NEAR-TERM INTERSTELLAR SAILING

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ABSTRACT: A number of techniques are investigated that allow the possibility of near-ecliptic exploration beyond the Sun's heliopause (200 AU) using contemporary solar-sail spacecraft (with areal mass thickness about 0.0082 kg/m^2). Maximum mission duration to the heliopause was defined as one human working lifetime; missions to the Sun's gravity focus at 550 AU from the sun must take less time than one human lifetime. Options include unfurling the sail at the 0.2-AU perihelion of a parabolic solar orbit, unfurling the sail at the 0.2-AU perihelion of a 2.5-AU aphelion solar orbit, and performing a grazing gravity-assist flyby of Jupiter. Although these techniques are capable of performing the defined mission, higher-technology sails are faster.

Introduction

This paper considers near-term possibilities of probes towards the heliopause (200 AU from the Sun) and the Sun's inner gravity focus (at 550 AU) using current-technology sails in conjunction with other propulsion options. Study requirements were a heliopause flight time approximating a human-working lifetime (40 years) and a solar-gravity-focus flight time approximating a human lifetime of 80 years. Exotic propulsion systems such as space warps were ruled out, as were those requiring great advances in technological capabilities such as fusion ramjets and antimatter rockets. We also elected not to consider near-term propulsion options such as nuclear electric that might strain budgets or elicit sociopolitical controversy.

Some otherwise acceptable near-term propulsion options were also rejected under analysis. Application of momentum-exchange, spinning or electrodynamic tethers to perform impulsive maneuvers during powered giant-planet gravity assists were problematical because of tether length, timing issues, and technological limitations. The solar-thermal rocket (STR) was also rejected for this application and powered solar flybys because of the difficulties of long-duration liquid-hydrogen storage.

The best propulsion mix included the current-technology solar sail combined with unpowered planetary gravity assists and the solar-electric rocket. Trade studies considered advantages of starting from parabolic and elliptical solar orbits.

A Reference Sailcraft was defined for all studies. This spacecraft has a very conservative sail areal mass thickness (σ_{sail}) of 0.005 kg/m^2 and an equivalent disc-sail-radius of 100 m. The total sail system mass is therefore 157 kg. Structure and payload contribute an additional 100 kg, which includes a 30-kg science payload. Total spacecraft mass is therefore 257 kg and the spacecraft areal mass thickness ($\sigma_{s/c}$) is 0.0082 kg/m^2. With McInnes, we assume a sail reflectivity (REF_{sail}) of 0.85 [1]. Sailcraft Lightness Factor ($\beta_{s/c}$), the ratio of solar radiation pressure acceleration on the sail to solar gravitational acceleration, is defined using Eq. (4.19) of Ref. 2 :

$$\beta_{s/c} = 0.000787\ [(1+REFsail) / \sigma_{s/c}]. \quad (1)$$

Substitution in Eq. (1) reveals that the Reference Sailcraft has a Lightness Factor of 0.18. When oriented normal to the Sun at a distance of 1-AU from the Sun, the characteristic acceleration of this sailcraft is therefore 0.00106 m/sec^2. Trajectory analyis in this study is approximate. For exact results, the Lightness factor must be treated as a vector, as suggested by Vulpetti [3].

Parabolic Pre-Perihelion Trajectories:

Vulpetti has suggested that interstellar missions utilizing solar sails and departing from elliptical solar orbits should be compared with equivalent missions departing from parabolic solar orbits [4]. In keeping with this suggestion, we define a reference mission. The initial phase of this mission includes launch from Earth on an Atlas / Delta-class booster, Earth-escape and injection on a trans-Jupiter trajectory with the sail furled. After a close flyby of Jupiter, the sailcraft is in a parabolic solar orbit with a perihelion of 0.2 AU. The sail is unfurled at perihelion and the spacecraft is ejected from the solar system.

Niehoff estimates that an Earth-departure velocity of 16.5 km/sec is required to achieve a perihelion distance of 0.1 AU in this manner [5]. Flandro calculates that Earth-departure velocities of 10-14 km/sec are required to achieve parabolic solar orbits with near-sun perihelia using Jupiter gravity assists.

Various options exist to obtain the requisite orbital energy other than a high-performance chemical upper stage. Koblik et al. have considered early unfurlment of the solar photon sail to modify the orbit in the inner solar system [6]. Randolph suggests inner-planet gravity assists or the solar-electric rocket [7]. References 5-7 indicate that about 3 years are required for maneuvers prior to Jupiter encounter, unless a high-energy, high-thrust upper stage is utilized.

Post-Jupiter-flyby-trajectory duration can be estimated using Eq. (1.3) of Ref. 2 :

$$T_{year} = 0.077\ R_{ap,au}^{3/2} \text{ years}, \quad (2)$$

where $R_{ap,au}$ is the initial distance of the spacecraft from the Sun (5.2 AU in this case. The time between Jupiter flyby and perihelion is approximately 0.9 years. We therefore conclude that pre-perihelion maneuvers add approximately 4 years to mission duration.

The sail is assumed to be directed towards the Sun at perihelion and is always normal to the Sun. The interstellar-cruise or hyperbolic-excess velocity (V_{in}) can be related to the sailcraft lightness factor and the solar escape velocity at perihelion, $V_{para-peri}$, using Eq. (4.27) of Ref. 2:

$$V_{in} = \beta_{s/c}^{1/2} V_{para-peri} . \quad (3)$$

Following the logic of Ref. 8, we can express $V_{para-peri}$ as $42R_{peri,au}^{-1/2}$ km/sec, where $R_{peri,au}$ is the perihelion solar distance in AU and expressing the sailcraft lightness factor as in Eq. (1), Eq. (3) becomes:

$$V_{in} = 1.178[(1+REF_{sail})/(\sigma_{s/c}R_{peri,au})]^{1/2} \text{ km/sec} = 0.247[(1+REF_{sail})/(\sigma_{s/c}R_{peri,au})]^{1/2} \text{ AU/year.} \quad (4)$$

Our Reference Sailcraft has REF_{sail} =0.85 and $\sigma_{s/c}$= 0.0082 kg/m^2. For a 0.2 AU perihelion pass, this sailcraft departs perihelion with an interstellar cruise velocity of 8.3 AU per year. After completing perihelion acceleration the sailcraft requires about 24 years to reach 200 AU and 66 years to reach 550 AU. Including the 4-years required for pre-perihelion maneuvers, the sailcraft reaches the heliopause about 28 years after launch and the Sun's inner gravitational focus about 70 years after launch.

Since the Sun's gravitational acceleration at 0.2 AU is 0.015g and the Lightness Factor is 0.18, the maximum solar-radiation-pressure acceleration is approximately 0.026 m/sec^2. Mechanical stress will not be a limiting factor.

We calculate peak temperature at the 0.2 AU perihelion for an assumed sail emissivity (ε) of 0.6 using Eq. 4.21 of Ref. 2 :

$$T_{peri} = 333 \, [(1-REF_{sail})/(\varepsilon \, R_{peri,au}2)]^{1/4} = 526.5 \text{ degrees Kelvin.} \quad (5)$$

From Ref. 1, this is certainly within the thermal capabilities of many contemporary sail designs.

Elliptical Pre-Perihelion Trajectories:

Several authors have considered sail solar-system departure from an elliptical solar orbit as opposed to a parabolic solar orbit [4, 9,10]. Less energy is required for elliptical-orbit departure, but (as will be demonstrated) the interstellar cruise velocity is lower. In the following comparison of solar-system departure from elliptical and parabolic orbits, it is assumed that sails are always oriented normal to the Sun, although some authors discuss the advantages of variable sail-Sun aspect angles [3,4,6,9].

The interstellar cruise velocity of a sail departing from an elliptical solar orbit is found using Eq. (6.15) of Ref. 1:

$$V_{in,ell} = V_{para\text{-}peri} \{[R_{ap,au}/(R_{ap,au} + R_{peri,au})] - 1 + \beta_{s/c}\}^{1/2} , \quad (6)$$

where $R_{ap,au}$ is the aphelion of the solar orbit, in AU. Dividing Eq. (6) by Eq.(3) allows comparison of elliptical- and parabolic-orbit departures for the same perihelion distance:

$$\Gamma = V_{in,ell}/V_{in,par} = \{ R_{ap,au}/[\beta_{s/c}(R_{ap,au} + R_{peri,au})] - (1/\beta_{s/c}) + 1 \}^{1/2} . \quad (7)$$

If we depart from a near-parabolic solar trajectory, $[R_{ap,au}/(R_{ap,au} + R_{peri,au})]$ is close to unity and Γ is close to 1. Also, as the perihelion distance approaches zero, Γ approaches 1. Figure 1 presents the parametric variation of Γ with aphelion distance and Lightness Factor, for a fixed perihelion distance of 0.2 AU. If the aphelion is greater than about 2.5 AU, the Reference Sailcraft departs the solar system at about 80% the velocity of an equivalent craft departing from a parabolic orbit. After the perihelion pass from such an elliptical orbit, about 30 years are required to reach 200 AU and about 83 years are required to reach traverse 550 AU. Reduced perihelion distances and increased Lightness Factors both substantially increase performance for elliptical-orbit departure.

The next issue to be addressed is transfer of the Reference Sailcraft from the 1-AU solar orbit of the Earth to a solar orbit with a perihelion of 0.2 AU and an aphelion of 2.5 AU. Following Bate et al. [11], the eccentricity of the final elliptical orbit is 0.852.

We select a two-step process to achieve this elliptical orbit. First, the spacecraft is injected after Earth escape into a Hohmann transfer orbit with a perihelion of 1-AU and an aphelion of 2.5 AU. The orbit is again modified at aphelion so that the new perihelion is 0.2 AU. From Hohmann-ellipse theory [11], a velocity increment of 5.75 km/sec must be supplied to the sailcraft after Earth departure to reach the 2.5-AU aphelion. At aphelion, the sailcraft's heliocentric velocity must be reduced from 14.21 to 7.2 km/sec. The total velocity increment after Earth escape is 12.75 km/sec and the time spent on the 1-AU to 2.5-AU transfer and the 2.5-AU to 0.2-AU transfer is about two years.

If a low-thrust propulsion system such as the solar-electric rocket performs the 1-AU and 2.5-AU maneuvers, the total pre-perihelion time is less than three years. Chemical rockets, Earth-Venus gravity assists, and pre-perihelion sail unfurlment are other options for these two powered maneuvers. But it is reasonable to conclude that our Reference Sailcraft departing from a 0.2-AU-perihelion, 2.5-AU-aphelion solar orbit reaches the heliopause within about 34 years after launch and the Sun's inner gravitational focus within about 87 years after launch. As shown in the next section, a post-perihelion Jupiter gravity-assist can significantly reduce flight time, at least for targets near the ecliptic.

Jupiter Unpowered Gravity Assists :

All giant-planet gravity-assist options examined considered unpowered giant planet flybys after solar-sail unfurlment from the perihelion of an initial elliptical solar orbit. It is assumed in all cases that the post-flyby sailcraft trajectory remains close to the ecliptic.

As described in Ref. 2, the highest velocity increment from unpowered giant-planet flyby occurs if the spacecraft approaches Jupiter in a retrograde solar orbit and has its trajectory deflected by 180 degrees. But application of Flandro's analysis [12] reveals that such a flyby—which increases spacecraft heliocentric velocity by about 26 km/sec—requires a very low pre-flyby spacecraft velocity relative to the giant planet. The maximum interstellar cruise velocity possible from such a maneuver is less than that achievable using other techniques.

In the manner of Pioneer 11 and Voyager 1 and 2, it is possible to gain additional orbital energy from a Saturn flyby after a Jupiter gravity-assist. But these two planets align to support a mission in any selected direction at 20-year intervals and the maximum velocity increment from a Saturn flyby is only a few kilometers per second.

Another interesting example of planetary billiards is the double-Jupiter flyby [13]. The spacecraft first uses Jupiter's gravitational field to place it in a parabolic solar orbit then grazes Jupiter again after an unpowered close solar approach. Limitations on the efficiency of this technique is the high relative velocity of Jupiter and the spacecraft on the outbound trajectory leg, which limits the spacecraft heliocentric velocity increment. If the sail is unfurled at perihelion during the close solar approach, however, interstellar cruise velocities possible using double-Jupiter flyby may approximate 50 km/sec.

The simplest gravity-assist option to engineer is the single-Jupiter grazing flyby, as presented in Fig. 2. It is assumed that the spacecraft crosses Jupiter's orbit perpendicular to that orbit and in the ecliptic. From orbital energy conservation, we calculate that a sailcraft with an interstellar cruise velocity of 30 km/sec will cross Jupiter's orbit at a heliocentric velocity ($V_{s/c/j}$) of 35.3 km/sec, after the sail is unfurled during a close perihelion pass. Since Jupiter orbits the Sun at $V_{j,s}$ = 13.1 km/sec [14], the pre-encounter velocity of the spacecraft relative to Jupiter is :

$$V_{s/c,j} = (V_{j,s}^2 + V_{s/c,j}^2)^{1/2} = 37.6 \text{ km/sec.} \quad (8)$$

Using an equation presented in Refs. 2 and 12, the trajectory bend angle during Jupiter encounter (ψ), is calculated:

$$\psi = 2 \sin^{-1}\{1/[1+2(V_{s/c,j}/V_{para,j})^2]\}, \quad (9)$$

where $V_{para,j}$ is Jupiter's escape velocity at the periapsis of the Jupiter flyby. For a cloud-grazing Jupiter periapsis, $V_{para,j}$ = 60.2 km/sec [14]. Substituting in Eq. (9), ψ = 68.3 degrees.

If ψ were 90 degrees, the sailcraft's heliocentric velocity after Jupiter encounter would be increased by Jupiter's heliocentric velocity (13.1 km/sec). Figure 2 can be used to determine that the post-encounter spacecraft heliocentric velocity increment for trajectory bend angles less than 90 degrees is 13.1 sin ψ or 12.1 km/sec in this case. Shortly after the Jupiter encounter, the heliocentric velocity of the sailcraft has been increased to 47.4 km/sec.

Applying orbital-energy conservation, the sailcraft's interstellar-cruise velocity is 43.6 km/sec or 9.16 AU/year. At this velocity, the sailcraft reaches 200 AU after about 22 years and 550 AU after approximately 60 years, not including the time required for inner solar-system maneuvers.

Conclusions :

We have found a number of viable approaches to near-term interstellar exploration using robotic spacecraft propelled by solar-photon sails. These include sail unfurlment at the perihelion of a parabolic solar orbit, sail unfurlment at the perihelion of an elliptical solar orbit, and Jupiter-gravity-assist after sail unfurlment from an elliptical solar orbit.

Although all of these techniques are capable of propelling a 257-kg sailcraft with an areal mass thickness of 0.0082 kg/m^2 on a mission to the heliopause (200 AU) from the Sun within a human working lifetime or a mission to the Sun's inner gravitational focus at 550 AU from the Sun in a human lifetime, they are all slower than equivalent missions launched using higher technology sails and sailcraft.

For comparison, a near-term sailcraft departing from a 0.2-AU perihelion, 2.5-AU aphelion elliptical solar orbit and then grazing Jupiter on the outbound trajectory leg, can depart the solar system at about 9.2 AU/year towards a near-ecliptic destination. Vulpetti has reported that sailcraft with areal mass thicknesses in the range 0.001-0.002 kg/m^2 that depart from elliptical solar orbits with 0.175-0.248 perihelia and 1.099-2.636 aphelia can leave the solar system with interstellar cruise velocities in the vicinity of 11.02-23.57 AU/year [4].

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Fig. 1. Comparison of Interstellar Cruise Velocities for Departure from Solar Elliptical Orbit ($V_{in,ell}$) and Solar Parabolic Orbit ($V_{in,par}$) for various values of Lightness Factor $\beta_{s/c}$ and Aphelion Distance (Rap,au). Perihelion Distance = 0.2 AU.

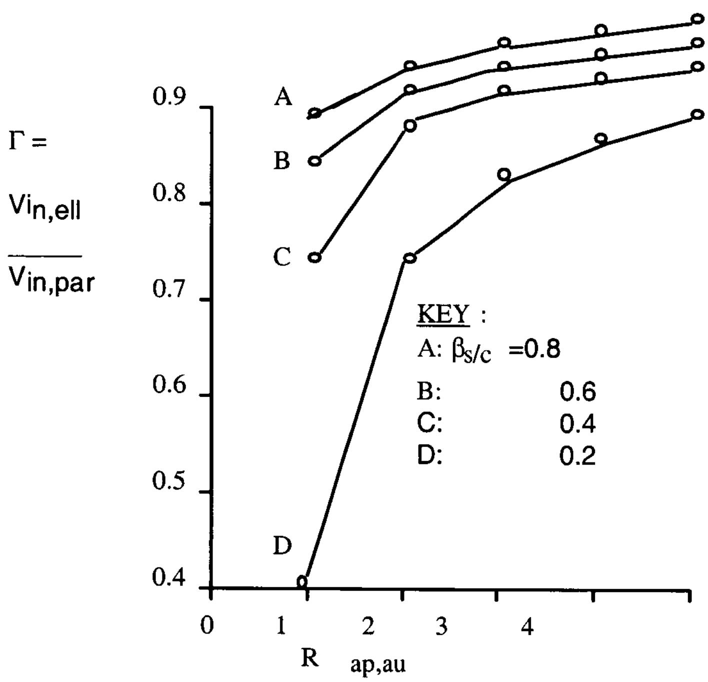

Fig. 2. Geometry of Jupiter Flyby

Note : $\Delta V_{jp,s/c}$ is the component of Jupiter's solar-orbital velocity along the sailcraft's post-Jupiter trajectory direction.