Solar Cruiser: towards the new era of space exploration

Samuel Capellas Coderque

INTRODUCTION

Solar sails are one of the most promising applications of photonics to space science. They are based on the concept of radiation force: when light is incident on a surface, a variation in photons' momentum takes place due to their reflection and absorption, which creates a net force. Solar sails are very large and thin mirrors which provide a very efficient alternative to fuel-based propulsion of spacecrafts, taking advantage of sunlight's radiation force. The first space mission applying solar sails was the Japanese IKAROS in 2010, and such technology has been in expansion ever since.

One of the main reasons why solar sails are so promising is they can theoretically allow interstellar travel. Indeed, by using a gravity assist maneuver to distance of 0.1 AU from the Sun, an ultra-light solar Sail (with a high area-to-mass ratio, $A/m > 200\,\mathrm{m}^2/\mathrm{Kg}$) can be propelled to a speed of 25 AU/year, which lies far beyond the well known Voyager 1's speed of 3.6 AU/year. Nevertheless, exposure to such high-power solar flux can easily damage materials due to absorption heating. Article [1] discusses the material and design challenges required to overcome this problem, suggesting it will be possible in a near future.

Another important application of solar sails is travelling through regions which are currently inaccessible to current propulsion technology, such as leaving the ecliptic (that is, the Solar System's orbital plane). This would allow us to image the Sun's poles and drastically increase our understanding of solar wind and space weather, as aimed by NASA's future High Inclination Solar Mission (HISM), [3].

This report will focus on NASA's Solar Cruiser mission, which was approved in December 2020 and is predicted to launch in February 2025. Having only 90 Kg of mass it is the biggest solar sail ever sent to space, with an area of $1672\,\mathrm{m}^2$, accounting for more than six tennis courts. The principal investigator of the mission is Dr. Les Johnson, author of articles [1] and [2], which have been taken as a base for this report. The Solar Cruiser mission is aimed at demonstrating solar sail technology, serving as a key step towards future solar sail missions such as HISM. It will do so by achieving a geosynchronous trajectory at an equilibrium distance which can only be reached by solar sails.

Many spacecrafts studying the Sun lie at Lagrange's equilibrium point L1, that is, the point in the Earth-Sun line with balanced gravitational forces towards each body, leading only to a centripetal acceleration. A solar sail experiences an additional outward radiation force, so its equilibrium point lies closer to the Sun and is thus called Sub-L1. This will provide mankind with a new point of study for the Sun's magnetic field structures, leading to a better warning system for solar storms and coronal mass ejections (CMEs). The latter are large eruptions of magnetized plasma with the ability to severely impact telecommunications, space systems and astronauts. Their high unpredictability and potential damage make it crucial to improve their monitoring systems, as in the case of Solar Cruiser.

Figure 1 shows a diagram of Solar Cruiser's trajectory, starting from Earth until it reaches the Sub-L1 orbit, at approximately $r = 0.986$ AU from the Sun (while L1 lies at 0.990 AU from it). However, no calculation has been provided in [2] to back this up. In this report we will explore the physics of radiation force, in order to include it in Newton's equations and numerically determine the Sub-L1 equilibrium point for the Solar Cruiser. This will also allow us to estimate the gained warning time thanks to the the Solar Cruiser mission. Finally, we will cover some similar applications and the state of the art.

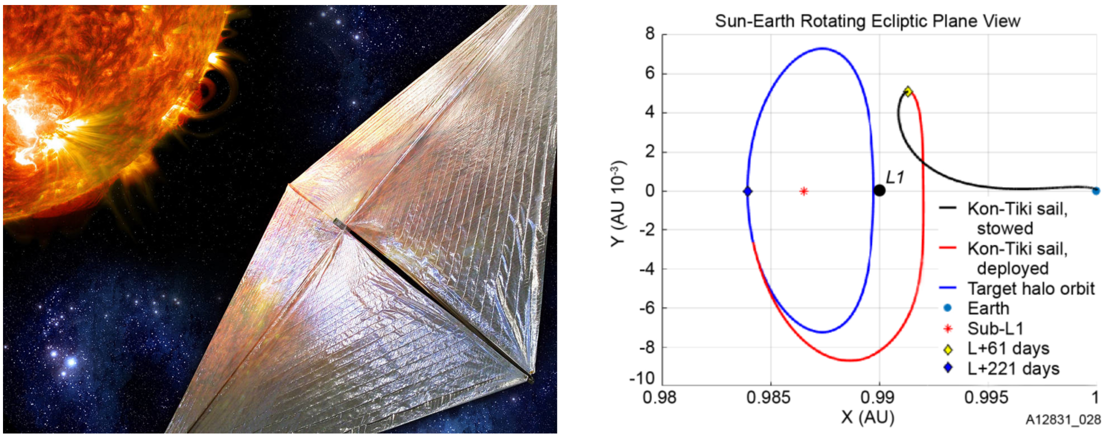

Figure 1: To the left, illustration of the Solar Cruiser approaching the Sun, by NASA. To the right, trajectory of the Solar Cruiser, showing both L1 and Sub-L1; from [2].

APPLICATION DETAILS

Radiation force acting on a solar sail

According to Newton's Second Law of motion, the change in linear momentum of photons when illuminating a surface causes an outward net radiation force that pushes it, given by

$$\boldsymbol{F} = \frac{d\boldsymbol{p}}{dt}. \tag{1}$$

A solar sail can be modelled as a flat surface that is tilted with respect to the Sun by an angle θ, where $\theta = 0$ corresponds to the maximum (normal) exposure of the surface towards it. Let's consider a reference frame where the z axis goes from the Sun to the surface. Then, the x and y axis can be chosen conveniently so the incident and final linear momentum of all photons combined are given by:

$$\boldsymbol{p}_i = (p\sin\theta, 0, p\cos\theta), \quad \boldsymbol{p}_f = R(p\sin\theta, 0, -p\cos\theta) + T\boldsymbol{p}_i, \tag{2}$$

where $R \in [0,1]$ is the *reflectivity* of the surface, that is, the ratio of incident solar photons being reflected, and T is the fraction of transmitted photons. Indeed, photons absorbed by the surface do not have a final momentum.

Solar sails are built using highly reflective materials, so ideally absorption and transmission can be neglected in a simplified model. Thus, taking $R \approx 1$ and $T \approx 0$, the infinitesimal variation in momentum will be given by: $\boldsymbol{dp} = -(0, 0, dp(1+R)\cos\theta)$. Now, we can compute the magnitude of the force acting on the surface, using the momentum carried by photons related to their energy through $p = E/c$. We find

$$F = \left|\frac{d\boldsymbol{p}}{dt}\right| = (1+R)\cos\theta\frac{dp}{dt} = \frac{(1+R)\cos\theta}{c}\frac{dE}{dt} = \frac{(1+R)\cos\theta}{c}\int_A \boldsymbol{S}\cdot\boldsymbol{dA}, \tag{3}$$

where we have introduced the Poynting vector $\boldsymbol{S}$ accounting for the power per unit area reaching the surface. Letting L_s be the power emitted by the Sun (its luminosity), and assuming a uniform spherical distribution of power, the magnitude of the outward radiation force acting on the surface of area A lying at distance r from the Sun is:

$$F = \frac{(1+R)L_s A}{4\pi r^2 c}\cos^2\theta. \tag{4}$$

Interestingly, this result means shows the acceleration experimented by the solar sail of mass m due to radiation force is proportional to the reason A/m. It shall also be commented that equation 4 coincides with the expression taught in class: $F = (1+R)P/c$, where P is the power reaching the surface.

Effect of radiation force in equilibrium

Once an expression for the radiation force acting on a solar sail is known, we can proceed to determine the Sub-L1 point of equilibrium: it is found at distance r from the Sun, which can be found through the application of Newton's Second Law of motion:

$$G\frac{M_s m}{r^2} - G\frac{M_e m}{(d-r)^2} - \frac{(1+R)L_s A}{4\pi r^2 c}\cos^2\theta = m\frac{4\pi^2}{T^2}r, \tag{5}$$

being M_s, M_e, m the mass of the Sun, Earth and solar sail respectively, T the period of rotation of the Earth around the Sun, and d the Earth-Sun average distance. One may realize the effect of the radiation force is a reduction of the effective mass of the Sun. Indeed, introducing the term M_{eff} as this effective mass, equation 5 can be rearranged as if only gravitational forces where acting on the solar sail:

$$G\frac{M_{\text{eff}}\, m}{r^2} - G\frac{M_e m}{(d-r)^2} = m\frac{4\pi^2}{T^2}r, \qquad M_{\text{eff}} = M_s - \frac{(1+R)L_s A}{4\pi c G m}\cos^2\theta, \tag{6}$$

This can be rearranged into a quintic polynomial equation in r, which is given by

$$\gamma r^5 - 2d\gamma r^4 + d^2\gamma r^3 + (\beta-\alpha)r^2 + 2d\alpha r - \alpha d^2 = 0, \tag{7}$$

where the following coefficients have been introduced:

$$\alpha = GM_{\text{eff}}\, m, \quad \beta = GM_e m, \quad \gamma = m\frac{4\pi^2}{T^2}. \tag{8}$$

These constants have been computed for the Solar Cruiser, under the assumption of ideal reflectivity and normal incidence. Then, equation 7 has been solved using a `Matlab` code to find its only real solution r_S for the Sub-L1 equilibrium point. The same code has been executed setting $M_{\text{eff}} = M_s$ to find the L1 equilibrium distance from the Sun, r_L. The results are the following:

$$r_S \approx 0.98570\, d,$$
$$r_L \approx 0.99005\, d.$$

These values are consistent with article [2], as seen in the right hand side of figure 1. The distance from Earth to Sub-L1 increases roughly 44% with respect to L1, with a difference of roughly 652000 Km. Taking into account the average speed of solar wind is 400 Km/s, we conclude Solar Cruiser would be able to inform of adverse space weather conditions 27 minutes before a conventional spacecraft orbiting the Sun from L1.

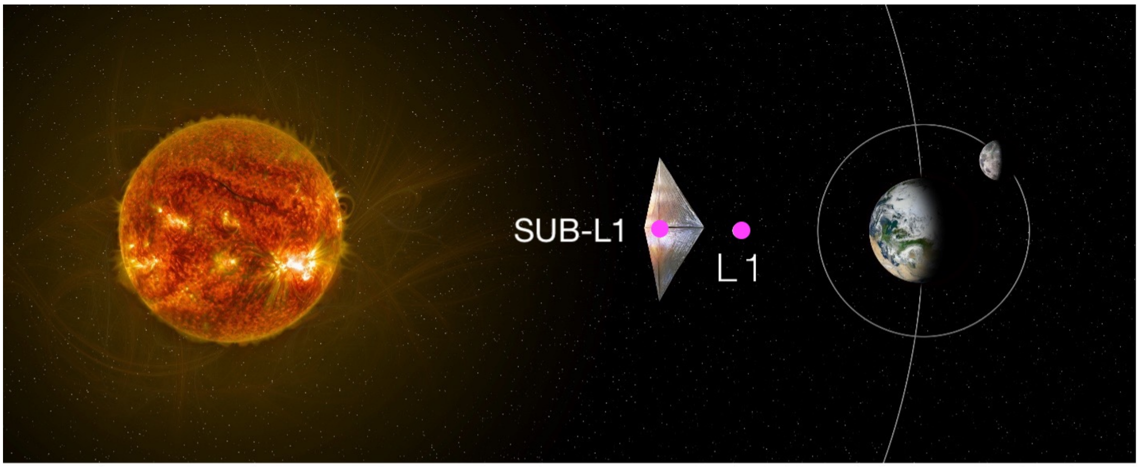

Figure 2: Artistic representation of Lagrange's equilibrium point L1, and the Sub-L1 equilibrium point achieved by the Solar Cruiser. Extracted from article [4] (edited).

SIMILAR APPLICATIONS AND STATE OF THE ART

Until now, only a few solar sails have been sent to space successfully. As mentioned in the introduction, the Japanese Space Exploration Agency (JAXA) was the first to achieve solar sail flight with IKAROS in 2010. NASA was a few months behind launching NanoSail-D2, the successor of the failed NanoSail-D, which in 2008 was hoping to be the first solar sail. Moreover, The Planetary Society developed the LightSails mission, which successfully launched the solar sail CubeSat LightSail-2 in 2019 [5].

Apart from NASA's Solar Cruiser, other interesting projects concerning solar sails are also planned for a near future. An interesting one launching in November 2021 is NASA's Near-Earth Asteroid Scout, which will apply solar sail technology to improve small asteroid characterisation. The aforementioned missions are summarized in figure 3, and have been arranged by the surface area and area to mass ratio of their sails. The rapid rate at which solar sail technology is improving suggests it will soon become our most effective way to explore our Universe, apart from being the most sustainable one.

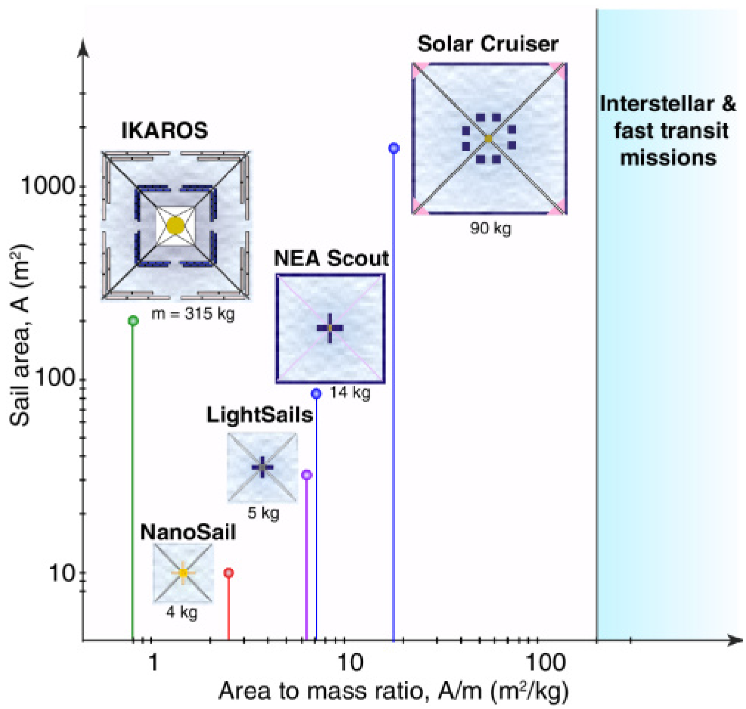

Figure 3: Some flown and planned solar sail missions. $A/m \geq 200\,\mathrm{m}^2/\mathrm{kg}$ is required for ultra-fast solar system exploration and interstellar travel, according to the source [1].

REFERENCES

[1] Arthur R. Davoyan, Les Johnson et al. *Photonic materials for interstellar solar sailing.* OSA Publishing; Vol. 8, Issue 5, pp. 722-734 (2021). Link.

[2] Les Johnson, Frank M. Curran et al. *The Solar Cruiser Mission - Demonstrating Large Solar Sails for Deep Space Missions.* Preprint; (2020). Link.

[3] K. Kobayashi, Les Johnson, Herbert D. Thomas et. al. *The High Inclination Solar Mission.* Preprint; (2020). Link.

[4] NASA Science. *Solar Sail Propulsion: Enabling New Destinations for Science Missions.* NASA Website; (2021). Link.

[5] Wikipedia. *Solar sail.* Wikipedia Foundation; (2021). Link.