Advanced Technologies.

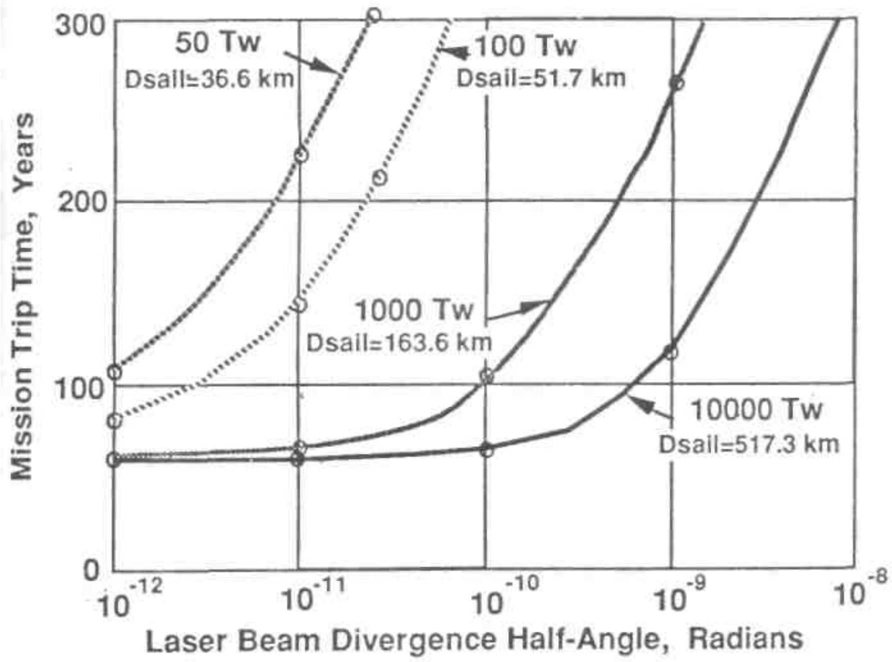

Fig. 9 Laser-Pushed Lightsail Performance for Ten Lightyear Manned Exploration Missions using Advanced Technologies.

(2) The optimum mission velocities are low enough for this initial ten lightyear mission that the Magsail is cost effective, but does not prohibit use of a straight fusion rocket.

(3) A ton of Magsail worth about $ 1,000,000 does the work of sixteen tons of D ^{3}He worth about $16 B at current energy prices.

Since there would be few volunteers for a 180 year voyage, we examined the laser-pushed lightsail as a means to shorten trip time and show the utility of the Magsail.

5.2 Laser-Pushed Lightsail Performance

The real advantage of the laser-pushed lightsail is its high acceleration capability, coming from the fact it does have to carry any power supply or propellant. On the other hand, it is not an efficient user of energy in that the exploration mission described above, which required a one Terawatt fusion power plant, would require a 500 Terawatt laser to complete the same mission in the same time. Obviously, this mission will never be flown with a laser lightsail if the cost of space-based energy isn't orders of magnitude below current rates. The payoff for the high energy consumption is reduced trip time at very high laser powers. Trip time for the 1000 ton manned exploration ten lightyear mission is 107 years assuming a 1000 Terrawatt laser with a beam divergence half-angle of $1.0\text{x}10^{-10}$ radians. The vehicle dry mass is 3035 tons, of which 1000 tons is payload, 1156 tons is lightsail, 687 tons is Magsail, and 193 tons is fusfon rocket and propellant for the final deceleration maneuvering.

Lightsail performance is very sensitive to beam divergence angle as shown in fig. 9. The lower limit on mission trip time shown at high laser powers is caused by a maximum velocity constaint of 0.5 c imposed to avoid the need for relativistic performance equations, and by the thirty to forty year deceleration period for the Magsail.

Beam divergence can be decreased significantly by throwing away the most dispersed portions of the beam. In fact, beam divergence half-angles approaching 1x10" can be obtained by throwing away two-thirds of the beam, so a complete range of beam divergence angles was investigated in fig. 9.

In summary, performance of the laser-pushed lightsail shows promise for interstellar missions within a single human lifetime, but either tremendous laser power (i.e. 10 watts), or orders of magnitude breakthroughs in laser beam quality are required.

6 CONCLUSIONS

The Magsail represents a totally new concept in interstellar propulsion, a field effect device which transforms the kinet energy of the spacecraft into increased temperature of the interstellar medium over cubic lightyears of volume. It could provide significant cost advantages to a fusion rocket based exploration scenario, and provides a workable method for decelerating laser-pushed lightsail.

The principal disadvantage of the Magsail is its lack of thrust at low relative velocity. This was overcome by completing the final deceleration to interplanetary velocities in a close pass of the target star (0.6 AU) where the high velocity and density (the stellar wind provides high deceleration. We also investigate augmenting the Magsail drag with rocket thrust during the low deceleration phase between 1800 and 600 km/sec, and this provided significant mission time savings for very little mass penalty (assuming advanced technology fusion rocket).

In conclusion, we see the Magsail as a promising addition to the stable of interstellar propulsion options and recommend further investigation of its characteristics and capabilities.

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