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Interstellar Transportation using Today's Physics

Dana G. Andrews

Andrews Space
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Dana G. Andrews
Andrews Space
505 5th Ave # 300, Seattle WA 98104
Ph 206-342-9934 X 230
dandrews@andrews-space.com

Abstract

Interstellar transportation over periods shorter than the human lifetime requires speeds in the range of 0.2 c to 0.3 c. These speeds are not attainable using rockets, even with advanced fusion engines. Anti-matter engines are theoretically possible but current physical limitations would have to be suspended to get the mass densities required. Interstellar ramjets have not proven practicable, so this leaves beamed momentum propulsion as the remaining candidate. This paper reviews the state of beamed-momentum in-space propulsion and presents a point design system suitable for human exploration of nearby stars using today's physics and resources known to exist in the solar system.

The total beam energy requirement for an interstellar probe mission is roughly 10^{20} joules, which would require the complete fissioning of one thousand tons of Uranium assuming thirty-five percent power plant efficiency. This is roughly equivalent to a recurring cost per flight of 3.0 Billion dollars in reactor grade enriched uranium using today's prices. Therefore, interstellar flight is an expensive proposition, but not unaffordable, if the nonrecurring costs of building the power plant can be minimized.

Introduction

Interstellar travel is difficult, but not impossible. The technology to launch slow Interstellar exploration missions, total delta velocities (ΔVs) of a few hundreds of kilometers per second, has been demonstrated in laboratories. However, slow interstellar probes will probably never be launched because no current organization would ever start a project which has no return for thousands of years; especially if it can wait a few dozens of years for improved technology and get the results quicker. One answer to the famous Fermi paradox is that no civilization ever launches colony ships because the colonists are always waiting for faster transportation!

Therefore, the first criteria for a successful interstellar mission is that it must return results within the lifetime of the principal investigator, or the average colonist. This is very difficult, but still possible. To obtain results this quick, the probe must be accelerated to a significant fraction of the speed of light, with resultant kinetic energies of the order of 4 $\times 10^{15}$ joules per kilogram. Not surprisingly, the second criteria for a successful interstellar mission is cost effective energy generation and an efficient means of converting raw energy into directed momentum. In this paper, several candidate propulsion systems theoretically capable of delivering probes to nearby star systems twenty-five to thirty-five years after launch are defined and sized for prospective missions using both current and near term technologies.

Rockets have limited ΔV capability because they must carry their entire source of energy and propellant. Therefore, they

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must live with the famous rocket equation, i.e.

$$\Delta V = c_{eff} * \ln(M_o/M_f) \qquad (1)$$

Where c_{eff} is the effective exhaust velocity of the propellant, and M_o/M_f is the ratio of the vehicle mass with full propellant, over the vehicle mass after all propellants are spent. Chemical combustion energy limits conventional rockets to c_{eff}'s ≤ 5km/sec and M_o/M_f ratios ≤10 (each stage) which means total ΔV's are limited to 10 to 20 km/sec. Therefore, conventional chemical rockets have their place in exploring cis-lunar space and the nearby planets, but when we address interstellar missions with three orders of magnitude higher ΔV requirements we must seek rockets with orders of magnitude increased energy density, or non-rockets which carry no propellant or energy source but rely on interactions with artificial or naturally occurring phenomena to generate thrust or drag[1].

Exploration of the nearest star systems during the lifetime of the principal investigators will require ΔVs of fifteen to twenty percent of the speed of light (45,000 to 60,000 km/sec), and twice that if the probe is to decelerate and actually explore the distant star system. Are there candidate propulsion systems with that level of performance? Actually, there are at least three propulsion systems using well-characterized physics and with theoretical performance adequate to meet this extremely high ΔV requirement. They are: the laser-propelled lightsail, the particle beam propelled Magsail, and a new concept, the laser-boosted-microsail-propelled Magsail. The anti-matter rocket is not included for two reasons. First storage of antimatter at densities necessary for efficient rockets hasn’t been conceived of yet, and the cost of antimatter exceeds the other propulsion options discussed by several orders of magnitude.

Laser-Propelled Lightsail - Laser-driven Lightsails are not rockets since the power source remains behind and no propellants are expended. Therefore, the rocket equation doesn't apply and extremely high ΔVs are possible if adequate laser power can be focused on the lightsail for a sufficient acceleration time period. The acceleration, a_{sc} , of a laser-propelled lightsail spacecraft in meters per second is:

$$a_{sc} = 2P_L / M_s c \qquad (2)$$

where P_L is the laser power impinging on the sail in watts, M_s is the mass of the spacecraft (sail and payload) in kilograms, and c is the speed of light in meters/ second. In practical units, a perfectly reflecting laser lightsail will experience a force of 6.7 newtons for every gigawatt of incident laser power. Herein lies the problem, since extremely high power levels are required to accelerate even small probes at a few gravities.

The late Dr. Robert Forward in his papers on interstellar lightsail missions postulated a 7,200-gigawatt laser to accelerate his 785 ton unmanned probe and a 75,000,000-gigawatt laser to accelerate his 78,500 ton manned vehicle[2,3]. To achieve velocities of 0.21 c and 0.5 c, respectively, the laser beam must be focused on the sail for literally years at distances out to a couple of light years. In addition, the laser beam was to be used to decelerate the payload at the target star by staging the lightsail and using the outer annular portion as a mirror to reflect and direct most of the laser beam back onto the central portion of the lightsail, which does the decelerating. To enable this optical performance, a one thousand kilometer diameter Fresnel lens would be placed fifteen Astronomical Units (AU) beyond the laser and its position relative to the stabilized laser beam axis maintained to within a meter. If the laser beam axis is not stable over hours relative to the fixed background stars (drift $<10^{-12}$ radians), or if the lens is not maintained within a fraction of a meter of the laser axis; the beam at the spacecraft will wander across the sail fast enough to destabilize the system[4]. While this scenario is not physically impossible, it appears difficult enough to delay any serious consideration of using the large lens/long focus approach to laser-propelled light sails.

The alternative approach is to build really large solar-pumped or electrically powered lasers in the million gigawatt range, where we could accelerate a decent size spacecraft to thirty percent the speed of light within a fraction of a light year using more achievable optics (e.g., a reflector 50 kilometers in diameter). Even though space construction projects of this magnitude must be termed highly speculative, the technology required is well understood and LPL systems utilizing dielectric quarter wave Lightsails could accelerate at twenty to thirty meters per second or more[4]. An example of an LPL star system explorer is shown in figure 1 below.

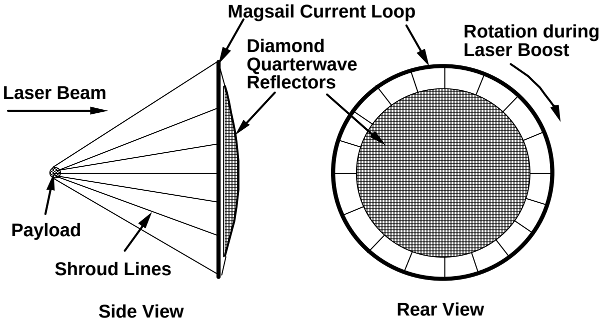

Figure 1 Laser Propelled Lightsail

The Magsail current loop carries no current during the laser boost and is just a rotating coil of superconducting cable acting as ballast to balance the thrust forces on the dielectric quarter wave reflector. After coast when the spacecraft approaches the target star system the lightsail is jettisoned and the Magsail is allowed to uncoil to its full diameter (80 km for a 2000 kg probe mission). It is then energized either from an onboard reactor or laser illuminated photovoltaic panels and begins its long deceleration.

Example interstellar missions have been simulated using state-of-the-art optics designs and the resulting LPL design characteristics are shown in Table 1 below. A constant beam power is chosen such that the spacecraft reaches the desired velocity just at the limit of acceleration with fifty-kilometer diameter optics.

Even though the high-powered LPL appears to meet all mission requirements, this paper explores alternative propulsion systems with potential for significant reductions in power, size, cost, and complexity.

Particle Beam Boosted Magsail (PBBM) - A PBBM substitutes a neutral plasma beam for the laser and a magnetic sail or Magsail for the light sail. The primary reason for switching from lasers and Lightsails to particle beams and Magsails is roughly six orders of magnitude reduction in the power required during initial acceleration, and a like reduction in spacecraft cost and complexity. Specific benefits found with this approach are: 1) improved electrical efficiency of particle beam generators relative to lasers (50% vs 25%), 2) two to three orders of magnitude increased force on the sail for the same beam power, and 3) elimination of a separate deceleration system since the acceleration Magsail can serve dual purpose.

Particle beam accelerator technology is well advanced but largely classified, so only general characteristics will be discussed in the following. Magsail technology is based only on theoretical results to date, but a detailed description is available in references 5. Only a brief description of Magsail characteristics is presented in this paper.

Table 1. Laser-Propelled Lightsail Characteristics

Mission Type	**Probe**	**Explorer**	**Manned**
Spacecraft Payload, kg	2000	20,000	50,000
Deceleration Spacecraft Mass, kg	2637	26,700	76,700
Acceleration Spacecraft Mass, kg	5160	42500	117,000
Spacecraft Coast Velocity, v/c	0.3	0.3	0.3
S/C Kinetic Energy, Joules	$1.05\text{x}10^{19}$	$1.08\text{x}10^{20}$	$3.1\text{x}10^{20}$
Acceleration Characteristics			
Laser Beam Power, Terawatts	50	200	1000
Beam Director Diameter, meters	50,000	50,000	50,000
Lightsail Diameter, meters	2000	5000	8000
Acceleration time, days	37	45	37
Radius at Cutoff, AU	1114	1235	1021
Total Beam Energy, Joules	$1.6\text{x}10^{20}$	$1.2\text{x}10^{21}$	$3.2\text{x}10^{21}$
Deceleration Characteristics			
Magnetic Dipole Moment, a-m^2	$1.0\text{x}10^{15}$	$2.0\text{x}10^{16}$	$1.0\text{x}10^{17}$
Deceleration Time, years	10.7	15.7	15.3

Use of a neutral particle beam to drive a Magsail was first mentioned by Geoffrey Landis as an alternate to laser-propelled Lightsails in Reference 4. He suggested a particle beam to reduce the wavelength and eliminate the diffraction limit on laser lightsail optics and increase the effective thrusting distance.

Use of a particle beam certainly reduces the diffraction problem, but introduces two new problems; a beam divergence caused by residual thermal motions of the atoms after acceleration, and a tendency for any charged particles to deflect off course in the solar or interstellar magnetic field. Both these problems have theoretical solutions discussed later, but they have never been demonstrated outside a laboratory, and the combined effects are difficult to quantify; so an effective beam divergence of $\geq 10^{-8}$ radians has been assumed for this study[6]. With this assumption, particle beams can provide very high thrust for limited power, but only out to medium ranges (i.e. maximum effective range ~ one Astronomical Unit (AU)).

The magnetic sail, or Magsail, is a device, which can be used to accelerate or decelerate a spacecraft by using a magnetic field to decelerate/deflect the plasma naturally found in the solar wind and interstellar medium. Its principle of operation is as follows: A loop of superconducting cable kilometers in diameter is stored on a drum attached to a payload spacecraft. When the time comes to accelerate, 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^{-4} to 10^{-6} Tesla, so little structural strengthening is required. The proposed configuration for this application is shown in figure 2.

In operation, charged particles entering the field are deflected by the B-field, thus imparting momentum to the loop. If a net plasma flow, 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 flow.

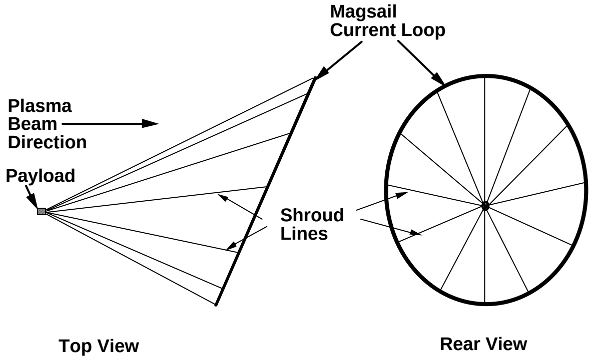

Figure 2. Magsail Configuration at Angle of Attack

When a neutrally charged beam of positively and negatively charged particles is directed at the Magsail a similar reaction occurs. When the dipole field is inclined to the flow vector the Magsail also generates a force perpendicular to the flow (i.e. lift). This feature allows the Magsail to center itself in the particle beam, which is especially important when the Magsail is light minutes from the particle accelerators.

The Magsail also makes an excellent brake for an interstellar spacecraft traveling at fractions of the speed of light. A magnetic field moving at relativistic speeds 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 a systems performance trade presented later. A typical plasma-Magsail interaction is shown in figure 3.

PBBM System Description

The acceleration phase of the PBBM system is shown schematically in figure 4. Equal numbers of positive and negative particle accelerators are ganged together on an asteroid or airless moon, which serves as a solid base, heat sink, and momentum absorber

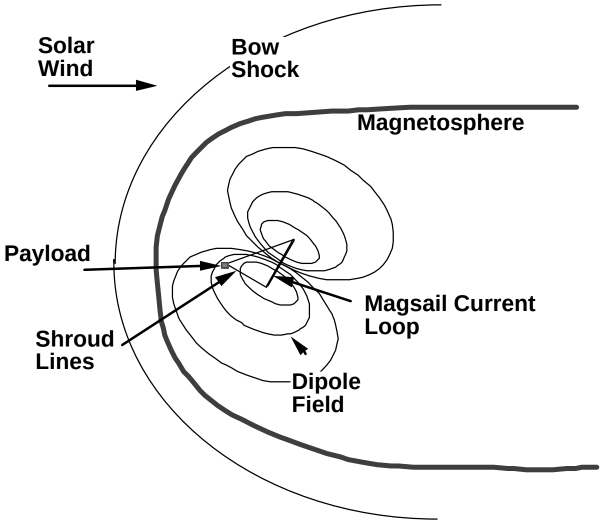

Figure 3. Dipole Plasma Interaction

. The ganged projectors produce a collimated stream of equal numbers of positively and negatively charged atoms (probably hydrogen atoms). These charged particles form a neutral streaming plasma, which should have little tendency to diffuse since it contains equal numbers of oppositely charged particles. However, interplanetary space is not empty, but filled by an outward streaming solar wind with magnetic fields which were frozen in as the plasma left the solar corona.

The rapidly moving plasma stream will interact with the interplanetary medium in two ways. The simplest interaction is elastic particle-to-particle collisions between the plasma stream and the particles in the solar wind. This will not be a factor since the mean free path is over 10^{+20} meters for hydrogen ions at the proposed energy levels. The second interaction is with interplanetary magnetic field, which although quite weak (10^{-10} Tesla at three AU), could deflect the plasma beam. Fortunately, the solar wind carried magnetic field spirals out from the sun in fairly homogeneous sectors, which become more radial in direction as they travel out from the sun (Figure 5). PBBM interstellar design solutions are shown in Table 2.

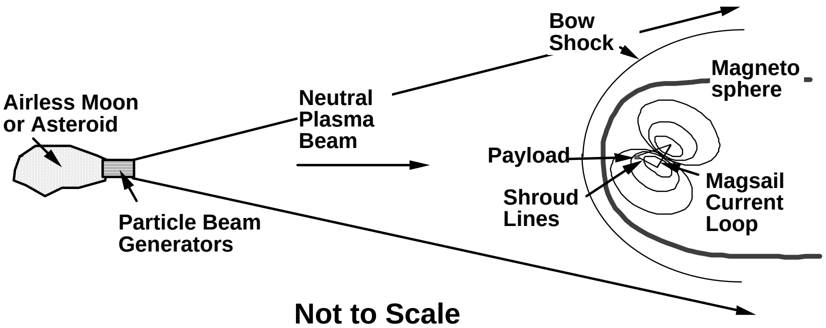

Figure 4. Beamed Momentum propulsion Schematic

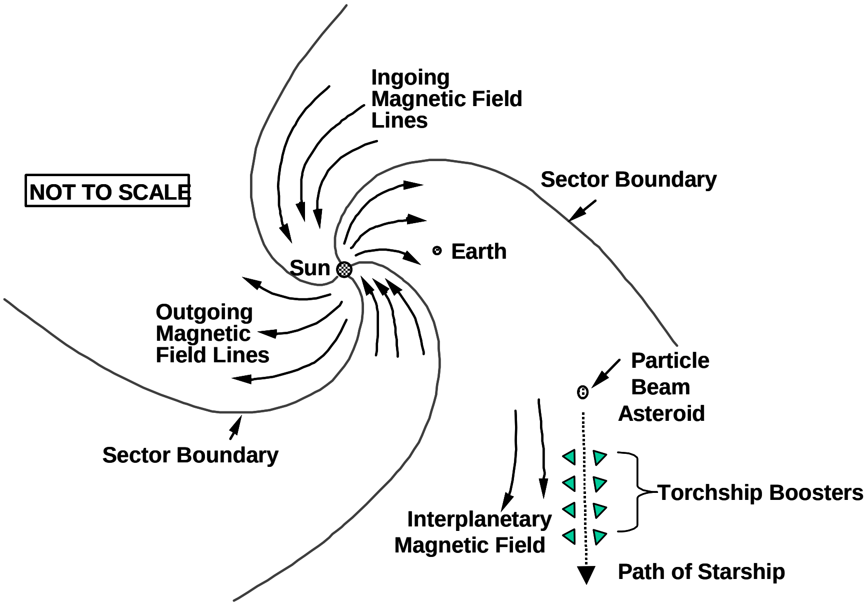

Figure 5. Schematic of Interplanetary Magnetic Field

Table 2. PBBM Performance Characteristics

Mission Type	**Small Probe**	**Explorer**	**Manned**
Probe Payload, kg	2000	20,000	50,000
Coast Spacecraft Mass, kg	2637	26,700	76,730
Spacecraft Coast Velocity, v/c	0.3	0.3	0.3
S/C Kinetic Energy, Joules	1.05×10^{19}	1.08×10^{20}	3.1×10^{20}
Acceleration Phase			
Beam Divergence, Radians	3×10^{-9}	3×10^{-9}	3×10^{-9}
Total Beam Energy, Joules	3.5×10^{19}	1.1×10^{20}	3.1×10^{20}
Max Design Accel, m/sec^2	10,000	3000	2000
Max Beam Power, Watts	1.0×10^{16}	7.2×10^{15}	1.4×10^{16}
Acceleration Time, Hours	2.6	8.3	12.5
Acceleration Distance, AU	2.9	9.4	13.1
Deceleration Phase			
Magnetic Dipole Moment, a-m^2	1.0×10^{15}	2.0×10^{16}	1.0×10^{17}
Deceleration Time, years	10.7	15.7	15.3

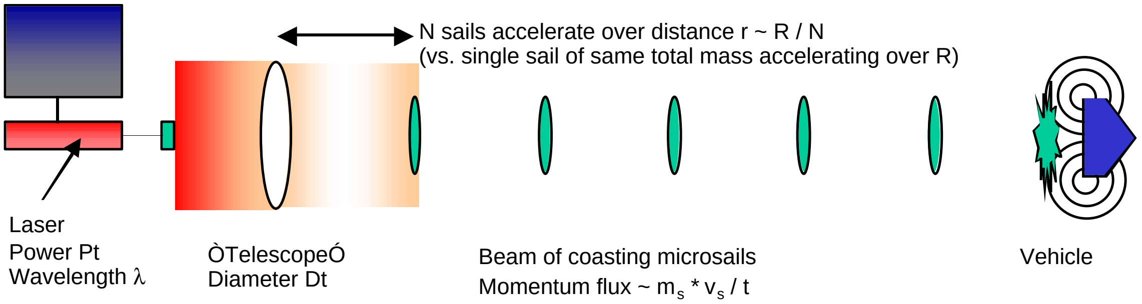

Figure 6: SailBeam Concept

With careful timing and a launch base at three AU, the particle-driven phase of the overall mission (one to several days) could take place with the plasma beam aligned with the interplanetary magnetic field. Those times when the beam and the field are not perfectly aligned should result in some charge separation as the negative and positive particles try to turn in separate directions. Since all the particles have the same mass, the center of mass will remain on course and the electric field caused by the separation of charges will prevent significant spreading (The electric forces exceed the magnetic forces after millimeters of separation).

The neutrally-charged beam will disperse to the point where it is too diffuse to be effective after approximately one AU, so for limited acceleration payloads additional booster beams will be required spaced along the flight path. These are envisioned as large interplanetary freighters, the equivalent of Robert L. Heinlein's fusion-powered "Torchships" which can rendezvous once or twice a year along a predetermined flight path to provide power to a bank of particle-beam accelerators they would carry as cargo for that mission. Fusion-powered, interplanetary fast-transports would require several terawatts of power for normal propulsion so energy should not be an issue by that era.

SailBeam Boosted Magsail (SBBM)

One way to overcome the problem of dispersion of a neutral particle beam is to fire macroscopic objects at the Magsail and use an on-board laser to vaporize and ionize this "propellant beam".. One variant, first proposed by Kare,[7] uses the momentum of a high-power laser beam to accelerate a stream of small, very low-mass microsails to high velocity. The stream of microsails transfer their momentum to a much larger mission vehicle, as shown in Figure 6. Unlike conventional laser sails, SailBeam is not limited by diffraction, and can transmit momentum over an arbitrarily large distance. Laser acceleration of microsails is made (comparatively) practical by the use of low-absorption quarter-wavelength-thick dielectric sails, as proposed by Landis,[4] which avoid the thermal limitations on laser flux, and thus acceleration, that apply to metallic sails.

Although the original MagSail was designed to work with a continuous flow of low-density plasma (the solar wind), a concept much closer to that required for a SailBeam system has been explored. This is the MagOrion, in which the vehicle is propelled by pulses of dense plasma generated by small nuclear explosions.[8] The MagOrion concept is shown in Figure 7. It is worth noting that a 10 milligram sail traveling at 0.3c has a kinetic energy of 40 GJ, or about 10 tons high-explosive equivalent.

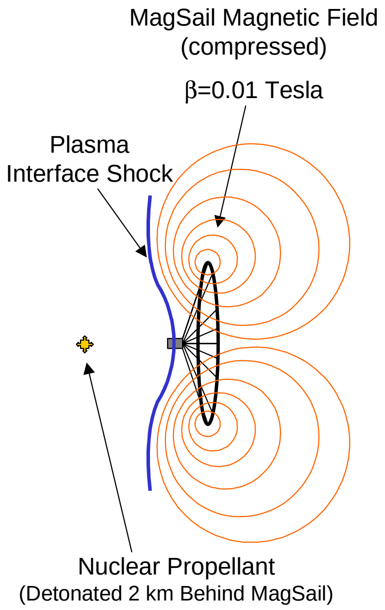

Figure 7: MagOrion Plasma Interaction

For a microsail to interact efficiently with a MagSail field, it must be converted nearly completely to ions. Neutral atoms or molecules will not be deflected by the field, and will indeed be a radiation hazard to the vehicle; at 0.1c relative velocity, a neutral atom is effectively a cosmic ray with an energy of ~5 MeV/nucleon. Particles much larger than molecules, even if ionized, will not be deflected by practical field strengths. Note that even if the characteristic dimensions of the MagSail field are kilometers, the acceleration required to significantly slow the microsail material is large even compared to the microsail's launch acceleration, so the sail probably cannot use a macroscopic structure (such as a superconducting ring) to interact with the vehicle field.

Three approaches to ionizing the microsail appear plausible: laser, particle beam, and impact.

Laser ionization would use an array of vehicle-mounted lasers operating at a wavelength (probably ultraviolet) where the solid microsail material is a reasonably strong absorber. A short, intense laser pulse can then convert the sail directly to plasma; alternatively, it may be more efficient to convert the sail to vapor and then excite and ionize the vapor using lasers tuned to atomic absorption lines.

The theoretical minimum energy requirement to ionize a microsail is slightly greater than the first-ionization energy of all the atoms making up the sail; the extra energy is required to vaporize the sail and break molecular bonds. The atomic ionization energy for Si is ~13 eV, and for O ~ 8 eV, so the approximate sail ionization energy for SiO_2 is 29 eV/molecule (60 atomic mass units) or 47 MJ/kg. Ionization of a 7 mg microsail would therefore take approximately 330 J. Considerable margin must be allowed to ensure the entire sail is ionized; allowing a factor of 10, the vehicle must mount redundant lasers capable of supplying a total pulse >3.3 kJ to ionize a beam of 7 mg sails. Packaging such an array of lasers (and associated power supply, optics, etc.) sets the lower limit on interstellar payloads, but a laser mass of a few hundred kilograms is not unreasonable with extrapolated solid-state laser technology.

Particle beam ionization would be very similar to laser ionization except a dense pulse of ionized hydrogen atoms traveling at about 0.5 c would be used to replace the UV photons. The idea would be to ionize with the first impact and not generate enough impacts to seriously deflect the resultant plasma. Advantages for particle beam ionization is more efficient utilization of on-board power and the fact that the system can be used to ionize oncoming dust particles during coast.

Impact ionization (also suggested by Singer[9]) would use the microsail's own velocity (in the vehicle frame) to provide the energy for ionization. A small impact mass of solid, gas, or plasma placed in the path of the incoming sail would release collision energy, primarily in the form of X-rays and (depending on the density of the impact mass) hydrodynamic shockwaves, which would evaporate and ionize the sail. This approach has the advantage of requiring little complex vehicle hardware, but the disadvantage that the vehicle must supply mass to intercept each sail, at least some of which is lost. The effective specific impulse of the vehicle propulsion is thus no longer infinite, and unless the impact mass lost is comparable to or less than the sail mass, the maximum vehicle velocity will be a fraction of the sail velocity.

The problem of designing an impact ionization system that would keep the lost mass small while minimizing the vehicle complexity is beyond the scope of this paper, but possibilities would include using open meshes or sprays of fine charged particles trapped in a weak outer magnetic field (as in the Mini-Magnetospheric Plasma Propulsion concept)[10] such that the column density is sufficient to ionize the sail, and most of the "collision products" are retained. The trick is to achieve a mean areal density of the impact mass smaller than the microsail areal density, to minimize the loss of on-board "propellant".

The characteristics of a SailBeam acceleration system suitable for a hypothetical interstellar probe mission are shown in Table 3. This is a relatively affordable system, but does not address the issues with respect to ionizing the microsail.

Interstellar Vehicle Design

The overriding factor in designing for low cost is keeping the nonrecurring cost and the total energy bill affordable. This means minimizing the peak power required and use of an efficient energy to momentum converter. Today, particle beams can be generated more efficiently than laser beams. That may not be true in the future, but the coupling of particle beam energy to the vehicle will always be more efficient, because the particle beam velocity can be selected to be twice the velocity of the vehicle, thereby leaving no energy in the reflected particles. This is shown visually in figure 8 below, which plots net thrust per gigawatt for both lightsails and ideal velocity particle beams.

Table 3: Characteristics of a possible SailBeam system

Parameter	Value	Comment
Vehicle mass, kg	2000	1000 kg payload
Vehicle velocity, km/s	30,000	0.1 c
Total sail mass, kg	2000	= $M_{vehicle}$
Sail velocity, km/s	36,000	0.12 c
Sail acceleration, m/s^2	$1.8 \text{x} 10^7$	**1.8 million G's**
Sail acceleration time, s	2.0	
Sail accel. range, km	36,000	
Laser power, GW	100	
Laser wavelength, µm	1	
Transmitter diameter, m	600	2.44 λR/d
Sail diameter, m	0.15	
Sail density, g/cm^3	2.6	glass
Sail refractive inde (n)	1.6	
Sail thickness, nm	156	λ/4 in medium
Sail mass (m_s), mg	7	400 mg/m^2
Sail reflectivity	0.19	$(n^2\text{-}1/n^2\text{+}1)^2$
Force on sail, N	125	9 kN/m^2
Number of sails	$2.8 \text{x} 10^8$	
Laser run time, s	$5.6 \text{x} 10^8$	~18 years

Note, that particle beams are much more efficient until the spacecraft velocity approaches 0.3 c. The issue with particle beams is their relatively short effective radius, which then requires very high acceleration to achieve suitable velocities. Acceleration can be reduced using the "runway" several AU long lined with particle beam accelerators shown earlier.

Another possible solution is to launch a number of relatively small payloads at very high acceleration one after another and then link them up during the first year or two of coast to form a larger Magsail-braked vehicle that is more optimum for slowing down and more capable of sustaining life during the long crossing.

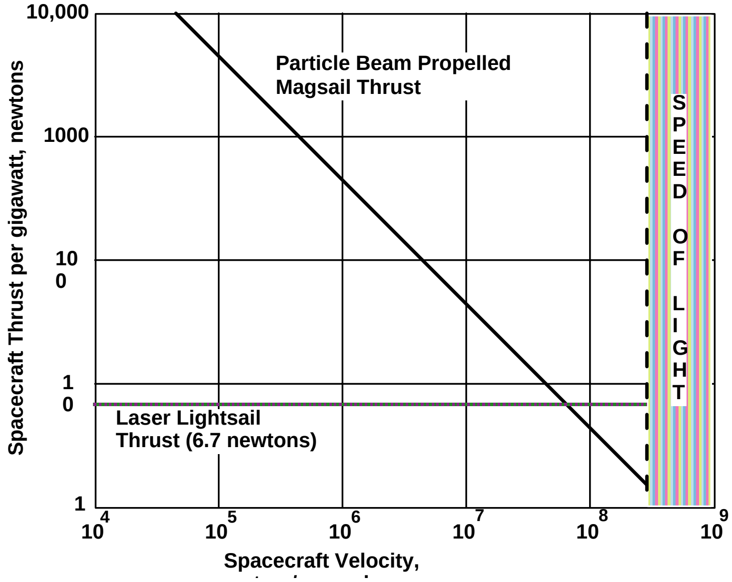

Figure 8. Spacecraft Thrust per gigawatt of Beam Power

This is the "wagon train" approach to interstellar transportation. Mass reductions of the order of 0.5% in each subsequent boost will results in initial velocity increases of about 0.5% and make for rendezvous opportunities every 104 days assuming a crossing velocity of about 0.3 c.

While the PBBM option minimizes the total energy bill it requires more infrastructure to provide equivalent performance. It is highly likely that in the future the price of busbar power in the asteroid belt will be very cheap because of automated factories producing solar cells. Cheap energy could make the SBBM cost competitive overall because of its lower nonrecurring cost. This is due to its low average power requirement and the relatively simple SailBeam accelerator, which can be built using near term optics.

The SBBM would have definite advantages for future colonization missions where a PBBM would require supplementary particle accelerators spaced out along an "interstellar runway" to achieve adequate total spacecraft mass without killing the crew with the high acceleration levels needed to achieve adequate speed within the useful range of a fixed particle beam base.

Conclusions

These data show that interstellar exploration is feasible, even with near term technologies, if the right system is selected and enough resources are available. Therefore, once the technology for low cost access to space is available, the primary risk to any organization embarking on a serious effort to develop interstellar exploration/ transportation is affordability, not technical feasibility.. The primary issue with respect to any of these systems actually being built is cost, both development cost and operating cost in the price of energy.

Computer simulations of the acceleration interactions of LPL, PBBM, and LBBM were completed and spacecraft configurations optimized for minimum energy usage are noted. The optimum LPL and LBBM transfer about ten percent of the laser beam energy into kinetic energy of the spacecraft while the optimum PBBM transfers about thirty percent. Since today's particle beam generators are roughly twice as energy efficient as today's large lasers, the PBBM propulsion system should require roughly one-sixth the busbar electrical energy a LPL or LBBM system would require to launch an identical payload.

However, the SailBeam Boosted Magsail appears to offer a significantly simpler acceleration system and lower average power (but more busbar energy .because of the longer acceleration period) Therefore, a Life Cycle Cost (LCC) analysis is required to determine which option would provide the lowest discounted cost per spacecraft. Either option could end up cheaper depending on the future cost of energy, but that analysis is well beyond the scope of this paper

In summary, the laser-propelled lightsail or the slightly more efficient SBBM alternate, while not as efficient as the PBPM, could well be the system of choice if the price of solar panels continues to drop over the next thirty years. Either way, we can watch the cost of space-based energy fall and predict the time when interstellar exploration becomes affordable.

The bottom line is that interstellar travel looks expensive, but possible. Therefore, the Fermi paradox is still a paradox. It is possible that we are alone in the galaxy, or that no civilization has acquired the necessary technologies, but the former is more likely than the latter.

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