Breakthrough Sun Diving: The Rectilinear Optiojn

Gregory L. Maloff1*, Les Johnson[2]

1Department of Physics, New York City College of Technology, Brooklyn NY USA
2NASA Marshall Space Flight Center, Mail Code ST20, NASA MSFC, Huntsville AL, USA
*Corresponding Author email: GMatloff@citytech.cuny.edu

- # ABSTRACT

- A near-term possibility for utilization of Breakthrough Initiatives Project Starshot technology is application of the Sun Diving Maneuver as a replacement for Laser acceleration of highly miniaturized photon sails to interstellar velocities. This possibility was discussed during the June 2022 Breakthrough Discuss meeting in Santa Cruz California. Here, we consider application of Statite-type photon sail probes to achieve rectilinear trajectories to explore outer solar system and near-interstellar destinations. Statute-Type solar photon sails sufficiently thin and reflective that solar radiation-pressure force on the sail exactly balances solar gravitational force. In such a force-free environment, the spacecraft exits the solar system at its pre-sail-deployment solar-orbital velocity. Here we consider departures from a circular 1-AU solar orbit, the perihelion of a 0.7-1 AU elliptical solar orbit and the perihelion of a 0.3-AU solar orbit. Possible outer-solar-system destinations of possible interest to Breakthrough initiatives extraterrestrial-life/artifact -search researchers include Europa, Titan, Enceladus, and Arrokoth. More distant possible objectives are Oumuamua and the Sun's Inner Gravitational Focus. To achieve a rectilinear trajectory, the sail must be oriented normal to the Sun and spacecraft areal mass thickness is .00146 kg/m^2. Current sail technology is reviewed to determine whether it can achieve the required areal mass thickness.

Introduction

- Breakthrough Initiatives seeks ET, technosignatures and biosignatures.
- As a near-term mission prior to a pico-sail boosted by terrestrial laser to 0.2c, Breakthrough Discuss 2022 began consideration of solar system or near-interstellar Sun diver mission.
- One goal of such a mission might be the Sun's Inner Gravity Focus at ~550 AU.
- This paper considers Rectilinear Sun Diver Trajectories in which the sail is always normal to the Sun and is deployed at perihelion. The solar gravitational force on the spacecraft equals solar radiation force on the sail. After sail deployment, s/c departs solar system in a straight line at the perihelion velocity. Bob Forward dubbed such sails "Statites".

Analytical Tools (1): Lightness Factor

- First we consider sail lightness factor (β), the ratio (Sun Rad. Press. Force /Sun Grav. Force)=1
- β = 0.000768 [(A +2R)/σ], where A =sail absorption, R = sail reflectivity, = s/c areal mass thickness. For β =1, R = 0.9, A = 0.1,σ = 0.00146 kg/m^2. A 30 X 30 m square sail has a mass of about 1.3 kg.

Analytical Tools 2: Solar System Exit Velocity (V_∞)

- From Colin McInnes Eq. (6.15) and the definition of gravitational parameter, it is easy to derive a relationship for V_∞ the case of sail deployment at perihelion from an initially elliptical solar orbit with $\beta = 1$. Sail is always oriented normal to the Sun. Perihelion distance is R_P and aphelion distance is R_A.

- $V_\infty = V_{es,p} [R_A / (R_A + R_P)^{1/2}$.

- $V_{es,p}$ is solar escape velocity at perihelion.

- Truth tests for this equation: Consider a s/c departing from a circular 1 AU solar orbit. Interstellar cruise velocity is 30 km/s as expected. Departure from a parabolic solar orbit with 1 AU perihelion. In this case, interstellar cruise velocity is 42 km/s as expected.

Three Scenarios

- **Scenario** 1: Perihelion = Aphelion = 1 AU. Solar system escape velocity = 42 km/s. S/C exits solar system at 30 km/s = 6.3 AU/yr, 87 yr to 550 AU inner solar grav. focus.
- **Scenario 2**: Perihelion = 0.7 AU, Aphelion = 1 AU. S/C departs solar system at 38 km/s = 8.4 AU/yr, 65.5 yr to 550 AU.
- **Scenario 3**: Perihelion = 0.3 AU, Aphelion = 1 AU. S/C exits solar system at 66 km/s = 14.5 AU/yr, 38 yr to 550 AU.

Possible Destinations (1)

- **Europa**: This satellite of Jupiter is the closest outer solar-system destination. With a diameter of 3230 km, Europa is 671,000 km from Jupiter. It orbits the giant planet every 3.55 days and has a mass 65% that of Earth's Moon. Although this small world is covered by a mostly frozen water ocean, cracks visible on the surface indicate that some liquid water may be present. Sub-Surface oceanic life therefore cannot be ruled out. On average, Jupiter is about 5.2 AU from the Sun. At 30 km/s, a spacecraft will cross Jupiter's solar orbit after a flight of about 300 days. Such a craft will cross Europa in about 100 seconds if the trajectory is along the satellite's equator.

Possible Destinations (2)

- **Titan**: At an average distance of 9 AU from the Sun, this satellite is an interesting candidate for the investigation of the possibility of non-Earth-like life. Traveling at 30 km/s, a spacecraft will reach this moon and other satellites of Saturn in about 1.5 years. Titan, with a diameter greater than 5,000 kilometers, is the only known satellite with a dense nitrogen/argon atmosphere. As discovered by the Cassini/Huygens mission, this satellite is dotted with bodies of liquid hydrocarbons. It is not impossible that sub-surface water is present. Titan has a diameter of about 5,000 kilometers. A spacecraft conducting a pass above Titan's equator at a constant velocity of 30 km/s requires almost three minutes to complete its pass.

- **Enceladus**: A much smaller object than Titan with a diameter of about 500 kilometers, this satellite of Saturn is also of interest to astrobiologists. Observations from Saturn-orbiting Cassini demonstrate that, in spite of its distance from the Sun, Enceladus apparently has a liquid water ocean with mineral-rich hydrothermal vents. There is a fine halo of ice dust around this small satellite. This is produced by icy geysers erupting from the surface with velocities of about 400 meters per second. As well as water vapor, gases including carbon dioxide and methane have been detected in these eruptive plumes. The density of organic material in the plumes is considerably greater than expected.

Possible Destinations (3)

- **Methone**: Some have suggested that we should search the solar system for anomalous objects that might be “lurkers”—active or inactive artifacts produced by extraterrestrials or extinct pre-human civilizations. Although it is much too small to be of interest to astrobiologists, this satellite of Saturn is certainly worth a post-Cassini visit.

- As shown the next slide, Methone is egg-shaped and has a very smooth, apparently crater- free surface. Its largest dimension is about 3 kilometers. It was imaged by Cassini on May 20, 2012 from a distance of about 1860 kilometers.

- It might be thought that instruments aboard a sail craft moving at 30 kilometers per second relative to the sun might have little opportunity to study this small satellite during a close pass. But things aren’t quite as bad as they seem at first glance. Saturn’s mean solar-orbital velocity us about 9.7 kilometers per second . Methone's orbital period is about 24 hours and the semi-major axis of its saturn-centered orbit is about 200,000 kilometers. So its average orbital velocity is about 12 kilometers per second. Therefore, a probe moving at 30 kilometers per second relative to the Sun could encounter Methone at a relative velocity less than 10 kilometers per second.

- Rather than studying Methone, the probe might encounter neighboring satellites Pauline and Anthy to determine whether Methone’s strange appearance is unique to it or a consequence of its position near Saturn.

Possible Destinations (4)

- **<u>Arrokoth (MU69)</u>**: In January 2019, the New Horizons spacecraft flew by this small Kuiper Belt Object. At a distance of 44 AU from the Sun, Arrokoth (with a maximum dimension of 35 kilometers) is too small to be or interest to astrobiologists. At 30 km/s or 6.3 AU/yr, a spacecraft will reach the vicinity of this object in about 6.5 years.
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- Arrokith seems to be binary object consisting of two joined flattened disks (see next slide). Analysts have not been able to explain the nature of the object's bright neck, which connects the two disk-like bodies. Anomalies of this nature may be of interest to those seeking lurkers.

Possible Destination Summary

Destination Flight Time Summary: Sail Deployment in 2030 for Oumuamua

- **Scenario 1**: 0.82 yrs to Jupiter system, 1.5 yrs to Saturn system, 6.6 yrs to Arrokoth, 87 yrs to Sun grav focus.

- **Scenario 2**: 0.61 yrs to Jupiter system, 1.1 yrs to Saturn system, 5.5 yrs to Arrokoth, 66 yrs to Sun grav. focus

- **Scenario 3**: 0.36 yrs to Jupiter System, 0.6 7rs to Saturn system, 3.0 yrs to Arrokoth, 15 yrs to Oumuamua at 220 AU, 38 yrs to Sun grav focus.

Issues and Mitigations

- Exploring the outer solar system or near extrasolar destinations using rectilinear sail trajectories will be challenging. One of thee is the mass of the payload. It is assumed in Breakthrough Starshot design studies that payload masses in the ~1 gram range will be possible for extrasolar or interstellar ventures. But in the near term, miniaturization techniques may not be sufficient to achieve such results. And ~1 kilogram payloads will necessitate larger sails.

- Another issue is the value and variability of the solar constant. Before about 2010, most researchers considered the value of the solar constant to be about 1,366 W/m^2[22] as assumed in this paper. More recent work indicates that a more exact value might be about 1,361 W/m^2. In any case, it seems that the solar constant is not actually a constant—it apparently varies by about 0.1% during the solar activity cycle.

- In addition, mission planners must contend with the possibility of timing errors in sail deployment. These will result in trajectory direction errors and are relatively easy to quantify.

- One way around these issues is to equip the sail with adjustable reflective vanes and ballast. Ballast could be used in the case of an increased solar constant. Vanes could compensate for increased or decreased solar constant and applied to alleviating sail- deployment timing errors.

- Another issue is probe autonomy. Unless a Scenario 1 sail is unfurled from a 1-AU circular solar orbit near Earth, communication delay time at sail deployment will be measured in minutes. The deeper the Sundive, the greater the requirement for probe autonomy.

Current Status of Photon Sail Tech.

- NASA and its industry partners are developing and flying solar sails applicable to a wide range of near-term space science missions, maturing the technology for more demanding missions in the mid-term and, with foresight, to support breakthrough sun diving missions in the future. Currently funded technology development activities support two classes of missions: Deep space interplanetary CubeSats (12 – 24 kg) and smallsats (up to ~125 kg). The sail size and spacecraft that accommodates it are highly connected and the technological maturity of one directly impacts the development of the other.

- **Solar Sail Propulsion for Deep Space Interplanetary CubeSats**: For NASA's Near-Earth Asteroid (NEA) Scout CubeSat mission that was to have traveled to and imaged an asteroid during a close flyby, an 86m2 solar sail was developed as its primary propulsion, capable of achieving a Characteristic Acceleration (Ac) of 0.06 mm/s^2. Unfortunately, no contact was made with the NEA Scout spacecraft after its launch on NASA's Artemis-1 mission in November 2022. Without making radio contact with the spacecraft, the unfurlment of the solar sail could not be tested.

- Developed by NASA's Marshall Space Flight Center (MSFC) and Jet Propulsion Laboratory (JPL), the NEA Scout was based on the industry-standard CubeSat form factor. The spacecraft measured 11 cm x 24 cm x 36 cm and weighed less than 14 kilograms. Following deployment and spacecraft checkout from the Space Launch System (SLS), the MSFC developed solar sail was deploy, and the spacecraft will begin its 2.0 – 2.5-year journey. The solar sail propulsion system for this class of mission is TRL-6. It is not impossible that near future sails will be capable of achieving rectilinear trajectories.

Conclusions

- Developing the technology of rectilinear Sun Diving will be challenging in the near term but certainly not impossible. There are numerous outer solar system sites that could be investigated by robotic photon-sail probes applying this technology that are of interest to those seeking extraterrestrial life or artifacts in the solar system. Even sail deployment at moderate perihelion distances opens the possibility of flights to the Sun’s inner gravitational focus with near-term technology within a human lifetime and fly-bys of interstellar visitors such as Oumuamua. Rectilinear Sun Diving may also provide a near-term testbed for techniques required for ultimate true interstellar probes such as the Breakthrough Initiative Project Starshot.