

Feasibility Study of Interstellar Missions Using Laser Sail Probes Ranging in Size from the Nano to the Macro

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Abstract

This paper presents the analysis examining the feasibility of interstellar travel using laser sail probes ranging in size from the nano to the macro. The relativistic differential equations of motion for a laser sail are set up and solved using the Pasic Method. The limitations of the analysis are presented and discussed. The requirements for the laser system are examined, including the thermal analysis of the laser sails. Black holes, plasma fields, atmospheric collisions and sun light are several methods discussed to enable the deceleration of the interstellar probe. A number of novel mission scenarios are presented including the embryonic transport of plant life as a precursor to the arrival of space colonies.

Introduction

Laser and light sails have been studied extensively in the literature as propulsion devices for interplanetary travel and even interstellar travel. Many new missions have been proposed, which have large masses, but few have contemplated micro or nano probes. A feasibility analysis of solar sails would help identify the key design parameters and benefit light sail design. Solving the special relativity equations of motion will give a first approximation to determine the distance and time it takes to reach near-light-speeds. Also, the study allows the development of new mission concepts based on the insight gained from the analysis.

Development of Equations

The development of the relevant equations is the first step to solve the special relativity equations of motion. The first step is to find the acceleration equation, which can be integrated twice to determine both the position and velocity. The reference frame of focus is the one moving with the probe and the others are not considered. The momentum for light P is the following equation

$$P = \frac{E}{c} \quad (1)$$

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where E is the energy of the photons in Joules hitting the sail and c is the speed of light $2.9979E8$ m/s. Differentiating with respect to time gives the following

$$\frac{dP}{dt_{light}} = \frac{dE}{dt} \cdot \frac{1}{c} \quad (2)$$

Since both the mass m and the velocity u change with time the momentum of the probe is

$$\frac{dP}{dt_{probe}} = \frac{d(mu)}{dt} = \frac{dm}{dt}u + \frac{du}{dt}m \quad (3)$$

Differentiating the mass with respect to time and applying algebra leads to

$$\frac{dP}{dt_{probe}} = \frac{ma}{\left(1 - \frac{u^2}{c^2}\right)} \quad (4)$$

where a is the acceleration m/sec², assuming no transverse acceleration [1]. The momentum of the light has two parts. The first part is due to the light hitting the sail, which includes both the light absorbed and the light reflected. The second part is the light reflected off the sail. Setting the momentum change per time equal for both the probe and the light gives

$$\frac{dE}{dt_{light}} \cdot (1 - \tau + \rho) \cdot \frac{1}{c} = \frac{ma}{\left(1 - \frac{u^2}{c^2}\right)} \quad (5)$$

If the solar flux is Q W/m² and the sail area projected on the normal surface of the photons is A_p m², then the acceleration a is

$$a = \frac{\left(1 - \frac{u^2}{c^2}\right) \cdot A_p Q \cdot [(1 - \tau) + \rho]}{m_o c} \quad (6)$$

The maximum heat reflected to deep space can be obtained by taking the energy balance on the sails. The heat absorbed into the sails is equal to the radiation emitted off the surface [2]

$$A_p Q \alpha_\lambda = \sigma [\varepsilon_{s1} A_{s1} + \varepsilon_{s2} A_{s2}] \cdot T^4$$

(7)

and solving for Q

$$Q = \frac{\sigma[\varepsilon_{s1}A_{s1} + \varepsilon_{s2}A_{s2}] \cdot T^4}{A_p \cdot \alpha_\lambda} \quad (8)$$

Substituting into the acceleration equation gives the relativity acceleration equation as a function of the temperature that the laser sail can withstand

$$a = \frac{\left(1 - \frac{u^2}{c^2}\right) \cdot \sigma[\varepsilon_{s1}A_{s1} + \varepsilon_{s2}A_{s2}] \cdot T^4 \cdot [(1 - \tau) + \rho]}{\alpha_\lambda m_0 c} \quad (9)$$

The critical design parameter is the areal density β kg/m² [3], which is the total mass of the probe divided by the effective area – area of the sail projected normal to the photons A_p . The total probe mass m_0 can be broken down into the mass of the sail, support structure, and payload. The effective areal density is the following:

$$\beta_{eff} = \frac{m_{sail} + m_{structure} + m_{payload}}{A_p} \quad (10)$$

Here the payload is considered any structure or extra mass that you wish to carry, such as avionics. Equation (6) can be rewritten as follows

$$a = \frac{\left(1 - \frac{u^2}{c^2}\right) \cdot Q \cdot [(1 - \tau) + \rho]}{\beta_{eff} c} \quad (11)$$

Substituting into equation (9) gives

$$a = \frac{\left(1 - \frac{u^2}{c^2}\right) \cdot \sigma[\varepsilon_{s1}A_{s1} + \varepsilon_{s2}A_{s2}] \cdot T^4 \cdot [(1 - \tau) + \rho]}{\alpha_\lambda \beta_{eff} A_p c} \quad (12)$$

The radiative front and backside surface area is related to the sail area projected on the normal surface of the photons by

$$A_{s1} = A_p F_{s1} \quad (\text{lighted side}) \quad (13a)$$

$$A_{s2} = A_p F_{s2} \quad (\text{dark side}) \quad (13b)$$

where F_{s1} and F_{s2} are factors. Substituting into equation (12) gives

$$a = \frac{\left(1 - \frac{u^2}{c^2}\right) \cdot \sigma [\varepsilon_{s1} F_{s1} + \varepsilon_{s2} F_{s2}] \cdot T^4 \cdot [(1 - \tau) + \rho]}{\alpha_\lambda \beta_{eff} c} \quad (14)$$

Both equations (11) and (14) highlight the importance of the areal density β_{eff} concerning the acceleration, where both the mass and area fall out and are not the most critical parameters, though indirectly they are important for they can impact the areal density. An increase in mass requires a proportional increase in the sail area. When the sail area increases, the laser power must increase proportionally and is the limiting factor. The larger the laser the greater is the cost to position it in space in the desired orbit [4].

Figure 1 shows the analysis results of an interstellar space probe design, which is highly optimized, and has an areal density much better than what has been proposed [5]. Essentially equation (14) is graphed for varying areal densities to get the acceleration. The maximum acceleration is over 2,500 m/sec² for a probe that has sails that can withstand 1200K temperature. If Forward's optical properties are used [3], the maximum acceleration of the high-temperature graph reduces to about 477 m/sec². Notice how the temperature has a strong impact on the acceleration. A designer can use the graph to determine the maximum acceleration if the optical properties are approximately the same as specified under the Figure 1 heading. The graph shows that small decreases in the areal density have profound impact on the acceleration, which is compounded when the material properties of the sails are improved to withstand greater temperatures. With nano engineering, the propulsion potential of laser sails will improve significantly making interstellar missions possible. Landis mentioned the benefit of small probes as opposed to large probes envisioned by Forward [6].

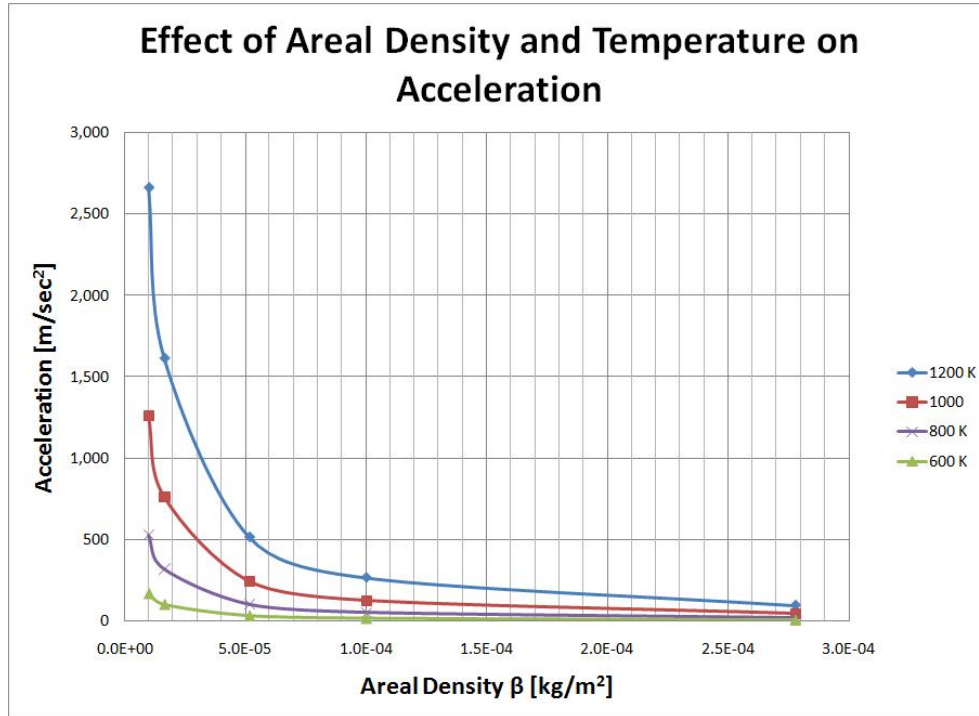


Figure 1. Both areal density and temperature impact the maximum possible acceleration of the probe. Here the temperature is the maximum temperature that the laser sails can withstand and the areal density is the effective value based on the total mass of the probe, which includes the sails, structural supports, and payload divided by the area hit by photons A_p . The assumption is made that with nano engineering the optical properties can be optimized so that the reflectance is 0.95, absorptance is 0.04, and emissivity is 0.70 for this case.

The term $\varepsilon_{s1}A_{s1}$ and $\varepsilon_{s2}A_{s2}$ are included in case there are differences in the surface area respectively from the laser sail side and the dark back side. A designer may want to increase the back surface to maximize the heat emitted away from the surface, as Forward recommended [3]. The emissivity of the two surfaces will likely be different since the laser surface will be optimized to reflect radiation, which may impact emissivity. Forward used an emissivity of 0.07 for the front laser sail side, and a much higher value for the back side [3]. For the analysis in Figure 1, the front and back side were treated the same for both area and emissivity. Also, equation (9) is the relativity equation, so the designer should be aware that the acceleration decreases as the laser probe approaches the speed of light. The analysis of Figure 1 uses a very low probe velocity u to avoid the relativity effects to get the highest acceleration, as a comparative value.

Figure 2 shows how the relativity equations for kinetic energy diverge from Newton's equations. Notice how this takes effect for speeds greater than half the speed of light. As the speed of light is approached, the energy is asymptotic - essentially going to infinity. For this reason, we are not able to travel greater than the speed of light unless space time itself is warped allowing travel through worm holes.

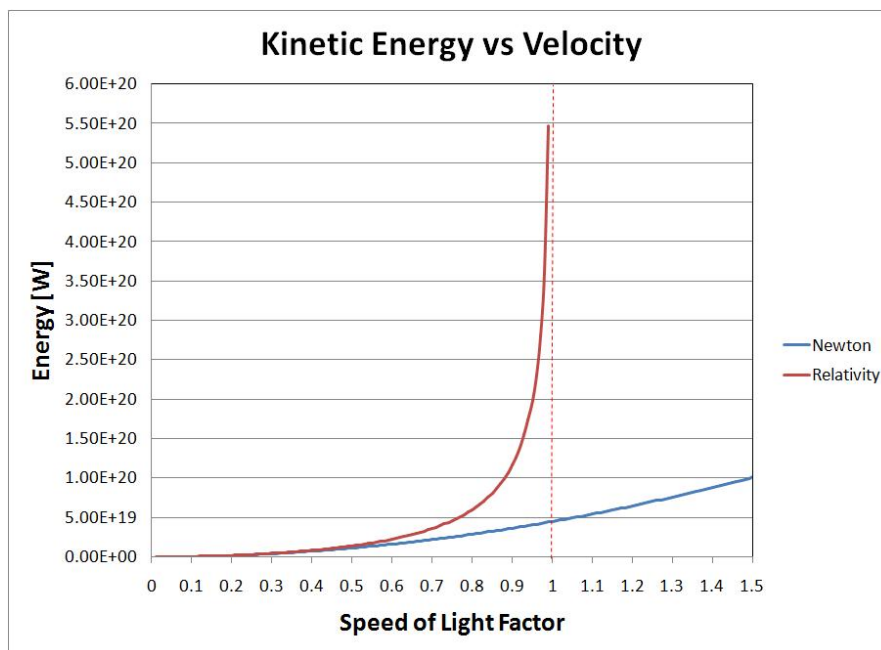


Figure 2. The kinetic energy effects based on the relativity equations become noticeable at about half the speed of light and are asymptotic at the speed of light.

Pasic Method Used to Solve Differential Equations

Once the relativity acceleration equation is developed, a numerical method can be used to solve the equations to determine the distance x , velocity u , and the acceleration a as a function of time. This is needed to assess how long and what distance it will take to attain near-light-speed velocities. We limit the analysis to one dimension to simplify solving, but it could be extended to three dimensions if desired. The Pasic method is an intuitive method to solve differential equations numerically. It is a combination of "Picard's method of successive approximations, the collocation method and the shooting method" [7]. The acceleration is essentially a second order initial-value ordinary differential equation. It is of the form

$$y'' = f(y', y, t) \quad (11a)$$

$$y(0) = C_0 \quad (11b)$$

$$y'(0) = C_1 \quad (11c)$$

The polynomial that needs to be solved for the second order differential equation is the following:

$$y(t) = C_0 + C_1t + A_1t^2 + A_2t^3 + A_3t^4 + A_4t^5 \quad (12)$$

Differentiating twice we obtain the acceleration polynomial with the unknown coefficients shown

$$y'' = 2A_1 + 6A_2t + 12A_3t^2 + 20A_4t^3 \quad (13)$$

The acceleration is calculated from the actual equation $f(y',y,t)$, which is equation (6), with Q being solved from equation (8) with the temperature being the maximum temperature that the solar sail can tolerate. We assume that we can apply a constant radiation flux equal to the maximum allowed radiation. These equations result in the following:

$$y_1''(t_1 = 0, y_1, y_1') = f_1 \quad (14)$$

$$y_2''(t_2 = h, y_2, y_2') = f_2$$

$$y_3''(t_3 = 2h, y_3, y_3') = f_3$$

$$y_4''(t_4 = 3h, y_4, y_4') = f_4$$

The time incremental between time steps is h with the domain 3h. We can solve for the coefficients A1, A2, A3 and A4 by using four collocation points. We have four unknowns with four equations, which in matrix form is

$$\mathbf{f}_n = \mathbf{B} \cdot \mathbf{A}_{n+1} \quad (15)$$

where

$$\mathbf{B} = \begin{bmatrix} 2 & 0 & 0 & 0 \\ 2 & 6h & 12h^2 & 20h^3 \\ 2 & 12h & 48h^2 & 160h^3 \\ 2 & 18h & 108h^2 & 540h^3 \end{bmatrix} \quad (16)$$

The linear system of equations is the following

$$\begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} = \begin{bmatrix} 2 & 0 & 0 & 0 \\ 2 & 6h & 12h^2 & 20h^3 \\ 2 & 12h & 48h^2 & 160h^3 \\ 2 & 18h & 108h^2 & 540h^3 \end{bmatrix} \cdot \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \end{bmatrix} \quad (17)$$

The coefficients are solved and the new calculated y , y' and y'' are used to calculate the acceleration by using equation (6). The distance and velocity are checked to see if the convergence requirement is met compared to the previous calculation. If convergence is not obtained, the coefficients are again solved. This iterative process continues until convergence (i.e. $E < |h^5|$) over the sub-domain ($3h$). The next sub-domain is solved and this iterative process continues until the desired time domain is covered. The model was set up and solved and results were generated.

Results and Discussion

There are two critical problems that need addressed to determine the feasibility of interstellar travel. The first is to find the time required to shine the laser beam on the sail in order to achieve near-light- speed travel, and the second is to find the distance traveled over this time. The latter problem is probably more critical for it determines the size of the laser and the general requirements of the laser regarding power, divergence specifications and tracking capabilities. Ideally, the designer would prefer to have the laser beam cover only the sail area A_p so the least amount of laser power is required, but the tracking requirements limit this and the angle $d\theta$ needs definition so all the sail is illuminated. The laser beam will also have an angle of divergence $d\psi$ of the beam over distance, which is required to control the spread of the beam over the sail. The optical designer can develop the lenses for this, but over vast distances the laser beam itself poses limits, since there is generally a divergence angle associated with a laser. The maximum power of the laser, the tracking angle $d\theta$ and $d\psi$ all impose limits on the power flux Q of the light over the sail. Also, the material that makes up the sail imposes a limit on the maximum allowed flux. The energy balance of equation (7) enables the designer to find the maximum allowed power flux Q on the sail, with equation (8) being used to calculate this value. This means that at the early stages of travel, the laser power may need throttling to prevent the sails from burning up. For the analysis, it is assumed that the laser could be designed to deliver the maximum power flux on the sail.

The Pasic method was used to solve the equations of motion in one dimension with the laser sail treated as a rigid body. The acceleration was calculated from equation (6) with the maximum allowed power flux calculated based on equation (8). Essentially, the acceleration is integrated twice to respectively get the velocity and distance. The properties for the Forward, Midrange and Sleek designs are given in Table 1, where they are respectively, a good, better and best design. Figure 3 shows the results of the Forward design with the distance traveled being over 20 times the distance from the sun to Pluto. The Forward design was given to show a feasible solar sail design that could be used for interstellar travel [3]. This design is somewhat optimized since the areal density is half that used by Forward and the assumed maximum

temperature is 1400K, assuming an improved material capable of withstanding high temperatures. Even with this design the difficulty of reaching near-light-speed travel is apparent. The time to reach this speed is about 14 days, but the real difficulty is the vast distance. Even a small divergence angle of the laser would require a very powerful laser with amazing tracking accuracy. Possibly, a series of lasers could be used, but the cost and time required to position the lasers would be great [4].

Table 1. Properties used for the different sail designs

Design	emissivity	transmissivity	reflectivity	density	thickness	absorptivity	Beta
Forward	0.5	0.045	0.82	1350	1.6E-8	0.135	2.16
Midrange	0.6	0.03	0.89	1175	6.5E-9	0.09	0.765E-5
Sleek	0.7	0.01	0.95	1000	5.0E-9	0.04	0.5E-5

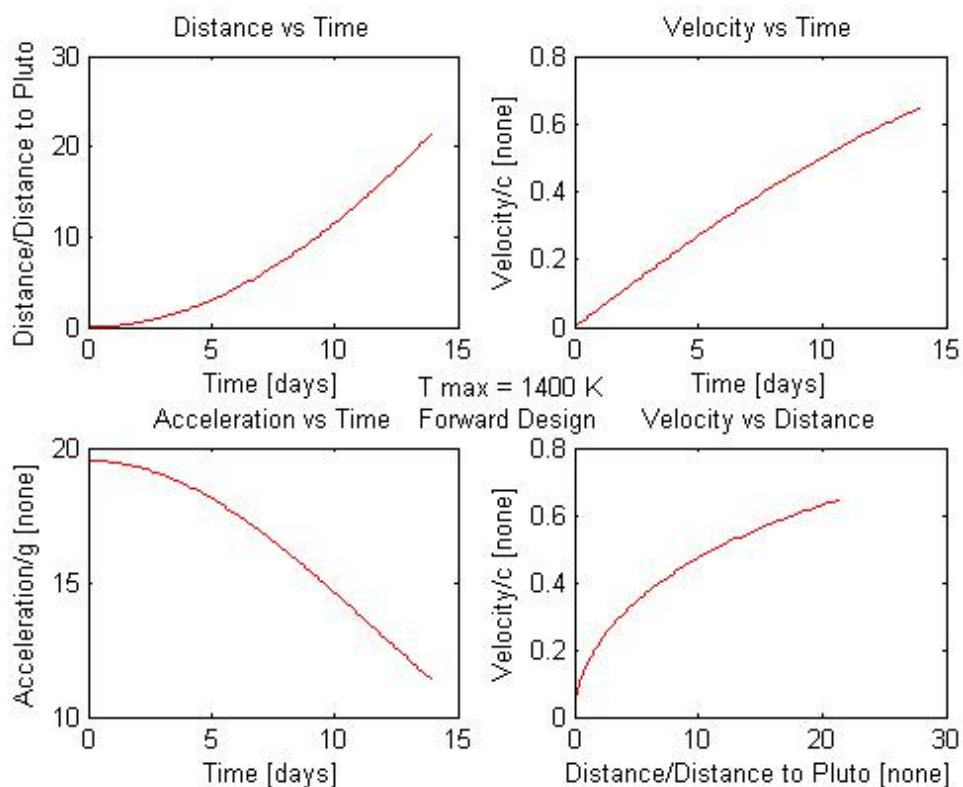


Figure 3. The results of the Forward design set at his optical properties with the areal density set at half his value and the maximum allowed surface temperature set at 1400K. This design is least optimal with a low acceleration compared to the other designs.

Figure 4 shows the Midrange design, which is an improved version since it only takes about 5 days to reach 0.8 the speed of light. The distance of travel is still great at nearly twelve times the distance from the sun to Pluto. The maximum acceleration is 80 times Earth's gravity, which would require the vehicle to have some strength. Swarms of nano sized probes would better withstand the high acceleration compared to large sails with large masses.

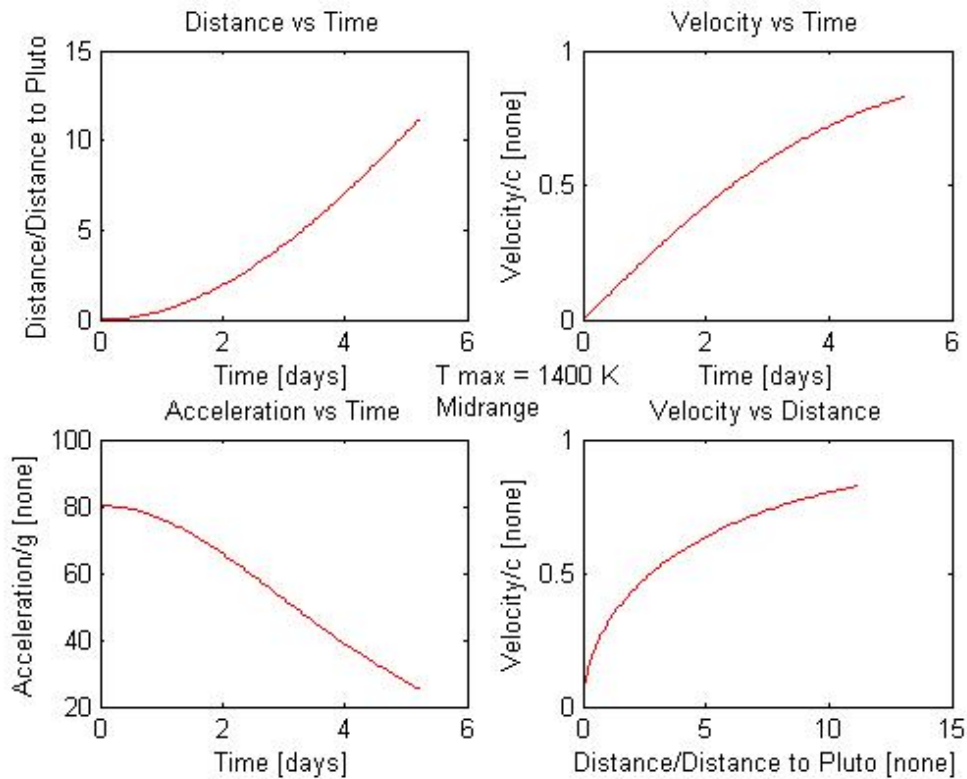


Figure 4. The Midrange design is better with a maximum acceleration of 80 times earth's gravitation. It takes over ten times the distance from the sun to Pluto to achieve a velocity of about 0.75 the speed of light.

Figure 5 shows the results of the Sleek design where it takes only one day to reach near-light-speed with a distance of only two times the distance from the sun to Pluto. The acceleration is even more extreme at 600 times the Earth's gravity, but the acceleration rapidly falls off due to the relativity affects. At this high acceleration a large solar sail would be hard to design since any slight increase in mass would result in huge stresses on the sail support. The optimal areal density may not be achieved, resulting in a slower design. Swarms of nano probes could better withstand the acceleration, assuming that nanotechnology can advance allowing advanced nano-systems at the molecular level with sails having low areal density and increased maximum temperatures.

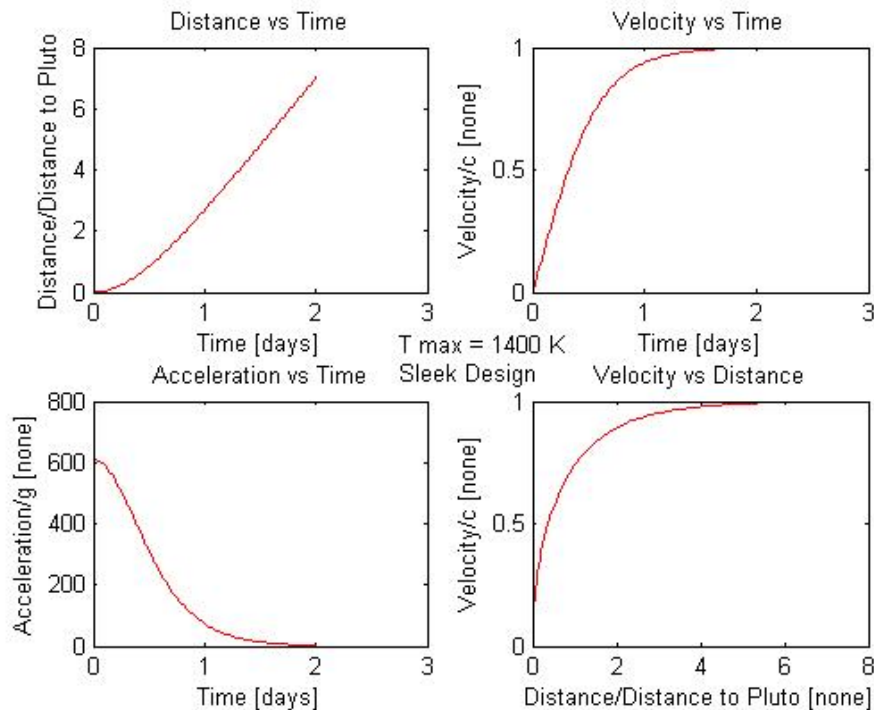


Figure 5. The sleek design is most optimal with a maximum acceleration of over 600 times the Earth’s gravity. Near light speeds are achieved in just one day while the distance travelled is about 2.5 times the distance from the sun to Pluto.

Figure 6 shows how the velocity changes with distance for the three designs. The Forward design has a slow increase in the velocity, the Midrange design experiences a larger increase and the Sleek design rapidly increases in velocity due to the high acceleration. Observe the growth of the hump for the three graphs, respectively. The charts illuminate the impact of both the areal density and the maximum allowable sail temperature on the distance traveled.

Limitations of the Analysis

Special relativity assumes a “flat” space-time and neglects the curvature of space-time due to gravity and acceleration, which general relativity addresses. As a space probe accelerates, space-time itself warps, so the analysis is a first approximation. Tolman says, “it is evident that the principles of the special theory of relativity are approximately true even in the permanent gravitational field at the surface of the earth, and would be valid to an extremely high degree of approximation in internebular space. The use of the special theory of relativity as an abstract idealization thus seems entirely legitimate [1].” Here we don’t mean to overinflate Tolman’s endorsement of this work for the analysis presented does go beyond an abstract idealization. In some sense, the micro changes in velocity can be viewed as stepping

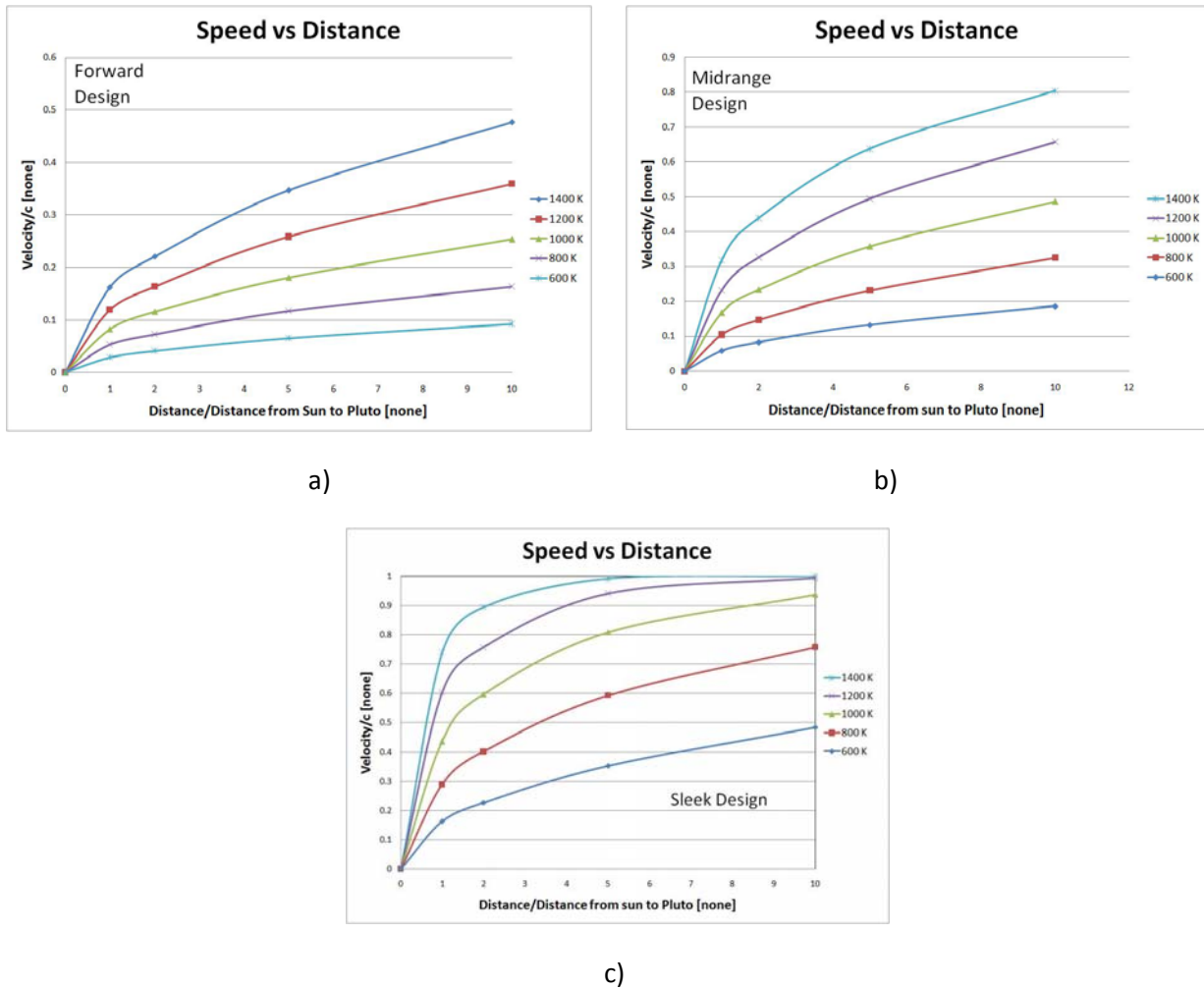


Figure 6. Results are shown for three designs: a) the Forward design which is least optimal; b) the midrange design which is a better design; and last c) the sleek design which is most optimal. The maximum temperature that the sails can withstand was varied for the three designs and the results presented.

through different reference frames, with greater error experienced at high acceleration and velocities approaching the speed of light. To exactly quantify this error, the results from this analysis need to be compared to results obtained from methods used in solving the general relativity equations [8], which is a major undertaking and not attempted here. The analysis is useful to gain an understanding of the trends expected in laser sail dynamics and is useful for a designer of such systems.

The cause of the space-time warping is ultimately the energy density, since mass is energy by Einstein's famous equation

$$E = \gamma mc^2 \quad (18)$$

which here includes the relativistic effects, due to the factor γ . The curvature of space-time is most noticeable above 0.5 c , where the total energy of the probe increases rapidly and the high energy density bends space-time. High acceleration has a bending effect too, since gravitational mass is equal to inertial mass [9]. The twin paradox highlights the importance of the acceleration [10].

The analysis makes some other idealizations. The shift of the laser light wavelength is not addressed in this analysis. It is assumed that the wavelength of the laser is controlled allowing the most reflective light wavelength to reflect off the sail surface. The details of light and matter interaction can be very involved and are not covered here. Also, the analysis is calculated in the reference frame of the probe so issues of other reference frames are not covered (e.g. time dilation, length contraction, etc.).

Some general discussion about the nature of the space-time bending is warranted. An example is the Earth, which bends space-time and creates a gravity well. As the space probe's total energy increases as velocities reach near-light-speed, the vehicle creates a distorted gravity well, where waves come off the vehicle something like a boat traveling over a quiet lake [11]. A three dimensional picture is a submarine moving under water with pressure waves coming off the vehicle. Although these pictures are incomplete, since we need to include the time dimension, it does allow intuitive questions to be asked about general relativity. Does the development of the energy well with the waves streaming off the vehicle create a resistive force? How does the high acceleration bend space-time and does that create a resistive force? What is the nature of the waves and does the "viscosity" in any sense correlate to water's viscosity? The questions here are left for those who model general relativity to address, where the true implications have not yet been worked out [12].

Mission Scenarios and Possibilities

Flyby Mission

One purpose of the analysis was to determine if a laser sail probe can accelerate rapidly enough to attain near-light-speed within an approximate span of the distance from the sun to Pluto. The analysis shows that it is possible if the sail can withstand higher temperatures and has a low areal density. Figure 7 shows the impact of the low areal density on surface area. The payload weight of a baseball - the highest weight shown in the graph – turns out to be a massive area of 150,000 meters squared. Table 2 shows the actual values of all the plots. At the low areal density where 10% of the sail mass is assumed to be the payload mass, even the mass of an ant would require a 3 m² sail. Given the requirement of large accelerations to reach near-

light-speed within the “short” distance from the sun to Pluto, a large sail would require structural mass for support and the issue of control would be of concern. Slight imbalances in the mass could send the probe hurling out of control, spinning wildly. One solution would be to build the probe at the nano-size, to keep the areal density low and the area small. Swarms of probes would make the probability of mission success high.

This type of mission is best suited as a fly-by mission, where the space probe takes pictures as it travels past the near star with its orbiting planets. The pictures can be sent back to earth by a relay system of probes sent at varying intervals – though significant advancements in nanoelectronics are required. Possibly the sail could serve a dual purpose as laser sail and antenna. Also, post processing would be required back at earth to reconstruct the distorted picture.

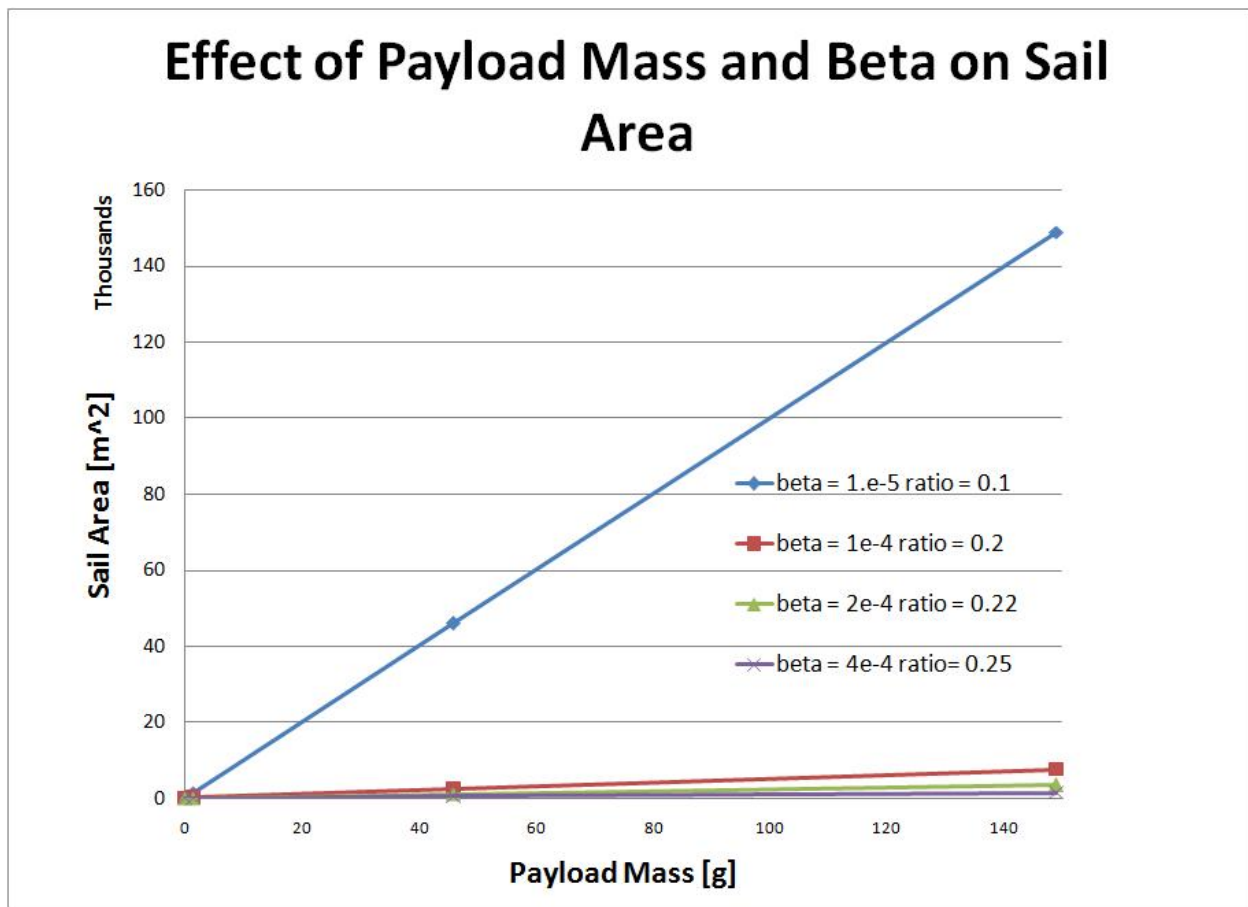


Figure 7. Sail area increases significantly as the payload weight increases and is compounded when the areal density (beta) is small.

Table 2. Sail Area Values

	Areal Density [kg/m ²]	Payload mass [g]	Ratio	Sail Area [m ²]
ant	1.00E-05	0.003	0.1	3.00E+00
pea	1.00E-05	1.4	0.1	1.40E+03
golf ball	1.00E-05	45.93	0.1	4.59E+04
baseball	1.00E-05	149	0.1	1.49E+05
ant	1.00E-04	0.003	0.2	1.50E-01
pea	1.00E-04	1.4	0.2	7.00E+01
golf ball	1.00E-04	45.93	0.2	2.30E+03
baseball	1.00E-04	149	0.2	7.45E+03
ant	2.00E-04	0.003	0.22	6.82E-02
pea	2.00E-04	1.4	0.22	3.18E+01
golf ball	2.00E-04	45.93	0.22	1.04E+03
baseball	2.00E-04	149	0.22	3.39E+03
ant	4.00E-04	0.003	0.25	3.00E-02
pea	4.00E-04	1.4	0.25	1.40E+01
golf ball	4.00E-04	45.93	0.25	4.59E+02
baseball	4.00E-04	149	0.25	1.49E+03

Possible Methods of Vehicle Deceleration

There are a number of possible methods to decelerate the near-light-speed probe. One method is to use a black hole near the destination star and tunnel in near the normal event horizon along the edge and allow the probe's momentum to carry the probe back out where the speed is significantly reduced after re-emerging. Essentially, the design is using the "gravity funnel" – a variation of "gravity well" – to slow the probe down, a reverse of the typical slingshot maneuver around a planet to gain velocity*. Of course this method has many difficulties to be worked out, but it does afford a possible deceleration method, which a modeler of general relativity could examine in detail. The extreme deceleration and the extreme environment near the black hole may present difficulties for this method.

Another method is to use a magnetic field in a charged plasma field to decelerate the probe. If the magnetic field is appropriately applied it will produce a force in the opposite direction of the velocity vector slowing the vehicle. A gas cloud or a planet's atmosphere can

*http://wopedia.mobi/en/Gravitational_slingshot Flying near the Schwarzschild radius slows space vehicle

provide a braking mechanism, which decelerates the probe. If a swarm of nano vehicles are used, a statistical analysis could determine the number of probes surviving the gas collisions using molecular dynamics modeling. Possibly, the laser sail could be used as a shield to protect the probe. The last method presented is to fly close by the sun using the light to decelerate the vehicle and jettisoning the sails or simply rotate them at the closest point to the sun. The deceleration of the sun coupled with some of the other methods previously presented, may be a viable way to decelerate and explore a near distant star with its planets.

Mission Concept of Swarming Nano Probes

Rapid acceleration of laser-sail probes require a very low average areal density. The low areal density, however, requires a large sail area as seen from Table 2, where even the mass of an ant requires 3 m² of area. The area explodes to 1.49E5 m² when the probe mass is equivalent to a baseball. The one assumption to note is that 10% of the average areal mass accounts for the payload mass. Swarms of nano probes are therefore seen as a method to minimize the sail area and keep the areal density to a minimum by reducing the required structural support and allowing additional payload. The assumption here is that nanoelectronics and nanomechanics will mature allowing new systems. The multifunctional characteristic of nanomaterials can be fully exploited to minimize sail thickness, optimize optical properties, and allow for the highest possible temperature on the sails. Figure 1 shows how this allows for the greatest possible acceleration, where Figure 6 shows how the sleek design enables near-light-speeds within the distance of Pluto. A laser space system could be realistically designed if the distance to shoot the laser was held to a minimum not more than the distance from the sun to Pluto. The probes would travel the interstellar distance rapidly within about 10 years to the nearby star, where the deceleration methods previously described (or a combination of them) could be used. The probe would take pictures and gather data from many types of sensors. The information would be sent back by the surviving probes, where the many probes would synergistically send back the signal. Possibly a relay system of probes could be set up, so the signal could traverse the vast distance of interstellar space.

The mission so far presented is a monumental undertaking and may take many years before it is attempted. Extending the ideas forward may seem fanciful for some leading even into the realm of science fiction, but by presenting the possibilities the door is opened for future exploration missions as the fields of science and engineering advance. Whether this takes 50, 100, 500 or 1000 years is to be seen, but future generations benefit when the possibilities are explored. The vision will enable future scientists to advance the technical areas specified, turning science fiction into reality in a shorter time span.

The first missions would gather information on the planets, such as the composition of the atmospheric gases, the surface structure and chemical composition, and the possible locations of water – assuming a suitable planet is found. Given the low areal density of the space probes, it may be possible to let special probes filter through the atmosphere something like confetti falling at a parade. Possibly, the laser sail could reconfigure itself just as it enters the atmosphere to allow an optimal descent onto the planet. Molecular dynamics could be used to examine this concept. Once the detailed information of the planet is obtained, terraforming could begin. Algae, mold, bacteria and other life-forms could be genetically designed for the planet to modify the atmosphere and transform the planet, so it is hospitable for humans. Embryonic travel would enable plant life and maybe even animal life to flourish in the new world. Even the notion of embryonic travel for humans could be considered, but the moral and ethical concerns are problematic [13]. As Table 2 shows, the low areal density required to achieve rapid acceleration significantly increases the sail surface area. Lightweight probes alleviate this problem, so the travel time is minimal and the required laser power is minimized. Embryonic travel would fit well in this scenario, since the mass is minimal. The goal would be to send the dense information of minimal mass over the vast interstellar region, utilizing self-replication and in-situ resources at the planet. Larger ships of low acceleration could then begin the long interstellar trip bringing humans [13]. Once on the planet, the space travelers could use the resources already sent, such as the many modified fauna and flora thriving on the new planet, ready for use, enabling survival and colonization.

Future Work

The feasibility study of interstellar missions opens up a number of areas for future study. The laser system was briefly discussed but further analysis could better define the laser power limits. A study to see the costs of putting the system in orbit would be productive. Modeling the dynamics of the laser sail probe would identify the acceleration limits. Many advances in nanotechnology would benefit and enable future missions. Specifically, the multifunctional properties of nanomaterials could enable high reflective sails with low areal density and tolerant of high temperatures. Much work could be done to benefit the sails. Swarming technologies need further development and refinement. Bioengineering needs further work to open up the possibility of fine-tuned terraforming.

Conclusions

A feasibility study was performed to understand the important parameters for a space probe propelled by light sails. The areal density and the maximum allowable temperature of the sail are the key parameter that determines the acceleration. The acceleration was very high compared to other work on light sails, but this is due to the low areal density used in the

analysis and the assumed high material temperatures of the sails. Advances in nanotechnology may enable high acceleration laser probes. For a low areal density even small masses result in large surface areas. The mass of an ant would require a sail size of 3 m² assuming 10% of the sail mass was for the payload. Given the potential stability problems of large sails, the possibility of using nano probes is more attractive but many technological hurdles in nanotechnology need to be addressed. Lightweight sails may open up interstellar travel so humans can colonize new planets in other solar systems.

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