

Sun Skimming: A Feasibility Study for Interstellar Travel

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Abstract

This paper researches upon a novel approach of using solar sails for interstellar travel, by a process called “Sun Skimming”. Sun Skimming refers to approaching the Sun closely, in order to gain acceleration, from high radiation pressure at the Perihelion. The paper addresses radiation shielding, weight of probe, factors affecting Δv and acceleration, crossing time of Solar Perihelion and the nearest distance of the Perihelion from the Sun, where the satellite can sustain the extreme heat and radiation.

1.0 Introduction

In today’s world, the usage of fuel-propelled engines for rockets and satellites is common and it used for every mission to outer space. We propose the usage of Solar sails, in order to have unlimited acceleration, which is ideal for satellites travelling with high speeds. In addition to this, we have long mission lifetimes and infinite propellant (Sunlight), though its intensity decreases exponentially. To combat this, we shall approach the Sun within a distance of $10 R_{\odot}$ (0.046AU), to get an initial higher velocity for the travel. The weight of the probe will not be more than 10kgs (including the body and the sail), for effective overall acceleration.

Using the inverse square law for intensity,

Intensity Ratio of Sunlight =

$$I(\text{Earth}) \left(\frac{1 \text{ AU}}{r \text{ of perihelion}} \right)^2$$

$$I(\text{Earth}) \left(\frac{1 \text{ AU}}{0.04652 \text{ AU}} \right)^2 \approx I(\text{Earth}) * 462.08$$

$r_{\text{perihelion}}$ = Distance of Perihelion from the Sun = 0.04652 AU

$I(\text{Earth})$ = Intensity of Sunlight at Earth $\approx 1360 \text{ W/m}^2$

At the Perihelion, the intensity of sunlight is approximately 462 times that of Earth’s, which is around 628,782 W/m^2 . Consequently, the body of the satellite will be made of materials with high radiation shielding properties. The sail shall be made for materials that are designed for Perihelion heat and radiation loads.

2.0 Factors affecting Δv and acceleration

There are several factors that may affect acceleration, such as distance and crossing time of Perihelion, weight of satellite embedded with radiation shielding, weight of sail, sail area, reflectivity of the sail and absorption factor. All of these together affect the acceleration of the spacecraft and will be discussed in detail in the upcoming sections.

2.1 Distance from and Crossing Time of Perihelion

At a distance of $10 R_{\odot}$ (around 4.2 million miles), the spacecraft would be able to bear the extreme radiation pressure, through light but effective radiation shielding materials. The crossing time at Perihelion is directly proportional to the distance. The lesser the distance from the Sun, the lesser the crossing time. Hence, we keep the satellite at the Perihelion at $10 R_{\odot}$ for the reasons stated above. The derivation for the crossing time w.r.t radius of perihelion is as below

$$time = \frac{2r}{v}$$

r =Radius of Perihelion

v = Velocity at Perihelion

Considering the sun skimming trajectory parabolic, semi major axis of orbit becomes ∞ .

Using the vis-viva equation,

$$v = \sqrt{\frac{2\mu}{r}}$$

From the above equations, we get,

$$time = \sqrt{\left(\frac{2}{\mu}\right) * r^{\frac{3}{2}}}$$

We derive that the crossing time varies with the $3/2^{\text{th}}$ power of the radius of the perihelion.

3.0 Radiation Shielding and Instruments in the Probe

At the Perihelion, the satellite shall face extreme radiation pressure and heat. To avoid interior damage or melting, the satellite shall be composed of radiation shielding materials that are not only effective, but also extremely light in weight, so that our rate of acceleration at the Perihelion remains high, as acceleration is inversely proportional to the mass of the satellite at a constant force.

All the possible materials that can be used and satisfy the above criteria are listed in the table given below, along with their densities and properties. Some of the layers will be localized around electronics, to reduce weight and provide effective shielding from protons. The probe will be covered with reflective coating in the Sun facing areas. The Outer and the Middle layers will be sacrificial and ablative in nature for discarding them later.

Materials	Density (in g/cm ³)	Usage Layer	Properties
Aerographene (Mostly Used)	0.00016	Outer	Very Light, Blocks X/EUV Rays, Reflects heat, less dense
SiO ₂ Aerogel	0.10	Outer	Very Light, Excellent Thermal Insulation upto 1800 degree Fahrenheit
Carbon Carbon Composite	1.55	Outer	Offers thermal insulation to extreme heat upto 3000 degrees
Polyethylene (HDPE/UHMWPE) (Localized Only)	0.97	Middle	Excellent Proton Shielding
RXF1 (NASA Polymer)	0.96	Middle	Excellent Proton Shielding
Lithium Hydride	0.82	Middle	Optimum Proton Shielding
HP- Boron Nitride Nanotube (Localized only)	1.50	Inner	Absorbs Neutrons, Reflects Heat
Borated Polyethylene (Localized Only)	0.90	Inner Layer	Blocks protons, Absorbs Neutrons
Hydrogel Layer	1.0	Thermal Layer	Coolant and partial shielding

Table 3.1 (Radiation Shielding Material Composition- Probe)

The total weight of the probe will be below 10kgs, for it to have a greater velocity at the Perihelion and larger acceleration for the journey. A larger probe demands greater radiation shielding, cooling, which in turn increases weight. Δv and acceleration vary inversely with mass in a non-linear way. The probe shall have the following ultra-miniaturized sensors (like in CubeSats): - (a) magnetometer, (b) Sun sensors, (c)

Gyroscopes, (d) Temperature Sensors, (e) Megapixel fisheye color cameras, (f) Hall Sensors, (g) Plasma/Particle Detector, (h) Dust Detectors, (i) Radiation Monitoring chips (MiniPIX). The probe shall not have any heavy propulsion systems, and it will use minimal batteries, lightweight communication systems such as optical technologies (laser or visible light) and magnetic torquers.

All of the above shall weigh in grams, so that the probe remains compact and light weight and the optimum weight of 10kgs is attained, for a successful and effective Sun Skimming procedure.

4.0 Jettison Mechanism

The probe shall jettison (discard) the protective layers, one by one, to achieve a greater acceleration. Once jettisoned, the mass of the probe reduces significantly, increasing the rate of acceleration exponentially. Also, many of the protective layers become less efficient after the extreme radiation pressure exposure at Perihelion.

For Jettison,

We calculate the solar flux allowed, by using the Stefan Boltzmann Radiation Power Equation and the irradiance limit equation

$$\text{Solar Flux (Allowed)} = \frac{\sigma \epsilon (T_{max})^4}{f}$$

f = Absorption fraction (how much sunlight is absorbed)

σ = Stefan–Boltzmann constant

ϵ = Emissivity

T = Maximum safe temperature of electronics in the probe

When we reach far away from the Sun, where Solar Flux (Exterior) $\leq$ Solar Flux (Allowed) and Absorbed heat $\leq$ Radiated Heat, we can jettison the protective shielding layers.

The outer thick protective and ablative layers can be jettisoned first, as it can create excess debris and is generally heavier than the other protective layers. This should be jettisoned only when the probe has cooled down and is significantly away from the Perihelion. Next, the thermal layers along with the Aerogel layers of Silicon and Graphene can be jettisoned, once the heat can be safely radiated. The Proton shielding layers (Polyethylene, RXF1, BNNT, Lithium Hydride Layers) should be jettisoned at last, when the radiation pressure and exposure reduce significantly, which will not cause any damage to the electronics, as these layers provide shielding against the solar particles such as protons, which are extremely harmful to the probe's proper functioning.

5.0 The Solar Sail

The weight of the Solar Sail would be around 5kg, that accounts for 50% of the total weight of the entire probe. The areal density of the solar sail would be around 3.5g/m², to have a maximum acceleration, which can be practically and effectively engineered in the next few years.

$$\text{Sail Area} = \frac{\text{Weight}}{\text{Areal Density}}$$

$$\text{Sail Area} = \frac{5\text{kg}}{3.5\text{g/m}^2} \approx 1429\text{ m}^2$$

As the Solar sail would be square in shape,

$$\text{Length of Side of Sail} = \sqrt{1429\text{m}^2} = 37.8\text{m}$$

The lower the areal density, the higher the sail area, for larger photon momentum. It also increases reflectivity of the sail ($\geq 90\text{-}95\%$). The sail will also have low absorption factor ($\leq 2\%$).

At the Perihelion, the sail will face extreme UV radiation, which can break chemical bonds and can make the sail brittle. During Coronal Mass Ejections, Solar winds and flares can cause erosion and degradation of the sail. Finally, the extreme heat at the Perihelion can cause the thin standard films to melt. In order to combat these, which can cause structural damage, we shall use the following materials to make the sail, which have an overall areal density of 3.5g/m^2 , high reflectivity, low absorption, optimum radiation shielding properties and highly conductive and heat resistant for temperatures at the Perihelion. The following table shows the materials used in the sail, which satisfy the above constraints: -

Material	Areal Density (g/m^2)	Properties
Graphene Membrane (Multilayered)	0.5-1.0	Base Structure of Sail, Survives $> 2000\text{ K}$, Radiation Resistant
BNNT-mesh	0.5-1.0	Extremely radiation-hard, Survives $>1500\text{ K}$, micrometeoroid strength, Shields from protons
Silicon Carbide protective covering	0.1-0.2	Protects from sputtering, boosts emissivity, prevents erosion, Ceramic survives $> 2000\text{ K}$
Dielectric Reflective Stack	0.5-1.0	Main reflective coating, Thermal stability $> 1500\text{ K}$
Graphene Conductive Traces (Localized)	0.1-0.2	Charge Dissipation in plasma, Works during extreme charging environment, Prevents

		electrostatic failure
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Table 5.1 (Radiation Shielding Material Composition- Solar Sail)

6.0 Conclusion

This research paper brings a novel approach of Sun skimming, and analyses all the aspects affecting the procedure in detail. It addresses a variety of concern varying from weight and acceleration to radiation shielding and thermal resistivity at the Perihelion. Sun Skimming can give us an extremely high acceleration and Δv for much faster interplanetary and interstellar travels. It reduces the mission time exponentially. It also helps in orbit changes due to the geometry of radiation force. Also, we can jettison out the radiation layers from the probe, which further increases acceleration and disposes off the debris from the probe. Such a procedure is highly realistic and practical in the near foreseeable future with advanced engineering techniques and fine high-grade materials.

References

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