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LISBOA

SPACE PHYSICS

MIN-CTE

Solar Sails

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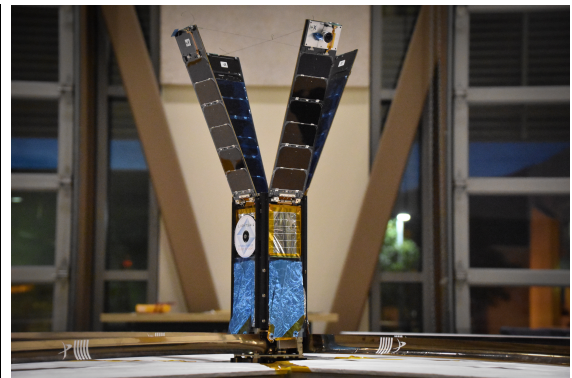
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1 Introduction

On November 3rd, 1973, the Mariner 10 probe (see Figure 1a) embarked on a mission to Venus, providing humanity with its initial close-up view of the planet. The probe utilized the gravitational pull of Venus to increase its velocity for its subsequent destination, Mercury. This significant undertaking introduced mankind to various aspects of space exploration. Firstly, it marked the inaugural instance of employing a planet's gravity for a gravity assist maneuver. Moreover, it represented the first occasion in which two planets were closely observed within a single mission. Furthermore, the mission pioneered the utilization of solar pressure to regulate the spacecraft's attitude. These achievements were not initially intended but emerged amidst significant challenges. The presence of debris surrounding the spacecraft disrupted the tracking navigation camera, necessitating corrective measures to regain lock on Canopus, the probe's reference star. [1, 2]



(a) Mariner 10. [3]



(b) LightSail 2. [4]

Figure 1: The two distinct spacecraft missions presented.

Compounding the difficulties, this interference occurred more frequently as the brightness of the particles increased due to Mariner 10's proximity to the Sun. Nevertheless, the probe completed its gravitational slingshot maneuver around Venus and continued its journey toward Mercury. However, Mariner 10 faced a critical shortage of nitrogen, the propellant required for executing necessary maneuvers. To resolve this predicament, the engineers devised an ingenious solution: by tilting the solar panels, they harnessed solar pressure, the force exerted by photons, to stabilize the spacecraft's position and control its roll. This breakthrough moment not only validated the feasibility of solar sails for future spacecraft but also served as a pivotal demonstration of their efficacy and cost-effectiveness in the case of small satellites. Notably, in 2019, LightSail 2 (see Figure 1b) further substantiated the potential of solar sails, providing a valuable technology demonstration in this domain. [5]

This project aims to research and present a few of the applications of solar sails and examine a few concrete use cases, like the feasibility of interstellar travel and the creation of an early warning system to protect against solar storms and other solar events. For this purpose, a simulator was created that was able to compute trajectories for solar pressure-based spacecraft.

2 State-of-the-Art

2.1 Momentum exchange in space sailing and environmental forces

Space flight achieves momentum exchange for spacecraft using two methods: propellant-based propulsion or spacecraft-environment interaction. With the latter approach, no onboard fuel or propellant is required, as momentum is obtained from the surrounding environment. Examples of such spacecraft include solar sails, electric solar wind sails, and magnetic sails [6], each utilizing distinct momentum exchange mechanisms. Solar sails utilize solar radiation for thrust, while electrical solar wind sails and magnetic sails rely on electric or magnetic fields to reflect charged solar wind particles, harnessing momentum from the solar wind.

Like sailing at sea, which exchanges momentum with the wind and seawater, sailing in space occurs through gravitational wells around massive bodies like planets and the Sun, but, in addition to gravity, there are many other kinds of environmental forces like solar radiation pressure.



Figure 2: Galileo space probe sent by NASA to study Jupiter and its moons. Launched in 1989, it arrived at Jupiter in 1995 and conducted a comprehensive exploration of the Jovian system. [7]

Longuski and Todd estimated the values presented in Table 1, which represent the environmental forces on the Galileo spacecraft (see Figure 2), in various locations between the Earth and Jupiter. Forces on the Galileo spacecraft due to solar radiation pressure are an order of magnitude higher than other space environmental forces, such as those from the solar wind, meteoroids, Newtonian drag, and magnetic fields. Therefore, large environmental forces indicate greater momentum exchange capabilities with the surrounding environment for a constant mass spacecraft. [6]

Table 1: Environmental forces on the Galileo spacecraft in Newtons, depending on its distance from the Sun, shown below the location. [6]

Source	Near Venus 0.7 au	Near Earth 1 au	Interplanetary 3 au	Near Jupiter 5 au
Solar radiation	1.7×10^{-4}	9×10^{-5}	1.1×10^{-5}	3.3×10^{-6}
Solar wind	5.9×10^{-8}	3.1×10^{-8}	3.6×10^{-9}	1.1×10^{-9}
Meteoroids	1.6×10^{-10}	1.1×10^{-10}	9.4×10^{-9}	4.2×10^{-9}
Newtonian drag	3.4×10^{-9}	7.9×10^{-11}	5.3×10^{-11}	5.7×10^{-7}
Magnetic field	5.4×10^{-14}	1.9×10^{-13}	2.1×10^{-11}	1.6×10^{-9}

Table 1 confirms that in areas of the solar system explored by the Galileo spacecraft, a solar sail exhibits a greater capacity for momentum harvesting relative to other propellantless space sail varieties. In interplanetary settings, the forces elicited by solar radiation exhibit greater consistency and predictability than other environmental forces, thus diminishing thrust uncertainties in solar sails, and enabling dependable trajectory design and execution. The efficient thrust capability coupled with reduced uncertainties, highlights solar sails as a superior choice among diverse space sail types, especially for interplanetary expeditions. [6]

2.2 Solar sail missions and milestones

The idea that solar radiation carries with it some form of pressure goes back to Johannes Kepler, who, in 1610, wrote a letter to Galileo Galilei saying

(...) provide ships or sails adapted to the heavenly breezes, and there will be some who will brave that void from the observation of comet tails that may be pointing away from the Sun.

In 1860, James Clerk Maxwell theorized that electromagnetic fields would carry not only energy but also momentum that conveys an effective force – therefore, radiation pressure is the average force per unit area of all incident and reflected radiation (as derived in Subsection 3.3). [8]

Konstantin Tsiolkovsky and Friedrich Tsander [6] were early pioneers of solar sailing, who realized that it is possible to attain cosmic velocities using the pressure of solar radiation. One of the first attempts to construct a functional sailcraft that uses solar radiation exclusively for its propulsion began at the Jet Propulsion Laboratory (JPL) in the 1970s. At the time, the development and design of a practical solar sail for the Halley Rendezvous mission (see Figure 3) had begun, but that was later dropped by NASA. However, the effort laid a solid foundation for solar sailing technology, and much of the work done then is documented by Wright (later work on solar sailing, which focuses on sail trajectory and mission design, is very well summarized by McInnes). [9]

The world's first spacecraft to use solar sailing as its main propulsion method was the Interplanetary Kite-craft Accelerated by Radiation Of the Sun mission (IKAROS), launched by the Japan Aerospace Exploration Agency in May 2010 (see Figure 4) and was a milestone in solar sail technology. [10]

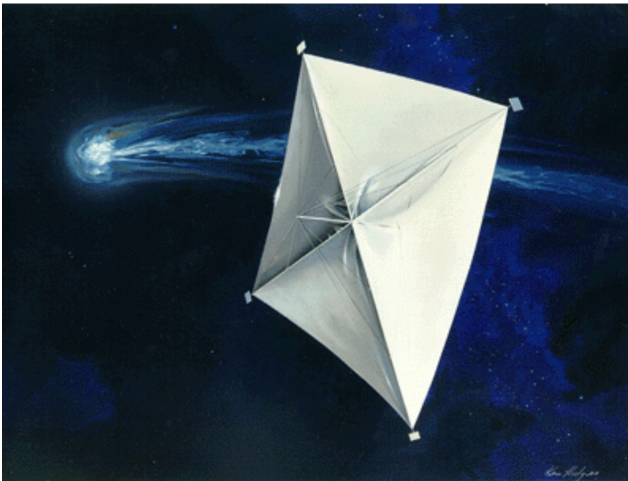


Figure 3: Proposed by JPL in 1977 for a 1986 rendezvous with Halley's comet, this 800-meter solar sail aimed to achieve a large orbital inclination change ($> 90^\circ$) and reverse the orbital flight direction. Although ultimately an ill-fated mission concept from the 1970s, it pioneered the propellant-less solar sailing concept. [11]

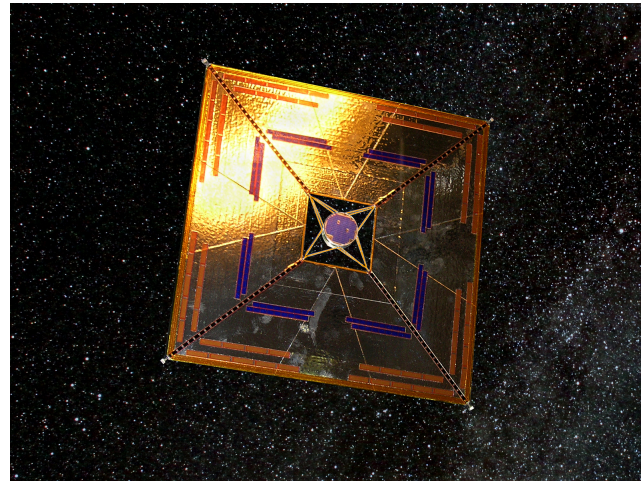


Figure 4: IKAROS, the innovative solar sail spacecraft launched in 2010, showcasing the future of propellant-less propulsion. This $40\text{ m} \times 40\text{ m}$ sail utilized sunlight pressure to achieve its celestial journey, exemplifying a groundbreaking step in space exploration and solar sailing technology. [10]

In May 2015, The Planetary Society completed an in-orbit deployment test with the solar sail LightSail 1. LightSail 1 served as an engineering demonstration mission with a primary focus on testing the sail deployment method in space. However, it did not engage in solar sailing during its operation. LightSail 2 (see Figure 5), a fully operational spacecraft, was designed with the primary objective of showcasing authentic solar sailing capabilities while implementing valuable insights gained from its predecessor, LightSail 1. [12]

LightSail 2, a CubeSat fitted with a solar sail the size of a boxing ring covering 32 m^2 , was launched in June 2019 as a ride share on a SpaceX Falcon Heavy mission, reaching an Earth orbit of 720 km. It optimizes acceleration by adjusting its orientation toward the Sun during outward travel and sideways during the return journey. However, due to Earth's atmosphere, its perigee decreased rapidly, leading to an expected deorbit within a year. On 17 November 2022, the mission was over as LightSail 2 reentered the atmosphere. [13, 14]

Table 2 shows some of the realized or proposed solar sail-based missions and what type

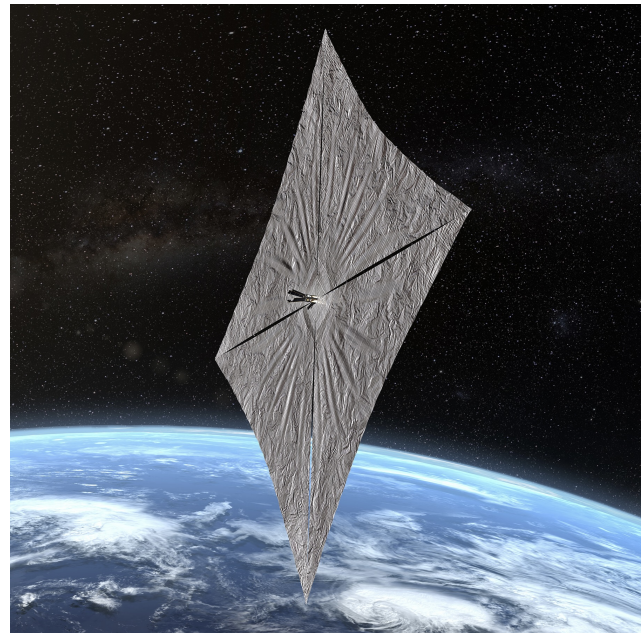


Figure 5: LightSail 2 (2019). [6]

of sail they would use. We can see that the sail area varies tremendously depending on the application, although the larger sail sizes like the ones for the Interstellar Heliopause Probe and Sunjammer remain technical challenges.

Table 2: Solar Sail propulsion missions operating or completed (inspired by [6]).

Mission	Sail type	Sail area [m ²]	Development stage
Illinois CubeSail	Non-rigid	20	Deployed in orbit
LightSail 1	Rigid-square	32	Deployed in orbit
LightSail 2	Rigid-square	32	Deployed in orbit
NanoSail-D	Rigid-square	10	Ground test
NanoSail-D2	Rigid-square	10	Deployed in orbit
IKAROS	Non-rigid	196	Sailed on SRP ¹
GeoSail	Rigid-square	1849	Conceptual
GeoStorm	Rigid-square	4489	Conceptual
Solar pole orbiter	Rigid-square	22 500	Conceptual
Interstellar Heliopause Probe	Rigid-square	60 000	Conceptual
Sunjammer	Rigid-square	1200	Ground test
Gossamer deorbit sail	Rigid-square	25	Ground test

3 Theoretical Framework – Physical Principles

3.1 Momentum

Although photons don't have mass, they do have momentum, which can be transferred into an object with a reflective surface. This can sound a bit counterintuitive because in Newtonian mechanics, momentum, more specifically linear momentum or translational momentum, is the product of the mass and velocity of an object, given by

$$p = mv, \quad (1)$$

so we need a new equation to describe the momentum of a photon.

A photon of frequency ν carries an energy that depends on its frequency expressed by $E = h\nu = hc/\lambda$, in which $h = 6.626 \times 10^{-34} \text{ J Hz}^{-1}$ is the Planck's constant. Einstein's relativistic expression gives us the response for the photon's momentum

$$E^2 = p^2c^2 + m^2c^4. \quad (2)$$

We see if we zero the mass term, we will still be having momentum, which relates itself with the energy by a factor of c , the speed of light. Therefore, the photon's momentum is given by

$$p = \frac{E}{c} = \frac{h}{\lambda}. \quad (3)$$

¹Solar Radiation Pressure

Since Planck's constant is constant, the momentum of a photon is entirely determined by its wavelength, with shorter wavelengths having higher momentum. For example, the momentum of a photon with a wavelength of 500 nm is given by

$$p = \frac{h}{\lambda} = \frac{6.626 \times 10^{-34} \text{ J Hz}^{-1}}{500 \times 10^{-9} \text{ m}} = \frac{6.626 \times 10^{-34} \text{ kg m}^2 \text{ Hz}^{-1} \text{ Hz}^{-1}}{500 \times 10^{-9} \text{ m}} = 1.3 \times 10^{-27} \text{ kg m s}^{-1}, \quad (4)$$

which is a very small amount, but when dealing with the vacuum of space, that can add up when every single collision of a photon with the solar sails provides an increase in the velocity of the spacecraft due to the conservation of momentum – since the photon is reflected, there is an equal and opposite change in the momentum of the sail.

3.2 Solar radiation pressure

The solar radiation pressure at different points in the Solar System can be calculated using the solar constant $G_{\text{SC}} = 1361 \text{ W m}^{-2}$ [15]. This quantity measures the amount of solar electromagnetic energy received by a given area one astronomical unit away from the Sun. For this distance, the pressure applied on a perfectly absorbing surface (reflectiveness $R = 0$) facing the Sun is given by

$$P_{\text{rad}}^{\text{a,1au}} = \frac{G_{\text{SC}}}{c} = \frac{1361 \text{ W m}^{-2}}{3 \times 10^8 \text{ m s}^{-1}} = \frac{1361 \text{ N m s}^{-2} \text{ m}^{-2}}{3 \times 10^8 \text{ m s}^{-1}} = 4.537 \times 10^{-6} \text{ Pa} = 4.537 \text{ }\mu\text{Pa} \quad (5)$$

and for a totally reflective one (reflectiveness $R = 1$) is

$$P_{\text{rad}}^{\text{r,1au}} = \frac{2G_{\text{SC}}}{c} = 2P_{\text{rad}}^{\text{a,1au}} = 9.073 \text{ }\mu\text{Pa}. \quad (6)$$

Since we know the solar pressure will change with the distance to the Sun according to the inverse square law, we can write the solar radiation pressure as a function of the distance to the Sun as follows

$$P_{\text{rad}}(r) = \frac{P_{\text{rad}}^{\text{a,1au}}}{r^2} = \frac{G_{\text{SC}}}{r^2 c}, \quad (7)$$

where r is the distance of the sail to the Sun in astronomical units. Equation (7) yields the graph on Figure 6.

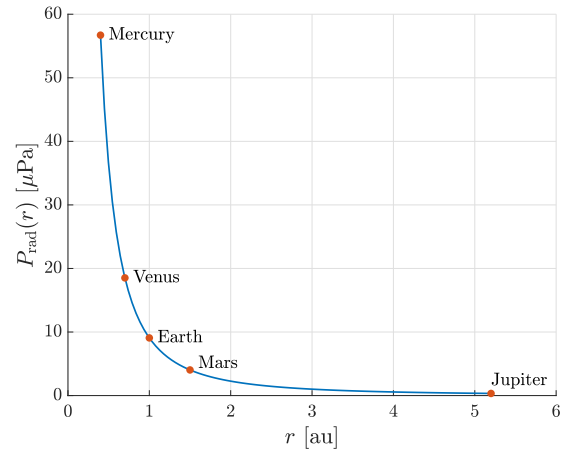


Figure 6: Solar radiation pressure with respect to the distance to the Sun.

3.3 Flat sail model

To maximize the transfer of momentum, it is crucial to optimize the reflectivity of the sail by ensuring the sail is as close to a perfect mirror as possible, minimizing energy loss due to sail heating.

In this sail model, it is assumed that part of the solar radiation particles are reflected (modeled by the reflectiveness $R \in [0, 1]$) from the sail surface and the remaining particles are absorbed (modeled by $1 - R$). As a result, the total force generated when the photons hit the sail is equal to the sum of the force generated by the incident particles' momentum exchange and the force generated by the reflected particles that bounced off the sail, which depends on R .

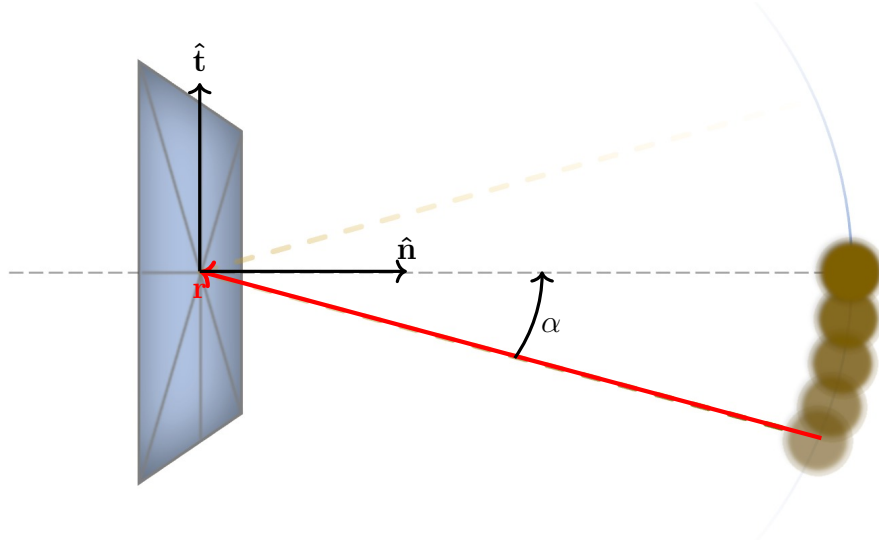


Figure 7: Flat sail model, where $\hat{\mathbf{n}}$ is the normal vector and $\hat{\mathbf{t}}$ is the transverse vector perpendicular to $\hat{\mathbf{n}}$ and in the plane of the incoming radiation and $\hat{\mathbf{n}}$.

From Figure 7 it can be seen that the force generated from impinging photons is (inspired by [16])

$$\mathbf{F}_i = P_{\text{rad}}(r)A_e (-\cos \alpha \hat{\mathbf{n}} + \sin \alpha \hat{\mathbf{t}}), \quad (8)$$

where $P_{\text{rad}}(r)$ is the solar radiation pressure defined in Equation (7), A_e is the effective sail area, and α is the angle between the incoming solar radiation and the sail normal $\hat{\mathbf{n}}$. The force due to the reflected radiation is

$$\mathbf{F}_r = RP_{\text{rad}}(r)A_e (-\cos \alpha \hat{\mathbf{n}} - \sin \alpha \hat{\mathbf{t}}) \quad (9)$$

where R is the reflectiveness of the sail surface's material. The effective surface area is the projected sail area orthogonal to the solar radiation, $A_e = A \cos \alpha$. Thus adding Equations (8) and (9), the total force acting on a flat sail is

$$\mathbf{F} = -P_{\text{rad}}(r)A \cos \alpha [(R + 1) \cos \alpha \hat{\mathbf{n}} + (R - 1) \sin \alpha \hat{\mathbf{t}}]. \quad (10)$$

It can be noted that for an angle $\alpha = \frac{\pi}{2}$ rad, the total force is equal to the null vector ($\mathbf{F} = \mathbf{0}$) because the resultant surface won't exist, that is, the projected area orthogonal to the radiation results in a line with no area. This can be interpreted as turning the sail away from the Sun, minimizing the radiation received at the observer in order to not accelerate.

On the other hand, when we want to maximize the number of particles at the observer, the sail is turned toward the source. This is the case of $\alpha = 0$, where the effective area is equal to

the real area of the sail itself and the total force is totally normal to the sail's surface, computed by

$$\mathbf{F} = -(R + 1) P_{\text{rad}}(r) A \hat{\mathbf{n}}. \quad (11)$$

From Equation (11):

- for a perfectly absorbent surface ($R = 0$), the total force is $\mathbf{F}_{R=0} = -P_{\text{rad}}(r) A \hat{\mathbf{n}}$;
- for a perfectly reflective surface ($R = 1$), the total force is $\mathbf{F}_{R=1} = -2P_{\text{rad}}(r) A \hat{\mathbf{n}}$;
- the two previous forces are related by $\mathbf{F}_{R=1} = 2\mathbf{F}_{R=0}$, analogously to the pressures in Equation (6).

3.4 Orbital Mechanics

When it comes to space travel and exploration, a basic framework of orbital mechanics is required. For this, we'll introduce some main concepts presented in [17] illustrated in Figure 8.

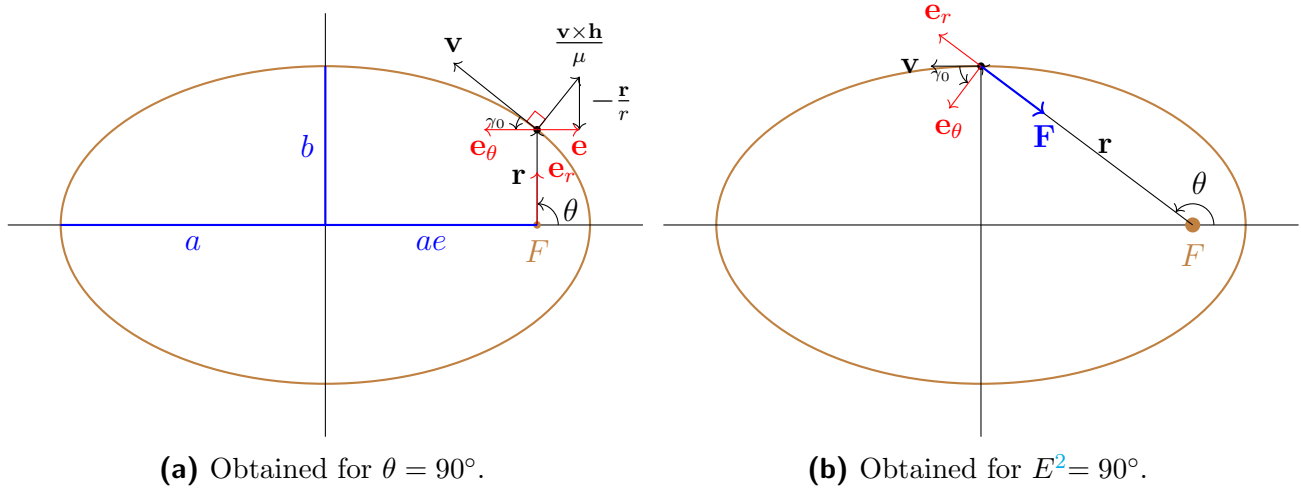


Figure 8: Elliptical orbits, set of vectors and nomenclature to ease the reading. a is the semi-major axis of the ellipse, b is the semi-minor axis of the ellipse, e is the eccentricity of the ellipse, F is the focus of the ellipse, $\mathbf{r}$ is the position vector, $\mathbf{v}$ is the velocity vector, $\mathbf{e}_r$ and $\mathbf{e}_\theta$ are respectively the normal and transverse unit vectors, $\gamma_0 = \angle(\mathbf{v}, \mathbf{e}_\theta)$ is the flight path angle, θ is the true anomaly, $\mathbf{e}$ is the eccentricity vector and $\mathbf{h} = \mathbf{r} \times \mathbf{v}$ is the angular momentum.

3.4.1 Gravitational central force

By Newton's law of universal gravitation, the interaction between two bodies (body $\leftrightarrow$ central body) with masses m and M ($m \ll M$) is given by

²Also known as eccentric anomaly, is the central angle of the auxiliary circle of radius a counted from the periapsis, related to the true anomaly by $\tan \frac{E}{2} = \sqrt{\frac{1-e}{1+e}} \tan \frac{\theta}{2}$ [17]

$$\mathbf{F} = -\frac{GMm}{r^2}\mathbf{e}_r, \quad (12)$$

where G is the universal gravitational constant and r is the distance between the two bodies. So, the force per unit mass is

$$\frac{F}{m} = f = -\frac{\mu}{r^2}, \quad (13)$$

where $\mu = GM$ is the gravitational parameter.

3.4.2 Gravitational potential and energy

The potential is the potential energy per unit charge. In the case of the gravitational force, the charge is the mass and can be written using f

$$U(r) = \int -f dr = \int_r^\infty \frac{-\mu}{\rho^2} d\rho = -\frac{\mu}{r}, \quad (14)$$

where ρ is the mute variable of integration and we chose as a reference the potential to be zero at infinity so that the potential is zero when the force is zero, *i.e.* when there is no interaction and the particle becomes free.

The kinetic energy T per unit mass is simply $T/m = v^2/2$, which, using Equation (14), results in the following expression for the energy per unit mass $\mathcal{E}$:

$$\mathcal{E} = \frac{v^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2a} \quad (15)$$

where a is the semi-major axis of any orbit.

3.4.3 Orbit equation

One of the most important aspects in orbital mechanics is to relate the distance between the central mass and the orbiting body, r , with the true anomaly, θ , (which is the angle between the direction of periapsis and the current position of the body). This is given by

$$r = \frac{p}{1 + e \cos \theta} = \frac{a(1 - e^2)}{1 + e \cos \theta}, \quad (16)$$

where p is the *semi latus rectum*, a the semi-major axis and e the eccentricity of any orbit.

3.4.4 Eccentricity vector

Also known as the Laplace-Runge-Lenz vector, the magnitude of this vector is always equal to the eccentricity, its direction points from the apoapsis to the periapsis and it is given by

$$\mathbf{e} = \frac{1}{\mu} \left(\dot{\mathbf{r}} \times \mathbf{h} - \mu \frac{\mathbf{r}}{r} \right), \quad (17)$$

where $\mathbf{h} = \mathbf{r} \times \dot{\mathbf{r}}$ is the angular momentum vector, that is, the cross product between the radial position and velocity vectors. This vector is quite useful to calculate the orientation of the orbit which may change after a maneuver.

3.4.5 Determination of any orbit's semi-major axis from $\mathbf{r}_0, \mathbf{v}_0$

We might know the initial conditions $\mathbf{r}_0, \mathbf{v}_0$, or measure those same conditions at a certain instant, and want to predict the location of the object in the future, *i.e.*, know its orbit and position as a function of time. From Equation (15), computed in the initial point

$$\mathcal{E} = -\frac{\mu}{2a} = \frac{v_0^2}{2} - \frac{\mu}{r_0}, \quad (18)$$

it is possible to compute the semi-major axis right away

$$a = \frac{r_0}{2 - \frac{r_0 v_0^2}{\mu}}. \quad (19)$$

3.4.6 Vis-viva equation and excess velocity

From Equation (15) solved to the velocity, we get

$$v = \sqrt{2\mu \left(\frac{1}{r} - \frac{1}{2a} \right)} \quad (20)$$

known as the *vis-viva* (life-force) equation, a term from the History of Mechanics when the concept of energy was being developed. We can see that the excess velocity on a hyperbolic trajectory is the velocity for which the body's velocity will converge when its distance from the central body goes to infinity. Thus, from applying $r \rightarrow \infty$ to the Equation (20), we get

$$v_\infty = \sqrt{\lim_{r \rightarrow \infty} 2\mu \left(\frac{1}{r} - \frac{1}{2a} \right)} = \sqrt{-\frac{\mu}{a}}. \quad (21)$$

4 Solar Sail Technologies

Figure 9 represents the solar sail technologies for realizing on-orbit applications aspects like system design, flexible materials, membrane dynamics, structure control, ground testing technology, and control strategy.

This section will discuss the current system design of a solar sail, the deployment mechanism design, the membrane of the sail (material and folding patterns), and the ground testing considerations, containing information obtained from [18–21].



Figure 9: Key technologies of solar sails. (inspired by [18])

4.1 System design

The current solar sail system design follows the design guidelines of miniaturization, modularity, economy, practicality, and reliability. The design methods and structural forms of solar sails are different, which mainly depends on different missions' requirements (as is shown in Table 2).

The overall design of the solar sailing system has many similarities with other spacecraft. For the purpose of achieving on-orbit operation and performing space missions, the system must be integrated including, at least, the following sub-systems: propulsion system, structural system, power supply system, measurement and control system, thermal control system, attitude and orbit control system, communication system and payloads. The structural system is the main body of the spacecraft, which provides structural support for other systems. The measurement

and control system including telemetry, remote control, and tracking forms a closed loop for the solar sail. The attitude and orbit control system, and thermal control system can jointly maneuver and maintain the normal operation of the spacecraft. The attitude control system is particularly interesting when it comes to solar sails: these systems are usually comprised of weaker thrusters (such as cold gas thrusters, small hypergolic engines, or reaction control wheels); however, in the case of solar sails, most of these methods are unsuitable. There are a few solutions unique to the solar sail design, such as a translating control mass – this solution would allow the change of the spacecraft's center of mass, introducing a rotation, and thus allowing for the modulation of the force acting on the sail.

4.2 Deployment mechanism design

Membrane deployment is the first step for solar sail design. The deployment methods of solar sails are mainly divided into two categories: sail exploit centrifugal force (spin-stabilized and deployed by the centrifugal force) and sails deployed by booms (remains stable at three axes in orbit).

4.2.1 Spinning solar sail deployment

A spinning solar sail deployment mechanism (see Figure 10) typically involves using centrifugal force to unfurl the sail. The design of this type of sail usually consists of a central hub around which the sail is wound during the launch phase. The central hub serves as the anchor point for the sail during launch. It should be sturdy and capable of withstanding the forces involved in the spinning deployment process, while the sail material should be lightweight, durable, and highly reflective to maximize the solar radiation pressure. Materials like Mylar® or other thin films are commonly used for solar sails. Deployment arms are attached to the central hub and extend outwards, holding the sail material and facilitating its controlled unwinding during the spinning process. The arms should be flexible yet strong enough to resist the forces exerted on them. To ensure proper sail deployment, mechanisms such as springs or lightweight cables can be used to maintain the necessary tension on the sail during spinning. It is important to have the means to control and adjust the spinning speed to achieve the desired deployment – this can be achieved with small thrusters or reaction wheels. Once the sail is fully deployed, stabilization mechanisms like reaction wheels or gyroscopes may be employed to maintain the desired orientation and stability of the spacecraft.

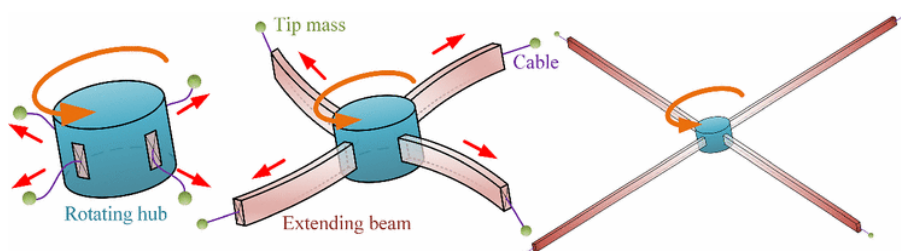


Figure 10: Spinning solar sail deployment. [20]

Taking the IKAROS mission as an example, the spinning deployment mechanism uses cen-

trifugal forces to deploy the membrane at a rotation speed of 25 rpm without any supporting structures. Eliminating the booms contributes to a major advantage of the spinning solar sail. The solar sail has only the central hub as its main structure, shown in Figure 11. The central circular groove is used to store the membrane, and the four supporting cylinders protruding from the central circular groove are used to fix the membrane. The deployment consists of two stages, being the first stage the draw out of the sail to make it into a cross shape, and in the second stage the cross-shaped sail is released into a fully deployed shape.

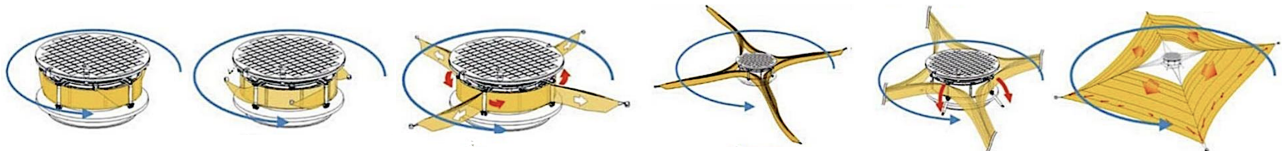


Figure 11: IKAROS mission deployment system process. [18]

4.2.2 Sails deployed by booms

Solar sails deployed by booms are another mechanism commonly used for solar sail deployment. In this design, booms or extendable arms are used to deploy the sail (see Figure 12), and they are lightweight and extendable structures typically made of materials such as carbon fiber or other lightweight composites to minimize mass while maintaining structural strength. The sail material should be thin, flexible, and reflective to maximize solar radiation pressure. Common materials include Mylar® or other lightweight reflective films. The boom is stored and folded during the launch phase and then extended or unfolded in space to deploy the sail. Different mechanisms can be used to achieve this, such as shape memory alloys, motor-driven mechanisms, or even inflatable booms. The sail is attached to the booms at multiple points along its edges to evenly distribute the load. These attachment points should be secure and designed to support the forces encountered during deployment and operation. To ensure controlled and synchronized deployment, the booms can be equipped with locking or latching mechanisms that hold them in place during launch and release them in space. Timing and sequencing mechanisms may also be incorporated to coordinate the deployment process. Once the sail is fully deployment, stabilization mechanisms such as reaction wheels, gyroscopes, or active control systems may be employed to maintain the desired orientation and stability of the spacecraft.

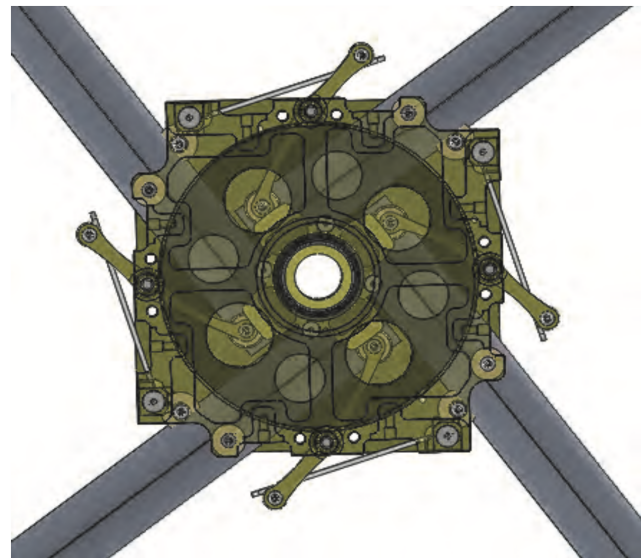


Figure 12: Sail deployment mechanism by booms. [22]

Also known as a three-axis stable solar sails deployment mechanism, this type of deployment method is relatively complicated due to the supportive way of deployment. They are normally

divided into three types according to different driven methods: Inflatable deployment, mechanical deployment, or elastic deployment. Similar design concepts comprised of a central scroll, guide cylinders, motors, and composite booms. Reliability and storage efficiency are indicators for evaluating deployment mechanisms, which determine the structure performance. For spinning solar sail, the deployment mechanism yields high packing efficiency but is very complicated and easy to fail.

4.2.3 Deployment booms

Boom plays the role of deploying and supporting the sail membrane in three-axis solar sails. Brown [21] proposed a novel deployment compression element, the NRL Super-string mast, which enabled trusses to deploy to be extremely long. The deployment booms have the advantages of lightweight and small storage volume and can reach 7 m. The composite booms with four different cross-section configurations are given in Figure 13.

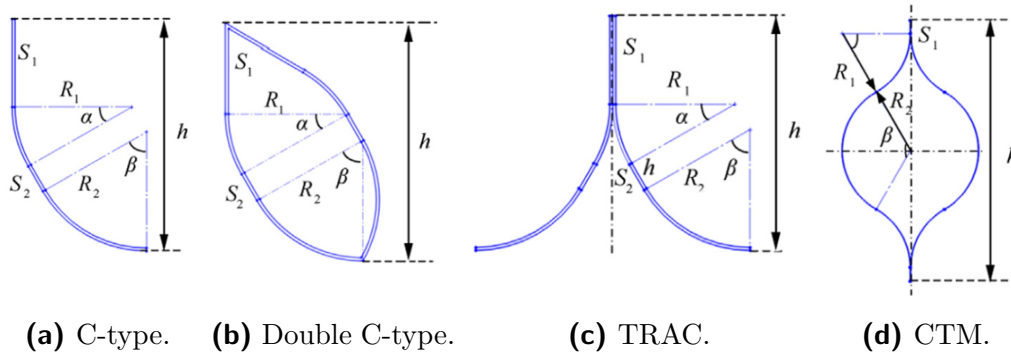


Figure 13: Geometries of boom cross sections. [18]

4.3 Membrane

The membrane is a functional component of solar sail systems, and the material and reflectivity efficiency affect the performance of the solar sail spacecraft directly.

4.3.1 Membrane material

The selection of the material is critical to the mechanical and dynamic performance of solar sails, in which it must not only have excellent mechanical proprieties, but also be able to withstand high and low temperatures, cycling stability, and radiation in space. Advance sail membrane materials with optical and infrared properties, as shown in Table 3, are normally used for solar sails.

As the most important functional component of solar sails, the optimization of membrane material properties and improvement of material degradation performance are always of importance. Innovative membrane materials with higher specific stiffness and strength, high-temperature resistance, and stronger resistance to oxygen atomic erosion or ultraviolet radiation exposure and tear propagation will be persistent technical issues.

Table 3: Sail membrane materials with optical and infrared properties. Note that α , ρ_{solar} , ε and ρ_{thermal} stand for absorbance, solar reflectance, emittance, and thermal reflectance, respectively. [18]

Material		Core Polymer	Coating	α	ρ_{solar}	ε	ρ_{thermal}
Metallized PI	Reflective	Kapton®EN	Al/100 nm	0.1	0.9	0.03	0.97
	Emissive	5 μm	Cr/30 nm	0.54	0.46	0.48	0.52
Aluminized CP1	Reflective	LaRC™CP1	Al/90 nm	0.1	0.9	0.03	0.97
	Emissive	2.54 μm	–	0.17	0.83	0.29	0.71
Aluminized PET	Reflective	Mylar®	Al/100 nm	0.09	0.91	0.02	0.98
	Emissive	2.54 μm	–	0.14	0.86	0.25	0.75
Aluminized PEN	Reflective	Teonex®Q72	Al/100 nm	0.1	0.9	0.03	0.97
	Emissive	2 μm	Cr/15 nm	0.57	0.43	0.6	0.4

4.3.2 Folding patterns

For the consideration of transportation expenses, the solar sail membrane is normally folded to fit the storage space of the deployment mechanism. Folding and deploying techniques also have profound impacts on the force transmission path and surface flatness of the deployment sail membrane. The principle of origami has been studied well and utilized to fold solar sail membranes.

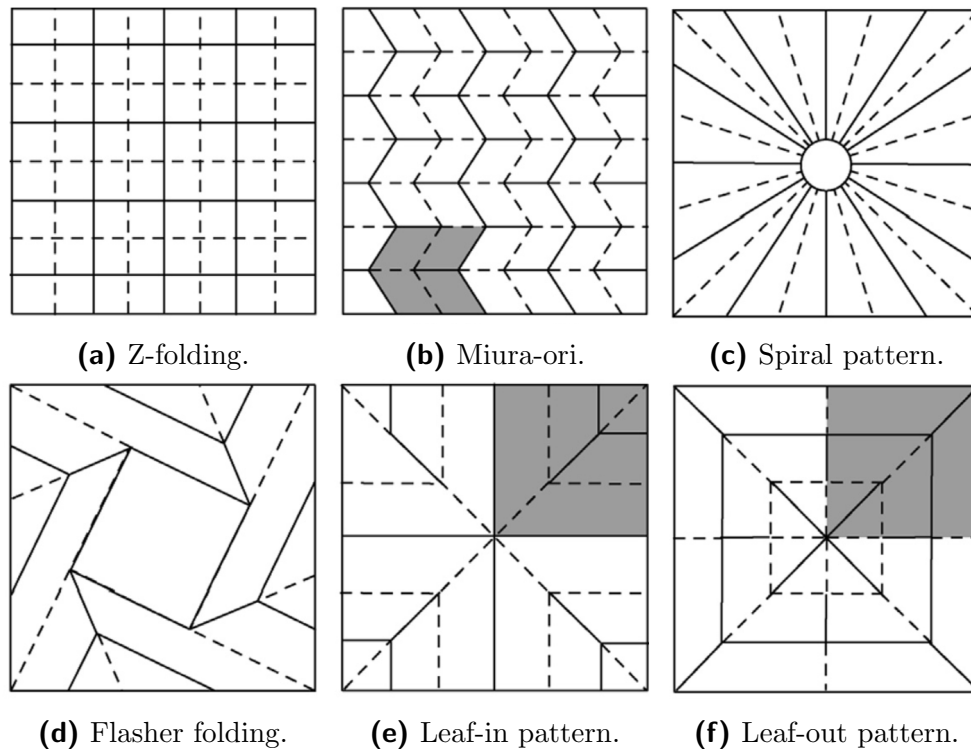


Figure 14: Typical origami configurations of folding solar sail membranes. [18]

The Z-fold, in Figure 14a, known as the accordion fold, is the most commonly used folding and deployment method for a solar sail deployed by booms, which compresses a large plane

horizontally or longitudinally folded into a small volume.

The folding patterns and sail storage are important considerations in the design of the solar sail because long-term storage of the folded sail membranes results in stickiness between adjacent folds, which makes membranes easy to be torn during the deployment process. Also, the direction of tension forces to deploy folded membranes and the residual creases in the sail should be carefully designed to achieve a planar sail shape.

4.4 Ground testing technology

Ground testing of solar sail deployment mechanisms (see Figure 15) is an important step in their development and validation. These tests allow engineers to assess the functionality, reliability, and performance of the deployment mechanism in a controlled environment before its actual implementation in space. Here are some common methods and considerations for ground-testing solar sail deployment mechanisms:

1. **Prototype testing:** Engineers often build full-scale or scaled-down prototypes of the deployment mechanism to simulate the actual deployment process. This allows them to evaluate the mechanism's functionality, structural integrity, and any potential issues that may arise during deployment.
2. **Environmental simulation:** Ground tests can simulate the environmental conditions that the solar sail will experience in space, such as vacuum, temperature variations, and vibration. These simulations help assess how the deployment mechanism performs under such conditions and identify any necessary modifications or improvements.
3. **Load testing:** The deployment mechanism should be subjected to load testing to evaluate its strength and endurance. Various load scenarios, including different sail sizes and orientations, can be applied to ensure the mechanism can handle the expected forces during deployment.
4. **Deployment timing and sequencing:** Timing and sequencing tests are performed to ensure proper coordination of the deployment process. This involves verifying that the mechanism deploys at the correct rate, in the right sequence, and with the desired tension on the sail.
5. **Reliability and failure analysis:** Ground testing allows engineers to assess the reliability of the deployment mechanism and identify potential failure points or weaknesses. This information is crucial for making design improvements and ensuring a successful deployment in space.
6. **Instrumentation and data collection:** Sensors and instrumentation can be incorporated into the ground test setup to capture data on deployment forces, structural behavior, and other relevant parameters. This data helps in analyzing the performance of the mechanism and validating its design.

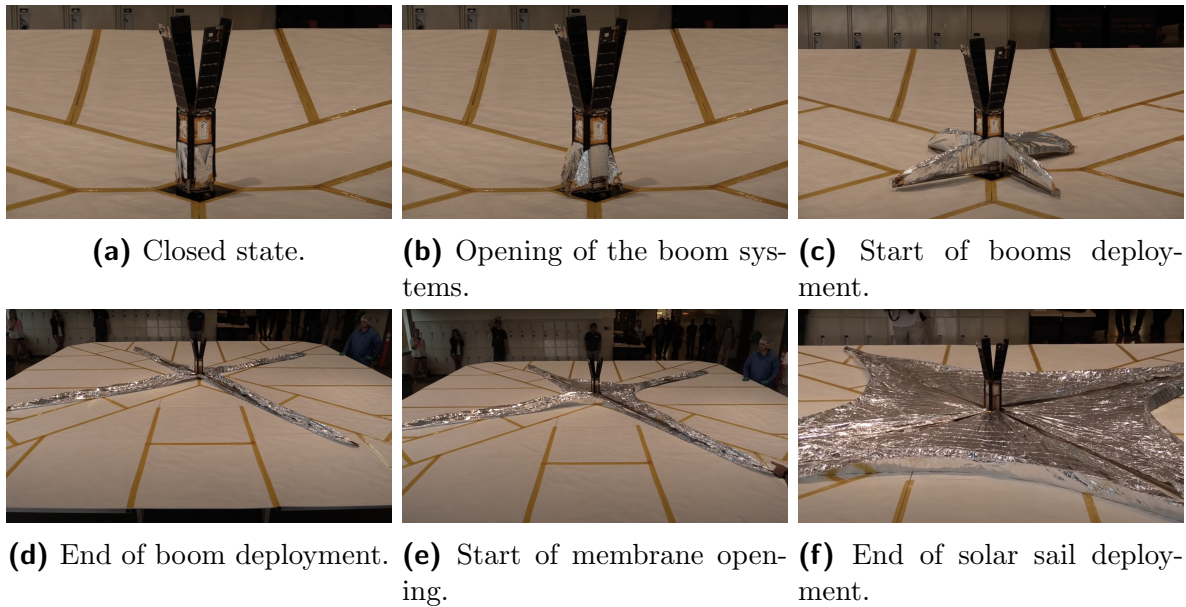


Figure 15: Ground testing of a solar sail deployment system phases. These images were obtained from frames of [this video](#).

By conducting thorough ground testing, engineers can refine and optimize the solar sail deployment mechanism to ensure its successful operation in space. It also helps mitigate risks and increases confidence in the deployment system's performance before its actual use in a space mission.

5 interstellar Simulator

Traditional orbital simulation methods (like the software [GMAT](#)), typically designed to handle short-duration thrust events, may not accurately reflect the dynamics and characteristics of solar sailing missions. Therefore, we decided to create a custom [Python](#) orbit simulator named [interstellar](#) that offers a tailored approach to analyzing these specific propulsion techniques and the impact they have on spacecraft trajectories.

With a custom orbit simulator, we can simulate various mission scenarios, optimize flight paths, and better understand the intricate factors influencing the behavior of solar sails. The custom simulator provides a toolset capable of handling a few continuous propulsion scenarios, thus offering a more accurate and detailed simulation of solar sail missions.

Our simulator supports a range of different options, such as specifying the initial orbit parameters (initial position, velocity, semi-major axis, eccentricity, and true anomaly) as well as the mass of the center body. The simulation time steps can be tweaked depending on the duration, and the output can include a video of the trajectory, snapshots at different time frames, or simply the raw positions and velocities at each time frame.

This simulator works by taking some set of initial conditions (which are provided through command-line arguments) and computing the initial position and velocity of the spacecraft, if needed. These will be the initial conditions of the initial value problem it must solve. We then take an optional external acceleration $\mathbf{a}_x$ provided by the user at every iteration and setup a system of equations that govern motion, described as follows

$$\ddot{\mathbf{x}} = \mathbf{a}_x + \mathbf{a}_G \stackrel{\text{Eq. (13)}}{\Leftrightarrow} \ddot{\mathbf{x}} = \mathbf{a}_x - \frac{\mu}{\|\mathbf{x}\|^2} \mathbf{e}_r \Leftrightarrow \begin{cases} \dot{\mathbf{v}} = \mathbf{a}_x - \frac{\mu}{\|\mathbf{x}\|^2} \mathbf{e}_r \\ \dot{\mathbf{x}} = \mathbf{v} \end{cases}, \quad (22)$$

where $\mathbf{a}_G$ is the gravitational acceleration replaced by Equation (13), $\mathbf{x}$ is the position vector, $\mathbf{v}$ is the velocity vector, and $\mathbf{e}_r$ is the radial unit vector, all of them being two-dimensional. We solve this system using the Runge–Kutta method to get an estimate of the trajectory.

A number of useful approximations were made in the simulator: it's assumed that there is a small body orbiting a stationary, much larger object and so, in the case of our solar system and a heliocentric orbit, only the Sun's pull on the spacecraft is considered; when modeling the sail's interaction with solar radiation, we always assume $\alpha = 0$, that is, the solar sail is orthogonal to the Sun and the exerted force is being maximized, or $\alpha = \frac{\pi}{2}$ where the force is zero.

The prediction of the trajectory is then computed by calculating the instantaneous values of the semi-major axis a and eccentricity vector $\mathbf{e}$, according to Equations (19) and (17), respectively.

The commands used to generate the trajectories presented throughout this project are shown in the Annex A.

6 Interstellar Travel Feasibility

6.1 Promise and challenges

In the grand arena of interstellar travel, the application of solar sails emerges as a promising yet challenging technology that may reshape our approach to the cosmos.

In the realm of manned missions, the use of solar sails could drastically increase living and storage space within the spacecraft, as the need for traditional fuel storage is eliminated. The same benefits apply to unmanned voyages, with the added boon of greater mission flexibility and potentially extended operational periods, due to the sustainable nature of this propulsion technique.

Yet, the prospect of such a revolution in space exploration doesn't come without its fair share of obstacles and potential hazards. The very act of deploying a vast, delicate sail in the brutal, unpredictable conditions of outer space poses significant technical challenges. The risk of damage from micrometeoroids and radiation effects is not negligible, and this risk becomes even more poignant when considering manned missions, where the safeguarding of human lives is of utmost importance.

Further, the promise of fuel-free propulsion does not guarantee swift journeys through the cosmos. Solar sail-propelled spacecraft, though free of the burden of fuel, will initially accelerate at a slower pace compared to their chemical rocket counterparts. However, given sustained exposure to sunlight, these spacecraft can continue to accelerate over time, potentially achieving impressive speeds suitable for interstellar travel.

In the following sections, we will take a look at the feasibility of this method of space travel and present some rough estimates regarding travel times and size requirements.

6.2 Travel times and size requirements

To evaluate the feasibility of interstellar travel using solar sails, it is useful to study some of the top speeds achievable with slingshot maneuvers around the Sun. Getting close to the Sun is important since solar radiation pressure gets weaker with the square of the distance to it. A NASA publication [23] talks about some rough estimates for target velocities and the fly-by distances required. The orbit is highly eccentric, with an eccentricity of $e = 0.9$, and has a semi-major axis of $a = 2.782 \times 10^7$ km. It's important to note that the eccentricity parameter was chosen as a “good-enough” value – it was not mentioned in any of the cited publications or obtained from any mathematical method. This is further discussed in Subsection 8.2.

Figure 16 shows a simulated trajectory of a probe with the characteristics in Table 4.

Table 4: Solar sail parameters.

Parameter	Value
Mass, m	75 kg
Reflective Area, A	10 000 m ²
Reflectiveness, R	1.0

In the depicted maneuver (Figure 16), the sail is tilted to minimize the area exposed to the Sun's light ($\alpha = \frac{\pi}{2}$) until the true anomaly θ is zero and its distance to the star is two solar radii (6.956×10^5 km). The sail is then turned to the Sun ($\alpha = 0$) which eventually turns the elliptical orbit into a hyperbolic one. This is done because the force felt by the sail due to the solar radiation pressure has the same direction as the radial vector, which is much more efficient and can be seen in Figure 17.

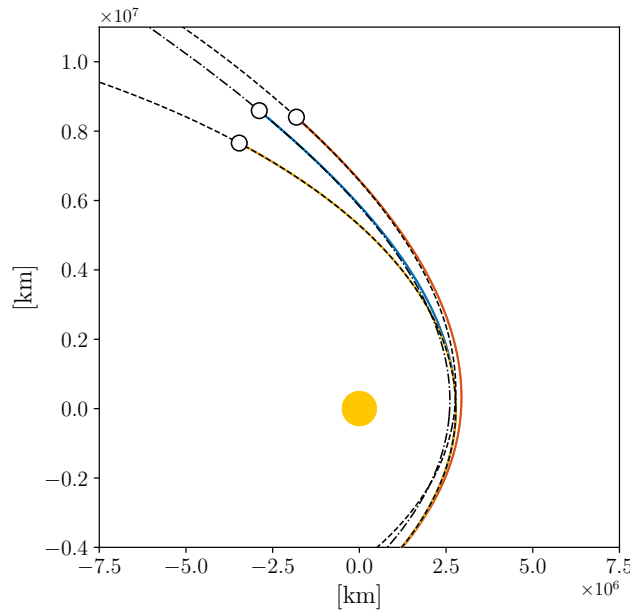


Figure 17: Comparison between 3 different trajectories. The yellow one is an elliptical trajectory where $\alpha = \frac{\pi}{2}$ and thus no pressure is felt; the blue one is our chosen trajectory for the maneuver and we can see that after just 13 hours and 53 minutes, it is already on an escape course from the solar system; the orange trajectory has the sail tilted orthogonally to the radiation source ($\alpha = 0$) since the beginning (before $\theta = 0$, the perihelion) and we can see it has not yet managed to escape the Sun's gravity well. The video for this simulation can be seen [here](#).

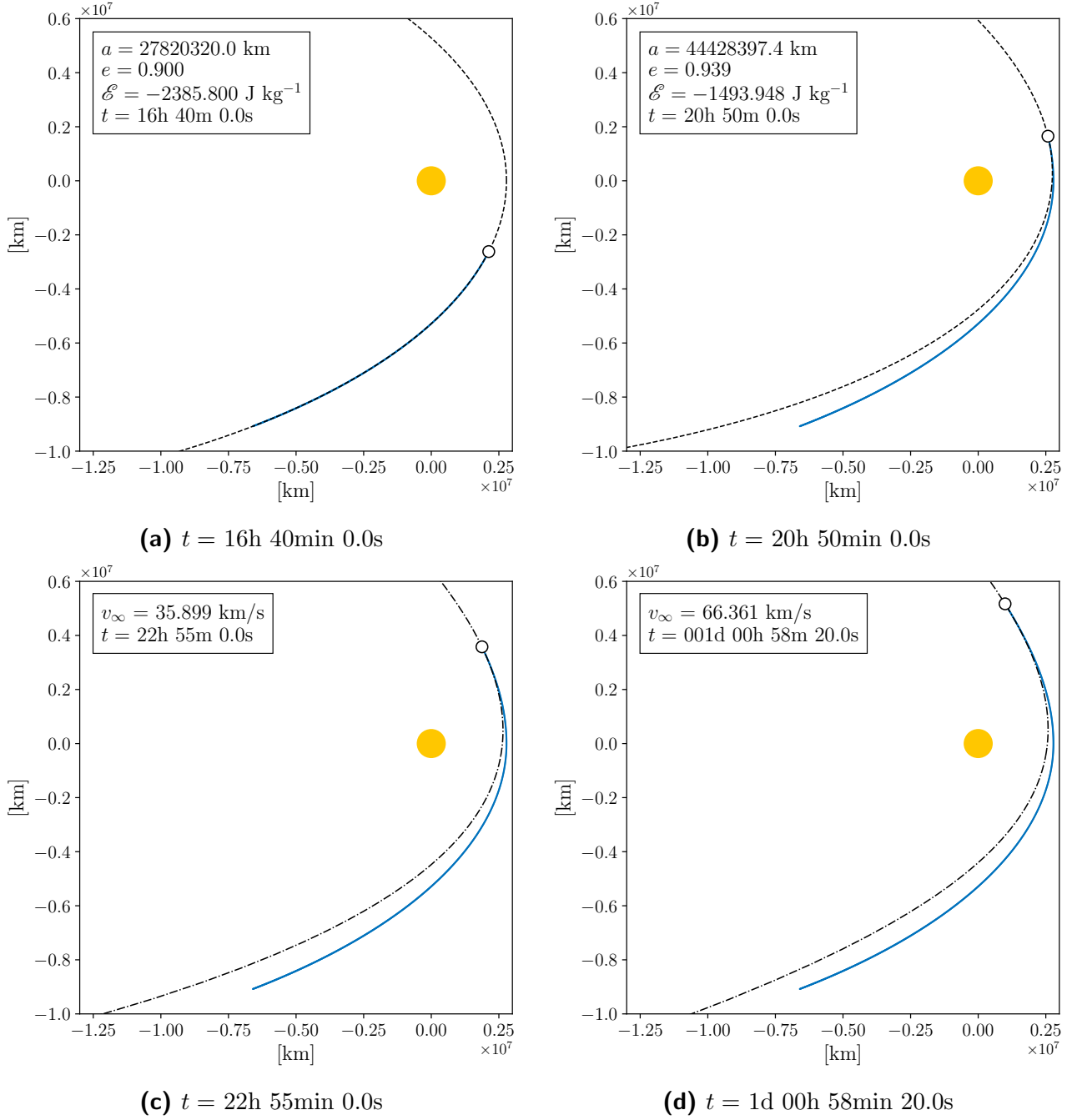


Figure 16: Simulated trajectory of a solar sail's solar system escape. In dashed and dash-dotted lines, the current elliptical and hyperbolic orbits, respectively. The trajectory from the beginning of the times is represented as a blue solid line. The video for this simulation can be seen [here](#).

It's important to note that for this to work (Figure 17), the solar sail must be placed into this highly elliptical orbit around the Sun, which is not an easy task. It would likely only deploy the sails once close to the perihelion and while not facing the Sun, as mentioned earlier.

After simulating this trajectory for 10 years, the probe was around 26.2 au away from the Sun and with a speed of around 121 km s^{-1} , and not increasing that much due to the huge distance between the sail and the source of the radiation – in fact, 95% of the speed is acquired in the first 72 hours of the trip.

Figure 18 shows the norm of the velocity vector and the estimated excess velocity v_∞ using Equation (21) along the trip. It can be seen that after the initial approach, the ship loses velocity gradually as it moves away from the Sun while the value of v_∞ increases, but they slowly converge to the same value.

Figure 19 shows the same plots but for various sails with different areas. As expected, increasing the area increases the final velocity of the craft. The smallest sail isn't represented in the right graph because it does not manage to escape the Sun's gravity well. We'll see below this threshold area value.

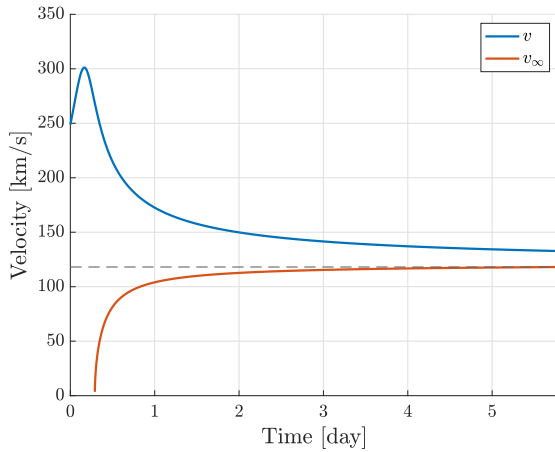


Figure 18: Norm of the velocity vector and the estimated excess velocity of the spacecraft over time. Note that the maximum happens for $\theta = 0$, the perihelion. The dashed line represents the final velocity upon leaving the Sun's gravity well.

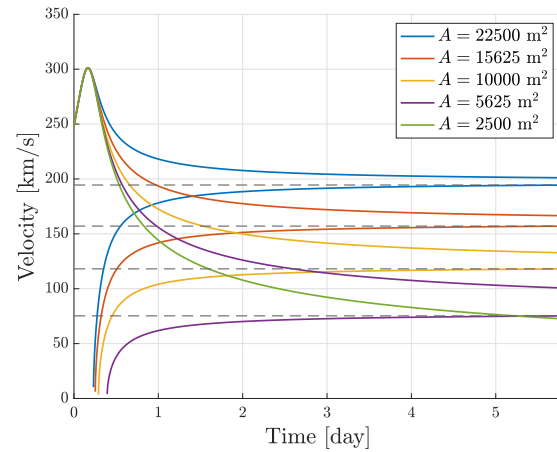


Figure 19: Norm of the velocity vector and the estimated excess velocity of different areas over time. The dashed line represents the final velocity upon leaving the Sun's gravity well.

We can also visualize the different trajectories of these spacecraft using `interstellar` to see how they are impacted. This is shown below in Figure 20.

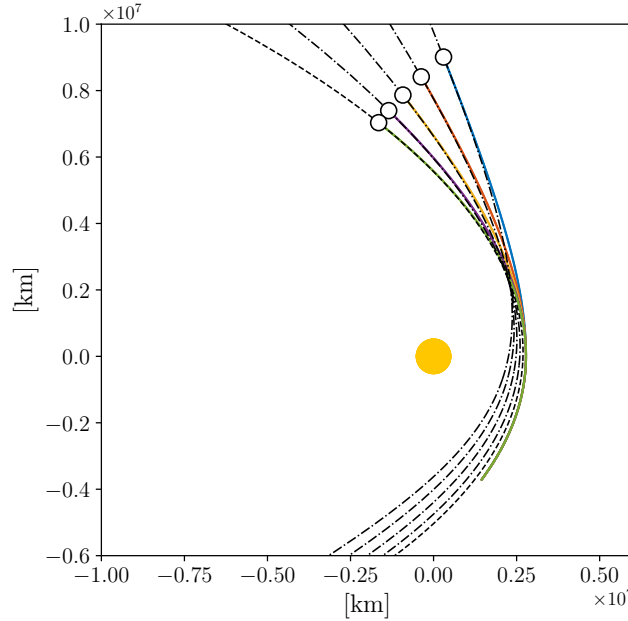


Figure 20: Trajectories of sails with different areas. Sail 1 – 22 500 m²; Sail 2 – 15 625 m²; Sail 3 – 10 000 m²; Sail 4 – 5625 m²; Sail 5 – 2500 m². The video for this simulation can be seen [here](#).

Plotting the value of v_∞ at the end of the simulation with respect to the sail's area, we find that it seems to be proportional to the square root of the area, as can be seen in Figure 21.

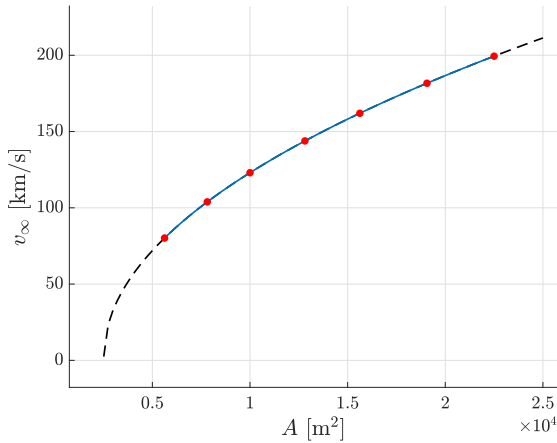


Figure 21: Final velocities for sails with different areas.

In fact, fitting a function $v_\infty(A) = k_1\sqrt{A - k_2} + k_3$ to the data, we obtain the following parameters:

Table 5: Velocity fit parameters.

Parameter	Value
k_1	1.393
k_2	2511 m ²
k_3	-2.459 km s ⁻¹
MSE	3.888×10^{-5} km s ⁻¹

We can see from this fit that a sail with an area of less than $k_2 = 2511$ m² cannot escape the solar system using this maneuver. Furthermore, using it we can compute some top speeds and travel times when sailing to different locations, such as 1000 au away from the Sun (as

mentioned in [23]) or to Proxima Centauri, the closest star system to ours, at a distance of around 4.2465 light years (2.6855×10^5 au) away.

Table 6: Travel speeds and times up to different distances.

Area [m ²]	Top Speed [km s ⁻¹]	1000 au [years]	Proxima Centauri [years]
5000	67.04	70.71	18989
10000	118.09	40.14	10780
22500 ³	194.49	24.37	6167
60000 ⁴	331.54	14.30	3840

These values were obtained using generous estimates for the parameters like sail area and mass. It can be seen in Table 6 that using current and proposed technology, the travel times to reach 1000 au are within a human lifetime, matching up with the NASA publication cited earlier. However, traveling to other stellar systems remains infeasible, at least when only considering these simple slingshot maneuvers.

The travel times are an approximation simply computed as $t = \frac{d}{v_\infty}$, disregarding the time it takes to accelerate to v_∞ . However, as shown in Figure 18, the velocity of the ship decreases with time, so the estimate presented in this table is a longer time than the simulation would yield.

6.3 Issues and future prospects

In conclusion, it seems that using a solar sail for interstellar travel to achieve relativistic speeds presents substantial challenges. The two primary obstacles are the physics of solar radiation pressure and the limitations of currently known material science.

Solar radiation pressure, although a reliable force, is extremely weak. It decreases with the square of the distance from the Sun, rendering it less effective as the spacecraft moves farther into space, and always points from the Sun towards the spaceship – which is not ideal for most maneuvers. These properties limit the acceleration a spacecraft can achieve, making relativistic speeds unattainable without a sustained and extremely powerful radiation source, extremely large reflective array, or extremely close fly-by of the Sun.

Moreover, the concept of a solar sail requires it to be large yet lightweight. Thus, it necessitates a material that is simultaneously extremely thin, highly reflective, tremendously durable, and capable of withstanding extreme temperatures.

While the concept of a solar sail offers an enticing means of propulsion that requires no onboard fuel, the challenges related to the physics of solar radiation pressure and the demands on material science make achieving relativistic speeds for interstellar travel a formidable task. Continued research and advancements in both physics and materials science are needed to make this form of interstellar travel a practical reality. Future exploration might also look into alternative propulsion mechanisms, such as laser sails, fusion rockets, or antimatter propulsion, as potential means to achieve our interstellar ambitions.

³Proposed size for the Solar Pole Orbiter

⁴Proposed size for the Interstellar Heliopause Probe

7 Early Warning System

7.1 Solar storms and CMEs

Solar storms and Coronal Mass Ejections (CMEs) are phenomenal events that take place in the active atmosphere of the Sun, commonly referred to as the solar corona. These activities are essentially a part of the Sun's natural weather patterns and are driven by powerful, complex forces within the Sun itself.

A solar storm, also known as a solar flare, is a sudden flash of increased brightness on the Sun, usually observed near its surface and in close proximity to a sunspot group. They are a result of an intense and sudden release of energy driven by the complex interaction between the Sun's magnetic field and its plasma environment. The energy expelled during such a flare can be equivalent to millions of 100-megaton hydrogen bombs exploding at the same time.

Coronal Mass Ejections, on the other hand, are massive bursts of solar wind and magnetic fields rising above the solar corona or being released into space. They occur when the magnetic field of the Sun, which is twisted and knotted by the Sun's rotation and the movement of plasma, becomes too entangled and realigns into a more stable configuration, releasing vast amounts of energy and matter in the process.

Both these phenomena are more frequent during the peak of solar activity of the roughly 11-year-long solar cycle. They can have significant impacts on the Earth, especially on our modern, technology-driven society. They are capable of causing geomagnetic storms that can disrupt satellite operations, communications, navigation systems, and even power grids. For example, in 1989, a large solar storm knocked out power for the entire province of Quebec, Canada. [24]

To prepare for these types of events, an observation satellite could be placed between the Earth and the Sun. When a solar event was detected, the satellite could relay the information to Earth, providing a significant head start (depending on the distance from the satellite to our planet) since the signal could travel faster than the emitted particles. However, a satellite in a Keplerian orbit between the Sun and the Earth would orbit at a different speed, and thus there would not be a constant communication channel. We could instead place the satellite in a non-keplerian orbit using constant propulsion, which is where solar sails come in: the fuel requirements for an extended mission would be infeasible for a normal spacecraft, but the pressure of the Sun's radiation could keep our satellite in the desired orbit.

7.2 Station keeping

To keep the spacecraft in this non-keplerian orbit, we can first compute the velocity necessary to achieve this for a given radius:

$$v = \frac{d}{t} \Leftrightarrow v(r) = \frac{2\pi r}{1 \text{ sidereal year}} \quad (23)$$

Now, since we want the probe to exhibit uniform circular motion around the Sun at a specific velocity, we can equate the centripetal acceleration a_c and the resultant force $F_G - F_{\text{rad}}$ to find the required area, A , for this purpose, noting that G is the gravitational constant and $M_{\odot}$ is the mass of the Sun:

$$ma_c = F_G - F_{\text{rad}} \Leftrightarrow \frac{mv^2}{r} = G \frac{M_\odot m}{r^2} - A \frac{P_{\text{rad}}}{\left(\frac{r}{1 \text{ a.u.}}\right)^2} \Leftrightarrow A = m \frac{GM_\odot - r^3 \left(\frac{2\pi}{1 \text{ sidereal year}}\right)^2}{P_{\text{rad}} \times (1 \text{ a.u.})^2} \quad (24)$$

We can see from Equation (24) that the necessary area increases linearly with the mass of our probe and decreases with the cube of the distance to the Sun. It's important to note that we are disregarding the gravitational force of the Earth (and all the other planets) as previously stated, which would still be relevant until a distance of $\sim 9.29 \times 10^5 \text{ km}$ ⁵, where a is the semi-major axis of the smaller object's (in this case, the Earth's) orbit around the larger body (in this case, the Sun), and m and M are the masses of those same objects, respectively.

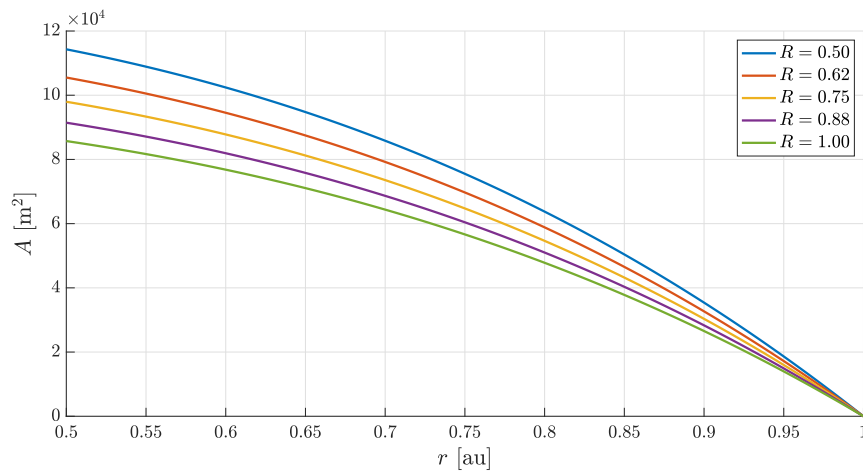


Figure 22: Required area for station keeping at different distances from the Sun for several reflectivenesses.

In Figure 22 we show the required area for a sail at a specific distance from the Sun, assuming a mass of 150 kg and 100% effective area.

Table 7: Warning times and required sail areas for different distances from the Earth.

Distance from the Earth [km]	Required Sail Area [m ²]	Warning Time [min]
1.5×10^6	2947	8.25 – 100
3×10^6	5808	16.5 – 200
4.5×10^6	8611	24.8 – 300

We can see in Table 7 that a solar sail placed 3 million kilometers away from the Earth (about twice as far as the L_1 ⁶) would require a sail with an area of 5808 m² corresponding to a square sail with a side length of around 72 meters. This would give Earth up to about 3 hours

⁵This number is computed using the expression for the sphere of influence, $r_{\text{SOI}} = a \left(\frac{m}{M}\right)^{2/5}$ [17]

⁶The L_1 point (first Lagrange point) sits between the Earth and the Sun in the place their gravitational forces cancel out

and 20 minutes of warning time, which might be enough to shut down critical infrastructure and prevent major damage to important electronic devices.

Using the data acquired here, we made use of our simulator to visualize what the orbit would look like for a giant sail stationed at $d = 0.5$ AU, which would require a sail area of $85\,807.455\text{ m}^2$ while weighing 150 kg , as shown in Figure 23. We chose this particular radius so that the difference between the “regular” orbital period⁷ and the observed one would be more apparent.

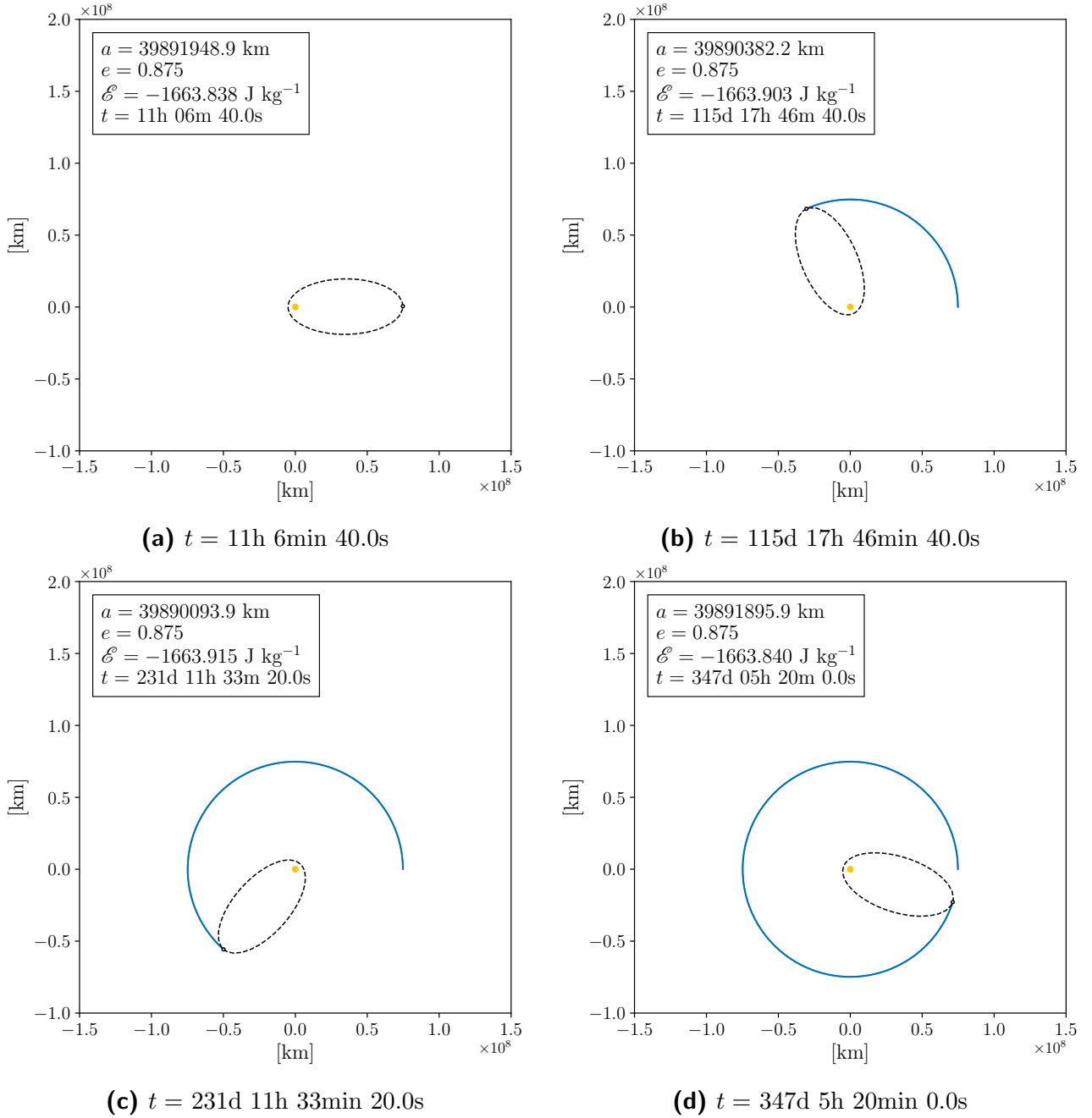


Figure 23: Simulated orbit of an early warning system satellite at different times. The video for this simulation can be seen [here](#).

⁷The orbital period for this heliocentric orbit is given by $T_{\odot} = \frac{2\pi}{\sqrt{\mu_{\odot}}}a^{3/2} \approx 129\text{ days}$ ($\odot$ refers to the Sun)

In red we see the simulated trajectory, while the dashed black line represents the predicted orbit if solar pressure was not a factor. We can see that our propulsion method rotates the immediate elliptical orbit resulting in a circular orbit with the desired period of one year.

7.3 Results and implications

As mentioned earlier, solar storms and CMEs pose a considerable risk to our modern, technology-dependent world. However, by stationing a solar sail-equipped observation satellite between the Earth and the Sun, we could significantly extend our warning times for these potentially devastating events. The calculations provided here indicate that such a satellite system, using a sail with an area of around 5808 m^2 and stationed around $3 \times 10^6\text{ km}$ away, could give Earth up to approximately 3 hours and 20 minutes of warning time. This timeframe could be crucial in preventing significant damage to vital electronic infrastructure.

A solar sail of this size seems to be within the capabilities of current technology. However, it's important to note that while the physics and engineering aspects of this idea discussed in this project seem feasible, there are still various practical and logistical challenges to overcome, including the manufacture and deployment of the solar sail, the design and operation of the observation satellite, and the coordination of Earth's response to the early warnings.

As our reliance on technology continues to grow, so does our vulnerability to solar events. With the recent advances in space technology and exploration, a solar sail-based early warning system as outlined in this work is becoming an increasingly appealing solution.

8 Conclusion

8.1 Achievements

In conclusion, this project has explored the potential applications of solar sails in the realm of space exploration, with a specific focus on interstellar travel and the creation of an early warning system against solar storms and other solar events.

It has demonstrated that while solar sails present an enticing means of propulsion that requires no onboard fuel, achieving relativistic speeds for interstellar travel presents substantial challenges, although reaching interstellar space itself seems to be doable with current technology. The two primary obstacles are the physics of solar radiation pressure and the limitations of currently known material science. Solar radiation pressure, although a reliable force, is extremely weak and decreases with the square of the distance from the Sun. This limits the acceleration a spacecraft can achieve, making relativistic speeds unattainable without a sustained and extremely powerful radiation source, extremely large reflective array, or extremely close fly-by of the Sun.

On the subject of material science, the concept of a solar sail requires it to be large yet lightweight, necessitating a material that is simultaneously extremely thin, highly reflective, tremendously durable, and capable of withstanding extreme temperatures. Continued research and advancements in both physics and materials science are needed to make this form of interstellar travel a practical reality.

The project has also shown that by stationing a solar sail-equipped observation satellite between the Earth and the Sun, we could significantly extend our warning times for potentially

devastating solar storms and Coronal Mass Ejections. The calculations provided here indicate that such a satellite system, using a sail with an area of around 5808 m^2 and stationed around 3 million kilometers away from the Sun could be a feasible solution.

8.2 Future work

In terms of future work, a study could be done on how much energy/ Δv would be needed to achieve the initial heliocentric orbit *versus* what the final velocity leaving the solar system, v_∞ , would be to potentially find an optimal starting orbit. The spacecraft's attitude control is also another interesting area of study, as how quickly we are able to perform attitude adjustments could impact the performance of the ship.

As an addendum, we would have also liked to understand why the fit in Table 5 seems to match the data so well. However, we did not have the time nor the scope to focus on this small detail (compared to the rest of the work) and try to derive the expression from other equations.

Overall, while the challenges are significant, the potential benefits of solar sail technology in terms of fuel-free propulsion and early warning systems for solar events make it a promising area for further research and development.

References

- [1] Pamela Clark. Mariner 10: A retrospective. *Mercury Messenger*, Issue 10, 2003.
- [2] B.C. Murray and E. Burgess. *Flight to Mercury*. Columbia University Press, 1977.
- [3] Eric Long. Mariner 10. <https://airandspace.si.edu/collection-media/NASM-A19830006000-NASM2019-01579>, 2017. [accessed 05/31/2023].
- [4] Jason Davis. Lightsail 2 ground finale. <https://www.planetary.org/space-images/lightsail-2-ground-finale>, 2016. [accessed 05/31/2023].
- [5] The Planetary Society. The story of lightsail, part 1. <https://www.planetary.org/sci-tech/the-story-of-lightsail-part-1>. [accessed 05/23/2023].
- [6] Bo Fu, Evan Sperber, and Fidelis Eke. Solar sail technology – a state of the art review. *Progress in Aerospace Sciences*, 86, 2016.
- [7] C. Sagan, W. Thompson, R. Carlson, et al. A search for life on earth from the galileo spacecraft. *Nature*, 365:715–721, 1993.
- [8] J. Kepler. Ioannis kepleri mathematici caesarei dissertatio cum nuncio sidereo: nuper ad mortales misso à galilaeo mathematico patavino. *H.F. Schulz in Kommission*, 1610.
- [9] Colin Robert McInnes. *Solar sailing – Technology, Dynamics and Mission Applications*. Springer London, 2013.
- [10] O. Mori et al. *Advances in Solar Sailing*, chapter Overview of IKAROS Mission. Springer, 2014.

- [11] Bong Wie. Solar sailing kinetic energy interceptor (kei) mission for impacting and deflecting near-earth asteroids. *Collection of Technical Papers - AIAA Guidance, Navigation, and Control Conference*, 2005.
- [12] Shannon Stirone. Lightsail 2 unfurls, next step toward space travel by solar sail. *The New York Times*, 2019.
- [13] Jason Davis / The Planetary Society. Lightsail 2 spacecraft successfully demonstrates flight by light. <https://www.planetary.org/articles/lightsail-2-successful-flight-by-light>, 2019. [accessed 06/01/2023].
- [14] Joel Grossman. Solar sailing: The next space craze? *Engineering & Science*, No. 4, 2000.
- [15] Greg Kopp and Judith L. Lean. A new, lower value of total solar irradiance: Evidence and climate significance. *Geophysical Research Letters*, 38, 2011.
- [16] Leonel Rios-Reyes. *Solar sails: modeling, estimation, and trajectory control*. Citeseer, 2006.
- [17] Paulo J. S. Gil. *Elementos de Mecânica Orbital*. Instituto Superior Técnico, 2015. Version: 1.1.6 (2020-01-11).
- [18] Yangmin LI Pengyuan ZHAO, Chenchen WU. Design and application of solar sailing: A review on key technologies. *Chinese Journal of Aeronautics*, 2022.
- [19] Bong Wie and David Murphy. Solar-sail attitude control design for a sail flight validation mission. *Journal of Spacecraft and Rockets*, 44, 2007.
- [20] Jialiang Sun, Qiang Tian, Haiyan Hu, and Niels Pedersen. Topology optimization of a flexible multibody system with variable-length bodies described by ale-ancf. *Nonlinear Dynamics*, 93, 2018.
- [21] Brown MA. A deployable mast for solar sails. *Adv Space Res*, 53, 2011.
- [22] C. Bidy and Tomas Svitek. Lightsail-1solarsail design and qualification, the 41st aerospace mechanism symposium. *Jet Propulsion Laboratory*, 2012.
- [23] Artur Davoyan. Extreme solar sailing for breakthrough space exploration. https://www.nasa.gov/directorates/spacetech/niac/2021_Phase_I/Extreme_Solar_Sailing_for_Breakthrough_Space_Exploration/, 2021. [accessed 07/15/2023].
- [24] NASA. The day the sun brought darkness. https://www.nasa.gov/topics/earth/features/sun_darkness.html, 2009. [accessed: 2023-07-02].

Appendices

A Simulator Commands

In each subsection below is represented the command line used in each simulation. Files `comparison.txt` and `escape.txt` used in these simulations are shown in Annex [B](#).

A.1 Experiment 1 – Figure [16](#)

```
python interstellar.py -a 27820320 -e 0.9 --theta 4.084070449666731 --timestep
↪ 100 -O hidden -o a27820320_e0.9_A10000_m75 --snapshots 600,750,825,899
↪ --frames 900 --limits "-1.3e7 0.3e7 -1e7 0.6e7"
↪ --acc-profile="acceleration_profiles.escape_up(1.0, 10000, 75)"
↪ --use-latex
```

A.2 Experiment 2 – Figure [17](#)

```
python interstellar.py --from-file comparison.txt --frames 700 --limits
↪ "-0.75e7 0.75e7 -0.4e7 1.1e7" --snapshots 700 --timestep 100 -O hidden -o
↪ comparison -E --use-latex
```

A.3 Experiment 3 – Figure [20](#)

```
python interstellar.py --from-file escape.txt --timestep 100 -O hidden -o
↪ a27820320_e0.9_Avar_m75 --frames 500 --limits "-1.3e7 0.3e7 -1e7 0.6e7" -E
↪ -s 500 --use-latex
```

A.4 Experiment 4 – Figure [23](#)

```
python interstellar.py -a 74798950 --velocity 0,14.892 -e 0 --frames 789
↪ --timestep 40000 -O hidden -o ews --limits "-1.5e8 1.5e8 -1e8 2e8"
↪ --acc-profile="acceleration_profiles.always(1, 85807.455, 150)"
↪ --snapshots 1,250,500,750 --use-latex
```

B Simulator Files

B.1 comparison.txt

This file is used in Figure 17 and contains the following text:

```
-a 27820320 -e 0.9 --theta 4.71238898038469
↪ --acc-profile="acceleration_profiles.escape_up(1, 10000, 155)" --color
↪ "#0072BD"
-a 27820320 -e 0.9 --theta 4.71238898038469
↪ --acc-profile="acceleration_profiles.always(1, 10000, 155)" --color
↪ "#D95319"
-a 27820320 -e 0.9 --theta 4.71238898038469 --color "#EDB120"
```

B.2 escape.txt

This file is used in Figures 19 and 20 and contains the following text:

```
-a 27820320 -e 0.9 --theta 5.084070449666731
↪ --acc-profile="acceleration_profiles.escape_up(1, 22500, 75)" --color
↪ "#0072BD"
-a 27820320 -e 0.9 --theta 5.084070449666731
↪ --acc-profile="acceleration_profiles.escape_up(1, 15625, 75)" --color
↪ "#D95319"
-a 27820320 -e 0.9 --theta 5.084070449666731
↪ --acc-profile="acceleration_profiles.escape_up(1, 10000, 75)" --color
↪ "#EDB120"
-a 27820320 -e 0.9 --theta 5.084070449666731
↪ --acc-profile="acceleration_profiles.escape_up(1, 5625, 75)" --color
↪ "#7E2F8E"
-a 27820320 -e 0.9 --theta 5.084070449666731
↪ --acc-profile="acceleration_profiles.escape_up(1, 2500, 75)" --color
↪ "#77AC30"
```