The beryllium hollow-body solar sail: exploration of the Sun’s gravitational focus and the inner Oort Cloud

Gregory L. Matloff and Roman Ya. Kezerashvili
Physics Department, New York City College of Technology,
The City University of New York
300 Jay Street, Brooklyn, NY 11201
GMatloff@CityTech.Cuny.Edu, RKezerashvili@citytech.cuny.edu

Claudio Maccone
Member of the International Academy of Astronautics,
Via Martorelli 43, Torino (TO), 10155, Italy
clmaccon@libero.it

Les Johnson
NASA Marshall Space Flight Center, Huntsville, AL 35812, USA
C.Les.Johnson@nasa.gov

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Abstract

Spacecraft kinematics, peak perihelion temperature and space environment effects during solar-radiation-pressure acceleration for a beryllium hollow-body interstellar solar sail inflated with hydrogen fill gas are investigated. We demonstrate that diffusion is alleviated by an on-board fill gas reserve and electrostatic pressure can be alleviated by increasing perihelion distance. For a 0.1 AU perihelion, a 937 m radius sail with a sail mass of 150 kg and a payload mass of 150 kg, perihelion sail temperature is about 1000 K, peak acceleration is about 0.6 g, and solar-system exit velocity is about 400 km/s. After sail deployments, the craft reaches the 200 AU heliopause in 2.5 years, the Sun’s inner gravitational focus at 550 AU in about 6.5 years and 2,550 AU in 30 years. The Be hollow-body sail could be applied in the post 2040 time frame to verify general relativity predictions regarding the Sun’s inner gravitational focus and to explore particles and fields in the Sun’s inner Oort Comet Cloud.
1 Introduction: an approach to extrasolar space exploration

The solar sail has emerged as one of the few ultimately feasible modes of extrasolar space exploration and travel. As demonstrated by Matloff and Mallove [1], a parachute-like space-manufactured metallic sail unfurled at the 0.01 AU perihelion of an initially parabolic solar orbit can reach solar-system exit velocities of about 0.003c-0.004c. Furthermore, sail and diamond-strength cables can be conceptually woven around payload to serve as cosmic-ray shielding during the long interstellar transfer and unfurled later for deceleration at a solar-type star [3]. Additional work on this concept has included studies of sail materials and spacecraft pre-perihelion trajectories.

The analytical studies of interstellar solar sailing led to the European ASTROSail and SETIsail extrasolar probe concepts of the early 1990’s, which would have explored the Sun’s near gravitational focus at 550 AU [4]. In turn, these studies were superseded by the less ambitious European Aurora sail, which would have explored the Sun’s heliopause, the boundary between solar and galactic influence at about 200 AU [5]. Aspects of Aurora have been incorporated in the planned NASA Heliopause Sail, which could be launched around 2020 [6].

For true extrasolar travel, the parachute-type sail of the early studies may not be ideal. Such craft do not scale easily between small, near term probes and ultimate human-occupied generation ships. The proportion of spacecraft mass that must be devoted to cable increases rapidly with payload [7]. The square-rigged NASA concept is also not ideal—it may not easily scale from low-acceleration extrasolar probes to ultimate higher acceleration generation ships.

2 The hollow-body solar sail

Strobl in Ref. [8] suggested a type of inflatable interstellar solar sail variously called the ”hollow-body” or ”pillow” sail. In a hollow-body sail, the Sun-facing sail surface is reflective and the space-facing sail surface is emissive. Both sail surfaces have thicknesses measured in tens of nanometers. The sail is inflated by low-pressure fill gas. Most studies to date have assumed hydrogen fill gas to minimize fill-gas mass. Payload is mounted on the space-facing sail surface. Unlike most solar photon sails, which pull the payload through space during acceleration, the hollow-body is a ”pusher” sail.

In order to minimize sail perihelion, in Ref. [8] assumed that the sail would be constructed using metals optimized for very high melting points. A disadvantage of this approach is that most such metals have high specific gravities, which reduces solar-system exit velocity.

Recently, in Ref. [9] evaluated an interstellar hollow-body solar photon sail constructed from beryllium. From a thermal point of view, a 0.05 AU perihelion was possible for beryllium hollow-body sails with a 20 nm thick Sun-facing surface and a 10 nm thick space-facing surface. Two configurations of the beryll-
Beryllium hollow-body solar photon sail were considered. Configuration A, a small generation ship, had a fully inflated sail radius of 541.5 km, a payload of $10^7$ kg, a separation between sail faces of 1 km and 30,000 kg of molecular hydrogen fill gas. Configuration B, a near-term extrasolar probe, had a sail radius of 937 m, a 30 kg payload, a 1.8 m separation between sail faces and 0.16 grams of hydrogen fill gas.

From the point of view of kinematics, mechanical stress, and thermal effects, the hollow-body solar photon sail scales well. Both configurations had a spacecraft areal mass density of $6.52 \times 10^{-5}$ kg/m$^2$, a peak internal gas pressure of $1.98 \times 10^{-4}$ Pa, and a peak perihelion temperature of 1412 K. If fully inflated at the 0.05 AU perihelion of an initially parabolic solar orbit, both had a peak radiation-pressure acceleration of 36.4 m/s$^2$ and exited the solar system at 0.00264$c$ after an acceleration duration less than one day.

3 The hollow-body sail and the space environment

In a series of recent papers [10], [11] dynamics and space-environment effects of a beryllium hollow-body interstellar solar sail inflated with hydrogen fill gas have been investigated for the case of sail deployment at the 0.05 AU perihelion of an initially parabolic solar orbit and the interaction of the solar radiation with the solar sail materials and the hydrogen fill gas was studied. These analyses evaluate worst-case solar radiation effects during solar-radiation-pressure acceleration. The diversity of physical processes of the interaction of photons, electrons and protons with the sail leading to electric charging of the sail material are analyzed. Issues include diffusion of hydrogen fill gas through the 10-20 nm sail walls at elevated perihelion temperatures and electrostatic pressure from sail charge build-up, which is an issue because beryllium’s tensile strength decreases with increasing temperature. It was realized that also necessary to analyze the interaction between the hollow-body sail and the near-perihelion space environment [10], [11]. It was assumed in these studies that near-Sun missions would most likely be conducted during Quiet-Sun periods. The near-Sun environment, even under Quiet-Sun conditions, is a most dynamic region of space. Spacecraft designers must cope with both the solar wind and copious amounts of ionizing solar radiation. In Refs. [10], [11], the perihelion pass was modeled using the simplifying, but conservative assumption of 7,000 seconds at a constant perihelion distance. The solar wind at 1 AU was assumed to have a velocity of 400 km/s relative to the Sun and an ion density of 10 ions per cubic centimeter. Solar wind velocity was assumed to be constant with solar distance, and ion density was assumed to follow an inverse square law.

Interactions between the sail and ionizing solar radiation were analyzed, as were interactions between solar wind ions and the sail. It was also necessary to consider the interactions of the solar radiation and solar wind with the hydrogen fill gas within the sail. It was found that the hollow-body solar photon sail
does not scale well when interactions between the hydrogen fill gas and solar radiation and solar wind are considered. Diffusion of hydrogen through sail walls at perihelion has little effect upon the large Configuration A. But, in the worst case, all hydrogen within the small Configuration B sail diffuses through the sail walls within about 70 seconds at a 0.05 AU perihelion. This problem could be alleviated by carrying a large hydrogen reserve. Both configurations are also limited by electrostatic pressure, which bursts the sail in the worst case. Although other mitigation approaches are possible, one approach to alleviating this problem is to increase perihelion distance, at the expense of performance.

4 The Oort Cloud explorer - gravity focus probe

We consider a modified Configuration B beryllium hollow-body solar-photon sail with a sail radius of 937 m and a sail mass of 150 kg. To perform a greater range of scientific observations, the payload mass is increased to 150 kg. Therefore, the total spacecraft mass is 300 kg. The perihelion has been increased to 0.1 AU. As is shown below, this action greatly alleviates the electrostatic pressure issue.

4.1 Kinematics

First we consider spacecraft kinematics by defining the lightness number \( \eta_{sail} \), which is the ratio of solar radiation pressure force on the sail to solar gravitational force on the spacecraft, assuming that the (opaque) sail is normal to the Sun [12, 7 and 9]:

\[
\eta_{sail} = \frac{(1 + R_{sail})}{c \sigma_{sail} G M_{\text{Sun}}} S R^2,
\]

(1)

where \( R_{sail} \) is sail reflectivity to sunlight, \( c \) is the speed of light, \( \sigma_{sail} \) is the spacecraft areal mass thickness, \( G \) is the universal gravitational constant, \( M_{\text{Sun}} \) is the solar mass, \( S \) is the average value of the Poynting vector, which is the average power per unit area transported by the solar light, and \( R \) is the distance between the spacecraft and the Sun’s center. At \( R_0 = 1 \) AU from the Sun, the average value of the Poynting vector (the Solar constant) is approximately equal to \( S_0 = 1,400 \) watts/m\(^2\). Applying the inverse square law we can determine the incident solar energy flux at the distance \( R \) from the Sun to the spacecraft as

\[
S = \frac{S_0 R_0^2}{R^2}.
\]

(2)

Substituting Eq. (2) into Eq. (1), we obtain:

\[
\eta_{sail} = \frac{(1 + R_{sail})}{c \sigma_{sail} G M_{\text{Sun}}} S_0 R_0^2.
\]

(3)

We next define a reflectivity factor \( R_f \). For opaque sails, \( R_f = (1 + R_{sail})/2 \). For thinner partially transparent sails such as the one under consideration here,
\[ R_f = \left( A_{sail} + 2R_{sail} \right)/2, \]
where \( A_{sail} \) is the fractional absorption of sunlight by the sail [9]. Taking into account this fact and substituting the numerical value of all constants into Eq. (3), finally for the the lightness number we are getting:

\[ \eta_{sail} \approx 1.574 \times 10^{-3} \frac{R_f}{\sigma_{sail}}. \]

(4)

Assuming a fully inflated disc-shaped sail with the radius of 937 m and sail mass of 150 kg., sail area is \( 2.76 \times 10^6 \) m\(^2\). The spacecraft areal mass density \( \sigma_{sail} \) is, therefore, \( 1.09 \times 10^{-4} \) kg/m\(^2\). From [9], the reflectivity factor of the sail, \( R_f \), is 0.636. Substituting these values of \( \sigma_s \) and \( R_f \) in Eq. (4), we find that \( \eta = 9.18 \).

At the 0.1 AU perihelion, the solar-gravitational acceleration on the spacecraft is 0.59 m/s\(^2\). The solar-radiation-pressure acceleration on the sail is therefore 5.42 m/s\(^2\) or about 0.55g.

Next we estimate solar-system exit velocity or interstellar cruise velocity, \( v_{in} \). Although this can be done for a spacecraft departing the solar system from an initially elliptical solar orbit [12], we choose here the higher performance case of departure from an initially parabolic solar orbit. For the case of constant sail orientation normal to the Sun during the acceleration process we get

\[ v_{in} \approx \sqrt{\eta_{sail}}v_{pp}, \]

(5)

where \( v_{pp} \) is the solar escape (or parabolic) velocity at perihelion. Using the definition of escape velocity [7] we can find interstellar the cruise velocity:

\[ v_{in} = 4.21 \times 10^4 \sqrt{\frac{\eta}{R_{AU}}}, \]

(6)

where \( R_{AU} \) is the solar perihelion distance in Astronomical Units. Applying this equation, our spacecraft departs the solar system at 403 km/s. At this velocity, the spacecraft reaches the 200 AU heliopause in about 2.4 years. It passes the Sun’s inner gravitational focus at 550 AU in about 6.5 years. During a thirty-year operational lifetime, the probe will travel more than 2,500 AU and, therefore will reach the inner Oort Cloud.

### 4.2 Peak perihelion temperature

Next we consider the peak temperature at perihelion, \( T_p \). From the Stefan-Boltzmann law for grey bodies, sail radiant emittance is expressed as \( W_{sail} = 2\varepsilon_{sail}\sigma T_p^4 \) (since the sail can radiate from both sun-facing and space-facing surfaces, there is the factor 2), where \( \varepsilon_{sail} \) is the sail emissivity and \( \sigma = 5.67 \times 10^{-8} \) Wm\(^2\)K\(^{-4}\) is the Stefan-Boltzmann constant. From the law of conservation of energy in thermal equilibrium radiant emittance should be equil to total absorbed energy by the solar sail. Therefore, \( W_{sail} = A_{sail}S \), where \( A_{sail} \) is sail absorption which relates to the intire sail From this condition we obtain

\[ T = 333 \left( \frac{A_{sail}}{\varepsilon_{sail}R_{AU}^2} \right)^{1/4}, \]

(7)
where \( R_{AU} \) is the separation between the sail and Sun at perihelion, in Astronomical Units. Follow [9], \( A_{sail} = 0.437 \) and \( \varepsilon_{sail} = 0.530 \), and substituting of these values into Eq. (7) we obtain that the temperature at the 0.1 AU perihelion is 1003 K, which is considerably less than the 1412 K perihelion temperature previously estimated for the 0.05 AU perihelion pass.

4.3 *Hydrogen fill gas requirement and diffusion mitigation*

The perihelion sail pressure is the ratio of radiation-pressure force on the sail to sail area. Since the payload is 150 kg and the peak radiation-pressure acceleration is 5.42 m/s\(^2\), the perihelion radiation-pressure force on the sail is 813 Newtons. Dividing this by the area of the 937 m radius disc-shaped sail, the perihelion sail pressure is calculated to equal \( 3 \times 10^{-4} \) Pa, which is about 50\% higher than the value considered by Matloff [9] because of the increased payload mass. But the number of moles of hydrogen fill gas required to maintain sail inflation is directly proportional to sail pressure and inversely proportional to sail temperature. Therefore, the number of moles of hydrogen required to maintain inflation at perihelion is about 7\% or about 0.086 moles (0.17 grams) higher for a Configuration B sail than it was considered previously.

In the worst case, as demonstrated in Ref. [11], all hydrogen fill gas diffuses from a Configuration B sail performing a 0.05 AU perihelion pass in about 70 seconds. Hydrogen fill gas must be replenished about 100 times during the solar acceleration process. But as shown in Figure 2 in Ref. [11], the rate of hydrogen diffusion is highly dependent upon temperature and results of calculations are very sensitive to the diffusion activation energy and diffusion constant. For the case of a 0.1 AU perihelion, hydrogen fill gas must be replenished about 50 times, in the worst case.

To err on the side of caution, it is assumed here that a hydrogen reserve of 100 times the required fill gas mass is carried aboard the spacecraft. This amounts to only 170 grams of hydrogen. If hydrogen fill gas is dissociated from water as required, no more than about one kilogram of water is required. Even water-storage and dissociation equipment will not add more that a few kilograms to the payload and have a very small effect on spacecraft performance.

4.4 *Electrostatic pressure*

From a study of Kezerashvili and Matloff [10], it is follows that solar ultraviolet radiation is constantly ionizing beryllium atoms in the sail surface during the spacecraft acceleration process and the main causes of the ionization are photoelectric effect, Compton scattering and electron-positron pair production processes. As a result of these processes the surface of the solar sail will lose electrons and become charged positively. Electrostatic pressure resulting from a net positive charge on the beryllium sail walls may cause the sail to burst at a 0.05 AU perihelion, because the tensile strength of beryllium degrades rapidly with temperature. Here, we mitigate this effect by increasing perihelion distance to 0.1 AU. As it follows from [13], the electrostatic pressure, \( P \), can be
expressed as:

\[ P = \frac{\sigma_c^2}{2\varepsilon_0} \]  

(8)

where \( \sigma_c \) is the surface charge density on the sail and \( \varepsilon_0 \) is the electric permittivity of free space. For Configuration A and B and a 0.05 AU perihelion, \( P = 59.6 \) MPa, which approximates beryllium’s tensile strength at 1100 K. An electron component of the solar wind plasma partially neutralizes the positively charged sail through radiative recombination processes as shown in Ref. [11]. Assuming that the spacecraft’s pre-perihelion velocity remains parabolic, its velocity relative to the Sun at a 0.1 AU perihelion is slower than at the original 0.05 AU perihelion. This implies that the velocity of solar-wind electrons at a 0.1 AU perihelion relative to the spacecraft is greater than at a 0.05 AU perihelion. Therefore, an increase in perihelion distance results in an increase in the flux of neutralizing electrons striking the positive charged sail. Conservatively, this factor is ignored here. At 0.1 AU, the flux of solar photons ionizing the sail is 0.25 times the corresponding flux at 0.05 AU, from the inverse square law. The 0.1 AU perihelion electrostatic pressure will therefore be less than 15 MPa, which is much lower than the tabulated tensile strength of vacuum hard-pressed block beryllium at 1000 K [14]. Electrostatic pressure should therefore not cause major problems at a 0.1 AU perihelion, for Quiet Sun conditions.

5 Scientific justification

Simply having the capability to launch a high performance extrasolar probe—actually a prototype starship—is not enough. For such a mission to be conducted in the foreseeable future, there must be scientific justifications. There are at least two scientific functions this craft could serve during its 30-year journey to 2,500 AU.

5.1 The Sun’s gravity focus

Einstein’s general relativity theory predicts that beyond 550 AU, the Sun’s gravitational field will focus and amplify emissions from distant celestial objects occulted by the Sun. Various coronal plasma effects might push the Sun’s inner gravitational focus out as far as about 1,000 AU [15]. As well as checking relativistic predictions, this probe could perform useful astrophysical observations if equipped with appropriate instrumentation. For instance, many astronomers expect the existence of terrestrial planets circling our near stellar neighbors Alpha Centauri A and B [16], [17]. It is not impossible that solar-gravitational focusing could provide highly resolved images of these worlds, if they exist and if the probe is directed towards the point on the celestial sphere opposite Alpha Centauri.
5.2 Oort Cloud exploration

At and beyond about 1,000 AU, the probe will be within the inner fringe of the Sun’s Oort Comet Cloud. NASA has considered exploration of this celestial region in the post-2040 time frame using a craft dubbed ‘‘Interstellar Trailblazer.’’ Since distant Oort Cloud comets are primordial remnants of the solar system’s formation, imaging these objects in their environment will be of interest to planetary scientists. Although Oort Cloud comets are still gravitationally attached to our solar system, particles and fields beyond about 200 AU will likely be of galactic rather than solar origin. Exploration of this region could yield information regarding our solar system’s formation, evolution, and future.

6 Conclusions

We have demonstrated here that an appropriately configured and equipped beryllium hollow-body solar-photon sail inflated using hydrogen fill gas could be utilized to explore the Sun’s near galactic vicinity within the not-too-distant future. No show stoppers have been uncovered, at least from our considerations of kinematics, thermal effects, interaction with the space environment, and related mission aspects. There are still unknowns. For instance, can a beryllium thin-film inflatable sail be launched from Earth, or is in-space manufacturing necessary? Better ways may exist to perform this mission. Is hydrogen the best fill gas for an inflatable sail deployed near the Sun? Are there sail-wall materials superior to beryllium? Other sail configurations than the inflatable might also be considered for the Interstellar Trailblazer. One is a hoop sail. The hoop sail and other contenders are worthy of further examination [7].

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