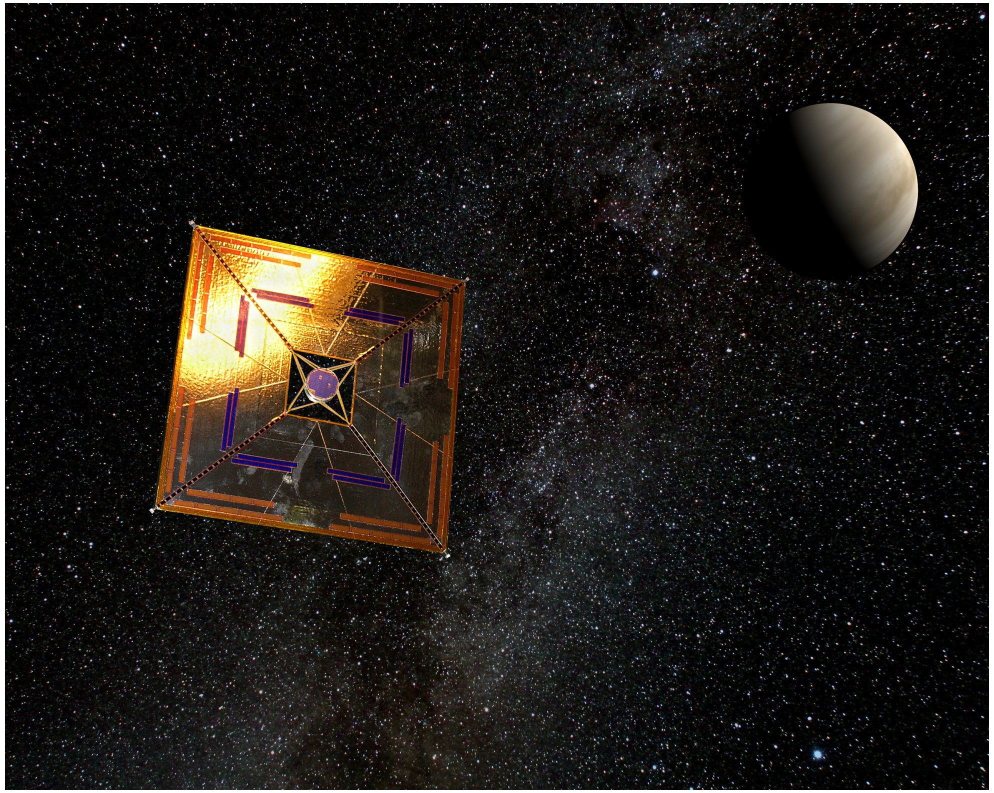
AA103
Air and Space Propulsion

Space Sailing



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Properties of light

- Momentum

$$p = \frac{h}{\lambda}$$

- Energy

$$E = h\nu = h\frac{c}{\lambda} = pc \quad ; \quad \begin{array}{l} h = 6.63 \times 10^{-34} \text{ Joule} - \text{sec} \\ c = 3.00 \times 10^{8} \text{ M / sec} \end{array}$$

Reference - *Space Sailing* by Jerome L. Wright, Gordon and Breach Science Publishers 1994

Much more current - https://en.wikipedia.org/wiki/Solar_sail

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Properties of light, cont'd

- Energy flux

$$W = \left[\frac{\text{Joules}}{\text{photon}}\right] \bullet \left[\frac{\text{photons}}{M^2 - \text{sec}}\right] = h\nu \bullet \left[\frac{\text{photons}}{M^2 - \text{sec}}\right] = \left[\frac{\text{Joules}}{M^2 - \text{sec}}\right]$$

At the earth's radius from the sun

$$W_{earth} = 1368 \ \text{Joules} / M^2 - \text{sec}$$

$$W_{earth} / c = 4.56 \times 10^{-6} N / M^2$$

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Properties of light, cont' d

- Light pressure on a perfectly reflecting surface normal to the incidence direction of light

$$P = 2W / c$$

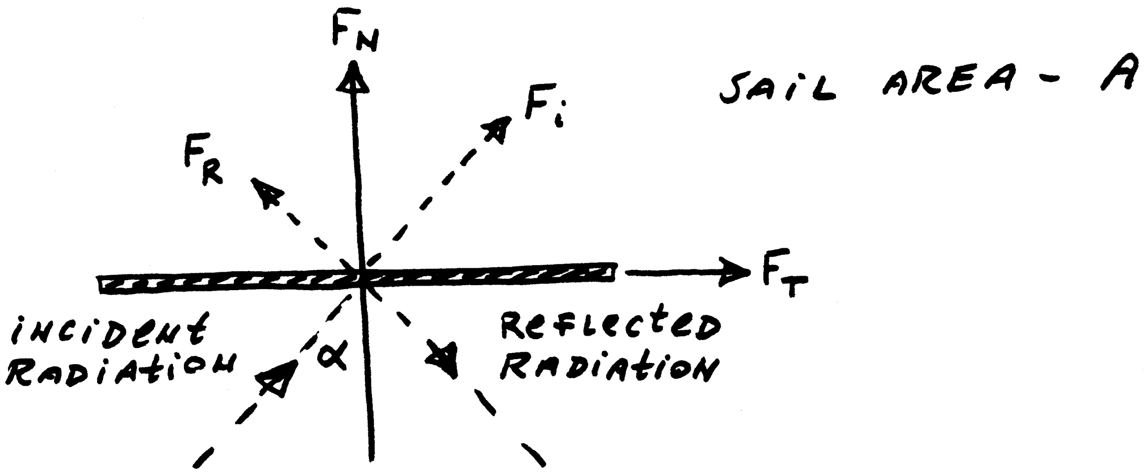
At the earths radius

$$P_{earth} = 9.12 \times 10^{-6} \quad N / M^2$$

At other radii

$$P = \left(9.12 \times 10^{-6} \quad N / M^2\right)\left(\frac{r_{earth}}{r}\right)^2 \quad ; \quad \frac{r}{r_{earth}} = \text{radius in AU}$$

Light Force on a Sail



$$F_N = F_i \cos\alpha + F_R \cos\alpha \quad ; \quad F_T = F_i \sin\alpha - F_R \sin\alpha$$

- Perfect reflection

$$F_i = \frac{W}{c} A \cos\alpha \quad ; \quad F_R = \frac{W}{c} A \cos\alpha$$

$$F_N = 2\frac{W}{c} A \cos^2\alpha \quad ; \quad F_T = 0$$

Light Force on a Sail, cont'd

- Taking account of reflected, absorbed and radiated energy

$$\frac{F_N}{\left(2\frac{W}{c}A\right)} = \frac{(1+rs)\cos^2\alpha + B_f r(1-s)\cos\alpha + \frac{B_f e_f - B_b e_b}{e_f + e_b}(1-r)\cos\alpha}{2}$$

$$\frac{F_T}{\left(2\frac{W}{c}A\right)} = \frac{(1-rs)\cos\alpha\sin\alpha}{2}$$

where

r = reflectivity of the front surface for the incident radiation
s = specular reflection coefficient
ef, eb = front and back surface IR emission coefficients for wavelength of emitted radiation based on sail temperature.
B_f, B_b= Non-Lambertian coefficients for front and back surfaces.

Sail acceleration

The size of a sail is determined by the mass of the payload and the characteristic acceleration required for a particular mission.

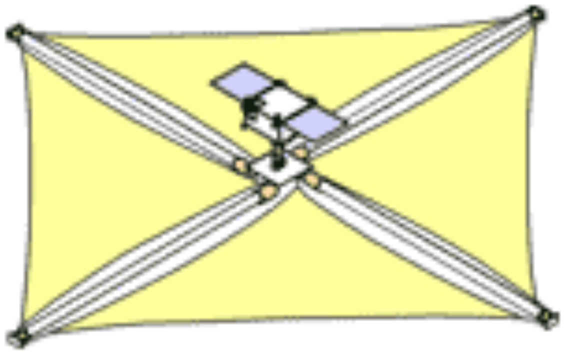
$$a_c = 2\eta \frac{W}{c}\left(\frac{A}{m_{total}}\right)$$

where m_{total} is the total mass of the ship and η is the sail efficiency (typically about 0.9). The key factor limiting the acceleration available is the mass loading of the sail.

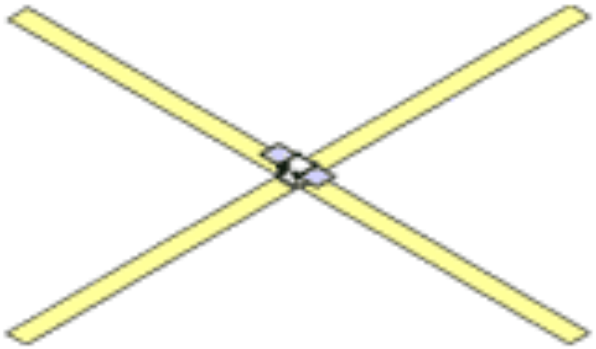
$$\sigma = \frac{m_{total}}{A}$$

The lowest available mass loading using currently available materials is about 5 gm/M^2

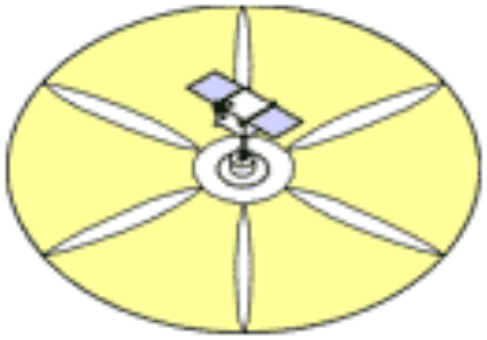
Sail design concepts



Square Sail (not to scale)



Heliogyro (not to scale)

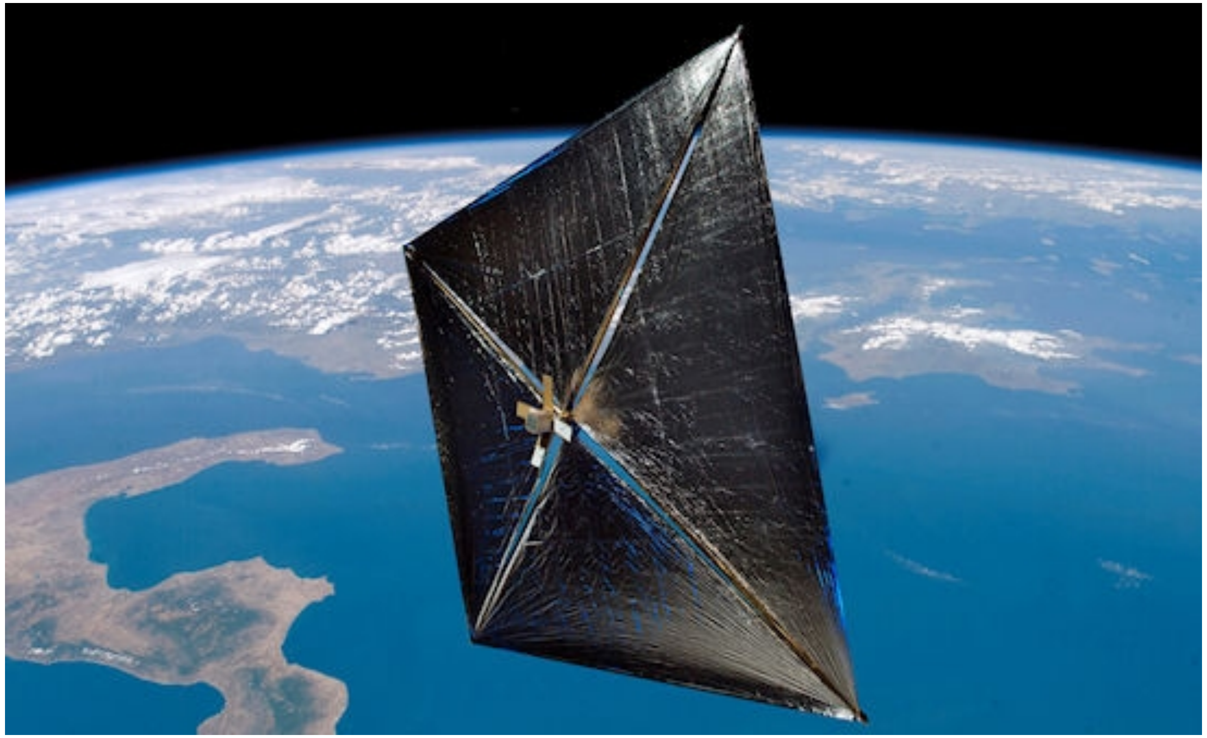


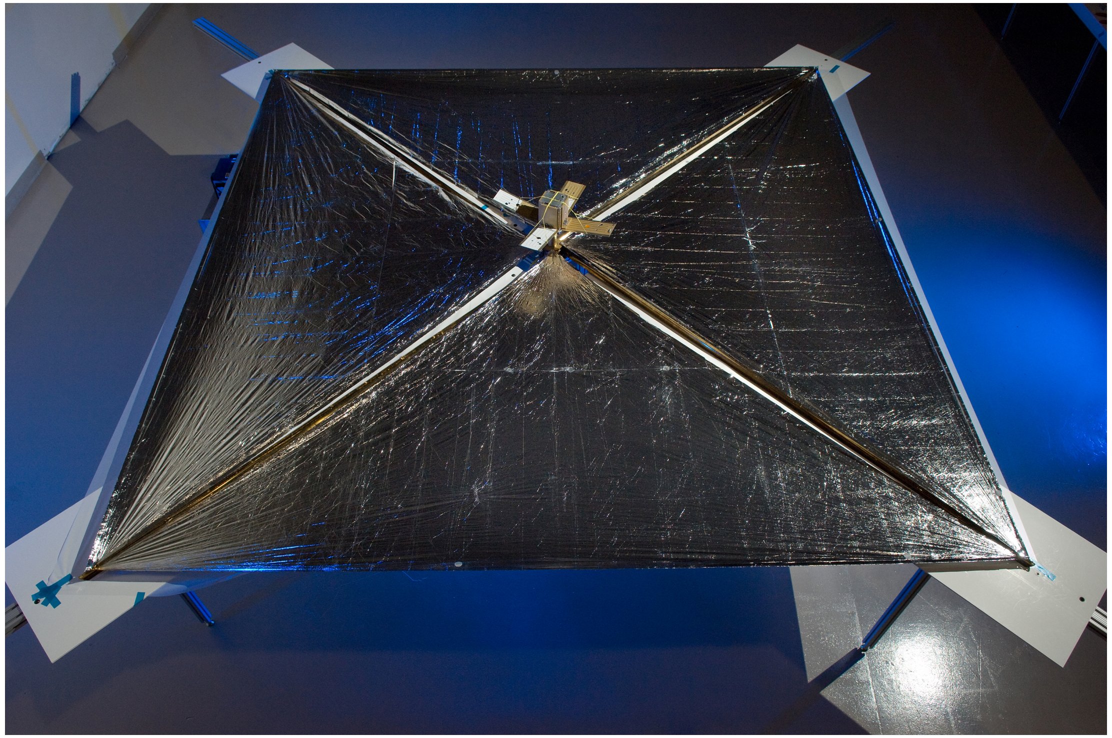
Spinning Disk Sail (not to scale)

Recent successful missions

NanoSail-D2 - NASA - Second try launched Nov 19, 2010
Mission complete - 240 days (tumbling) in Near Earth Orbit

Area = 10 m^2





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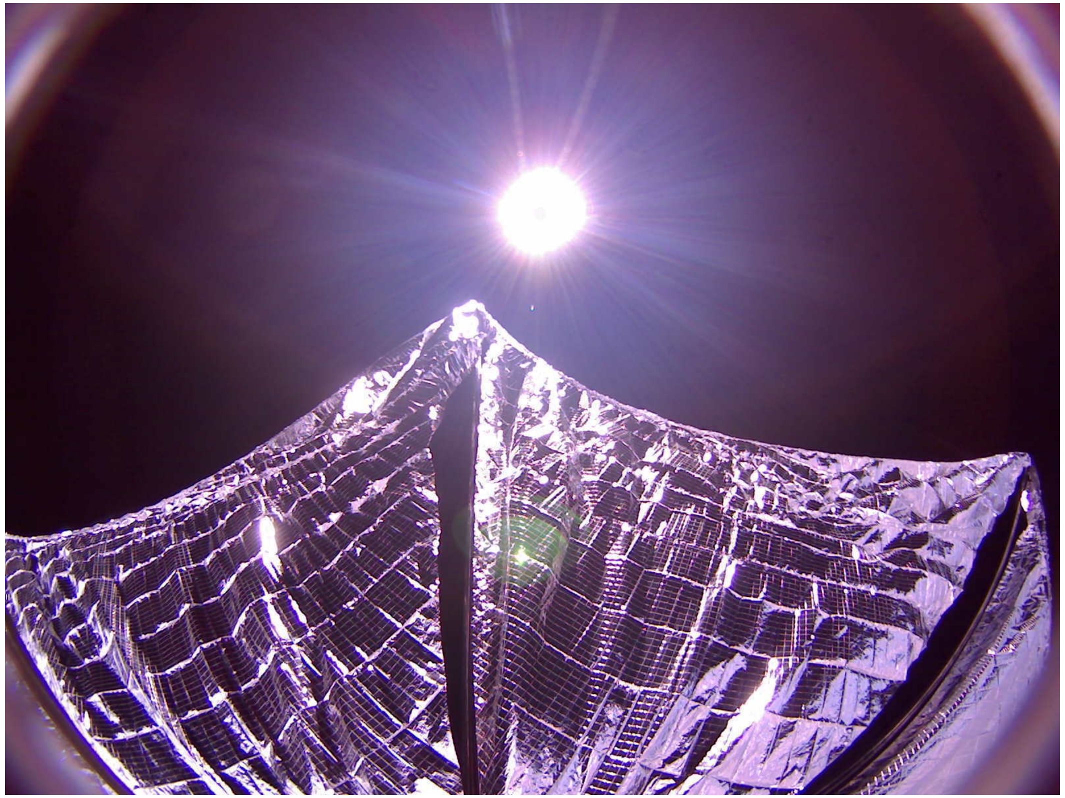
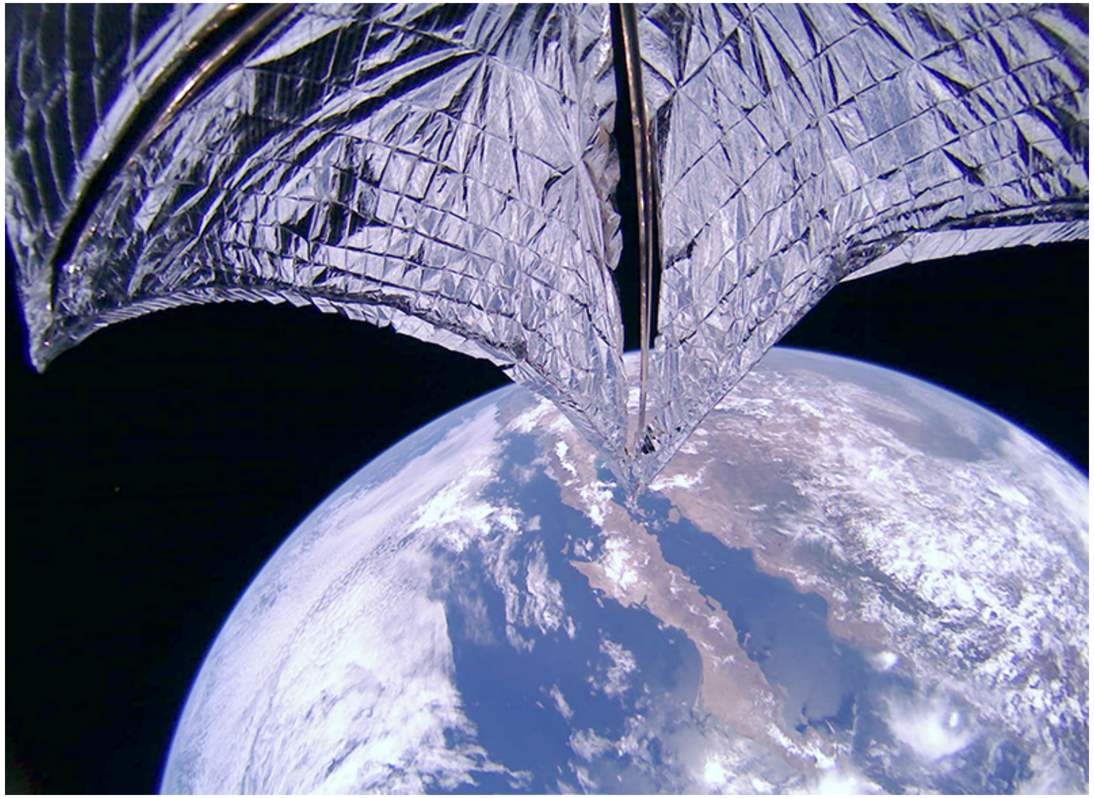
LightSail 1 and 2 – Launched by the Planetary Society in 2015 and 2019

Area = 32 m^2



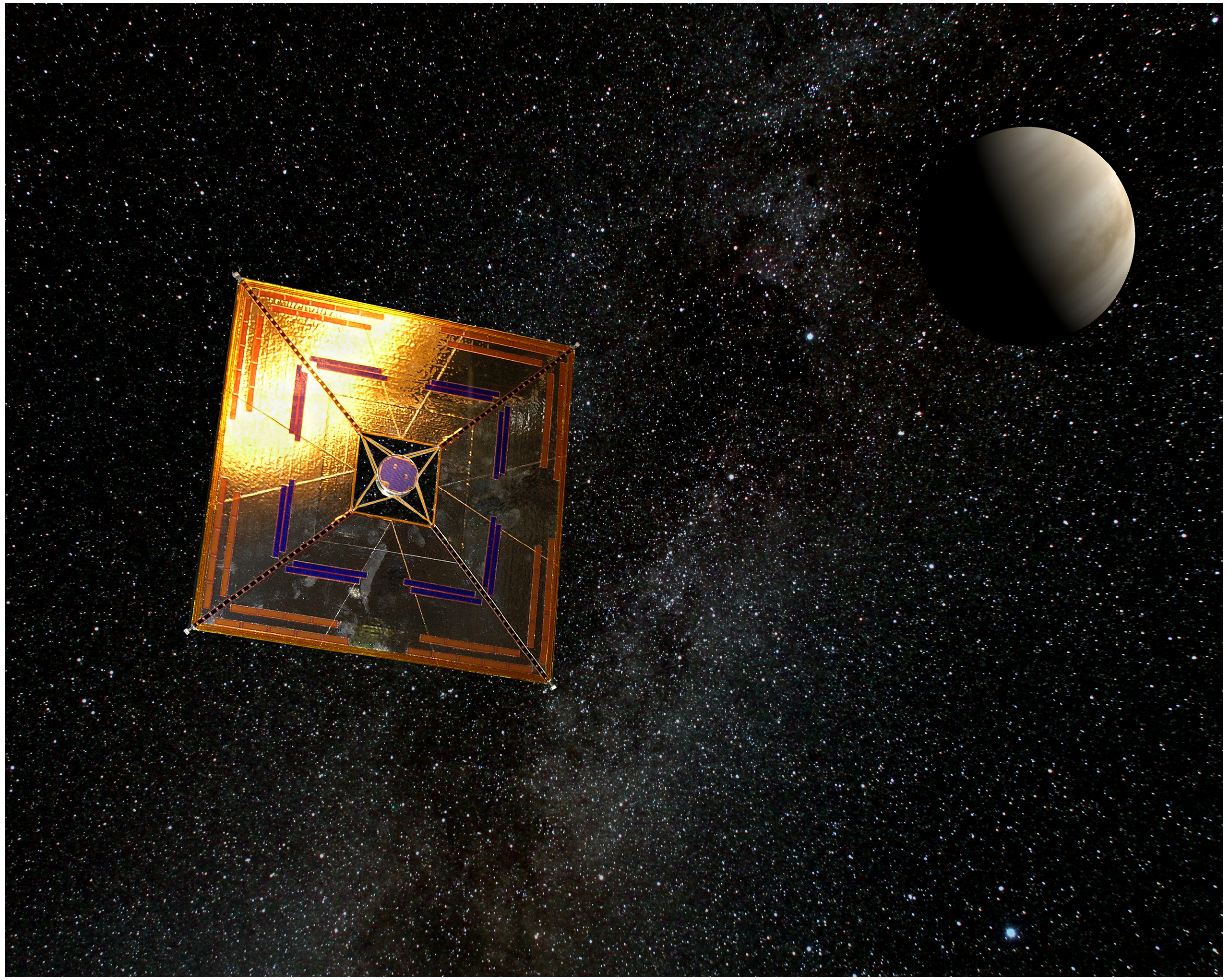


The sails are made of Mylar

IKAROS – Launched by JAXA in May 2010 reached Venus in Dec 2010
First successful planetary mission using a solar sail!

Artist rendering of IKAROS

Sail Area 196 m^2,
Thrust 1.12 milliNewtons



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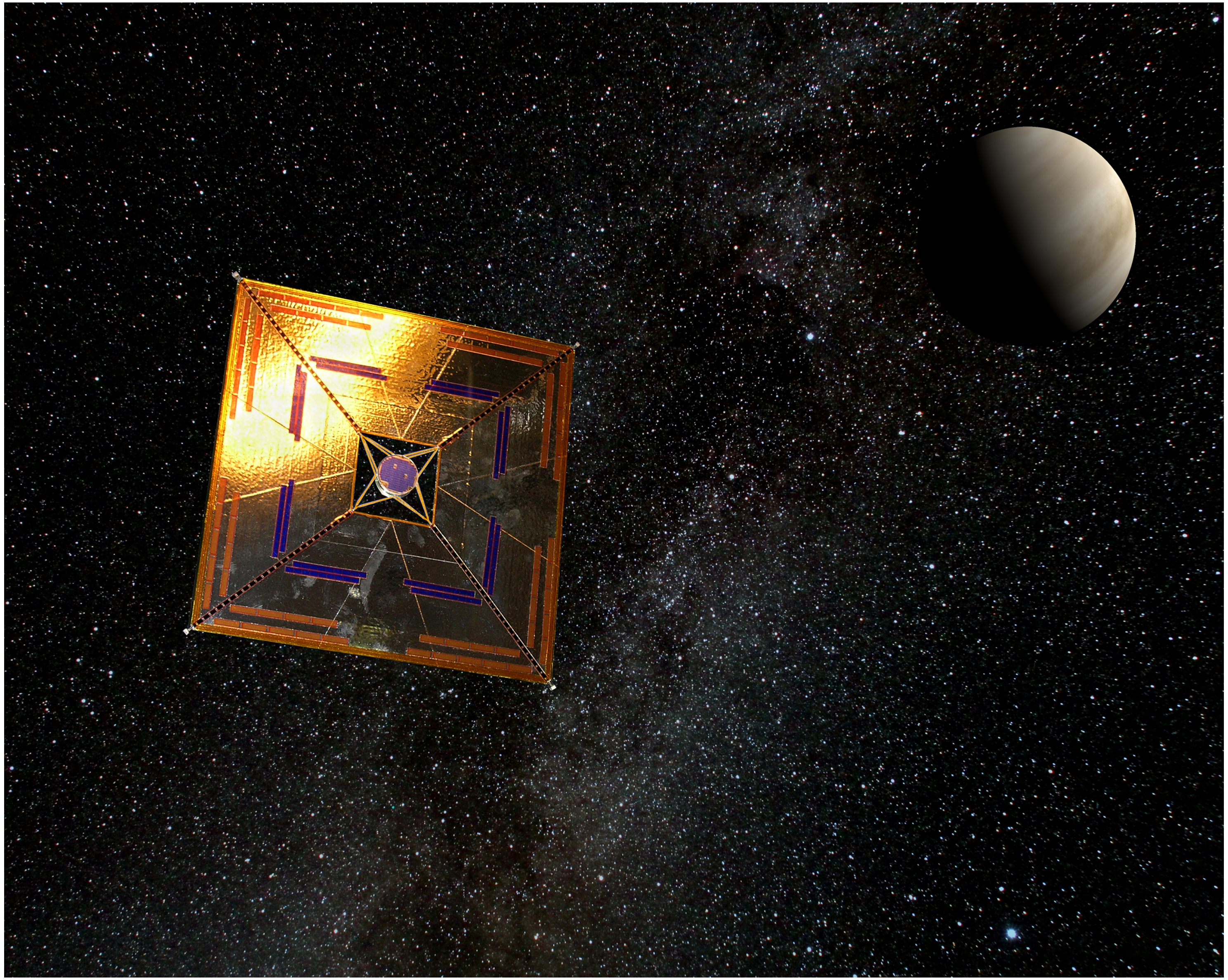
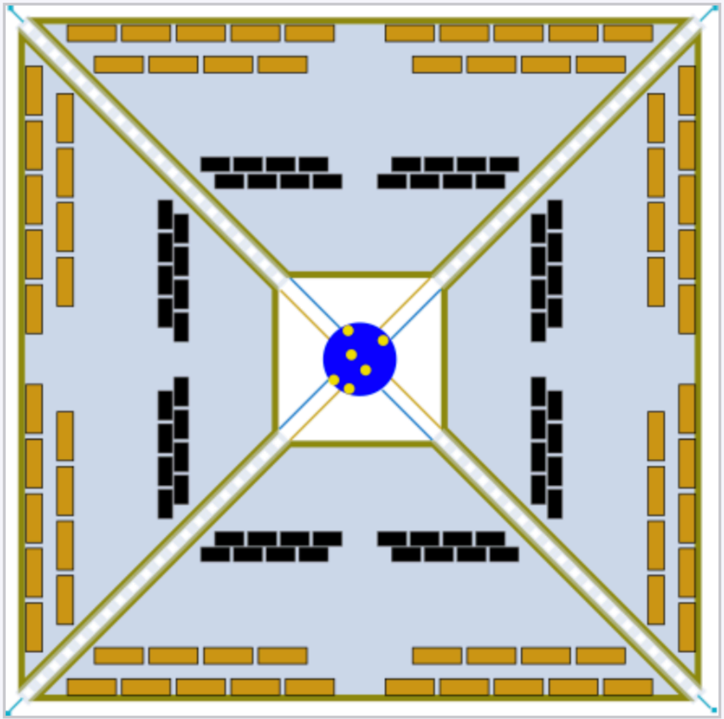


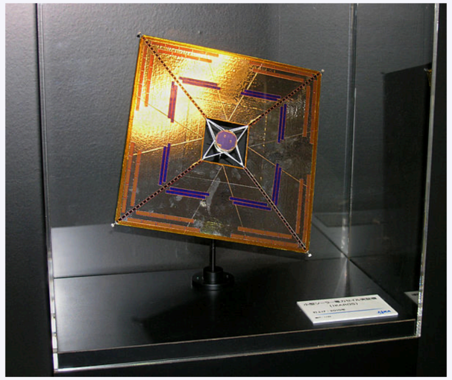
Differential absorption of light by the liquid crystal surfaces used for control.



Sun-facing IKAROS diagram without key

1. Tip mass 0.5 kg
2. Liquid crystal device
3. Membrane 7.5 um thick
4. Solar cells 25 um thick
5. Tethers
6. Main body
7. Instruments

IKAROS



A 1:64 scale model of the IKAROS spacecraft

Mission type	Solar sail technology
Operator	JAXA[1][2][3][4]
COSPAR ID	2010-020E
SATCAT no.	36577
Website	global.jaxa.jp/projects/sas/ikaros/
Mission duration	5 years launch to last contact in 2015
Spacecraft properties	
Launch mass	315 kg (694 lb)
Dimensions	Solar sail: 14 m × 14 m (46 ft × 46 ft) (area: 196 m^2 (2,110 sq ft))[5]
Start of mission	
Launch date	21:58:22, 20 May 2010 (UTC)
Rocket	H-IIA 202
Launch site	Tanegashima, LA-Y
End of mission	
Last contact	20 May 2015[6]
Orbital parameters	
Reference system	Heliocentric orbit
Flyby of Venus	
Closest approach	8 December 2010
Distance	80,800 kilometers (50,200 mi)

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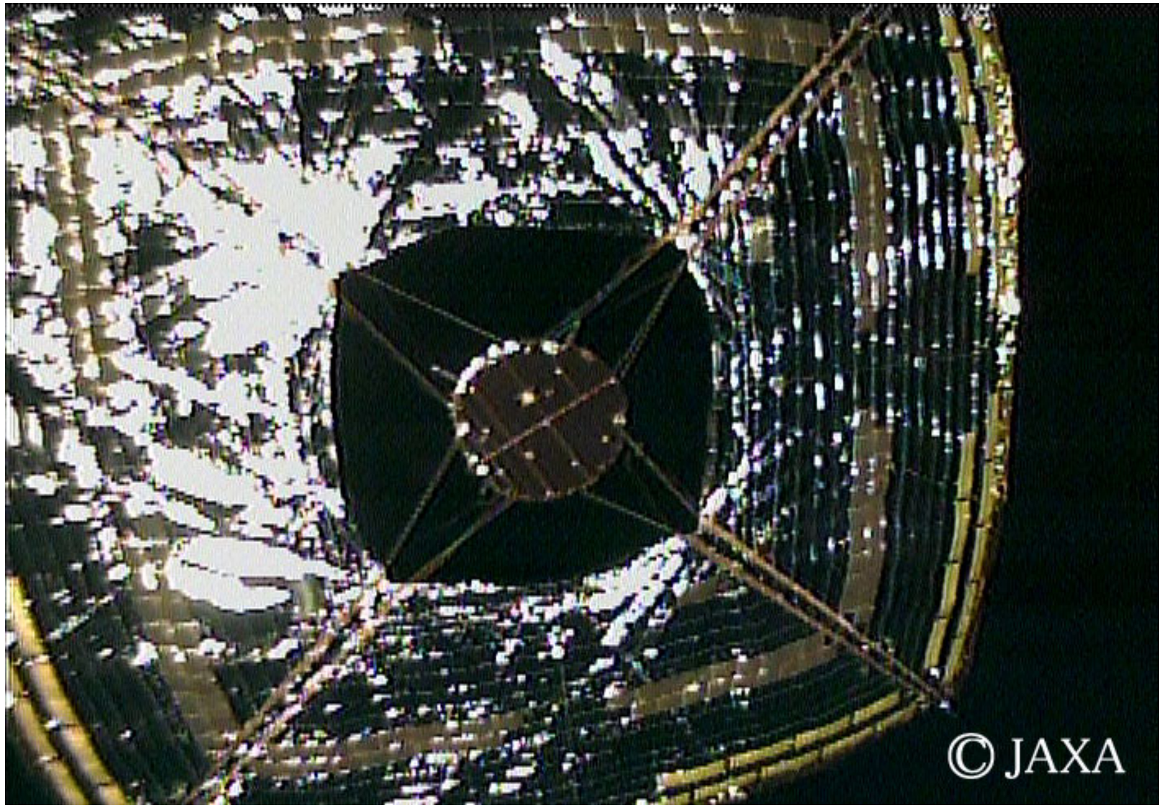
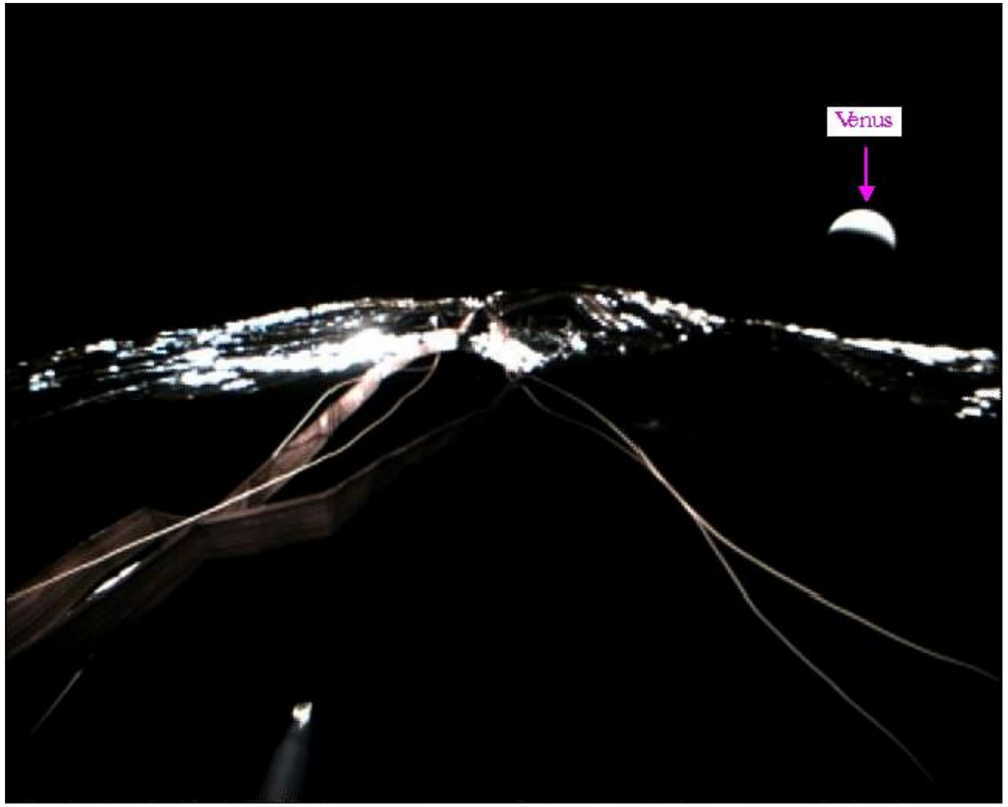
Self images of IKAROS in space



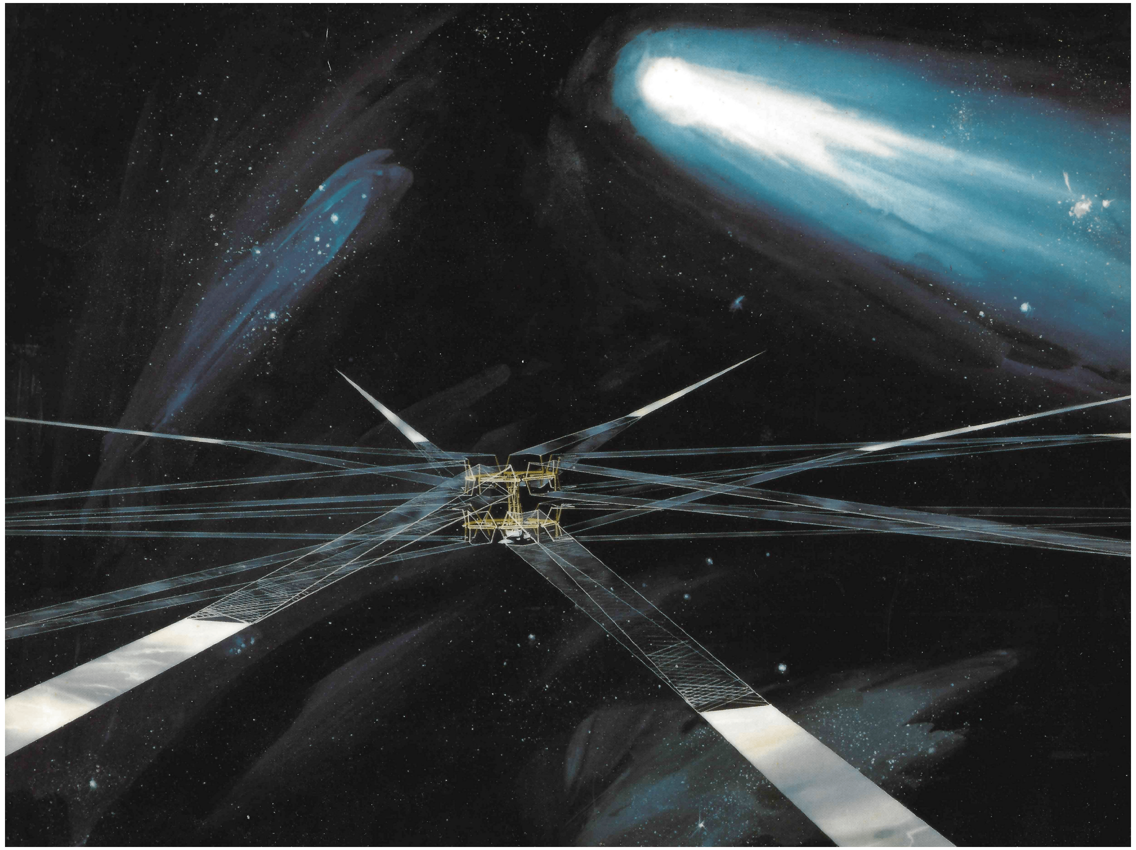


Several Mission Concepts

CubeSail, 20 m^2 launched on an Electron launch vehicle December 16, 2018 as a first step toward UltraSail

Artist's concept of a heliogyro, proposed to visit Halley's Comet in 1986. Each blade would be 8 m (26 ft) wide and 6.2 km (3.9 mi), for 0.6 km^2 (0.23 sq mi) of sail area.

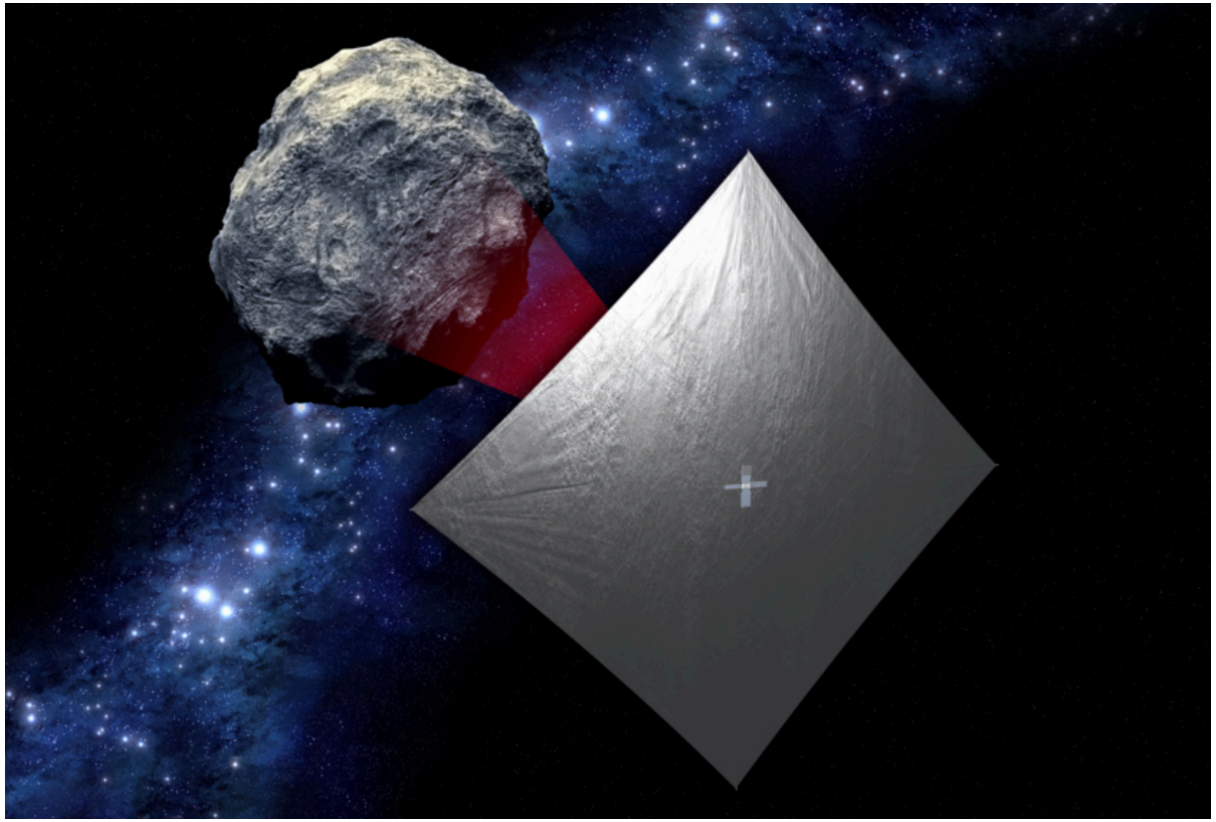
Each blade made of a polyimide film, eg. Kapton, coated with ripstop.



Was CubeSail Successful??

NEA Scout – SLS Pathfinder Launch date Nov 2021

Was supposed to launch on SLS in 2018.



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Typical mission times - Earth to Moon

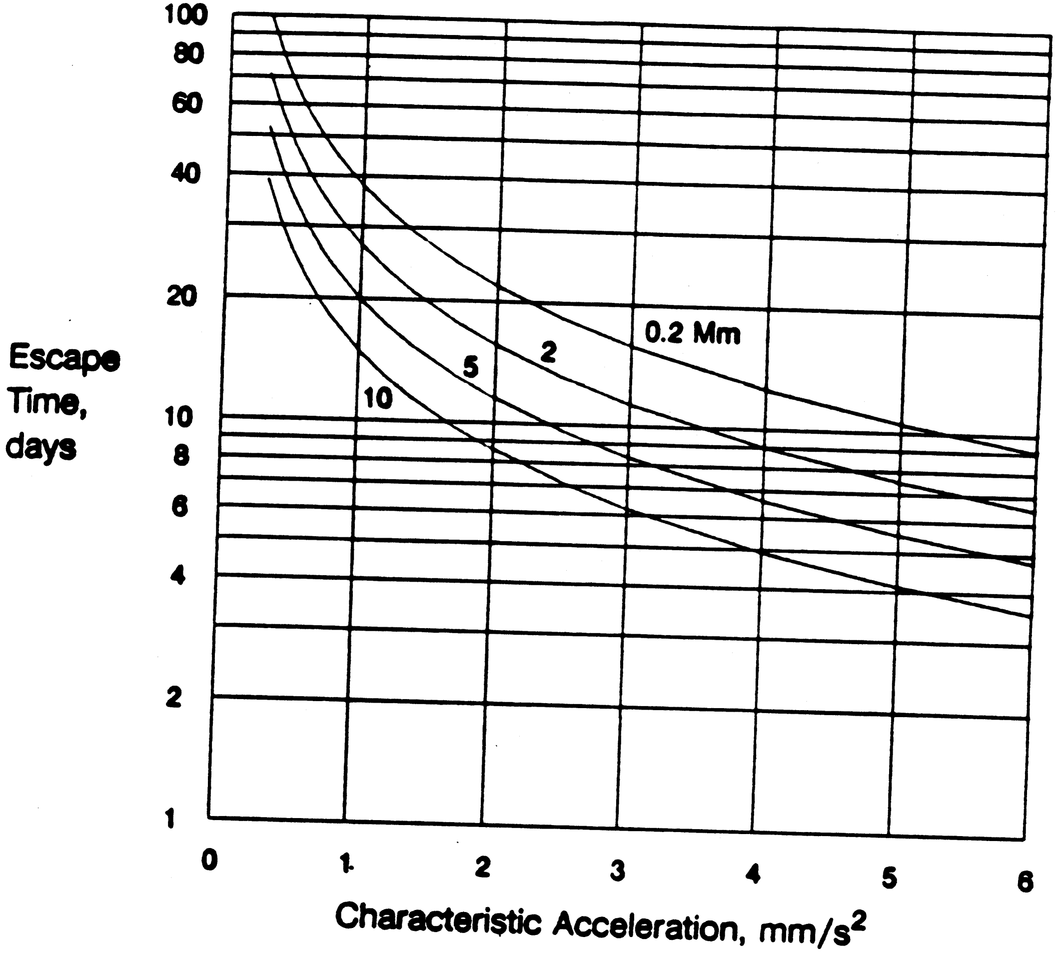


FIGURE 2.2 Lunar Spiral Times.

Mm - Megameters

Typical mission times - Earth Escape

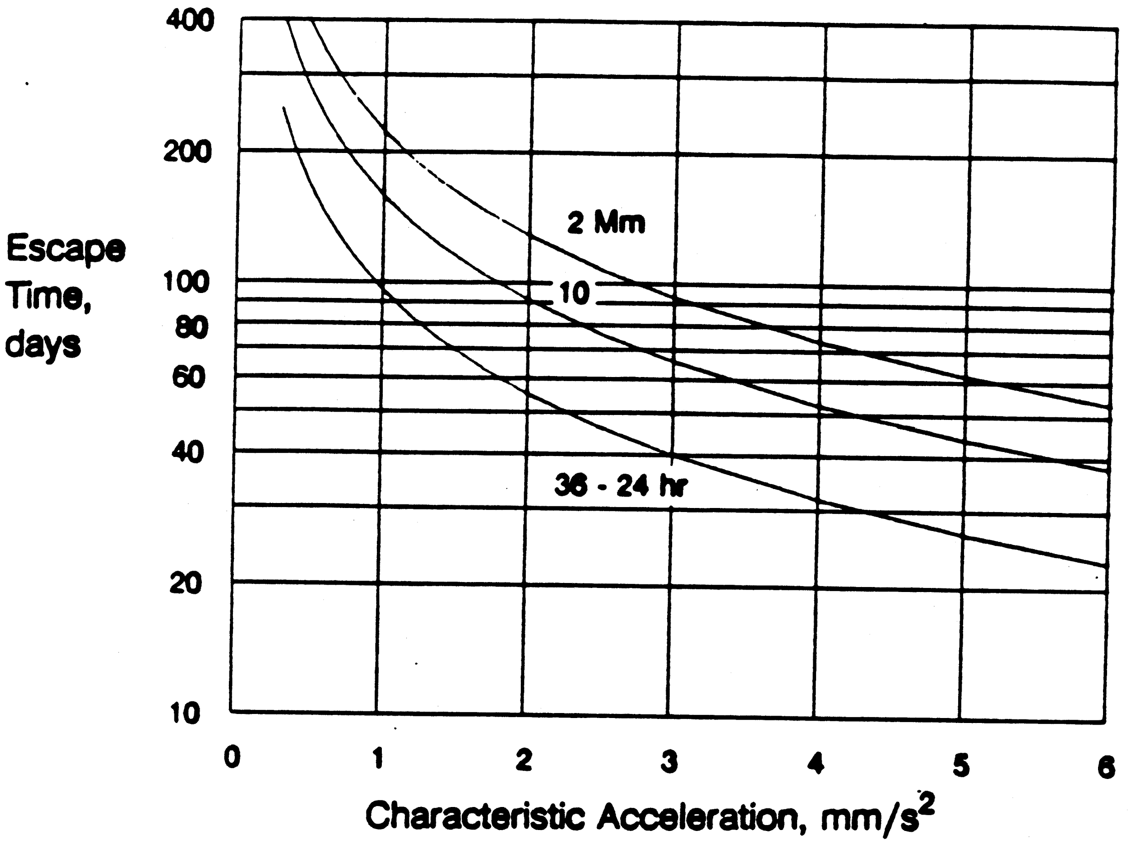


FIGURE 2.1 Earth Escape Times From Various Orbits.

Mm - Megameters

Typical mission times - Missions to the Planets

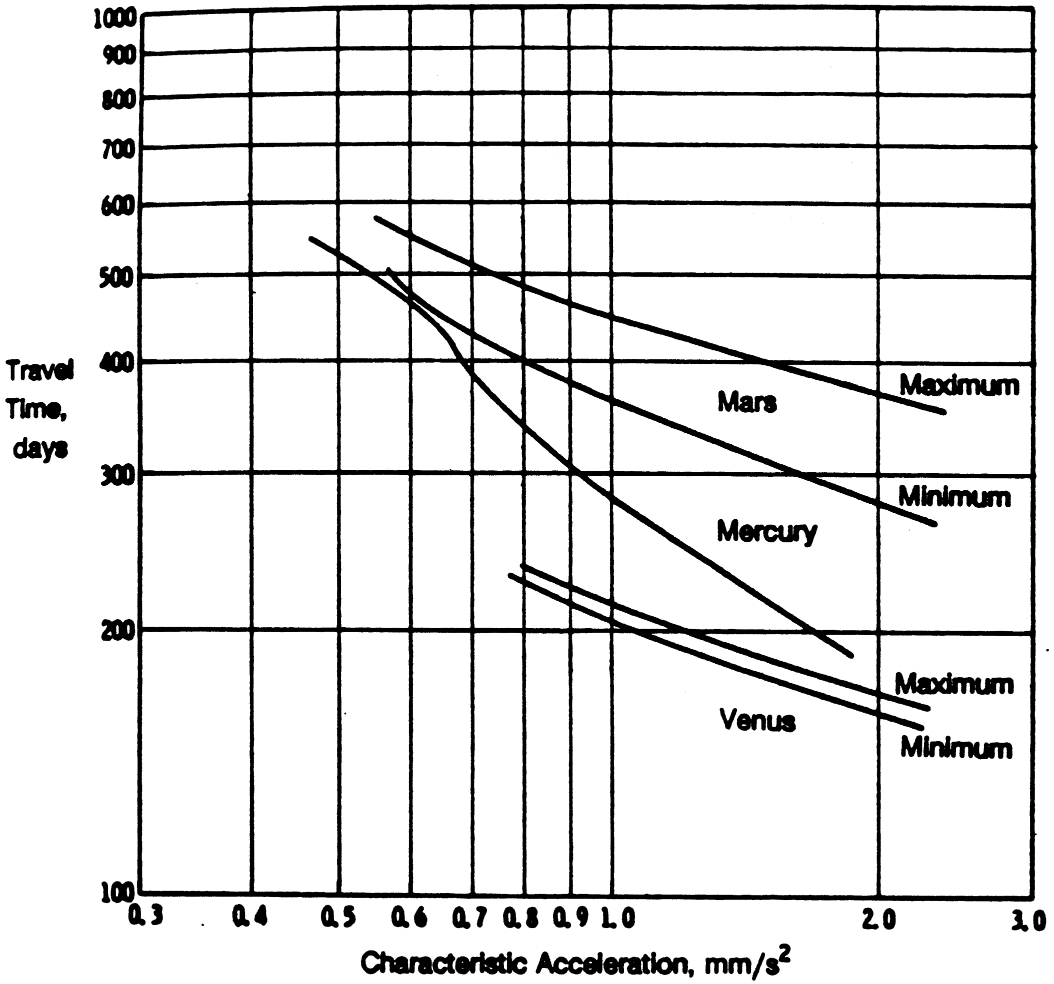
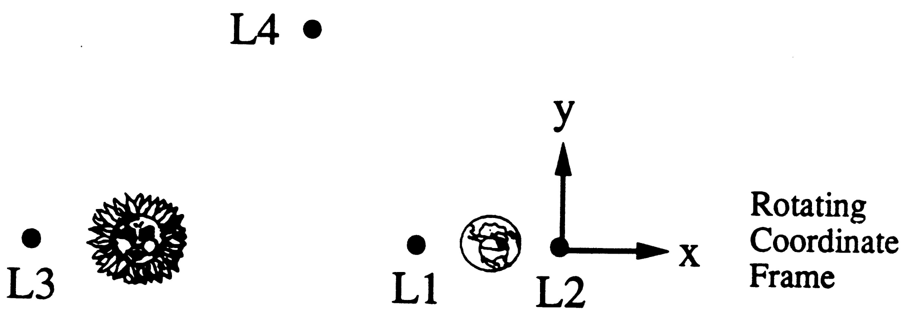


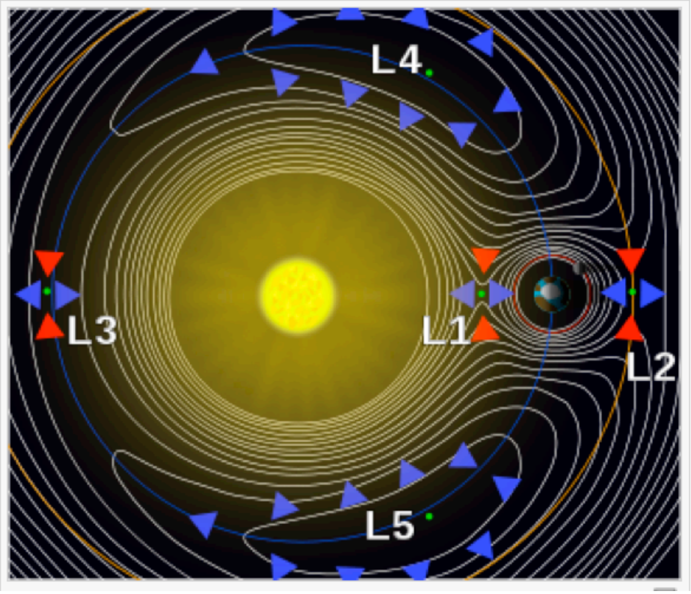
FIGURE 2.4 Typical Travel Times to the Inner Planets.

Mm - Megameters

Mission to L2 – PhD thesis Sun Hur 1992

What is L2 Libration Point?



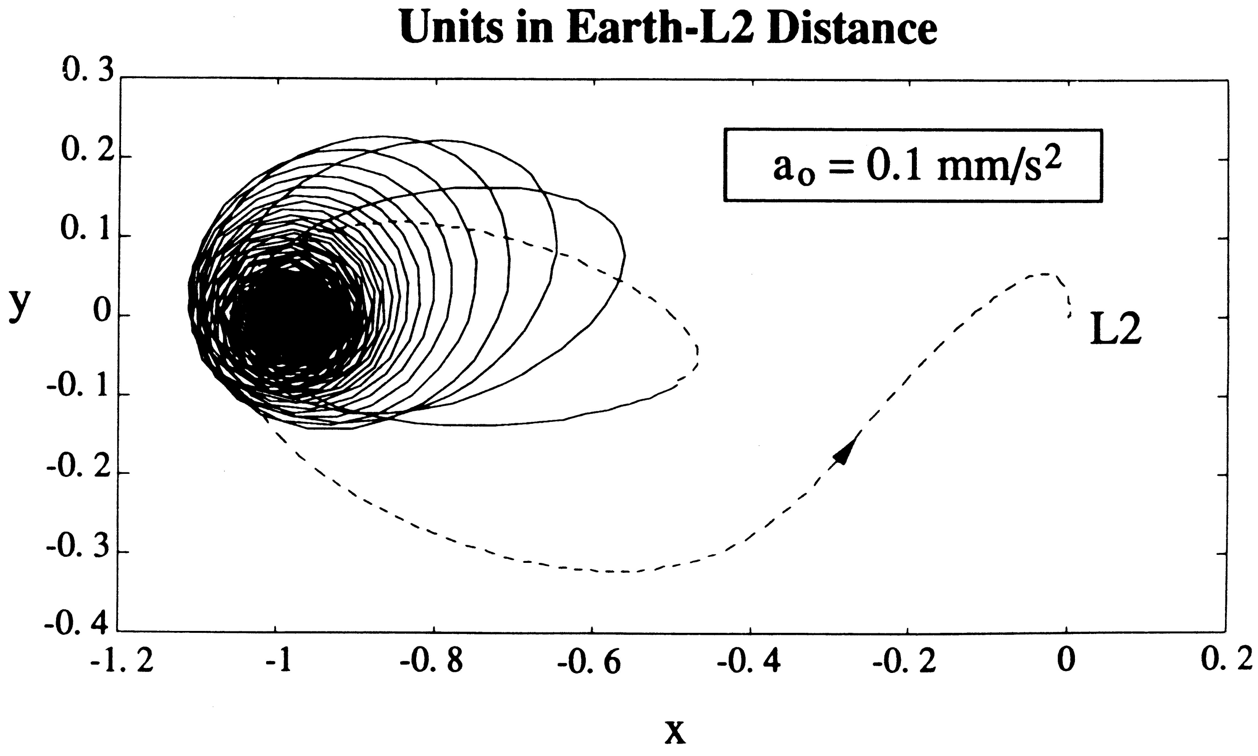


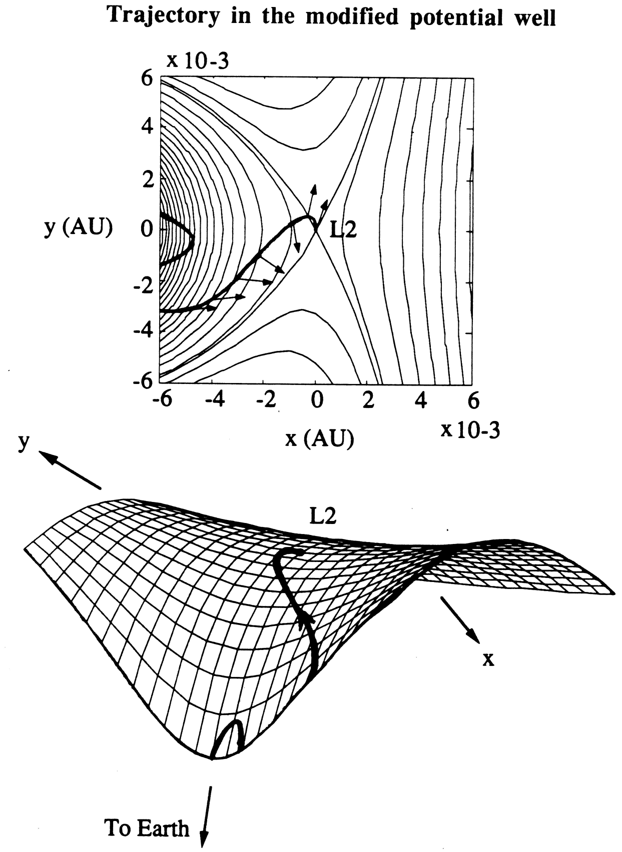
Gravitational potential

The L2 point is one of five equilibrium points the rotating Sun-Earth system where the gravitational force equals the centrifugal force is an unstable equlibrium point.

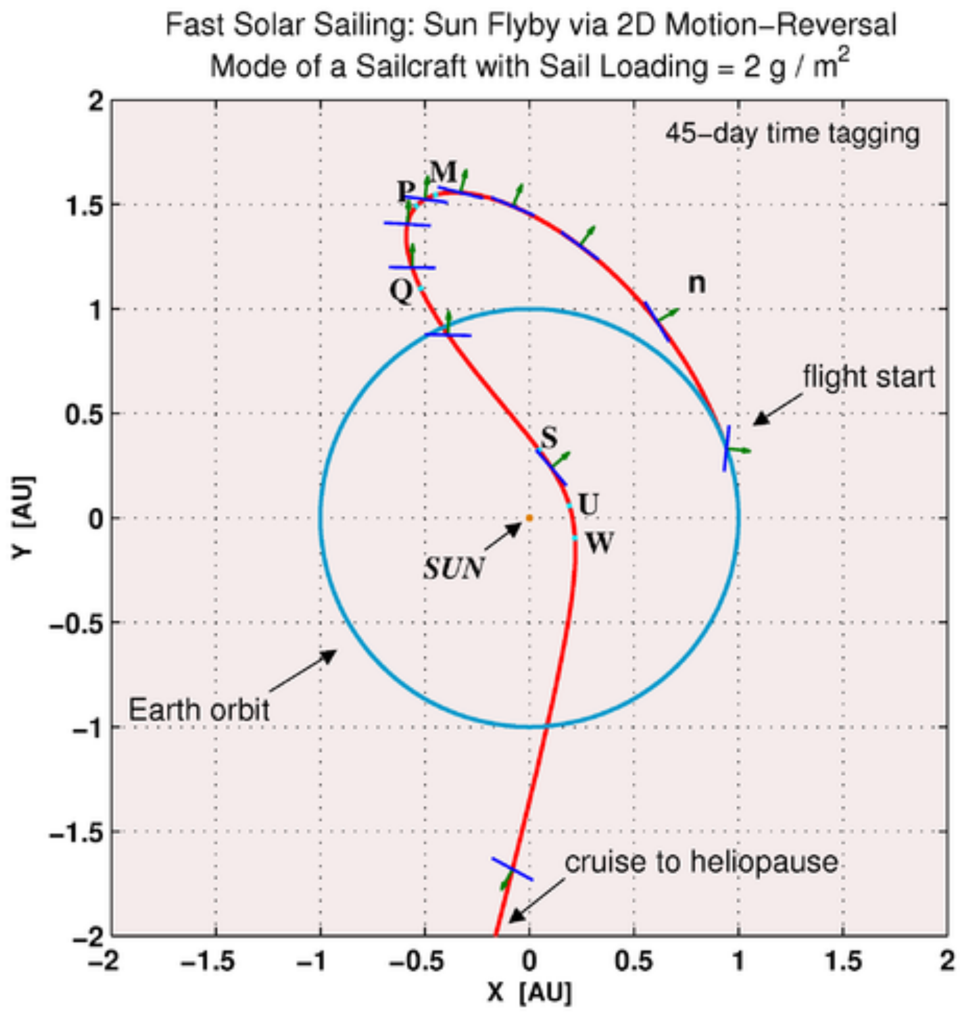
CENTRIFUGAL = GRAVITATIONAL

Feasible Trajectory

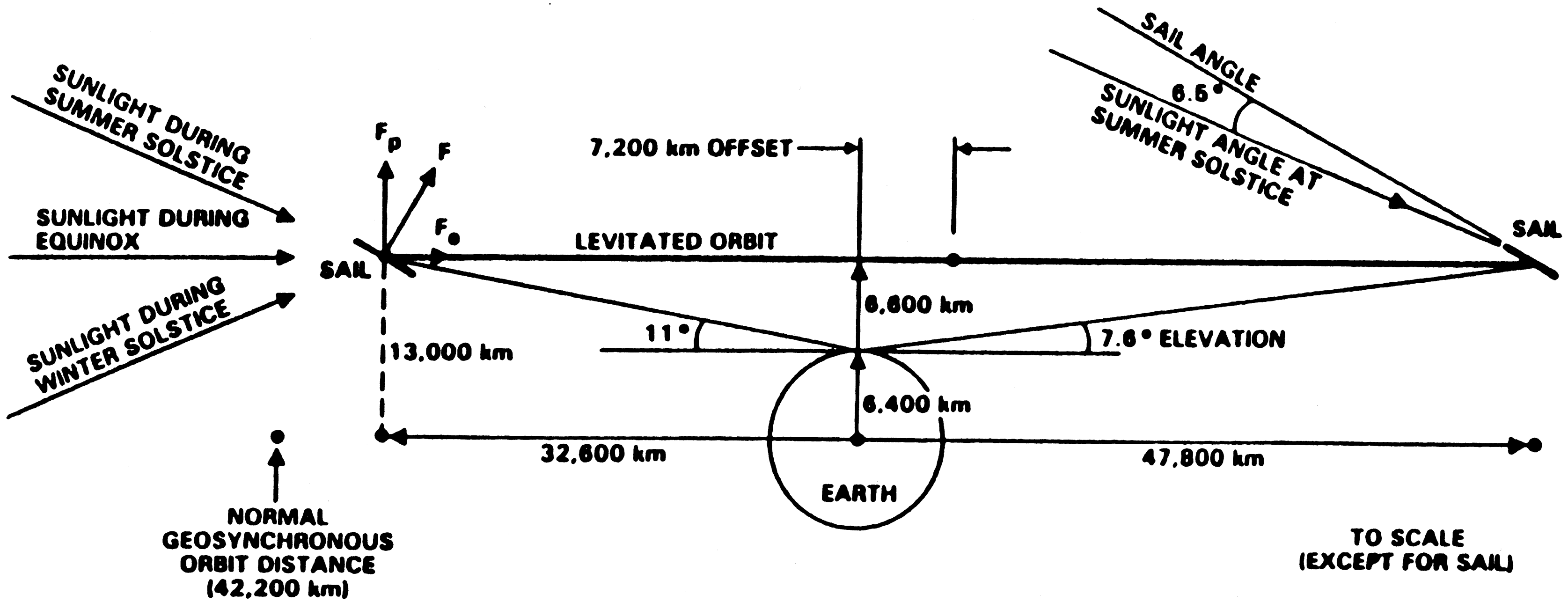




Mission Toward the Sun



Mission example - levitated orbit



Mission example - solar watchers

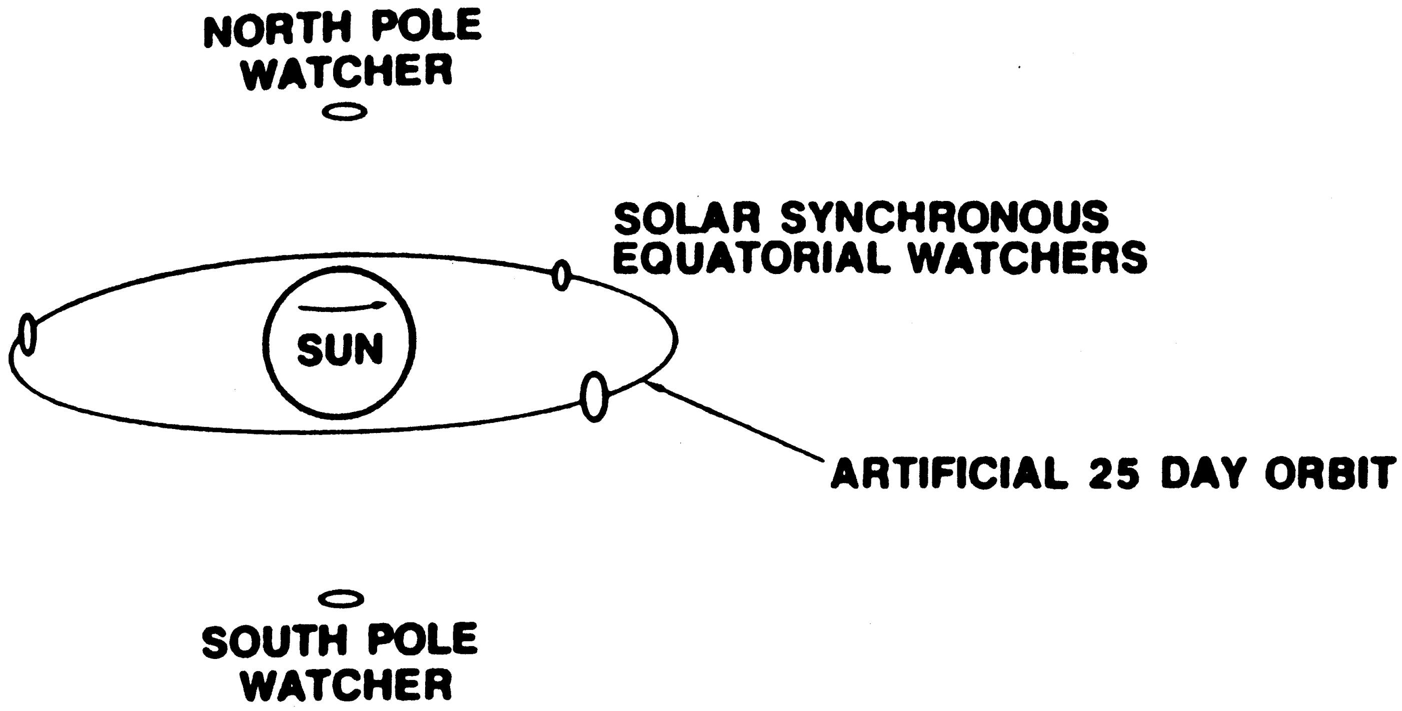


FIGURE 2.21 Synchronous Solar Orbits. (R.L. Forward/Hughes)

Microwave Thrust

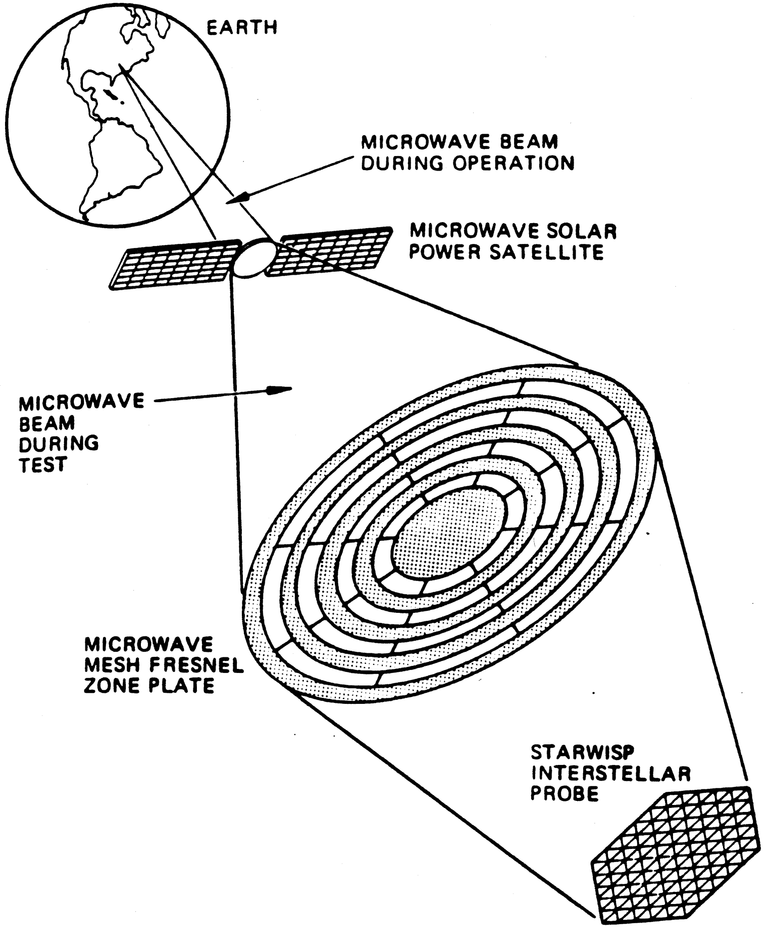


FIGURE 7.10 Operation of a Starwisp Probe. (R.L. Forward)

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Mission example - interstellar fly-by

GW - Gigawatts

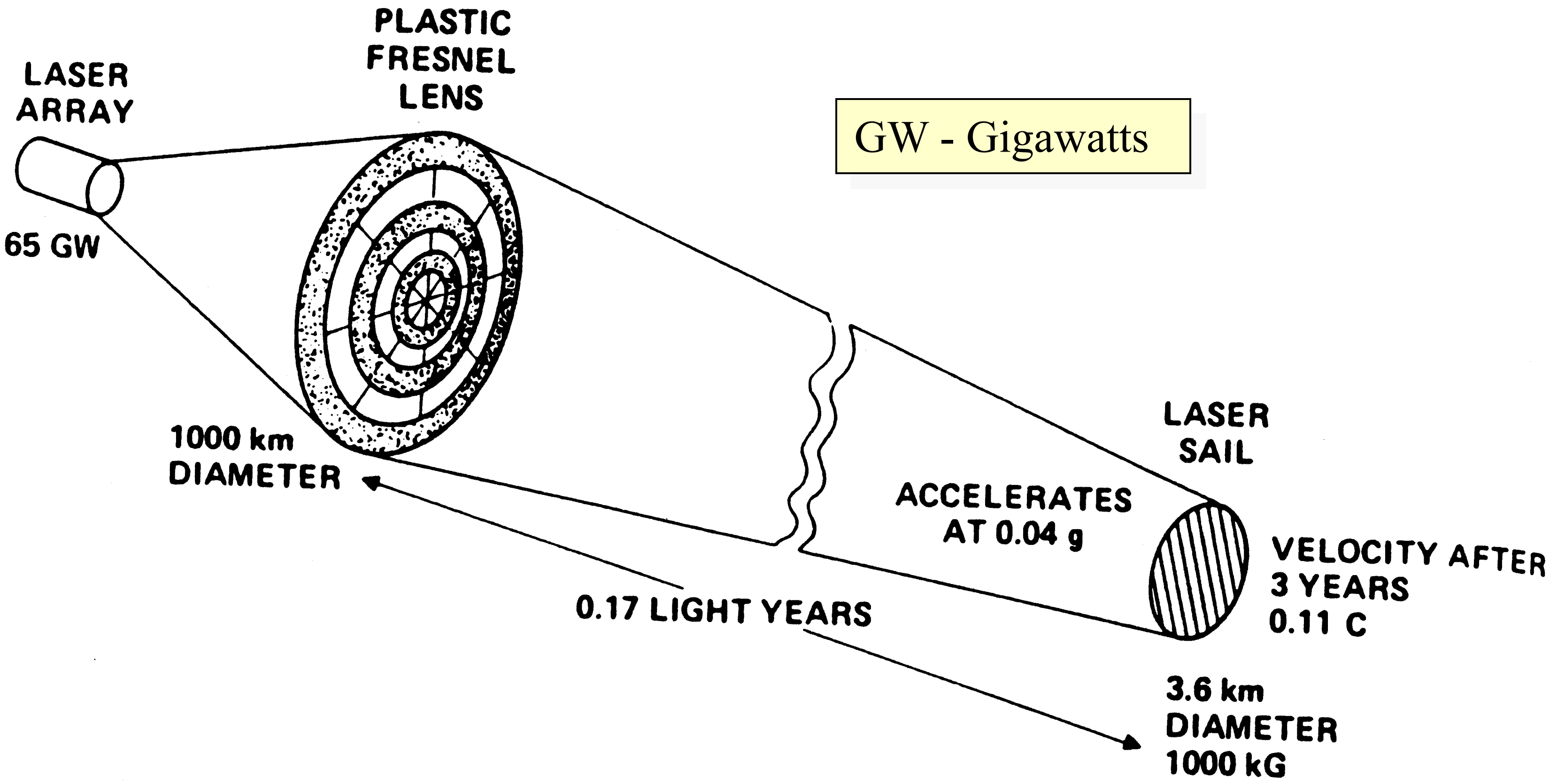

FIGURE 7.6 Profile of an Interstellar Fly-By Probe. (R.L. Forward)

Mission example - one-way interstellar flight

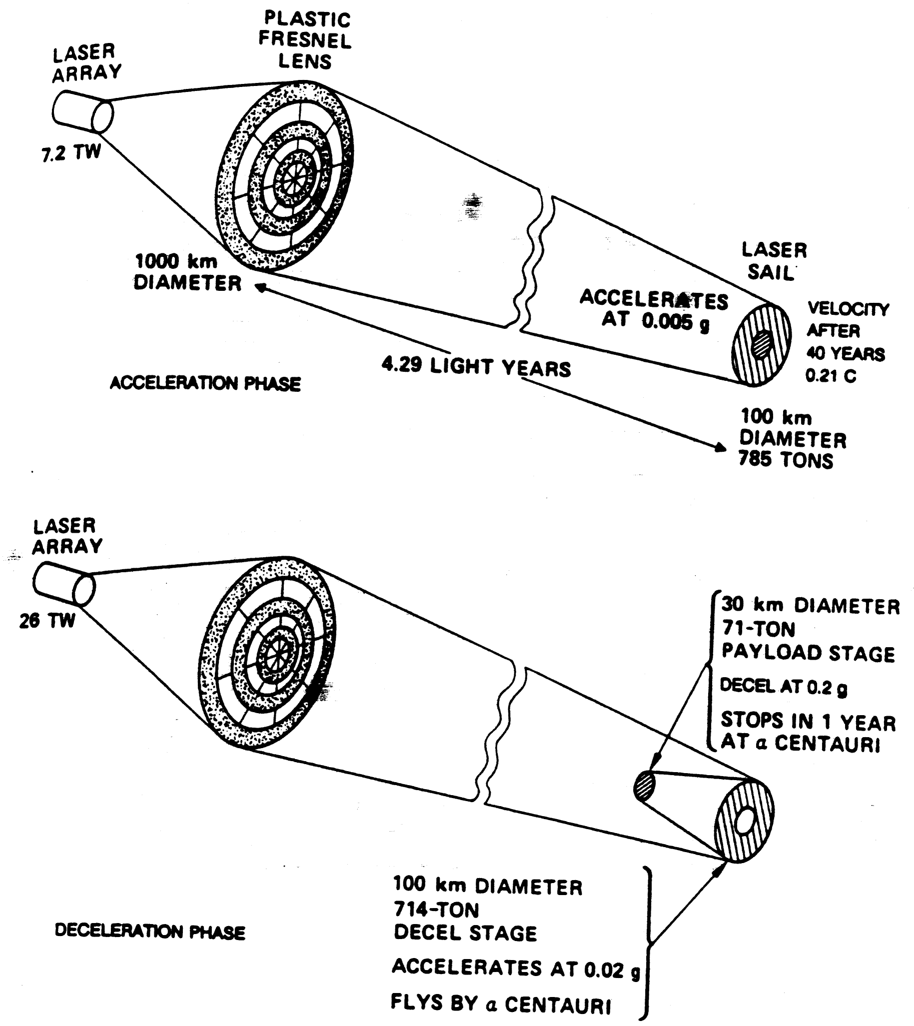

FIGURE 7.7 Profile of a Voyage to Alpha Centauri. (R.L. Forward)

TW - Terawatts

Mission example round-trip interstellar flight

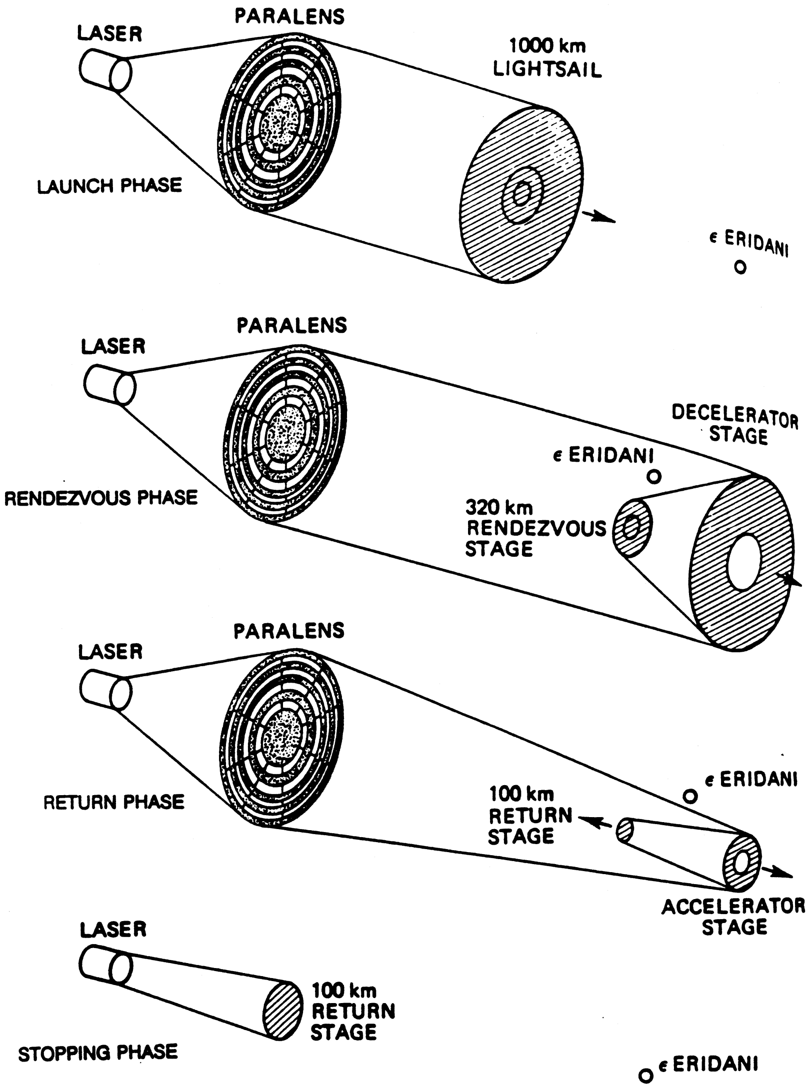

FIGURE 7.8 Profile of a Roundtrip Voyage to Epsilon Eridani. (R.L. Forward)

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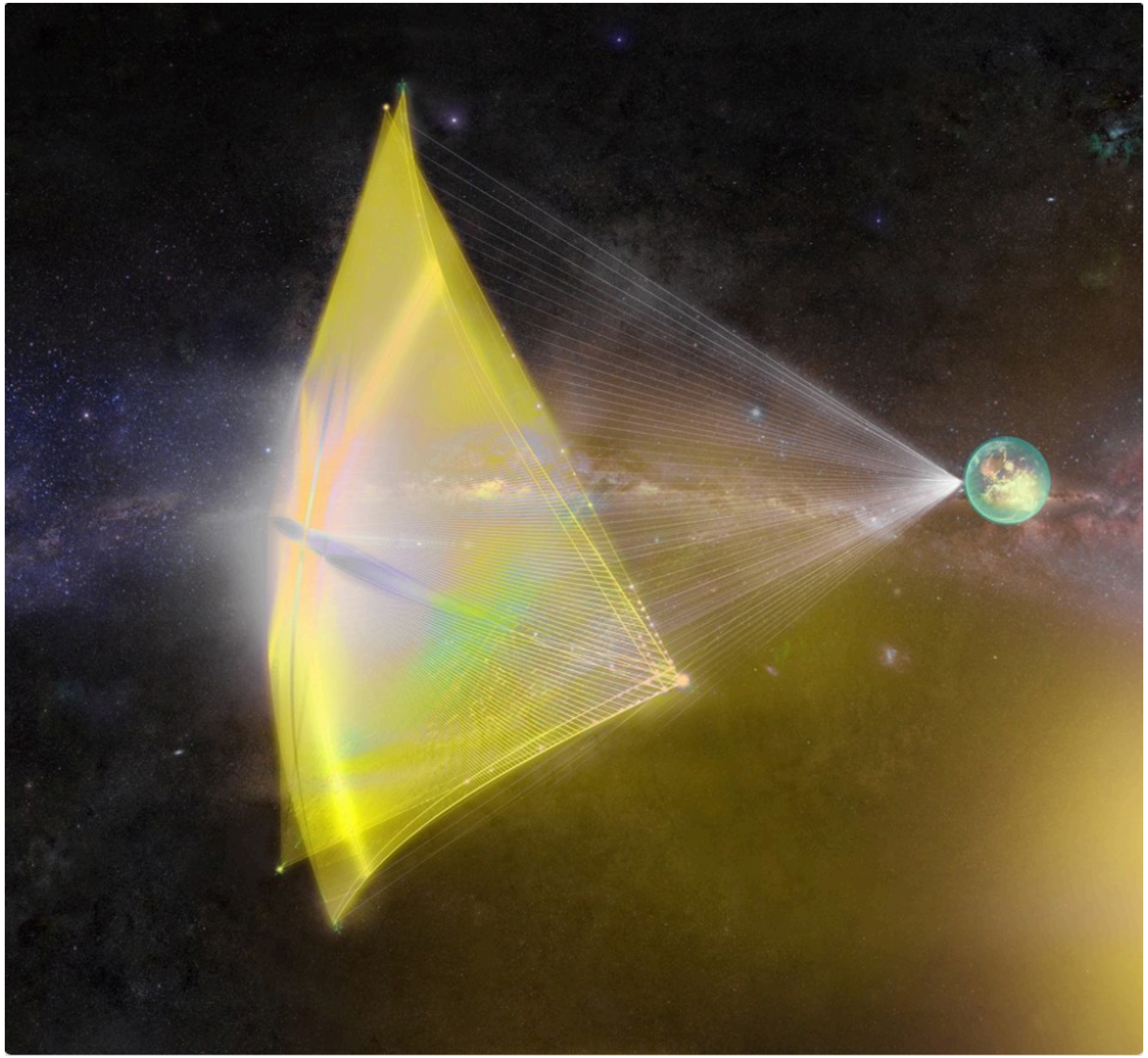
Breakthrough – Starshot - 2018



Use a Gigawatt scale laser to accelerate a 1 gram nano-sized spacecraft to 20% of the speed of light.

Reach the Alpha Centauri system 4.37 light years away in 20 years.

The *StarChip* – camera, photon thruster, power, navigation and communication.

The *LightSail* – several meters in diameter, only a few hundred atoms thick.

The *LightBeamer* – 100 Gigawatt laser tuned to maximize reflectivity from the sail.

The plan

Path to the stars

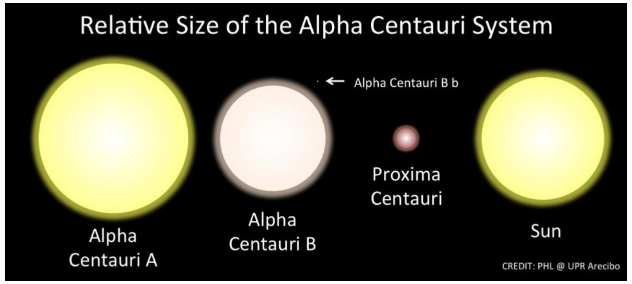
The research and engineering phase is expected to last a number of years. Following that, development of the ultimate mission to Alpha Centauri would require a budget comparable to the **largest current scientific experiments**, and would involve:

- Building a ground-based **kilometer-scale** light beamer at high altitude in dry conditions
- Generating and storing **a few gigawatt hours** of energy per launch
- Launching a 'mothership' carrying **thousands** of nanocrafts to a high-altitude orbit
- Taking advantage of **adaptive optics** technology in real time to compensate for atmospheric effects
- **Focusing** the light beam on the lightsail to accelerate individual nanocrafts to the target speed within minutes
- Accounting for **interstellar dust collisions** en route to the target
- **Capturing images** of a planet, and other scientific data, and transmitting them back to Earth using a compact on-board laser communications system
- Using the same light beamer that launched the nanocrafts to **receive** data from them over 4 years later.

Potential Planets in the Alpha Centauri system

Astronomers estimate that there is a reasonable chance of an **Earth-like planet** existing in the 'habitable zones' of Alpha Centauri's three-star system. A number of scientific instruments, ground-based and space-based, are being developed and enhanced, which will soon identify and characterize planets around nearby stars.

A separate Breakthrough Initiative will support some of these projects.



What would it take to reach the speed of light in a few minutes?

Spacecraft mass = 0.001 kg

Acceleration time to c/3 = 1000 sec

Final speed = 10^8 m/sec

Acceleration = 10^5 m/sec^2

Force = 10^2 kg-m/sec^2

Sail Area = 10 m^2

Required light pressure

$$P = \frac{2W}{c} = 10\ N/m^2$$

$$W = 1.5 \times 10^9\ J/m^2 - \text{sec}$$

The *LightBeamer* – 100 Gigawatt laser tuned to maximize reflectivity from the sail.

How much power does the sail have to dissipate? Assume 99.9999% of the incident energy is reflected by the sail. Only one part in a million is absorbed by the sail.

$$W_{absorbed} = 1.5 \times 10^3 \, J/m^2 - \sec$$

$$Power_{absorbed} = 10 \times W_{absorbed} = 1.5 \times 10^4 \, J/\sec$$

How fast will the sail heat up? Assume the heat capacity of water (very conservative – for metals C is much lower). C=4.184 J/gram-K

$$Power_{absorbed} = 1.5 \times 10^4 \, J/\sec = Cm\frac{dT}{dt}$$

$$C = 4.184 \times 10^3 \, J/kg - K$$

$$m = 10^{-3} \, kg$$

$$\frac{dT}{dt} = 3.58 \times 10^2 \, K/\sec$$

How far away is the spacecraft at the end of the acceleration?

$$r = a\frac{t^2}{2} = 0.5 \times 10^5 \times 10^6 = 5 \times 10^{10} \, m = 0.33 AU$$

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Drag caused by the cosmic microwave background

If the spacecraft speed approached the speed of light this would become an important drag mechanism

$$\text{Photons per unit volume} = 10^{9}\ \text{photons/m}^{3}$$

$$\text{Peak wavelength} = 10^{-6} m$$

$$\text{Light sail final speed} = 10^{8}\ \text{m/sec}$$

$$\text{Photon flux} = 10^{17} \text{photons/m}^{2} - \text{sec}$$

$$\text{Energy per photon} = \text{hc}/\lambda = 6.6 \times 10^{-34} \times 3 \times 10^{8} / 10^{-6} = 2 \times 10^{-16} J$$

$$\text{Momentum per photon} = \text{h}/\lambda = 6.6 \times 10^{-34} / 10^{-6} = 6.6 \times 10^{-28} kg - m/\sec$$

$$\text{Drag force on a ten square meter sail} = 6.6 \times 10^{-28} \times 10^{17} \times 10 = 6.6 \times 10^{-10} N$$

$$\text{Acceleration of a one gram light sail} = 6.6 \times 10^{-7} m/\sec^{2}$$

$$\Delta V \text{ over 1000 sec} = 6.6 \times 10^{-4} m/\sec$$

$$\Delta V \text{ over 20 years} = 20 \times 365 \times 24 \times 3600 \times 6.6 \times 10^{-7} m/\sec = 416 m/\sec$$

This does not account for the blue-shift in the wavelength of the background in the frame of reference of the spacecraft