42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
Sacramento, California, 9-12 July 2006.
AIAA 2006-5224

Impact of Interstellar Vehicle Acceleration and Cruise Velocity on Total Mission Mass and Trip Time

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Far-term interstellar missions, like their near-term solar system exploration counterparts, seek to minimize overall mission trip time and transportation system mass. Trip time is especially important in interstellar missions because of the enormous distances between stars and the finite limit of the speed of light (c). In this paper, we investigate the impact of vehicle acceleration and maximum or cruise velocity (V_{cruise}) on the total mission trip time. We also consider the impact that acceleration has on the transportation system mass (M) and power (P) (e.g., acceleration ~ power/mass and mass ~ power), as well as the impact that the cruise velocity has on the vehicle mass (e.g., the total mission change in velocity (ΔV) ~ V_{cruise}). For example, a Matter-Antimatter Annihilation Rocket's wet mass (M_{wet}) with propellant (M_p) will be a function of the dry mass of the vehicle (M_{dry}) and ΔV through the Rocket Equation. Similarly, a laser-driven LightSail's sail mass and laser power and mass will be a function of acceleration, V_{cruise}, and power-beaming distance (because of the need to focus the laser beam over interstellar distances).

I. INTRODUCTION

Over the past several years, we have presented a series of papers describing our evaluations of potential propulsion technologies that could perform fast (i.e., 0.5c cruise velocity) interstellar rendezvous missions (i.e., the vehicle stops at the target solar system).[1,2,3] In this paper, we present some "Lessons Learned" derived from these past studies that represent observations and issues of interest to the general subject of interstellar mission studies. We will emphasize the sometimes subtle interactions between propulsion system mass, vehicle acceleration, and peak coast or cruise velocity (V_{cruise}), and their impact on overall mission trip time. We will also discuss several other issues of interest to specific propulsion options and the general area of interstellar missions.

A. The Scale of Interstellar Missions

One of mankind's oldest dreams has been to visit the tiny pinpoints of light visible in the night sky. Over the last 50 years we have visited most of the major bodies in our solar system, reaching out far beyond the orbit of Pluto with our robotic spacecraft. For example, 29 years after its launch (September 5, 1977), the Voyager I spacecraft is about 100 astronomical units (AU, 149.6×10^6 km), or 13.9 light-hours, from the sun, traveling at 17.4 km/s (3.67 AU per year) or 0.006% of the speed of light (c). And yet this distance, which strains the limits of our technology, represents an almost negligible step towards the light-years that must be traversed to travel to the nearest stars. For example, even though the Voyager spacecraft is one of the fastest vehicles ever built, it would still require almost 74,000 years for it to traverse the distance to our nearest stellar neighbor. Thus, travel to the stars is not impossible; it will, however, represent a major commitment by a civilization simply because of the size and scale of any technology designed to accelerate a vehicle to speeds of a few tenths of the speed of light.

Thus, one of the most difficult aspects of comprehending the scale of an interstellar mission is the sheer size of any transportation system capable of reaching a significant fraction of the speed of light (e.g., 0.1c or faster). As a point of reference, a "payload" mass of 100 metric tons (MT = 1,000 kg), roughly the mass of the Space Shuttle Orbiter, traveling at 0.5c has a kinetic energy of 1.3×10^{21} Joules (including a relativistic mass correction of $1.15 = \{1/(1-[V/c]^2)\}^{1/2}$). This energy represents almost 3 years worth of the annual energy production of Human Civilization (4.4×10^{20} J in 2003). As we will see below, adding the propulsion system required to reach interstellar transportation speeds results in systems with dimensions on the order of planetary diameters, masses of hundreds of billions of tons, and power levels thousands of times that of Human Civilization (about 14 TW).[3]

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B. Interstellar Mission Requirements

In this study, we have assumed that the interstellar vehicle would be used to rendezvous with scientifically interesting planets circling about other stars. Mission targets, such as planets capable of harboring life (and, ultimately, planets habitable by humans), would be identified by the NASA Origins Program, which has the long-range goal (by ca. 2040) of detecting, remote-sensing spectral analysis, and imaging of potentially habitable planets around stars out to ~ 40 light-years (LY), corresponding to a sphere containing the nearest 1,000 stars. This will be accomplished by the use of progressively more sophisticated space-based observational techniques (e.g., telescopes, interferometers, etc.) to ultimately image Earth-like planets in the potentially habitable region – the "Goldilocks Zone": not too hot, not too cold – about a star.

Robotic interstellar missions can be viewed as a natural follow-on to the Origins Program; the Origins Program will tell us where to send the interstellar spacecraft that will provide close-up imaging with a flyby, and detailed in-situ science ("ground truth") with a rendezvous missions. Current emphasis is on a fast interstellar rendezvous mission where the spacecraft stops at its destination. Thus, there is a desire for a high cruise velocity to minimize trip time. For example, to travel 4.3 light-years (LY) with a 10-year trip time requires an average speed of 0.43c. However, a high-speed (≥0.1c) flyby is not thought to give significantly more science return than that provided by Origins Program capability in the time frame of interest; in effect, virtually as much imaging capability is provided by advanced telescopes at Earth as from a rapidly moving spacecraft in a flyby (e.g., a flythrough of our Solar System would only allow 110 hours of observation at 0.1c). Thus we see the need for a rendezvous mission, even though this has the effect of doubling the mission ΔV.

C. Selection of Interstellar Propulsion Options

Having established the requirements for our interstellar mission (i.e., $V_{cruise} = 0.5c$, corresponding to a total mission ΔV of 1c for a rendezvous mission), we now seek to identify viable propulsion candidates for interstellar missions. To do this, we ask three questions that are used as screening filters,[4] as shown in Figure 1. Note that this screening process is used to reduce the large possible number of propulsion options down to a manageable few; in effect, we have intentionally selected a set of mission requirements that are so demanding that only a limited number of propulsion options are applicable.

1. ΔV Capability

First, we ask the basic question of whether the propulsion system has the capability of providing the required ΔV for the mission. As a general rule, the "Rocket Equation" suggests that it is desirable to have the mission ΔV and propulsion system specific impulse (I_{sp}) or exhaust velocity (V_{ex}) comparable in size to prevent excessive propellant requirements. (For our case, this implies that $\Delta V = 1c = 3x10^5$ km/s ~ V_{ex}, corresponding to Isp = $30x10^6$ lb_f-s/lb_m.)

This evaluation criterion quickly eliminates Advanced Electric Propulsion (EP) and Electromagnetic (EM) Catapult Launchers from consideration for fast interstellar rendezvous missions. Similarly, Fusion Propulsion concepts have a maximum I_{sp} on the order of $1x10^6$ lb_f-s/lb_m (i.e., $V_{ex} = 0.03c$), which is too low even for a multi-stage (e.g., 4-stage) rocket. (However, a 2-stage Fusion Rocket is a reasonable choice for a slow, 0.1c interstellar flyby. REF) The one loophole to fusion I_{sp} or V_{ex} limitation is the Bussard Interstellar Fusion Ramjet REF that collects interstellar hydrogen for use in a Fusion Rocket; because all the propellant required for the mission is not carried on board the vehicle, the Interstellar Ramjet effectively "cheats" the Rocket Equation and is capable of supplying unlimited ΔV. Solar sails also "cheat" the I_{sp} limitations of the Rocket Equation; however, even with ultra-low areal density, they cannot achieve the required velocities because of the $1/R^2$ drop-off in sunlight intensity (i.e., decrease in photon momentum "push" per unit area) on the sail. LightSails overcome the $1/R^2$ limitation of a solar sail by using laser or microwave power (actually momentum) beaming. However, although microwave LightSails (e.g. Starwisp REF) can be used for interstellar flybys, they cannot be used for rendezvous missions because the long wavelength of microwaves (compared to near-visible laser wavelengths) results in impossibly large optics requirements for focusing the microwaves at interstellar distances. Thus, only Laser LightSails (with a laser near-visible wavelength on the order of 1 μm), Matter-Antimatter Annihilation Rockets (with an I_{sp} of $1x10^7$ s corresponding to a $V_{ex} = 0.33c$), and Fusion Ramjets strongly pass the ΔV filter, with Fission Fragment and Fusion Propulsion (both with a V_{ex} of 0.03c) weakly passing the filter.

2. Infrastructure Requirements

The second evaluation criterion deals with the potential need for a large, possibly space-based supporting infrastructure that is unique for the propulsion concept. The assumption here is that this infrastructure would represent a significant up-front cost that typically would have limited application beyond the interstellar mission.

For example, the Fission Fragment Propulsion concept would require the construction of a unique facility (ground- or space-based) to produce large amounts of short-lived, high-energy, highly-fissionable nuclear fuels such as americium (Am) or curium (Cm). REF Similarly, a relativistic particle beam that would "push" a magnetic sail (MagSail), REF analogously to the laser-driven LightSail), would require an enormous space-based particle beam facility that would have limited applicability beyond in-space transportation.

By contrast, "pure" Matter-Antimatter Annihilation Propulsion, where all of the propulsive energy comes from the annihilation reaction, will require major new antiproton production facilities to supply the tons of antimatter required for interstellar missions. However, it must be noted that there are a number of dual-use spin-offs of antiproton research, such as medical applications (e.g., imaging and destruction of cancer tumors in the 1 mm size range), REF that could justify the infrastructure investment. Similarly, laser (or microwave) LightSails will require a major space-based infrastructure consisting of the beam source and the associated optics, but the beamed-energy infrastructure has the unique capability of multiple use as a time-shared power and propulsion source as, for example, a "Public Utilities in Space," with a grid of laser/microwave beams supplying power in space analogous to the electric power and natural gas utilities on Earth. REF

Thus, the Fission Fragment and Particle Beam/MagSail concepts strongly fail the infrastructure test. Matter-Antimatter and Beamed-Energy LightSail propulsion concepts only weakly fail this test, either because of the potential for multiple in-space or spin-off applications Therefore, only Fusion, Matter-Antimatter Annihilation, and LightSail propulsion will be carried on to the third evaluation criterion, technology requirements.

3. Technology Requirements

Our third and final criterion relates to the current technology level and future technology development needs of the various systems. Not surprisingly for an interstellar propulsion system, the technology requirements for all of the three leading candidates will be formidable. Note that all of the concepts have numerous uncertainties and major unresolved feasibility issues; there is no clear winner. Rather, the challenge is to identify the approach that has the fewest number of developmental and operational "miracles" required for its implementation. Ironically, the Interstellar Fusion Ramjet has the greatest performance potential, but also the greatest number of technology challenges. However, from our perspective today, all three are equally "impossible;" only continued research and analysis will identify which ones are less "impossible" than the others.

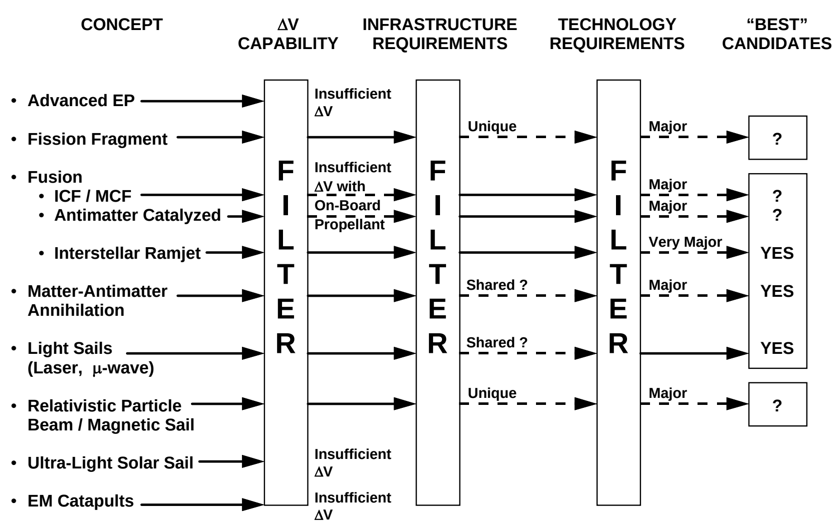


Figure 1. Interstellar Rendezvous Mission Propulsion Option Screening Process.

II. IMPACT OF INTERSTELLAR VEHICLE ACCELERATION AND CRUISE VELOCITY ON TOTAL MISSION MASS AND TRIP TIME

A. Introduction

In this section, we consider first the general problem of acceleration and cruise (coast) velocity and their impact on mission trip time for the case of a fast (0.5c) interstellar rendezvous mission. Later, we will illustrate how acceleration and cruise velocity impact the transportation (propulsion) system mass for Antimatter Rockets, Laser LightSails, and Interstellar Ramjets.

1. Cruise Velocity Required for a Given Acceleration, Distance, and Trip Time

For a given travel distance, trip time will be a function of acceleration as well as cruise velocity. For example, too low an acceleration can adversely impact trip time, because the vehicle spends too much time in the acceleration/deceleration phase and not enough time at peak (cruise) velocity. This problem can be illustrated several ways. For example, in **Figure 2**, we consider the case of a rendezvous mission with a given distance and total trip time. For this case, we assume a trip time in years numerically equal to twice the distance in LY, so that, ignoring acceleration or deceleration, the average cruise velocity would be 0.5c. However, in practice, there is some time spent (and distance traversed) during acceleration from Earth and deceleration at the target solar system. (For these analyses, the acceleration and deceleration phases are assumed equal.) Thus, a minimum acceleration is needed to reach the target star where the vehicle accelerates to the midpoint in the trajectory, turns around, and immediately begins to decelerate (i.e., there is no time spent coasting); this limiting case requires a peak velocity approaching the speed of light. As acceleration increases, some time is spent coasting, and the peak or cruise velocity approaches 0.5c as a limiting case for infinite acceleration.

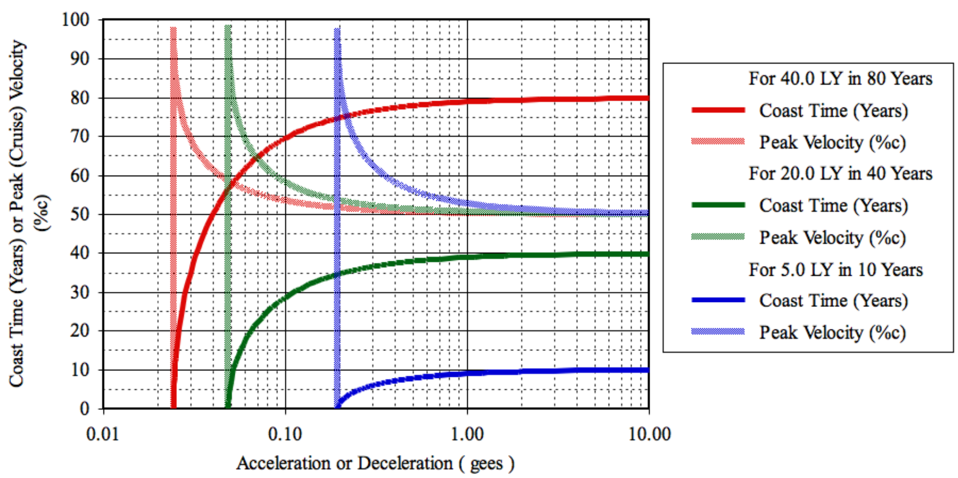


Figure 2. Coast (Cruise) Time and Peak (Cruise) Velocity vs. Acceleration for an Interstellar Rendezvous Mission. (Equal acceleration and deceleration phases.)

An alternative mission scenario is shown in **Figure 3**, where the maximum cruise velocity (V_{max}) is limited to some value (0.5c in this case) so as to constrain the overall mission ΔV and thus the vehicle wet mass. In this case, the mission total trip time is a function of acceleration (and deceleration) and distance traversed; in this case, the trip time at the limit of infinite acceleration is numerically twice the distance because the cruise velocity is limited to 0.5c. As shown in Figure 3, in order to minimize the trip time (by maximizing the time spent at peak velocity), the vehicle needs to accelerate (and decelerate) at about 0.01 gee (1 gee = 9.8 m/s^2 = 1.03 LY/Yr^2) as a minimum. At less than about 0.01 gee, the vehicle doesn't even reach the maximum allowed cruise velocity and the total trip time increases dramatically; this effect is seen to become worse as the total travel distance decreases. As above, higher acceleration is better, but higher acceleration will typically require more power, and thus more system mass. Interestingly, there is no significant benefit for acceleration > 1 gee.

Figure 3 also illustrates the somewhat counter-intuitive result that it can actually be harder to achieve a short trip time for nearby stars (i.e., less distance to travel) than those farther away. This is because, at low acceleration and short total distance, the vehicle doesn't have enough distance to accelerate to a high cruise velocity. For example, performing a 5 LY rendezvous mission at an acceleration of 0.01 gees takes about 45 years because the vehicle can only accelerate to less than ½ the nominal V_{cruise} (0.5c) before it has to turn around and begin deceleration. By contrast, at the same 0.01 gees, we can travel to 20 LY, 4 times the distance, in about 90 years, twice the time, because the vehicle has more distance to accelerate to roughly 0.45c before beginning deceleration.

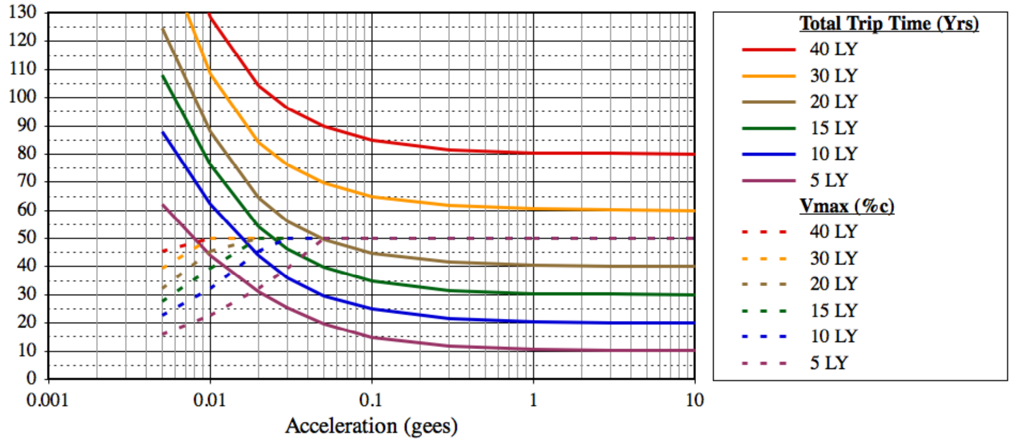


Figure 3. Trip Time and Maximum (Cruise) Velocity (V_{max}) vs. Acceleration for an Interstellar Rendezvous Mission. (Equal acceleration and deceleration phases.)

A. Impact of Antimatter Rocket Acceleration and Cruise Velocity on Total Mission Mass and Trip Time

As an example of the impact that acceleration and maximum (cruise) velocity can have on the interstellar vehicle's mass and power, we can consider the case of a four-stage Matter-Antimatter Annihilation Rocket. In the vehicle considered in Reference 2, each stage has a ΔV of 0.25c; two stages accelerate the vehicle to 0.5c, and the remaining two stages decelerate the vehicle to rest in the target star system. All stages have an acceleration of 0.01 gee. Also, as described in Reference 2, we initially sized a "baseline" 4-stage Antimatter Rocket based on near- to mid-term technologies. However, these technology assumptions did not fully embrace potential breakthroughs that might occur before actually building an Antimatter Rocket. For comparison, we then considered an advanced-technology 4-stage vehicle with a 10-fold reduction in its waste-heat radiator specific mass and 10-fold increase in the critical current density of its superconducting magnetic nozzle, as compared to the "baseline" vehicle.[2] Based on its dramatic performance improvement (by changing only the radiator and magnet assumptions), the advanced-technology vehicle became our new "nominal" vehicle for our mission studies. For example, using the "nominal" 4-stage vehicle for a 40-LY rendezvous mission gave us a vehicle with an initial "wet" mass (M_o) of 80.73 million MT and a total trip time of 128.5 years for an acceleration (and deceleration) of 0.01 gee.

It is important to note that the tradeoffs we find for varying vehicle acceleration and cruise velocity are highly dependant on the vehicle sizing assumptions. For the case of an Antimatter Rocket, as we increase acceleration (for a given I_{sp}), the engine power must increase, since thrust is proportional to power/I_{sp}. However, as power increases, the engine and thus vehicle mass increases. For example, as described in Reference 2 for the "baseline" vehicle in a 40-LY rendezvous mission, increasing acceleration from 0.01 to 0.03 gees (both with a cruise velocity of 0.5c) results in a 16.3-fold growth in total vehicle "wet" mass (M_o) with only a reduction in trip time from 128.5 years (at 0.01 gees and 0.5c) to 96.2 years (at 0.03 gees and 0.5c). However, reducing the cruise velocity to 0.35c (at 0.03 gees) brings the total vehicle mass back to the 0.01-gee/0.5c case (because of the reduction in the Rocket Equation mass ratio with reduced ΔV per stage), although the reduction in cruise velocity essentially eliminates the trip time benefits of higher acceleration (e.g., only a 2.5 year reduction in trip time from the reference case of 128.5 years).

However, the mass reductions inherent in the advanced-technology (10X better radiator and magnet) "nominal" vehicle dramatically reduce the impact of engine mass at higher accelerations. In this case (again for a 40-LY rendezvous mission), going from 0.01 to 0.03 gees (with a cruise velocity of 0.5c) only causes the total vehicle to grow by a factor of 1.53, but the trip time drops from 128.5 to 96.2 years. Furthermore, if we reduce the cruise velocity only slightly to 0.48c, the 0.03 gee vehicle has the same mass as its 0.01 gee, 0.5c counterpart, but with a trip time of 99.2 years. Thus, as shown in Figure 4, there is a potential to investigate an interesting trade space of acceleration, maximum (cruise) velocity, and transportation system mass assumptions so as to identify an optimum minimum mass and trip time case.

For example, in Figure 4 (for a 40-LY rendezvous mission) we see that an "optimum" acceleration occurs for accelerations between 0.03 and 0.05 gee, where the mass and trip time are both minimized as compared to higher or lower accelerations. Taking the 0.05-gee case, we see that a 0.05-gee/0.454c vehicle has the same mass as the 0.01-gee/0.5c vehicle, but saves 31 years in trip time, corresponding to a saving of roughly ¼ of the trip time of the 0.01-gee/0.5c vehicle. Conversely, a 0.05-gee/0.328c vehicle has the same trip time as the 0.01-gee/0.5c vehicle, but has an initial "wet" mass 11.6 times lighter than the 0.01-gee/0.5c vehicle. Again, it must be emphasized that these results are highly dependant on the vehicle mass scaling assumptions, where mass is typically some function of power. Nevertheless, these results suggest that there will be a "sweet spot" for an Antimatter Rocket that can minimize mass and trip time.

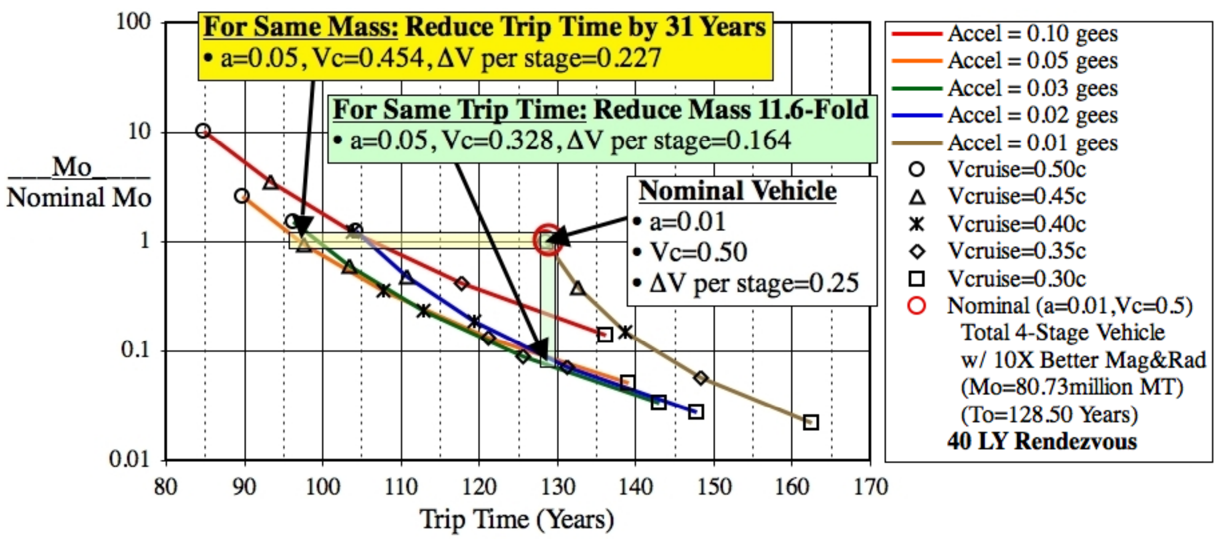


Figure 4. Tradeoffs in Acceleration, Cruise Velocity, Mass, and Trip Time for a Matter-Antimatter Annihilation Rocket.

B. Impact of Laser LightSail Acceleration and Cruise Velocity on Total Mission Mass and Trip Time

A classic 1984 paper by Robert L. Forward[5] discussed the use of laser-beam pushed sails (LightSails) for interstellar exploration missions. For interstellar missions, the use of a laser rather than sunlight is preferred because a laser makes it possible to illuminate a LightSail with a much higher photon power intensity than that available from sunlight; also, unlike sunlight with its $1/R^2$ drop-off in power, the laser beam intensity is constant out to the diffraction limit of the laser's transmission optics capability. For comparison, solar photon momentum pressure at 1 AU from the sun amounts to 9 Newtons per square kilometer of Solar Sail area (for a sail with perfect reflectivity); this force on the sail decreases as the square of the distance from the sun. By contrast, the use of a laser makes it possible to illuminate a LightSail with more than an order-of-magnitude greater intensity (depending on the thermal properties of the sail) with a constant beam intensity.

Like Forward, we have assumed a 1-µm wavelength beam and transmitter optics with a diameter of 1,000 km; this allows transmission of laser power over a distance of 40 LY with a LightSail "spot" size of less than 1,000 km assuming diffraction-limited optics. This concept requires very large transmitter lens and receiver (sail) optics (e.g., 1,000-km diameters for missions to 40 LY) and very high powers for rendezvous missions (e.g., tens of petawatts [PW=10^{15} W] power levels). Also, as with Forward, we have assumed an ultra-thin LightSail sheet material of aluminum that is 16 nm thick (63 atoms!) with a backside high-emissivity coating that allows the LightSail to be accelerated at a thermally-limited acceleration of 0.217 gees with a sail-only areal density ($\sigma_{sail\ only}$) of 0.1 g/m^2 (independent of sail size). Note that this acceleration is an upper limit for the Light Sail without any payload; because the sail is thermally-limited in the power intensity (35.925 kW/m^2 or 26.611 Suns) that it can accommodate, adding payload necessarily reduces the vehicle acceleration.

Interestingly, Forward[5] was the first to propose the use of a multi-stage LightSail to stop the vehicle at the target star system for rendezvous missions. As shown in Figure 5, a large outer sail ("1st Stage") reflects the laser beam back at a smaller inner sail ("2nd Stage") to stop the inner sail; the larger outer sail then accelerates out of the star system.) In this scenario, Forward arbitrarily assumed that Stage 2 would have one-tenth the area (or 0.316 times the diameter) of Stage 1. Not surprisingly, an interstellar rendezvous mission requirement to accelerate up to 0.5c and then decelerate from this velocity to perform a rendezvous at up to 40 LY from Earth represents a major challenge to all facets of the beamed-momentum system. In particular, the rendezvous portion of the mission essentially sizes the overall technology requirements in terms of the sail size and laser power.

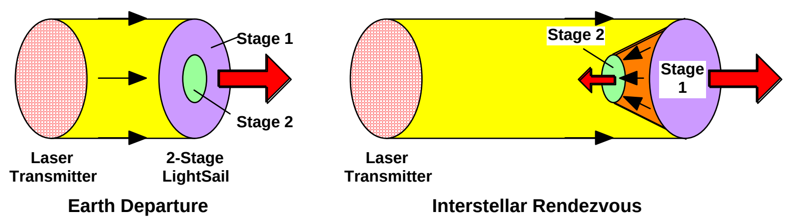


Figure 5. Laser-Driven LightSail Rendezvous. (After Ref. 5)

Figure 6 shows the mission results for a 40-LY rendezvous mission. For these analyses, we adjusted the laser power to a maximum power level needed at the end of the rendezvous. Note that because of relativistic effects at 0.5c, at the very end of the rendezvous, the decelerating Stage 2 LightSail sees the laser photons doubly red-shifted down to roughly ¼ of the nominal 1 μm laser wavelength. Specifically, at the beginning of the rendezvous deceleration, Stage 1 and 2 are both traveling at 0.5c, so Stage 2 sees photons coming from Stage 1 that are red-shifted (by a factor of roughly ½) corresponding to Stage 1's velocity relative to the laser transmitter (i.e., 0.5c). However, as Stage 2 begins to decelerate to rest, its velocity relative to Stage 1 increases to 0.6c (because Stage 1 has been accelerating), so that Stage 2 sees a double red-shift, once due to Stage 1's velocity relative to the laser transmitter, and a second time due to Stage 2's velocity relative to Stage 1.

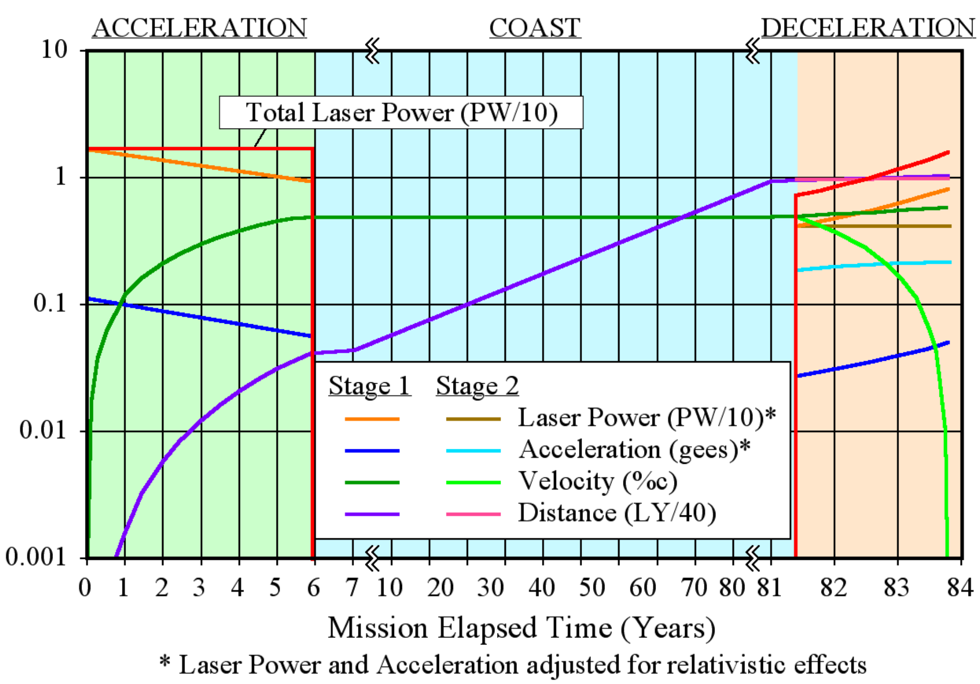


Figure 6. Mission Analysis Results for a 40 LY, 0.5c Cruise LightSail Interstellar Rendezvous Mission.

In our analyses, we assumed that the laser wavelength would remain constant, and varied the beam power to compensate for the red-shift. This allows us to decelerate Stage 2 at its thermal limit, although this has the effect of accelerating Stage 1 out of the target solar system. Also, because Stage 1 has an assumed 10 times greater area than Stage 2, Stage 1 is accelerated at less than its thermal limit, which is actually desirable since it limits the laser-beaming separation distance between Stage 1 and Stage 2. Also, because we limit the laser power during the acceleration phase to the maximum at the end of the deceleration phase, Stage 1 actually accelerates at less than its thermal limit. Finally, as Stage 1 accelerates to 0.5c, there is a factor of 2 drop in acceleration due to relativistic effects as the velocity increases.

Finally, note that there is a long coast distance because of the relatively high LightSail acceleration and deceleration (e.g., ~ 0.2 gees for Stage 2). Thus, if we removed the coast phase, we could reach much closer targets and have the same peak cruise velocity (0.5c). Interestingly, the problem of Stage 1 retro-reflecting light back onto Stage 2 becomes much worse for closer missions (out to ~ 15 LY) if the Stage 1 diameter is kept at the minimum allowed by the 1,000-km diameter laser transmitter. In this case, the smaller Stage 1 diameter makes it harder to focus the beam onto the correspondingly smaller Stage 2. Thus, it is necessary to either reduce the cruise velocity so as to minimize rendezvous separation distance, increase the size of Stage 2 (beyond its nominal 10% of the area of Stage 1), or make Stage 1 larger than the minimum size set by the laser transmission optics. The latter option of increasing the size of Stage 1 is illustrated in **Figure 7**and **Table 1**.

For example, the cruise velocity of a 4.3 LY rendezvous mission using a diffraction-limited Stage 1 diameter (102 km) must be constrained to 0.132c (35 year trip time) so that the Stage 2 / Stage 1 separation distance during rendezvous (0.12 LY) keeps the diffraction-limited spot size on Stage 2 less than the diameter of Stage 2 (32 km). Alternatively, it would be possible to make Stage 1 (and thus Stage 2) larger (e.g., 345 and 109 km, respectively) than the minimum size allowed by the laser optics. This results in the need for dramatically more laser power, but at least it allows acceleration to the maximum cruise velocity (0.5c) and minimizes trip time (e.g., 13 years to 4.3 LY).

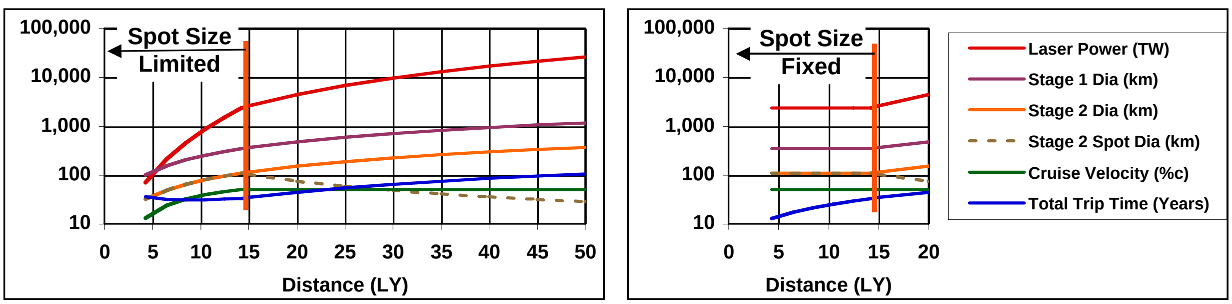


Figure 7. Impact of Stage 1/Stage 2 "Spot" (Airy Disk) Size as a Function of Interstellar Rendezvous Distance.

Table 1. Comparison of LightSail Diameter Options for 4.3 LY Rendezvous Mission.

Diameter Option	Stage 1 Dia. (km)	Stage 2 Dia. (km)*	Separation Dist. (LY)	Cruise Velocity (c)	Laser Power (TW)	Trip Time (Years)
Minimum	102	32	0.118	0.132	73	35
Maximum	345	109	0.805	0.500	2,384	13

* Same as spot size; Stage 2 area = 10% of Stage 1 area.

These analyses have shown that a laser-driven LightSail is a promising option for an interstellar rendezvous mission. This assumes, of course, that all of the various formidable technological requirements can be met. Also, as with any interstellar transportation system, the overall transportation system is very large, with a 17.2-PW laser and its 1,000-km diameter transmitter optics system, combined with a 941-km diameter 2-stage LightSail for a 40-LY rendezvous mission.

C. Impact of Fusion Ramjet Acceleration and Cruise Velocity on Total Mission Mass and Trip Time

The Interstellar Fusion Ramjet was originally conceived by Bussard. REF Its primary benefit for interstellar rendezvous missions is its ability to overcome the inherent I_{sp} limitation (10^6 lb_f-s/lb_s, or 0.03c) of Fusion Propulsion by collecting interstellar hydrogen. Without this capability, Fusion propulsion, like Fission Fragment propulsion (with a similar I_{sp}), is limited to relatively slow (i.e., 0.1 c) interstellar flybys. This option represents the highest risk, because of the need to overcome major technological obstacles, but also the highest payoff, because the Fusion Ramjet is capable of essentially unlimited range (and thus mission flexibility), and high relativistic speeds (>> 0.5 c). REF

For mission analysis purposes, a Fusion Ramjet with a dry mass of 3,000 MT is assumed.[24] As a Fusion Rocket, it operates at an I_{sp} of 10^6 lb_f-s/lb_s (0.03 c). For the purposes of illustrating the system's mission performance, we assumed that the fusion engine has a total "jet" power of 40 TW, which results in a thrust of 8.16 MN (for a dry vehicle acceleration of 0.278 gees) and a propellant mass flow rate (M-DOT) of 0.833 kg/s through the engine. (Note that the value of jet power selected is arbitrary; it may very well be unrealistic for a fusion engine weighing less than 3,000 MT to generate this much power even given many decades to centuries of technology development.) For an interstellar hydrogen density of 1 atom per cubic centimeter and a scoop diameter of 6,000 km, the speed required for the onset of ram-scoop operation (i.e., the speed at which the forward motion of the vehicle sweeps out a mass of hydrogen equal to the engine's propellant mass flow rate of 0.833 kg/s or 5.04×10^{26} atoms/s) is 5.91% c. Using the Rocket Equation, we find that the on-board hydrogen propellant required to reach this speed is 15,327 MT; thus, the vehicle has a total (wet) mass of 18,327 MT on departure. (Interestingly, unlike matter-antimatter annihilation, the amount of mass "lost" in a fusion or fission reaction is negligible.) Finally, if we assume a length-to diameter (L/D) of 5, such that the inward radial velocity of the collected hydrogen is one-tenth that of the vehicle's forward velocity), then the ram-scoop is 30,000-km long and 6,000-km in diameter.

The mission scenario for these assumptions is shown in Figure 8. First, we begin with a fullly-fueled vehicle. On-board hydrogen is used to accelerate the vehicle to a speed of 5.91% c, at which point ram-scoop operation begins. The vehicle continues to accelerate to a speed of 0.5 c, and then coasts. During the ram-scoop acceleration phase, the acceleration decreases slightly because even though the vehicle thrust and rest mass are constant, the vehicle relativistic mass increases (by about 15% at 0.5c). Thus far in the mission, operation of the vehicle has been similar to a conventional propulsion system with the exception of the ram-scoop collection of interstellar hydrogen. However, once the vehicles begins to decelerate, we begin to encounter some of the unique operational characteristics of the Fusion Ramjet.

To begin deceleration, the ram-scoop is then turned on and the hydrogen flow choked (to bring it to rest relative to the vehicle) to produce drag. In effect, the ram-scoop acts like an electromagnetic "parachute" to slow the vehicle. What is unique here is that the vehicle acts as if it had a rocket engine running with an I_{sp} (or exhaust velocity) equal to the vehicle's forward speed (and with the M-DOT that the ram-scoop is designed to collect). In effect, as long as we continue to use the ram-scoop to produce drag with the vehicle's speed greater than the I_{sp} of the fusion engine (0.03c), the ram-scoop is actually more efficient at decelerating the vehicle than the fusion engine. In fact, above about 0.12c the thrust is so high we have to limit it (to an assumed 1 gee) to prevent *too* high a deceleration. Near the end of the ram-scoop drag phase, a small amount of the scooped hydrogen is collected and stored to replenish the on-board propellant tanks (thus the increase in vehicle mass seen in Figure 8) to supply the propellant needed for a final deceleration from 0.03c using the fusion engine. (This amount of propellant is less than the initial propellant load needed for acceleration to onset of ram-scoop operation because the ΔV is less, i.e., 0.03c vs 0.0591c.) Finally, once a speed of 0.03c is reached, the vehicle is turned around and on-board hydrogen used in the Fusion Rocket (and the vehicle mass drops back down to its dry mass value) to bring the vehicle into orbit about the target star. As an example of the potential versatility of the Fusion Ramjet concept, if the on-board hydrogen tanks are refilled, either from local resources or a second set of propellant tanks filled during the deceleration phase, the Fusion Ramjet could then continue on to another stellar system.

III. OTHER CONSIDERATIONS

A. Introduction

Thus far we have concentrated on the interplay between acceleration, cruise velocity, mass, and trip time. However, during the course of our studies we have identified additional issues that need to be emphasized in considering interstellar missions. Several of these are propulsion system specific, but some areas are cross-cutting and somewhat independent of specific technologies.

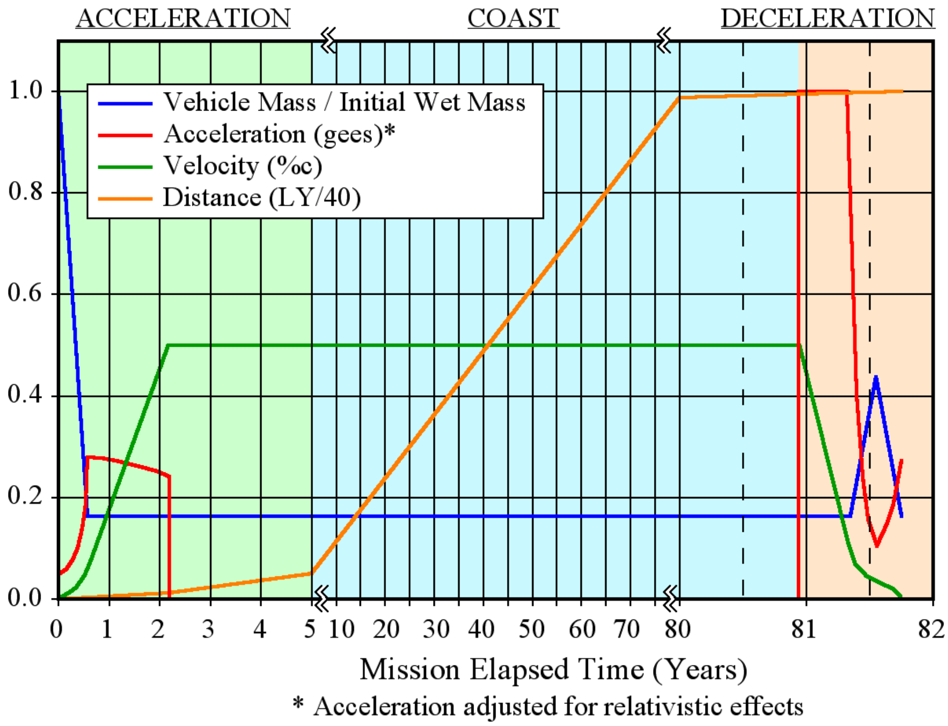


Figure 8. Interstellar Fusion Ramjet 40-LY Rendezvous mission.
(Representative results only; an actual Fusion Ramjet may not be able to achieve an acceleration as high as 0.28 gees for the dry vehicle.)

B. Antimatter Rocket Issues

First, it is important to emphasize that positrons are a poor choice for a Matter-Antimatter Annihilation Rocket because the electron-positron reaction produces gamma rays with an isotropic direction distribution. Because there is no efficient way to focus the gamma rays, there would be no net thrust. Furthermore, even if they could be focused, the gamma-ray beam would have very low thrust, resulting in poor acceleration of the vehicle. By contrast, the proton-antiproton reaction produces charged pions that can be directed by a magnetic nozzle, Also, because they possess mass, the pion exhaust will produce more thrust, and thus more useable acceleration, than a pure gamma-ray beam. However, unlike an electron-positron reaction that produces gamma-rays at 100% efficiency, a proton-antiproton reaction yields only 22% of the initial rest mass in the form of rest mass of the charged pions. Thus, only 22% of the initial mass of propellant in the rocket is available to produce the momentum that drives the rocket forward. (It is as if you designed a rocket that expelled 78% of the propellant mass sideways, perpendicular to the vehicle velocity, in a fashion that cancelled out any sideways motion and contributed nothing to the forward motion of the rocket.) This effect represents a major impact to the Rocket Equation.[1,2] Also, it is necessary to use a Relativistic Rocket Equation that takes into account the relativistic effects of both the vehicle and propellant exhaust (charged pions) moving near the speed of light. As shown in Figure 9, these two modifications results in a mass ratio of "wet" mass divided by "dry" mass (M_o/M_b) for a given ΔV and I_{sp} that is much higher for a relativistic matter-Antimatter Rocket (with "loss" of propellant) than for either a classical or relativistic "conventional" rocket (where only a negligible amount of propellant mass is converted into energy). In each case, as ΔV becomes large, the relativistic Rocket Equation mass ratio (M_o/M_b) is somewhat larger than its classical counterpart. However, a larger divergence is seen in the effect of "loss" of propellant mass for thrust (i.e., momentum) production. Thus, the mass ratio M_o/M_b for a relativistic rocket with an I_{sp} of 0.33c requiring a ΔV of 0.25c is around 2.15 if the "loss" of propellant is ignored; however, if the "loss" of propellant (with only 22% left) is included, the mass ratio more than doubles to about 5.45. We thus have the surprising result that, even with its extraordinarily high I_{sp}, the Antimatter Rocket is limited to a ΔV per stage of around 0.25c.

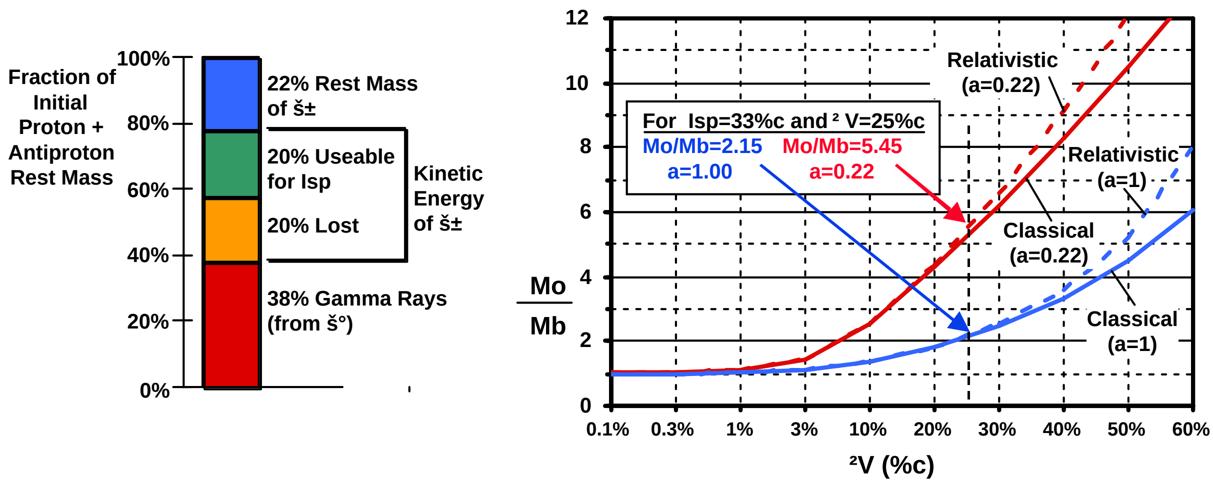


Figure 9. Comparison of Classical and Relativistic Rocket Equations with and without "Loss" of Propellant.

A second important factor is the enormous mass of antiprotons needed, combined with the low energy efficiency of producing antiprotons. Ultimately, to perform interstellar missions with Antimatter Rockets, we will need tens of millions of tons of antimatter produced at near-ideal efficiency (ca. 0.01%); by contrast, today we make tens of ng at 10^{-9} efficiency. A related issue is storage of the antimatter once produced. First, it is necessary to recognize that we need to store the propellant as relatively high-density condensed-phase (liquid or solid) anti-H_2 molecules to have both a reasonable tankage mass (i.e., propellant density of solid or liquid rather than gas or plasma), and be able to use a diamagnetic trap to confine the propellant so that it does not contact the (normal matter) tank. Additionally, we need to store the anti-H_2 as a very low temperature solid (anti-SH_2) to minimize sublimation of the solid, because any sublimation/vaporization would produce gas molecules that would escape the diamagnetic trap and reach the walls. This implies the very challenging requirement for the conversion of antiprotons (and positrons) into anti-H atoms, then into anti-H_2 molecules and finally into anti-SH_2 ice. Again, this is a potential major show-stopper; as with antiproton production, we will need a "non-contact" process capable of high throughput and high efficiency. Some of the required steps have been demonstrated for antimatter but at low rates and efficiencies (e.g., production of thousands of anti-H atoms), and some steps have been demonstrated for normal matter using "non-contact" techniques (e.g., laser cooling). We recommend research programs to demonstrate all the required steps. Initially, this can be done using normal-matter with non-contact technologies (to emulate eventual use with antimatter). An important part of this experimental program would be the demonstration of scalability to high throughput and high efficiency. Finally, we would recommend improved measurements of solid H_2 properties (especially sublimation vapor pressure) at very low temperatures (e.g., < 4 K).

C. Laser LightSail Issues

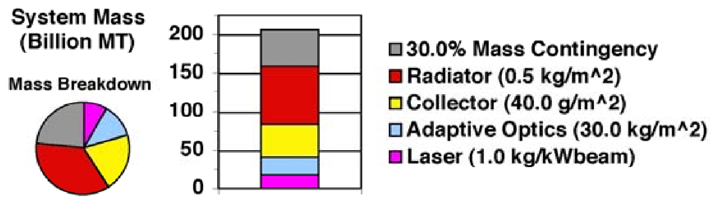
To achieve thermally-limited deceleration during rendezvous, enormous laser powers are required, primarily because the decelerating Stage 2 LightSail sees the initial laser photons doubly red-shifted. Thus, the laser power system represents major challenges of scale, but not necessarily unrealizable in comparison to existing large, mass-production systems. Likewise, the pointing and tracking requirements of the laser, though far beyond today's technology, will be comparable to capabilities already established in the astronomical community in the time frame of interest. Also, one interesting result of the optics analyses was the identification of an optimum sail size that captures about 70% of the laser beam, rather than the usual assumption of 84% with a LightSail sized to capture the central diffraction disk. Finally, in a diffraction-limited optics system, the beam intensity across the face of the LightSail is not uniform, with a central peak almost four times the average intensity. Several methods of accommodating this peak intensity have been discussed; future analysis will be needed to determine the best overall solution.

By contrast to the issues discussed above, the use of Stage 1 as a transmitter to retro-reflect laser light back onto Stage 2 during rendezvous represents a significant feasibility issue to the whole concept of using LightSails for interstellar rendezvous missions. This is an area that will require considerable additional work. Fortunately, dust impact with the LightSail is a relatively minor concern; for example, only 2.3% of the sail area is lost during a 40 LY mission.

Also, a number of high-temperature materials other than the baseline aluminum have been considered for LightSails. REF However, these analyses have been severely limited by a lack of experimental data on the optical properties (reflectivity, absorbtivity, or transmissivity) of ultra-thin films at near-optical wavelengths (e.g., 1 μm). It is recommended that these measurements be made to facilitate analyses of alternative LightSail systems.

Finally, although it is possible to determine a LightSail's mass based on its area and areal density (0.1 g/m^2 in these analyses), it would at first glance seem impossible to determine the mass of the laser transmitter system. However, we can at least attempt to bound the problem by using subsystem assumptions based on similar contemporary systems. For example, we can approximate the mass of the laser subsystem by first assuming that it is a solar-pumped glass laser, and then assuming that it has a specific mass (kg/kW) comparable to an advanced solar photovoltaic (solar cell) power system, because both use doped glasses to convert sunlight into useful power. For the transmitter optics, we assumed the use of adaptive optics segmented mirrors. Because this is a solar-pumped laser, we need a sunlight collector; for this we assumed inflatable optics structures technology. We also assumed the need for a radiator to reject waste heat from the laser system, and a final overall 30% dry mass contingency to give a total laser transmitter system mass of 206x10^9 MT for a 17.2-PW laser system. The mass breakdown is illustrated in Figure 10; the radiator mass dominates the system mass as is often the case in space-based power systems.

Figure 10. Laser System Mass Breakdown.



D. Interstellar Fusion Ramjet Issues

The Interstellar Fusion Ramjet is still highly conceptual; however, it has the potential advantage of providing unlimited range and mission flexibility and so warrants continued study. One of the major feasibility issues is the need to use hydrogen (H) in a fusion reaction; the H-H reaction is inordinately difficult to ignite and may simply be unobtainable in any technological system. However, there is on the order of 1 deuterium (D) atom per hydrogen atom in space (left over after D-D fusion created helium during the Big Bang); thus, in principal, it may be possible to collect D rather than H and use the deuterium in a D-D fusion reaction, which is commonly done today. Interestingly, the ram-scoop is not a physical structure, but a magnetic field; however, it is more complex than a magnetic nozzle "run backwards". (A magnetic nozzle run this way would "choke" and exclude hydrogen at the throat of the scoop.) Another unique requirement of the scoop magnetic field is tits immense size (e.g., dimensions of thousands of kilometers), implying powerful magnetic fields. Also, a laser capable of ionizing hydrogen is required because the magnetic scoop cannot collect neutral atoms.

A final major feasibility issue associated with the Interstellar Fusion Ramjet is the same one encountered in supersonic ramjet (scramjet) systems, where the engine thrust must be greater than the ram inlet drag. This suggests a cylindrical-geometry Magnetic Confinement Fusion (MCF) reactor, such as a tandem-mirror reactor, where solenoid magnets confine the plasma radialy. Momentum drag would also be an issue for the magnetic scoop, because the ionized H (or D) atoms must be accelerated radially inward towards the centerline of the scoop without being axially accelerated to produce drag. This suggests that the scoop magnetic field would need to have a very large length-to-diameter (L/D) ratio to minimize the axial contact angle of the ions with the field.

E. General Issues

1. Communications

Interestingly, Lesh REF has already shown that optical (laser) communication over interstellar distances is feasible given modest extrapolations of the technology. This also suggests that programs like SETI (Search for Extraterrestrial Intelligence) may have better success when observations are made at near-visible wavelengths, rather than the current microwave searches.

2. Reparability vs Reliability

Any long-duration space system will require a high level of reliability and system lifetime. With a requirement for systems to operate for decades to centuries, it may be necessary to re-think our traditional assumptions about trading performance and lifetime. For example, instead of pursuing the goal of maximum performance, we may need to design systems for ease of maintenance, repair, or replacement, even if this means sacrificing some level of performance. Also, in the context of a highly intelligent robotic spacecraft, or ultimately a piloted mission, it is possible to imagine a completely autonomous vehicle where replacement parts are manufactured on the vehicle as needed; in effect, the vehicle would have its own "machine shop" and robots to perform the needed work. This also introduces the idea of sacrificing performance for ease of manufacturability in a completely autonomous robotic environment.

3. Societal Investments in Interstellar Missions

Given the inherent enormous scale of any interstellar mission, one question that can be asked is what resources will a civilization be willing to expend on an interstellar mission? To try and answer this question, we used historical data for the U.S. Gross National Product (GNP) and Federal budgets during the Apollo era to see how much we spend on "luxury" items like space exploration (or War?). However, even during the "Good Old Days" of Apollo, NASA's budget was less than 0.75% of the U.S. GNP (now ~0.13%). For comparison, in 2001, total U.S. Pet Industry expenditures were $28.5B; NASA's budget was less than one-half this ($13.4B).

As an alternative to NASA, we might consider military spending as a "luxury" that a saner civilization could divert to more productive uses. For example, starting in the 1960s, Defense spending has been decreasing from 9% of the GNP (during the height of the Cold War) to today's 3% of GNP. In this context, Sir Arthur C. Clarke has described the state of humanity in his fictional worlds of 2001: "Mankind had finally found something [space exploration] as expensive, and as much *fun*, as war . . ." This suggests that a wiser human society might find more interesting uses for military spending. Based on these arguments, baring an impending disaster of Solar System wide proportions, we can estimate that around ~10% of a civilization's resources might be applied to an interstellar mission. Of course, something capable of rendering the Solar System uninhabitable (a nearby supernova?) might dramatically increase the priority of humanity's investment in an interstellar mission, just as the threat to survival that the Cold War represented increased the priority for Apollo.

More generally, it is worth noting that any civilization capable of marshalling the technologies and energies required for an Interstellar Mission had better be grown up! For comparison, the energy content of annihilating the antimatter in the nominal 4-stage Antimatter Rocket is capable of vaporizing the entire surface of the Earth to a depth on the order of 100 m.[2] Similarly, the 17.2-PW laser required for a 40-LY LightSail mission has the capability of delivering the energy equivalent of a 4-megaton nuclear weapon per second into a 0.7-m diameter spot at a distance of 2 AU from the laser.[3] (This suggests that it would be prudent to base an antimatter "factory" or LightSail laser in a 1 AU orbit on the side of the sun opposite Earth.) More generally, the ability of an advanced civilization to destroy itself has been an on-going issue with estimating the lifetime of a technological civilization for use in the Drake Equation.

IV. CONCLUSIONS AND RECOMMENDATIONS

These analyses have illustrated the strong interaction between an interstellar vehicle's acceleration, cruise (maximum) velocity, mass (e.g., as a function of power and thus thrust), and overall mission trip time. The specific results obtained are very technology dependent; generally, for vehicles like an Antimatter Rocket or Fusion Ramjet, there will be an especially noticeable tradeoff because of the direct interrelation between the propulsion system's mass, power, thrust, and acceleration. By contrast, the Laser LightSail system places the "rocket engine," the laser, back in Earth's solar system so the vehicle can have an arbitrarily high power and thrust (up to the LightSail's thermal limit) without increasing the mass of the vehicle. (In practice, there might be a small mass dependency on power for the LightSail if different high-emissivity heat-rejection coatings are used.) However, the LightSail's mass (and area) increases with square of the mission (i.e., laser beaming) distance for a rendezvous mission due to the assumed fixed diameter of the laser transmitting optics.[3] At the other extreme, the mass of the Antimatter Rocket and the Fusion Ramjet should increase only slightly with distance due to the increased thickness of an interstellar dust shield.

One of the more surprising results is that it can be more difficult to achieve a short trip time for nearby stars than for those more distant depending on the vehicle's acceleration. Figure 11 illustrates this for the case of different vehicle accelerations and mission distances, all with a maximum coast speed of 0.5c. Thus we see that for a 4.3-LY mission, a low-acceleration vehicle cannot even reach a 0.5c cruise velocity before it has to turn around and begin decelerating. Similarly, at low accelerations, the trip time required to go twice as far (e.g., 8.6 vs 4.3 LY) does not take twice the time; instead, trip time only becomes proportional to distance in the limit of high acceleration where the vehicle spends most of its time at the maximum cruise velocity.

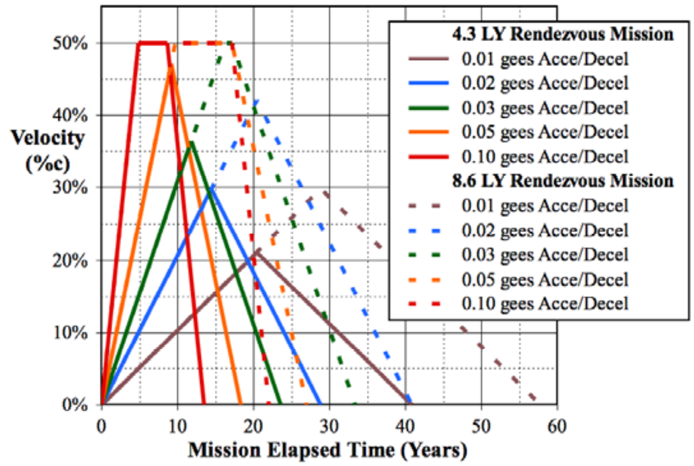


Figure 11. Vehicle Velocity vs Trip Time for a 4.3 and 8.6 LY Interstellar Rendezvous Missions as a Function of Vehicle Acceleration, Deceleration, and Maximum Cruise Velocity (0.5c).

Several additional issues were identified, including the relative ease of communicating over interstellar distances (using optical/laser communications rather than radio), the potential to emphasize on-board repairability of vehicle systems (even at the expense of some level of performance and reliability). Finally, we have used historical data to try and estimate the fraction of a civilization's resources (ca. 10%) that it might allocate to an interstellar exploration mission.

Also, during the course of these studies we have identified several additional areas that we would recommend be pursued In several cases, this work would consist of systems-level studies of various elements of the interstellar propulsion systems. For example, the Bussard Interstellar Fusion Ramjet has been far less studied than Antimatter Rockets or Laser LightSails. Thus, we would recommend detailed modeling of all aspects of the Fusion Ramjet, and especially the ram-scoop structure and electromagnetic field, as well as investigation of fusion reactor concepts that would lend themselves to the "drag free" fusion engine requirement of the Fusion Ramjet.

Beyond system studies, we would recommend experimental research on determining "engineering" properties of interest to Laser LightSails, and especially the optical properties of ultra-thin films (e.g., high-temperature metals, carbon, etc.). Also, there are several fundamental feasibility issues associated with Antimatter Rockets that need to be demonstrated experimentally, although in several cases normal-matter protons, electrons, hydrogen atoms, and hydrogen molecules can be used instead of antimatter (in appropriate "non-contact" experiments to simulate what would be needed to handle antimatter). For example, although a modest number of anti-H atoms have been produced, the complete process of "non-contact" conversion of H atoms to H_2 molecules to H_2 molecular solid ice needs to be demonstrated. Also, additional work needs to be done investigating high-efficiency, high-production rate processes for the production of antiprotons, and ultimately conversion into anti-H_2 ice. Finally, as described above, one of the major inefficiencies of Antimatter Rockets is the low fraction of proton-antiproton annihilation products with charge and mass (i.e., charged pions) that can be used to produce thrust. Thus, we also recommend research that would seek to increase the fraction of useable annihilation products and thereby reduce the effective "loss" of propellant mass, while still maintaining the extraordinarily high I_{sp} of the Antimatter Rocket engine.

Finally, we would like to close with the often-noted observation that interstellar missions are <u>not</u> impossible, they are just enormously demanding in terms of size and resources. What is remarkable is that in the brief time we have been a space-faring species (less than a half century!), we have already identified three potential propulsion concepts with the potential for performing the most propulsion-intensive space missions of all, and allowing us to respond to Konstantin Tsiolkovsky's classic challenge:[6]

"Earth is the cradle of humanity, but one cannot live in a cradle forever."

V. ACKNOWLEDGEMENTS

The work described in this paper was carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA).

The author would like to thank John Cole (former Head of the Revolutionary Propulsion Program at NASA Marshall Spaceflight Center) for providing overall funding support for this task in previous years. Although the Revolutionary Propulsion Program was cancelled in fiscal year 2003, we hope that it will be reinitiated in coming years so as to provide an opportunity to continue investigation of this and other advanced propulsion concepts for interstellar missions.

VI. DEDICATION

This paper is dedicated to the memory of Dr. Robert L. Forward (1932-2002). So much of what we think of when we consider interstellar propulsion concepts and technologies was first conceptualized and evaluated by Dr. Forward; our debt to him cannot be overemphasized. Isaac Newton said it best when he said that we see further only because we stand on the shoulders of giants; Bob Forward was one of those giants.

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