Solar Sail Trajectories for Solar Polar and Heliopause Missions*

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ABSTRACT

Over the last several years, interest in a more vigorous space exploration program has renewed interest in the use of solar sails for the more demanding space missions. Solar sail is eminently suited for some of the higher energy missions since no fuel is consumed and the only criteria is that of the total time required to perform a particular mission. Although solar sail missions to planets and small bodies have been examined previously and reported in the literature[1,2], classes of space missions with no well defined target body have received little attention. These *Space Physics* missions include some with extremely high energy requirements. Not only are these missions difficult, if not impractical, to accomplish with conventional chemical propulsion spacecraft, but they are also difficult to perform in the near future using projected electric-propulsion systems.

Solar sail trajectories for two of the high energy *Space Physics* missions, a Solar Polar mission and a Heliopause mission, are examined in this paper. The object of the Solar Polar mission is to place a payload into a short period orbit around the Sun at a 90 degree inclination to either the ecliptic plane or the equatorial plane of the sun. A forerunner for this type of mission was the Ulysses spacecraft which used a gravity assist of Jupiter to place the spacecraft into a 90 degree inclination orbit around the Sun with a perihelion distance of around .55 AU. The orbital period for the Ulysses mission was around 5 years however, and future Solar Polar missions require many observational passes over the pole of the Sun each year thus implying a significantly shorter orbit period than that for Ulysses.

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The object of a solar sail Heliopause mission is to place a spacecraft on a trajectory that will reach 100 to 200 AU in 10 to 20 years in the direction of the solar apex at a heliocentric longitude of around 255 degrees. This requirement dictates trajectories that are much more energetic than the trajectories for either Voyager spacecraft. The Heliopause mission does not appear feasible with either a chemically propulsion spacecraft or a solar electric propulsion spacecraft even when a gravity assist of Jupiter is used to achieve additional energy.

Solar Sail Characteristics

A flat, perfectly reflecting solar sail was assumed for the preliminary mission feasibility studies for these two missions. The sail steering profile for these trajectories was optimized using the methods described in reference 1. Trajectories for both missions were examined for a broad range of solar sail characteristic accelerations where the characteristic acceleration is defined as that experienced by the sail at 1 AU aligned normal to the sun direction. The rationale of using characteristic acceleration to define sail performance is to enable the results to be independent of either payload size or the sail areal density or sail loading. A section of the proposed paper will address the relationship between payload mass, sail loading and characteristic acceleration. The optimization criteria for these sail missions was either to minimize flight time for a fixed sail acceleration or to minimize the sail acceleration for a fixed heliocentric flight time.

Only the heliocentric portion of the transfer trajectory is examined in this paper. All the trajectories were calculated assuming a zero energy escape trajectory from the Earth. This was done so that the trajectory results can be used assuming either a high thrust escape using a launch vehicle or patched together with a solar sail Earth spiral escape trajectory. This latter type of escape was investigated around 20-25 years ago at the Draper Labs by T. Edelbaum and L. Sackett[4] and is currently being investigated at both the Jet Propulsion Laboratory and the University of Illinois.

Solar Polar Solar Sail

This mission is the less demanding of the two missions considered in this paper. A range of characteristic accelerations from 0.4 mm/s^2 to 1.5 mm/s^2 were covered in this study. This range of characteristic accelerations covers sails designs with a areal densities of around 10 g/m^2 and less. As a basis of comparison, the sail characteristic acceleration for the solar sail Halley rendezvous mission proposed 20 years ago[3] was slightly greater than 1 mm/s^2.

Like the Halley mission mentioned above, the shortest transfer time for the Solar Polar sail mission involved a transfer from the orbit of the Earth to a circular "Cranking Orbit" with an initial inclination of 15-20 degrees to the ecliptic. The sail was then oriented in this circular orbit to get the remainder of the inclination change. The solar distance of this "Cranking Orbit" was selected based on the acceptable thermal limits of the sail material. Two values of solar distance were examined, .5 AU for a conservative sail design and .3 AU for a more advanced sail. In this cranking orbit the sail was set at an optimum fixed cone angle and oriented such that the force vector was normal to the velocity direction. The orientation of the sail was changed by 180 degrees at the maximum and minimum heliocentric latitude in order to achieve a continual increase in inclination. This steering profile resulted in the line of nodes of the orbit remaining relatively constant during the cranking phase. Figure 1 shows the averaged inclination change per day for the .5 and .3 AU cranking orbits over the selected range of characteristic accelerations.

Several examples of final solar orbits were examined ranging from a circular orbit at 0.5 AU to a 0.5 x 1.5 AU orbit. Total heliocentric transfer time is shown in figures 2 and 3 as a function of characteristic acceleration for the 0.5 AU final circular orbit and the 0.5 x 1.5 AU orbit respectively.

Heliopause Solar Sail

This mission demands a more advance solar sail than that for the Solar Polar mission with characteristic accelerations covering the range from 1 mm/s^2 upwards to 14 mm/s^2. The requirements placed on the Heliopause mission was to reach a heliocentric distance of 100 to 200 AU in 10 to 20 years. An example of one such sail transfer trajectory for a 200 AU in 20 year mission is shown in figure 4. All the Heliopause trajectories are characterized by a close passage to the Sun where much of the heliocentric energy gain is produced. One consequence of the optimization of these trajectories was to constrain the minimum heliocentric distance since very close passages to the Sun resulted when the trajectories were unconstrained. Consequently solar sail Heliopause trajectories were examined with solar distance constraints ranging from .2 AU to .35 AU. The result of constraining the minimum solar distance of these trajectories is shown in figure 5 which shows the time to reach 200 AU as a function of sail characteristic acceleration. Curves are shown for a number of minimum solar distance constraints. Note that a relatively small spread of characteristic acceleration of around 1.5 to 2.5 mm/s^2 is required to reach 200 AU in 20 years. To reach that distance in 10 years however, characteristic accelerations of 5 to 9 mm/s^2 are required.

Summary

This proposed paper presents certain basic trajectory performance data for both Solar Polar and Heliopause missions that enables reliable estimates to be made of the sail technologies required to support these missions. A number of trajectory options have been examined for both missions that should cover the expected range of solar sail technologies being considered.

1. Sauer, Carl G., Jr. *Optimum Solar-Sail Interplanetary Trajectories*, AIAA Paper 76-792, AIAA/AAS Astrodynamics Conference, San Diego, CA, Aug 18-20,1976

2. Wright, Jerome L., *Solar Sail Mission Applications*, AIAA Paper 76-808, AIAA/AAS Astrodynamics Conference, San Diego, CA, Aug 18-20, 1976

3. Sauer, Carl G. Jr, *A Comparison of Solar Sail and Ion Drive Trajectories for a Halley's Comet Rendezvous Mission*, AAS Paper 77-4, AAS/AIAA Astrodynamics Conference, Jackson, WY, Sep 7-9, 1977

4. Sackett, Lester L., and Edelbaum, Theodore N., *Optimal Solar Sail Spiral to Escape,* AAS Paper 77-??, AAS/AIAA Astrodynamics Conference, Jackson, WY, Sep 7-9, 1977

Figure 1
Solar Sail Cranking Orbit

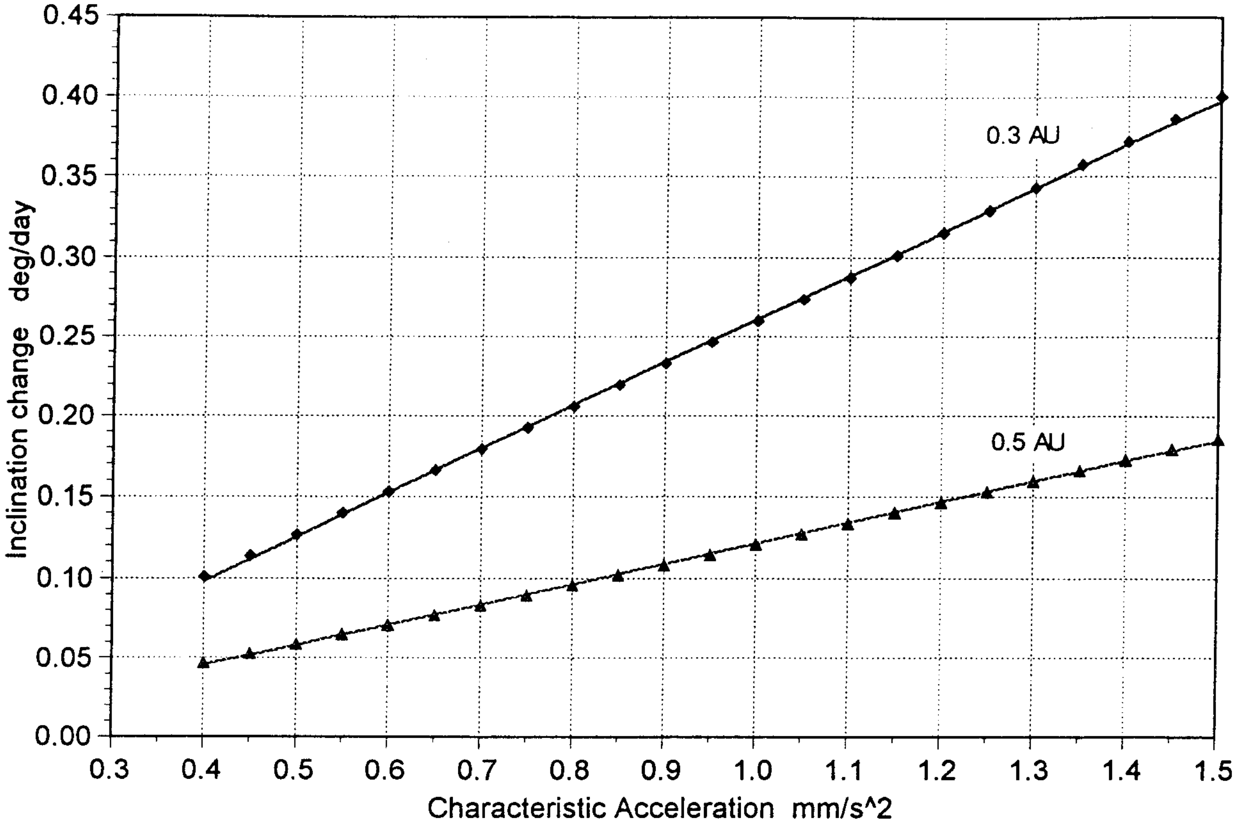

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Figure 2
Solar Sail Solar Polar
0.5 AU Circular Launch C_3=0. km^2/s^2

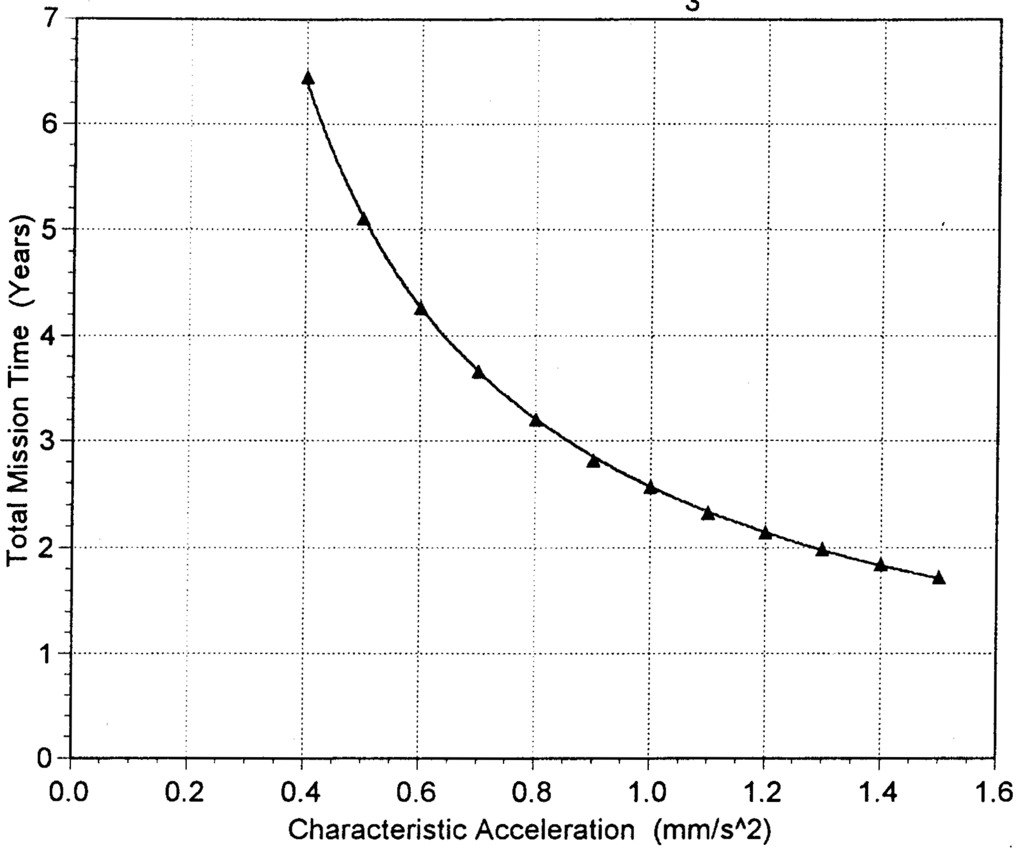

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Figure 3
Solar Sail Solar Polar
0.5×1.5 AU Launch C_3=0. km^2/s^2

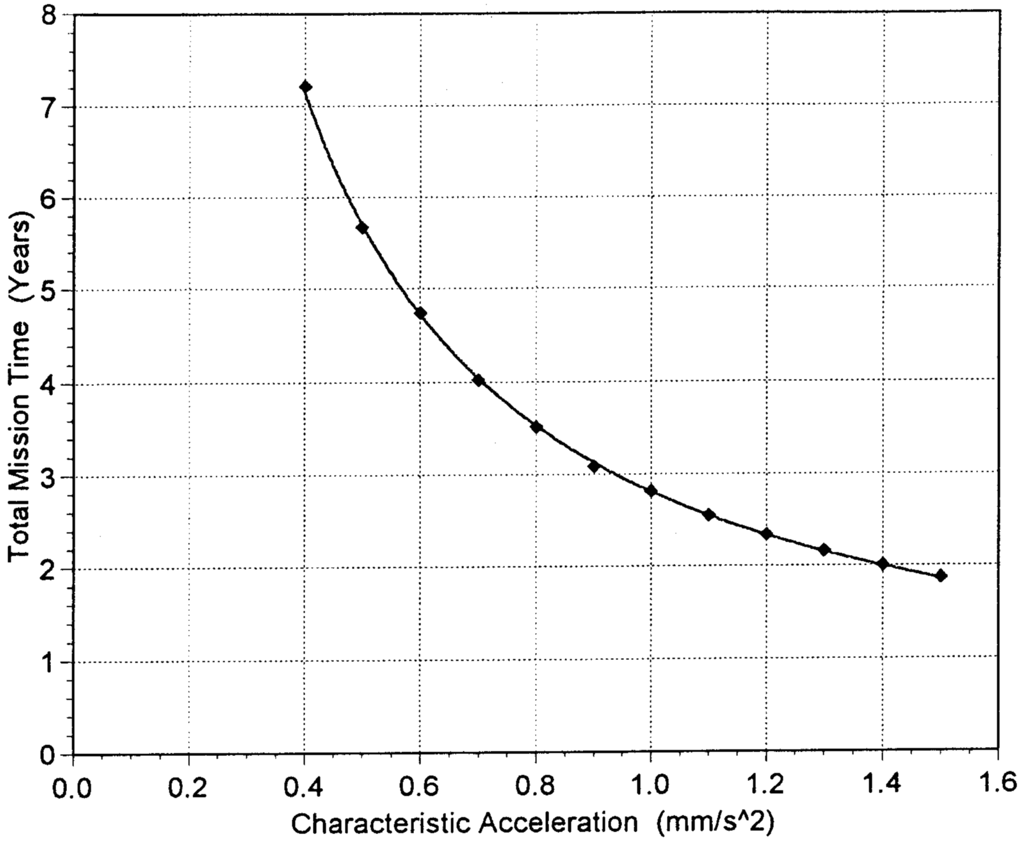

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Figure 4
20 Year Solar Sail to 200 AU
$a_c = 1.780\ mm/s^2$
$V_H = 10.90\ au/y \quad R_{min} = .25\ AU$

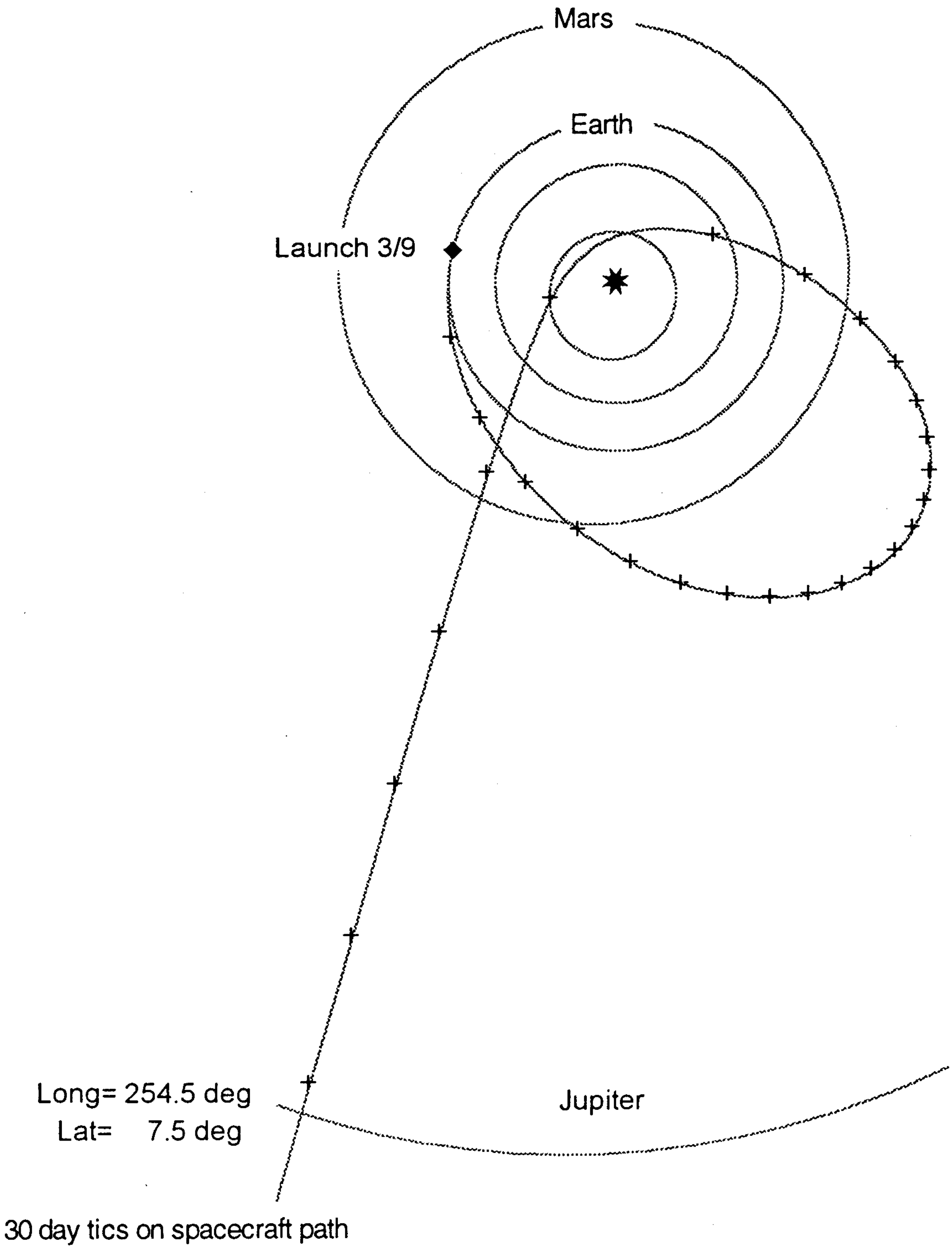
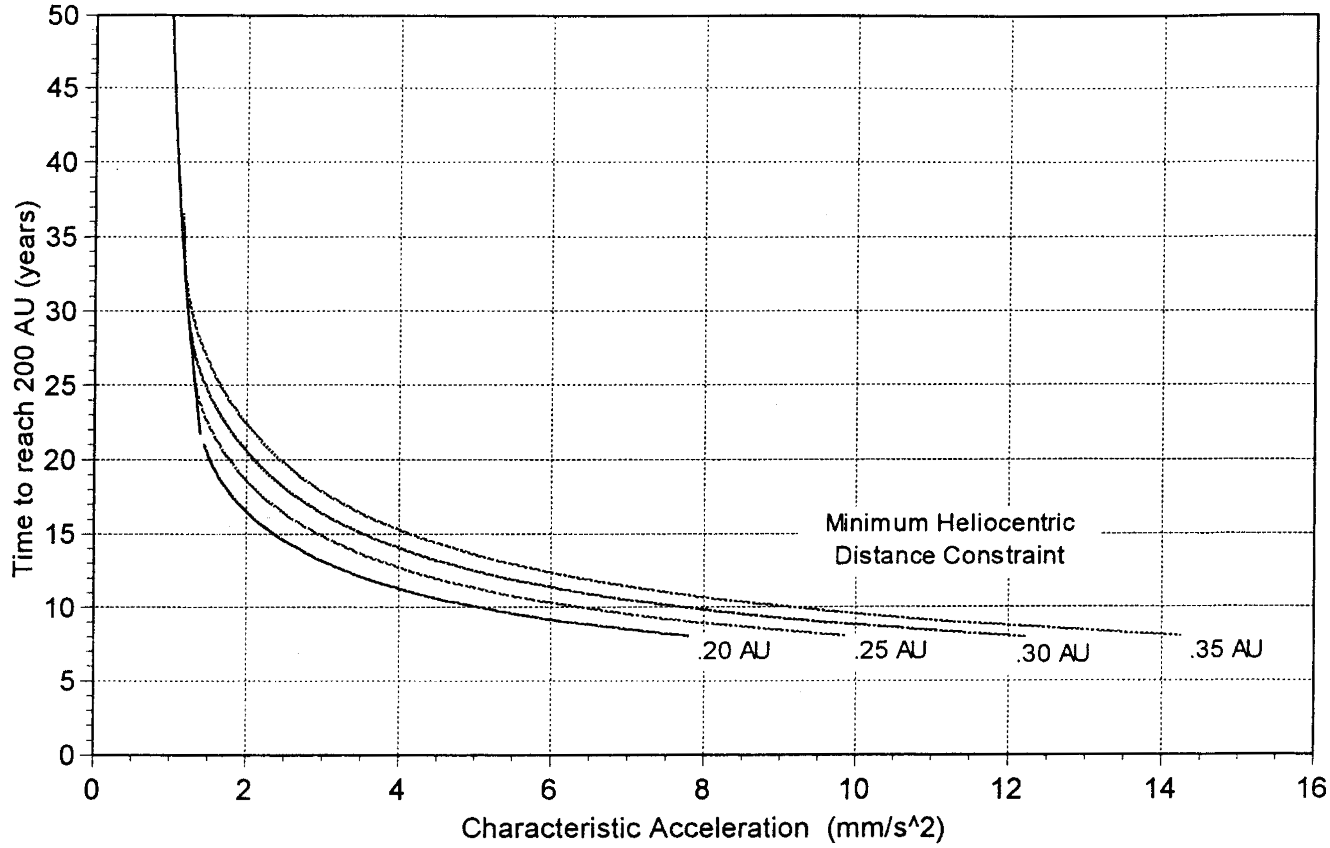


Figure 5
Solar Sail Escape to 200 AU
Time to Reach 200 AU



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