STANFORD
AERONAUTICS &
ASTRONAUTICS

AA283
Aircraft and Rocket Propulsion

Space Sailing

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

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

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

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

Properties of light, cont' d

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

$$P = 2W / c$$

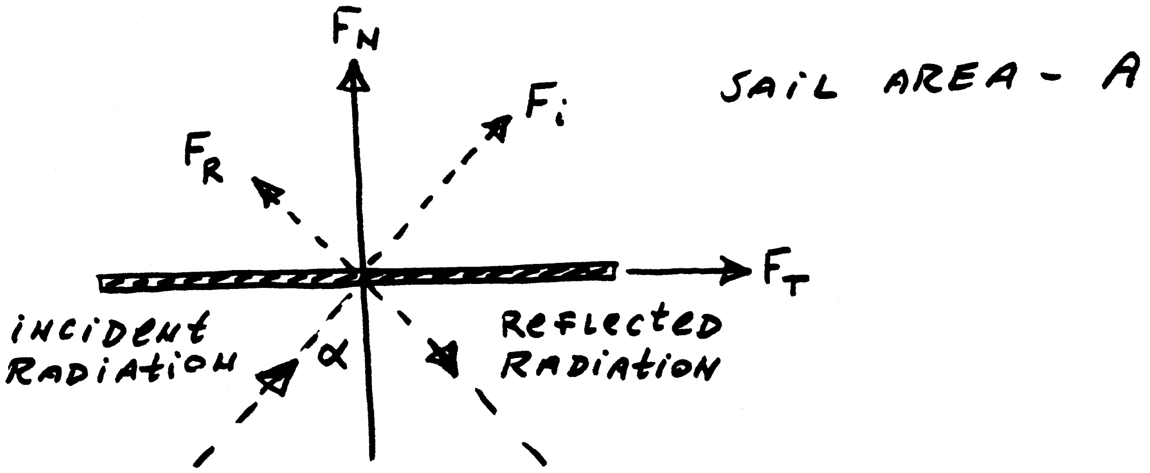
At the earths radius

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

At other radii

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

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

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

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

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.

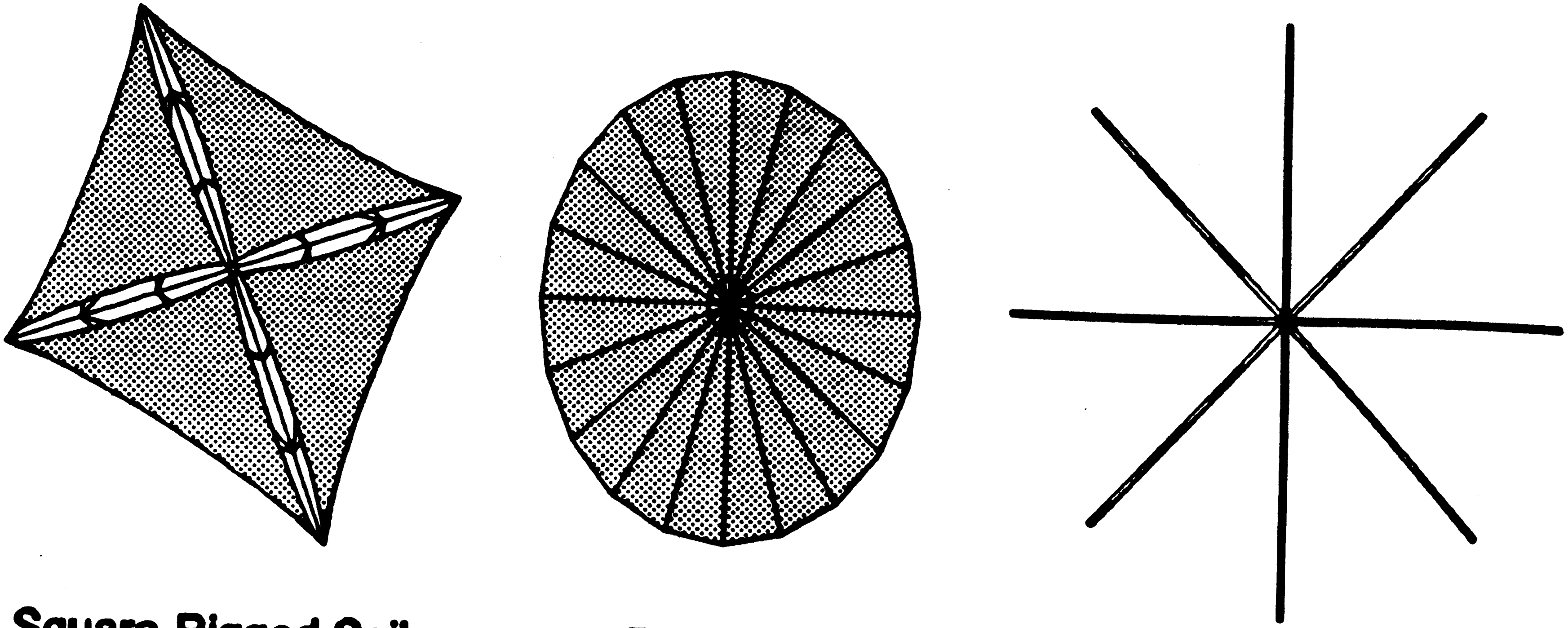
$$a_c = 2\eta \frac{W}{c} \left(\frac{A}{m_{total}} \right)$$

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 Concepts



Square-Rigged Sail

Disk Sail

Heliogyro

FIGURE 3.1 Basic Types of Solar Sailing Craft.

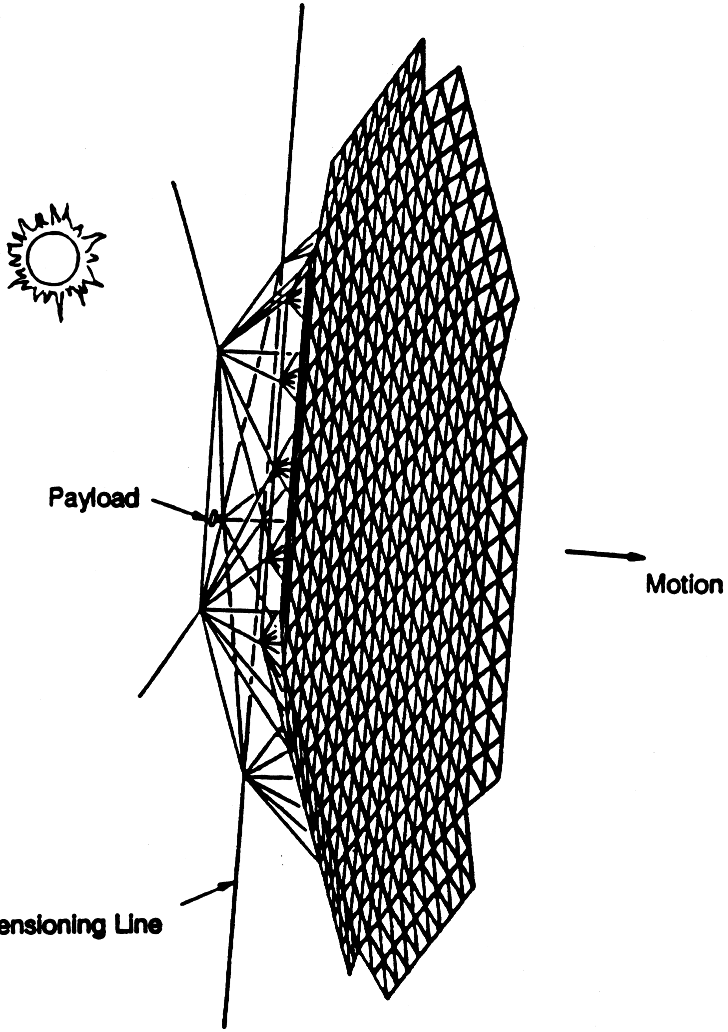
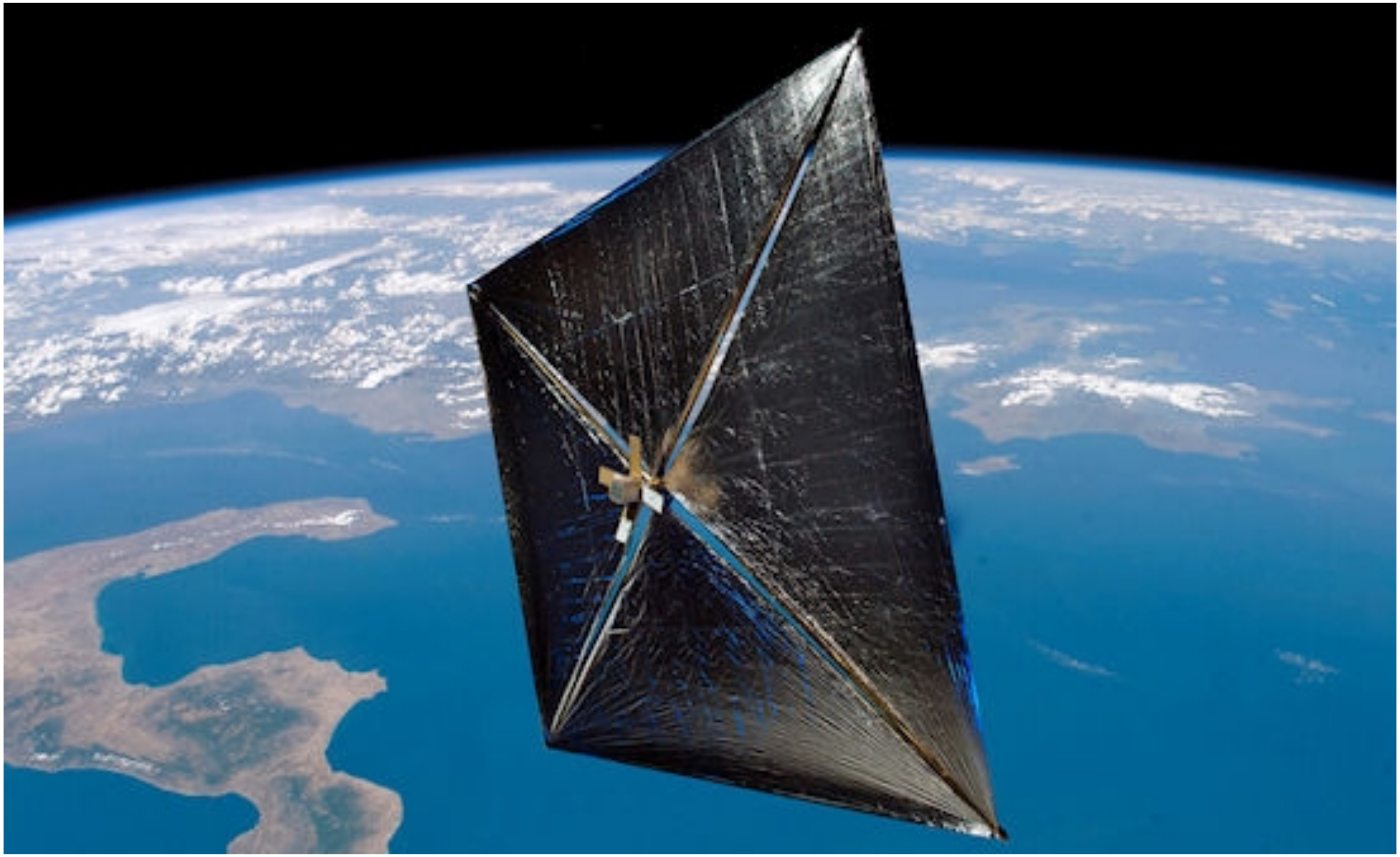


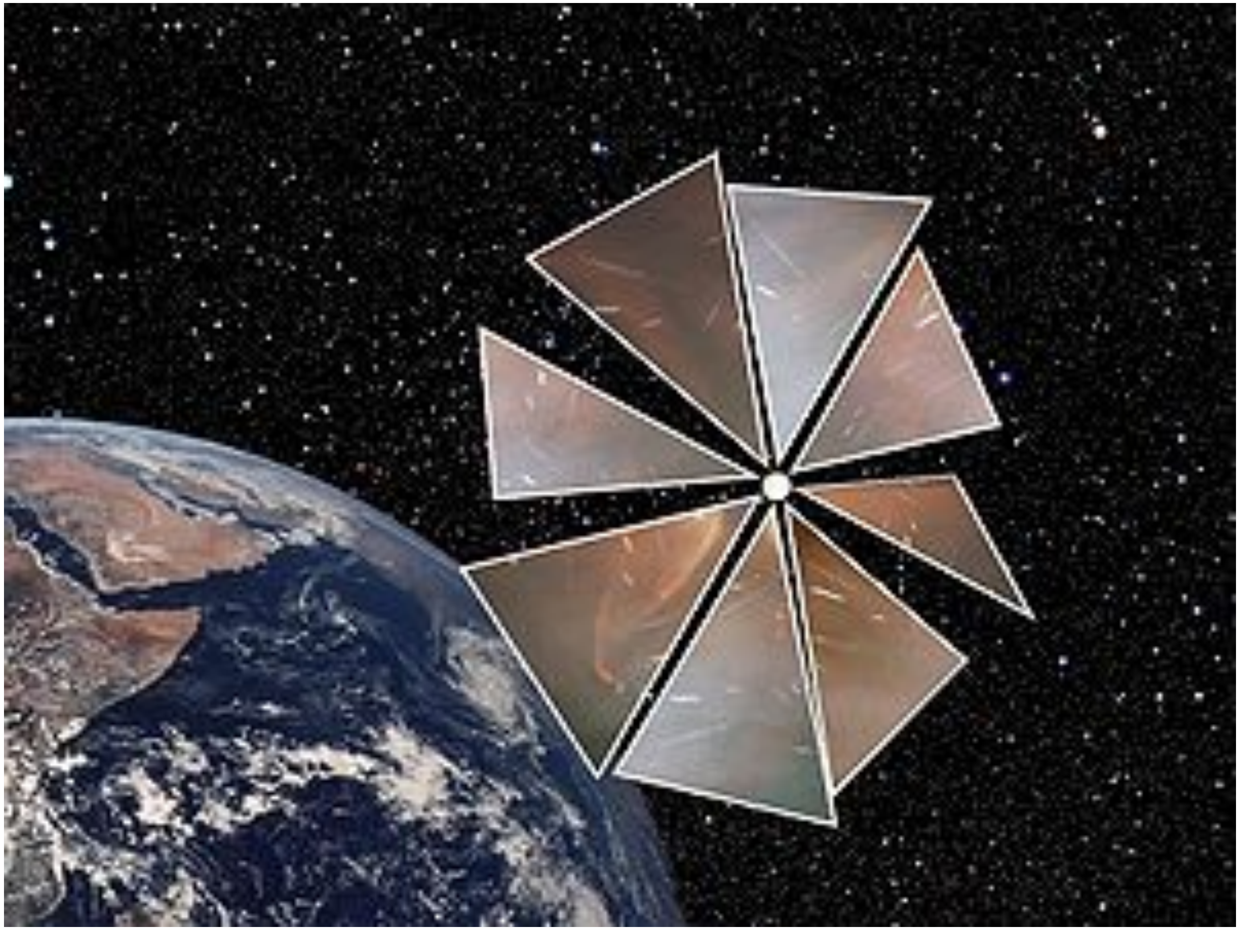
FIGURE 3.16 The Lattice Ship. (K.E. Drexler)

http://www.space.com/26488-solar-sails-could-beat-the-rocket-equation-animation.html#ooid=pjY2V5cDpVU5cY3qPtYv3wNXstzeSAWW

NanoSail-D, Jan 2011



A Recent Private Effort – Cosmos 1



Mass Estimates

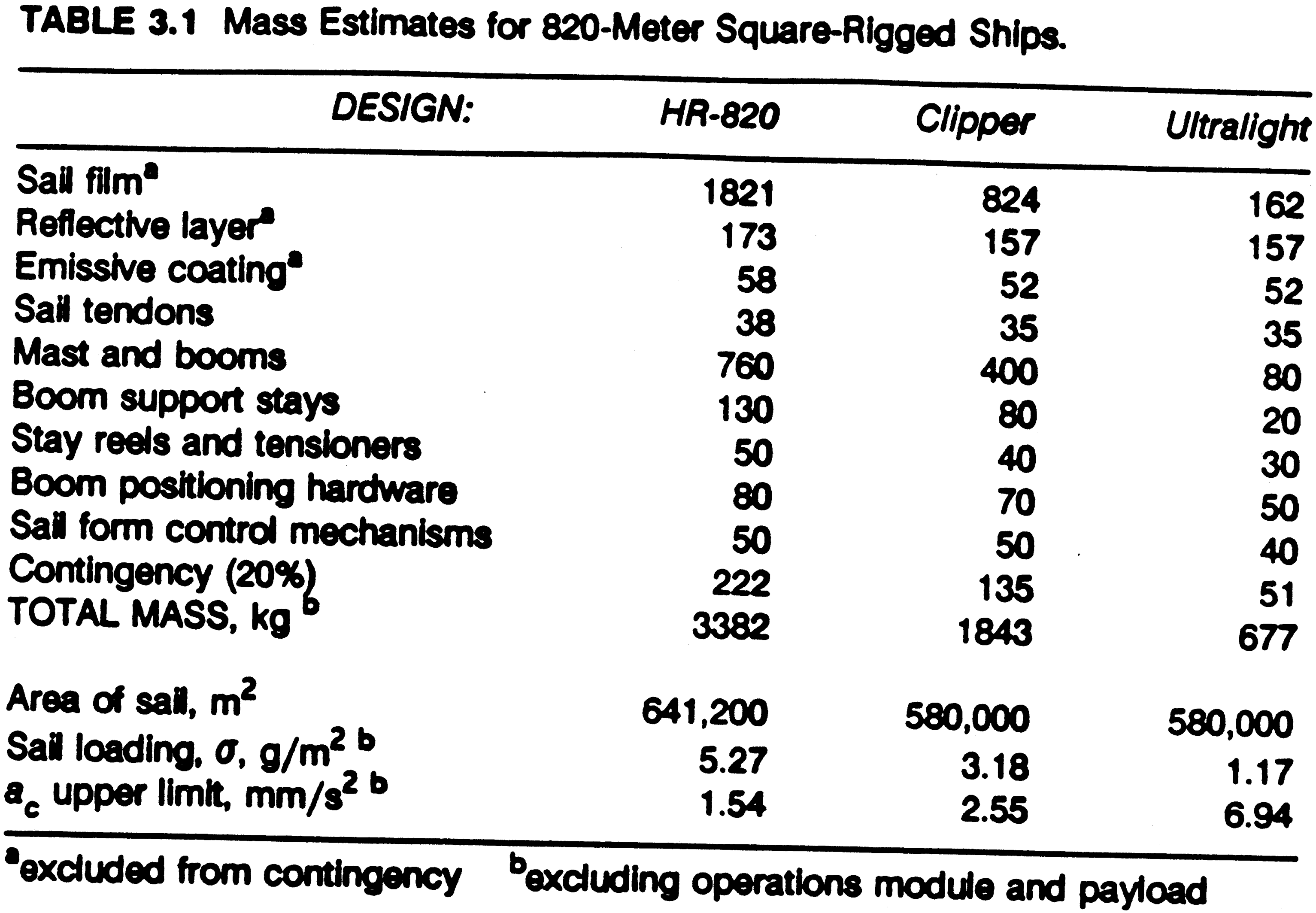
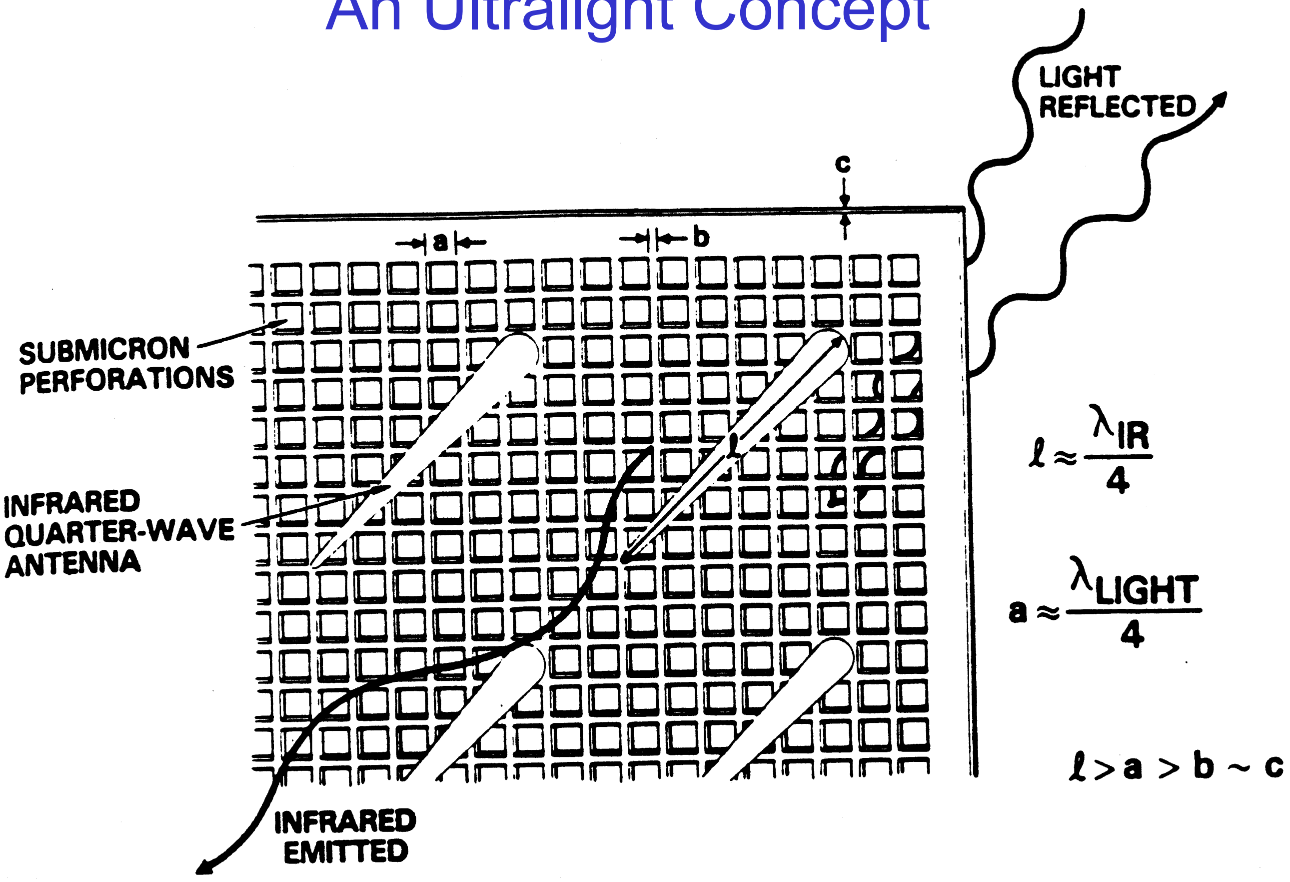


TABLE 3.1 Mass Estimates for 820-Meter Square-Rigged Ships.

DESIGN:	*HR-820*	*Clipper*	*Ultralight*
Sail film[a]	1821	824	162
Reflective layer[a]	173	157	157
Emissive coating[a]	58	52	52
Sail tendons	38	35	35
Mast and booms	760	400	80
Boom support stays	130	80	20
Stay reels and tensioners	50	40	30
Boom positioning hardware	80	70	50
Sail form control mechanisms	50	50	40
Contingency (20%)	222	135	51
TOTAL MASS, kg [b]	3382	1843	677
Area of sail, m^2	641,200	580,000	580,000
Sail loading, σ, g/m^2 [b]	5.27	3.18	1.17
a_c upper limit, mm/s^2 [b]	1.54	2.55	6.94

[a] excluded from contingency [b] excluding operations module and payload

An Ultralight Concept



$\ell \approx \frac{\lambda_{IR}}{4}$

$a \approx \frac{\lambda_{LIGHT}}{4}$

$\ell > a > b \sim c$

FIGURE 4.23 Perforated Solar Sail With Microstructures. (R.L. Forward/Hughes)

Payload Fraction

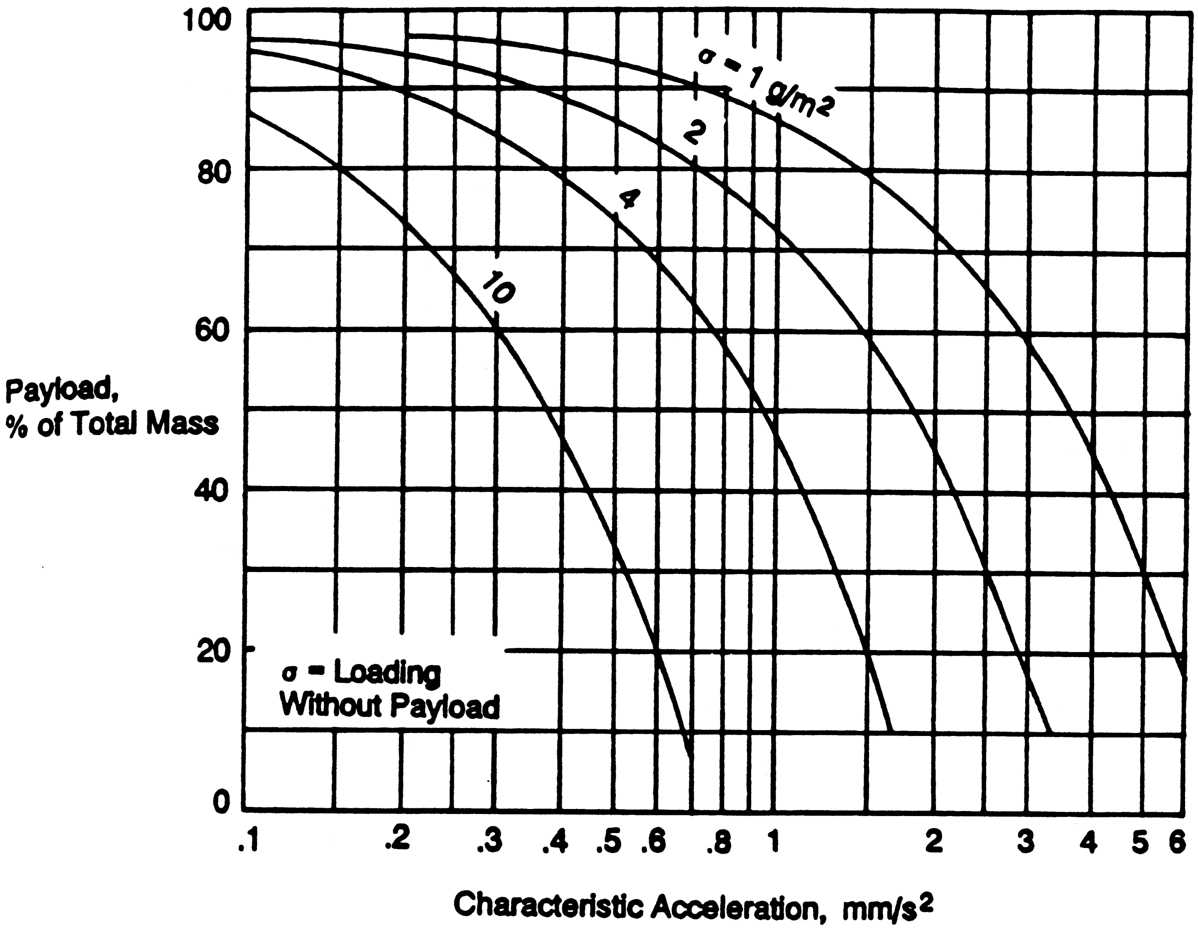


FIGURE 3.2 Payload Variation with Characteristic Acceleration.

Earth to Moon

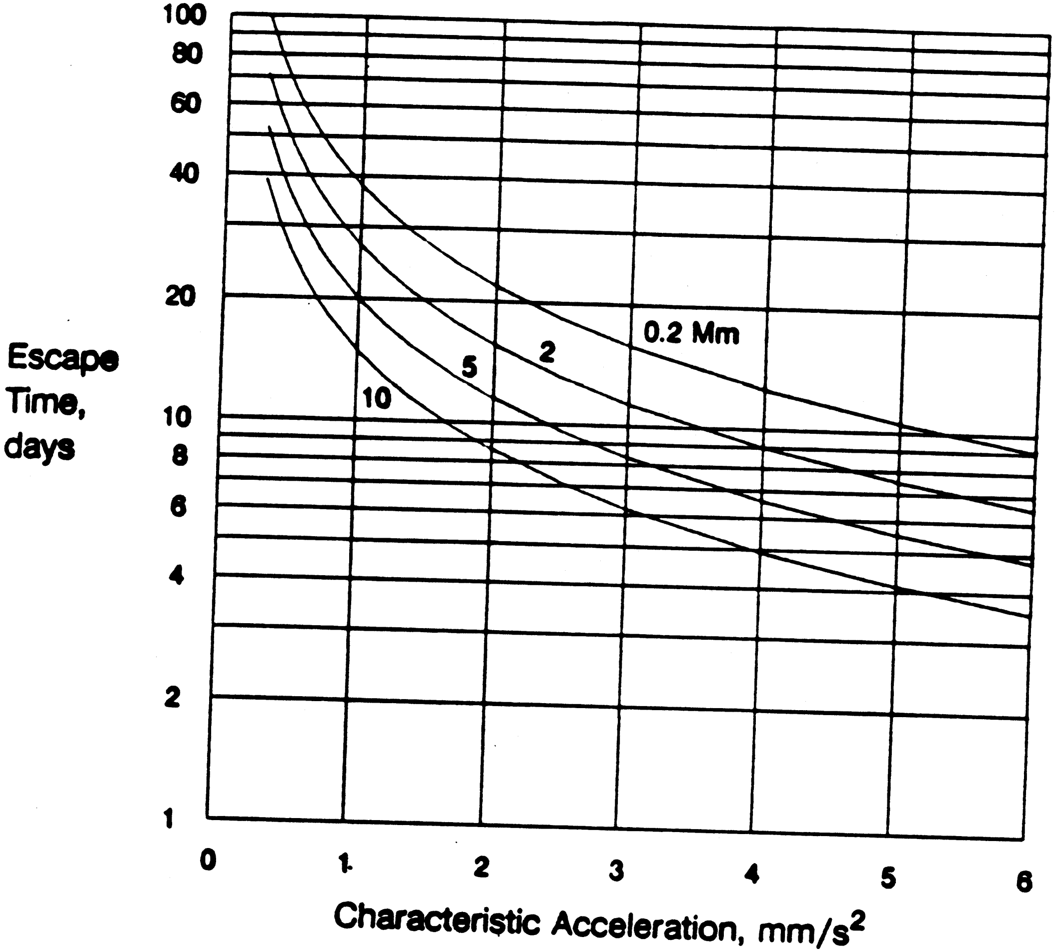
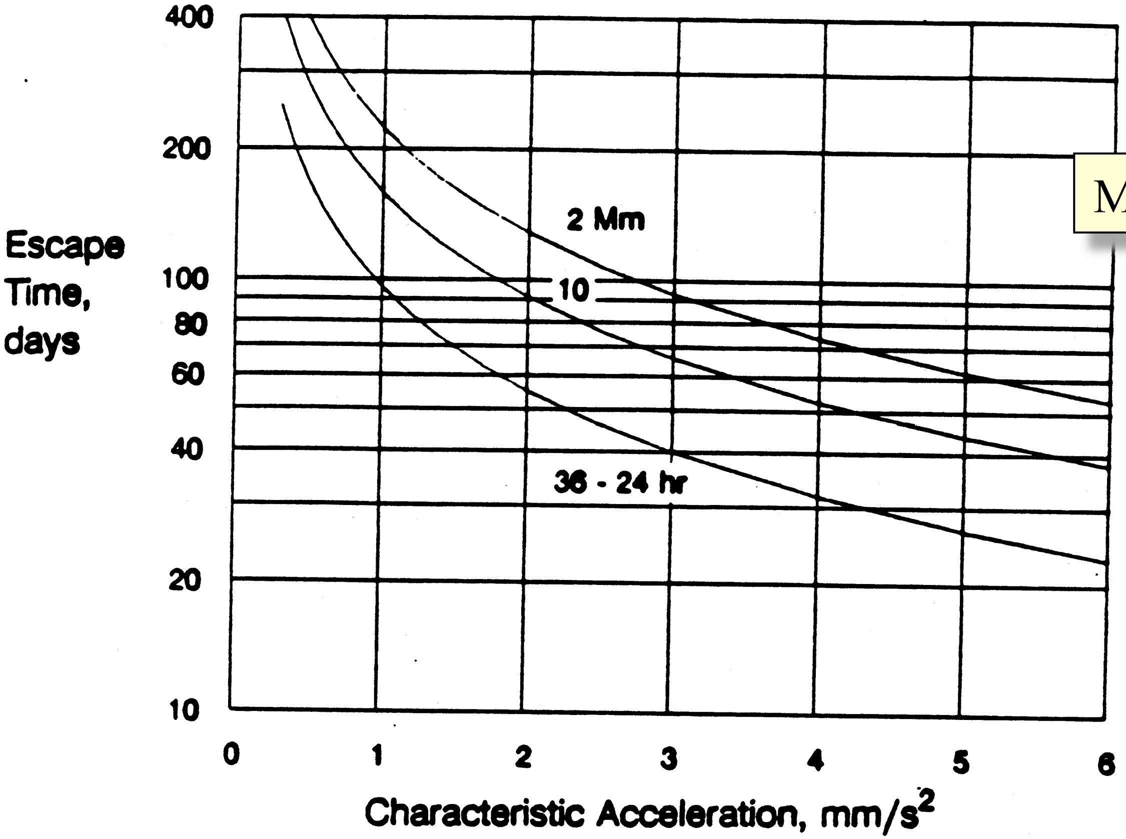


FIGURE 2.2 Lunar Spiral Times.

Earth Escape

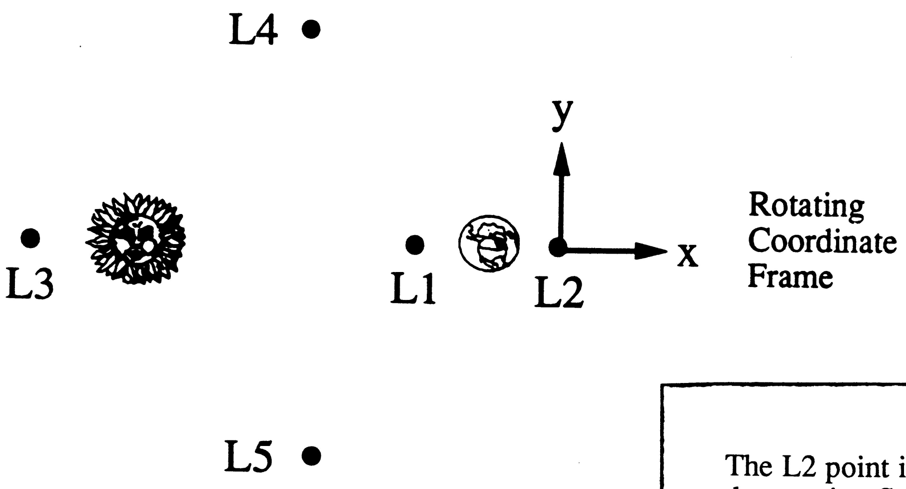


Mm - Megameters

FIGURE 2.1 Earth Escape Times From Various Orbits.

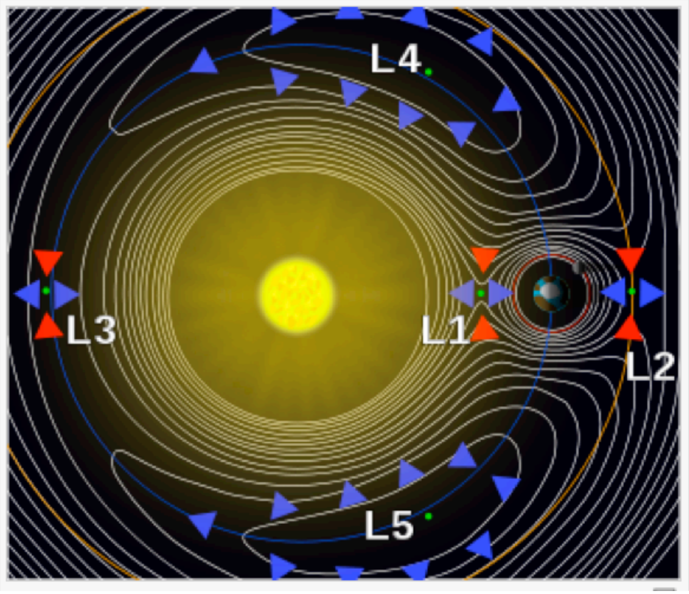
Mission to L2 – PhD thesis Sun Hur 1992

What is L2 Libration Point?



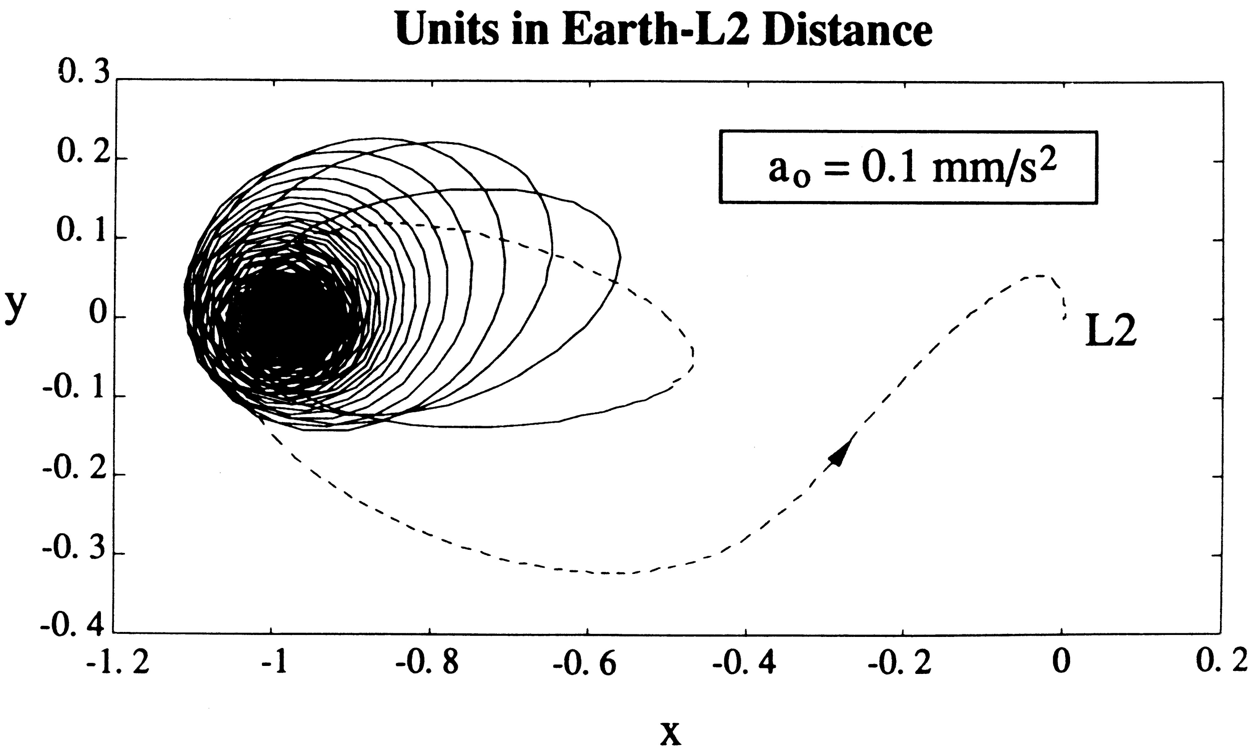
The L2 point is one of five equilibrium points the rotating Sun-Earth system where the gravitational force equals the centrifugal force is an unstable equlibrium point.

CENTRIFUGAL = GRAVITATIONAL

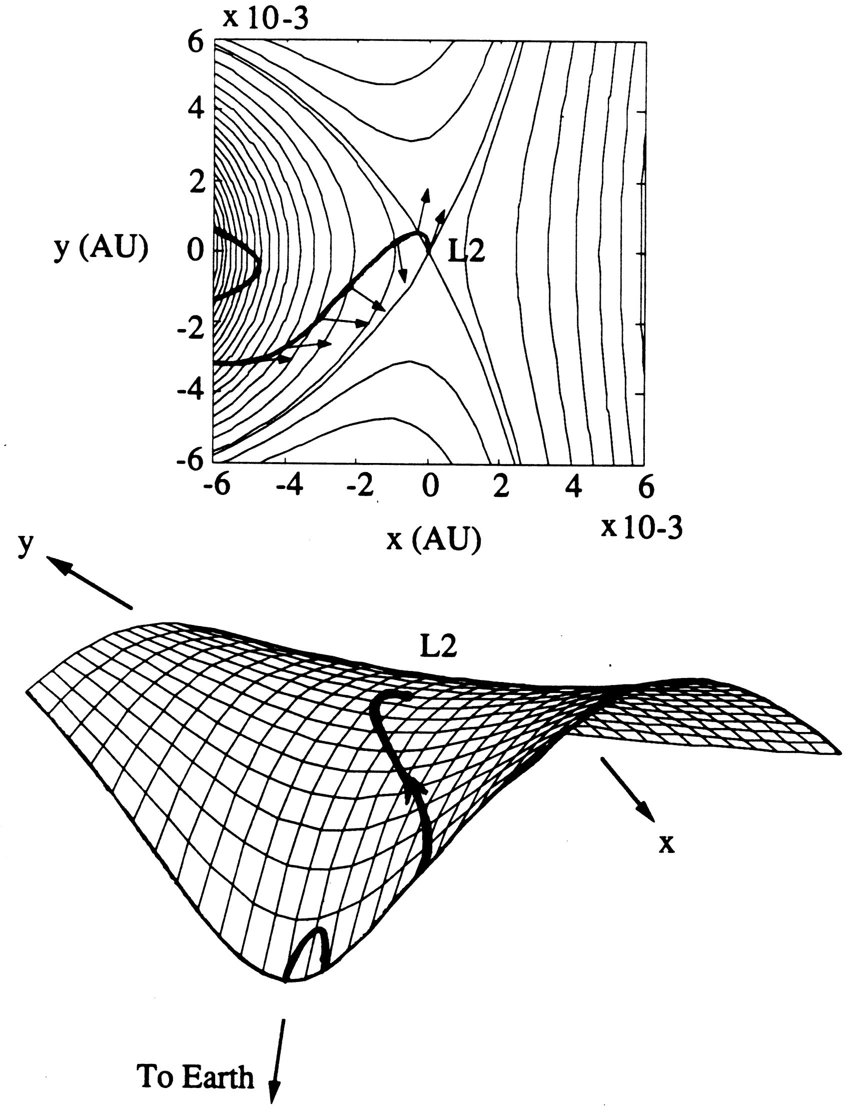


Gravitational potential

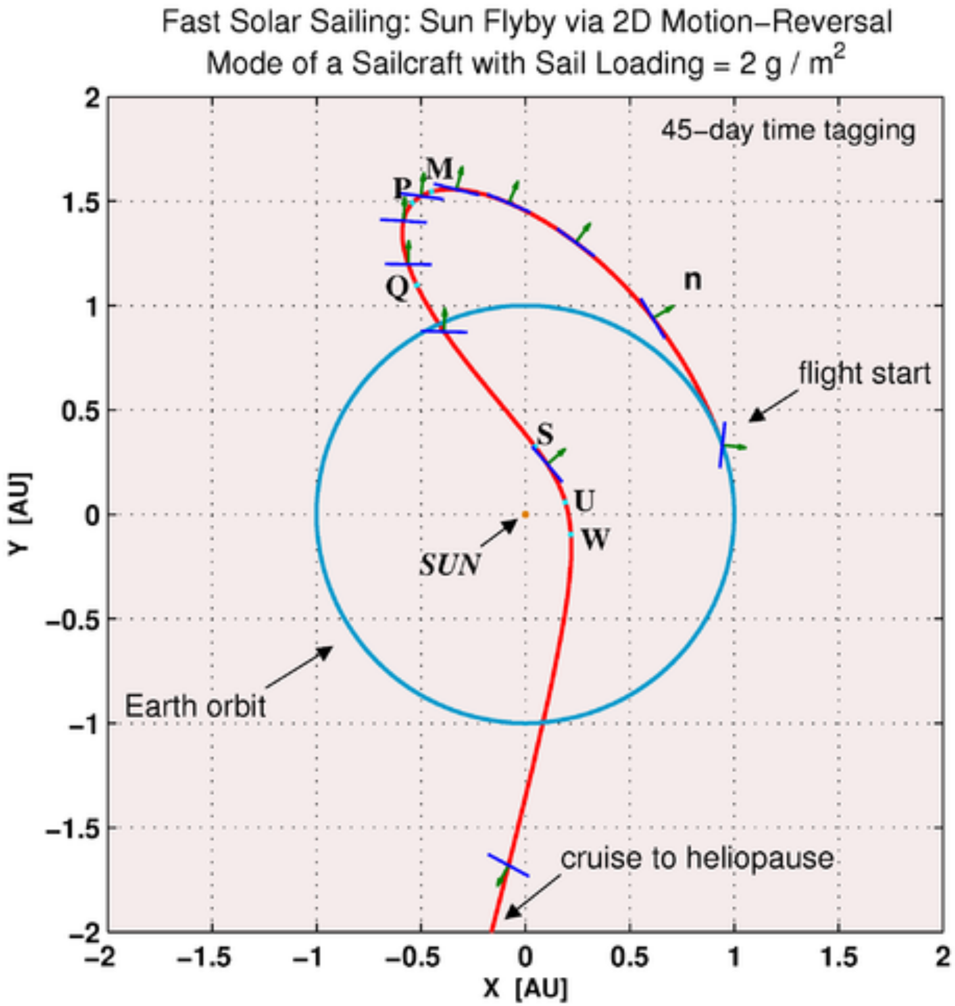
Feasible Trajectory


Units in Earth-L2 Distance

Trajectory in the modified potential well



Mission Toward the Sun



Missions to the Planets

TABLE 2.1 Inner Planets Missions Summary.

Sail Size m	*Mercury Rendezvous*		*Venus Rendezvous*		*Mars Rendezvous*		*Mars Aerobrake*	
	days	*tons*	*days*	*tons*	*days*	*tons*	*days*	*tons*
800[a]	600	9.4	200	1.4	400	2.4	131	1.9
	900	19	270	4.6	500	5.2	200	5.2
	1200	28			700	9.4	338	10
2000[b]	600	66	200	17	400	23	131	20
	900	124	270	36	500	40	200	40
	1200	184			700	66	338	70

[a] $\sigma = 5.0$ g/m^2 [b] $\sigma = 3.0$ g/m^2 (excluding payloads)

Missions to the Planets – Cont’d

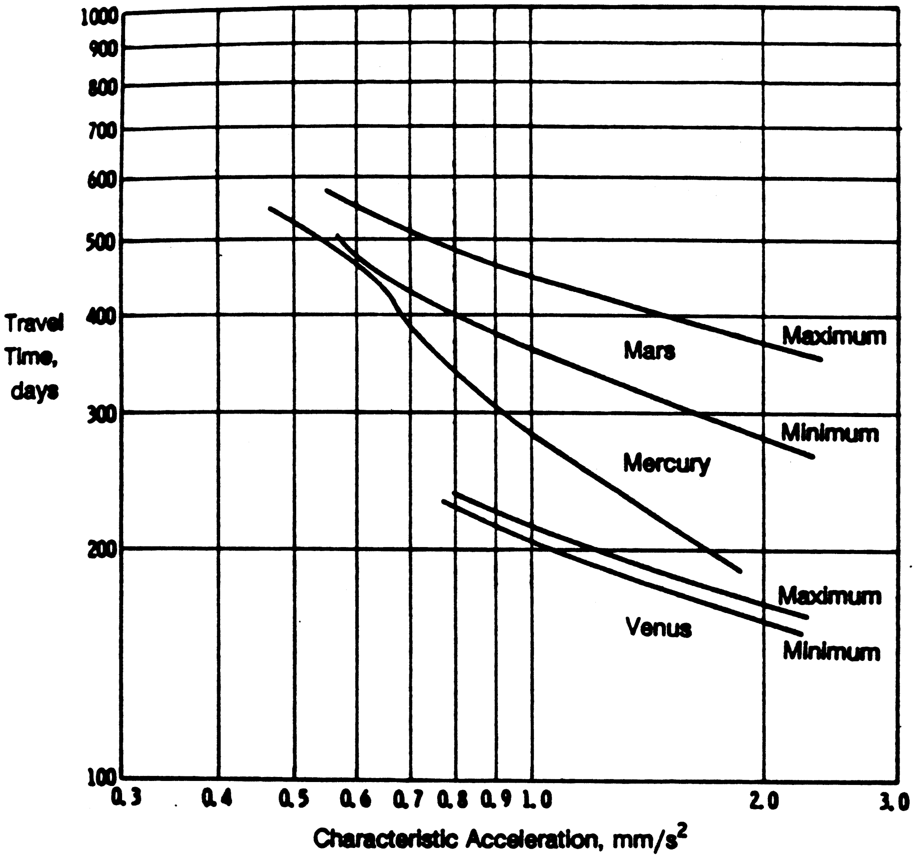
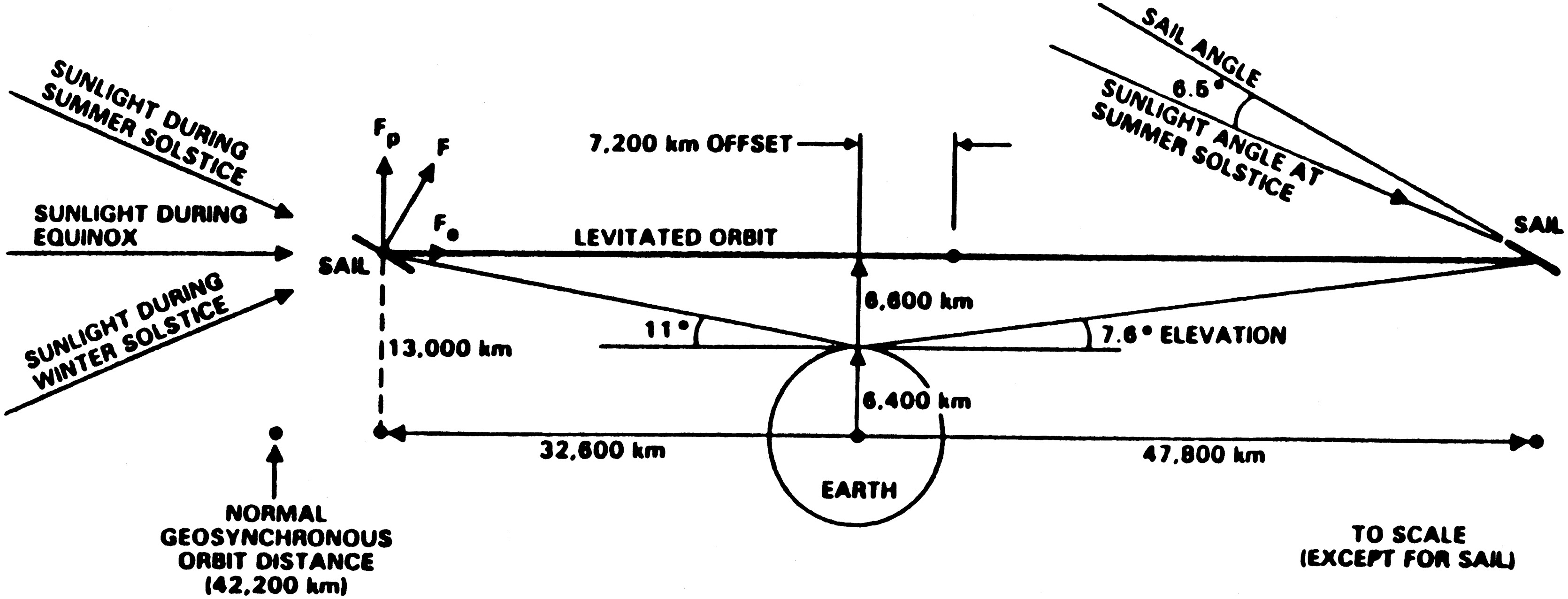


FIGURE 2.4 Typical Travel Times to the Inner Planets.

Mission example - levitated orbit



Mission example - solar watchers

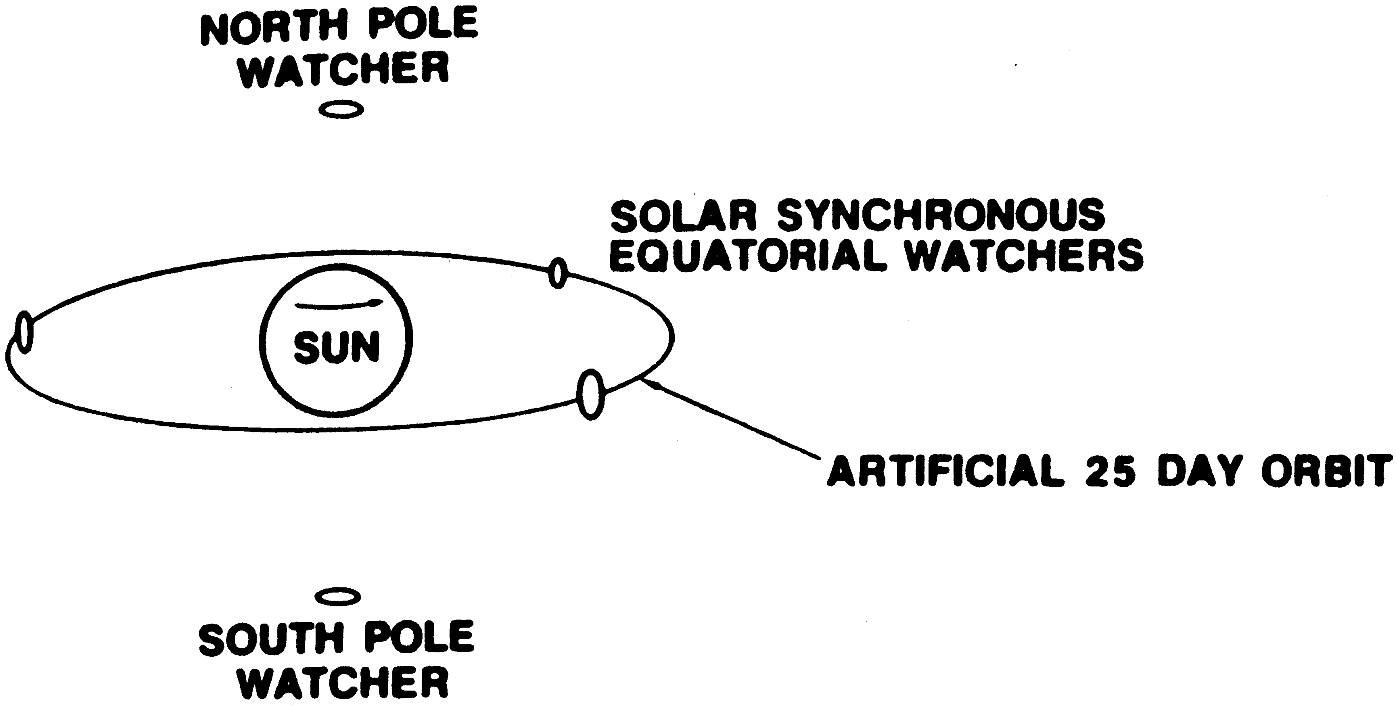


FIGURE 2.21 Synchronous Solar Orbits. (R.L. Forward/Hughes)

Microwave Thrust

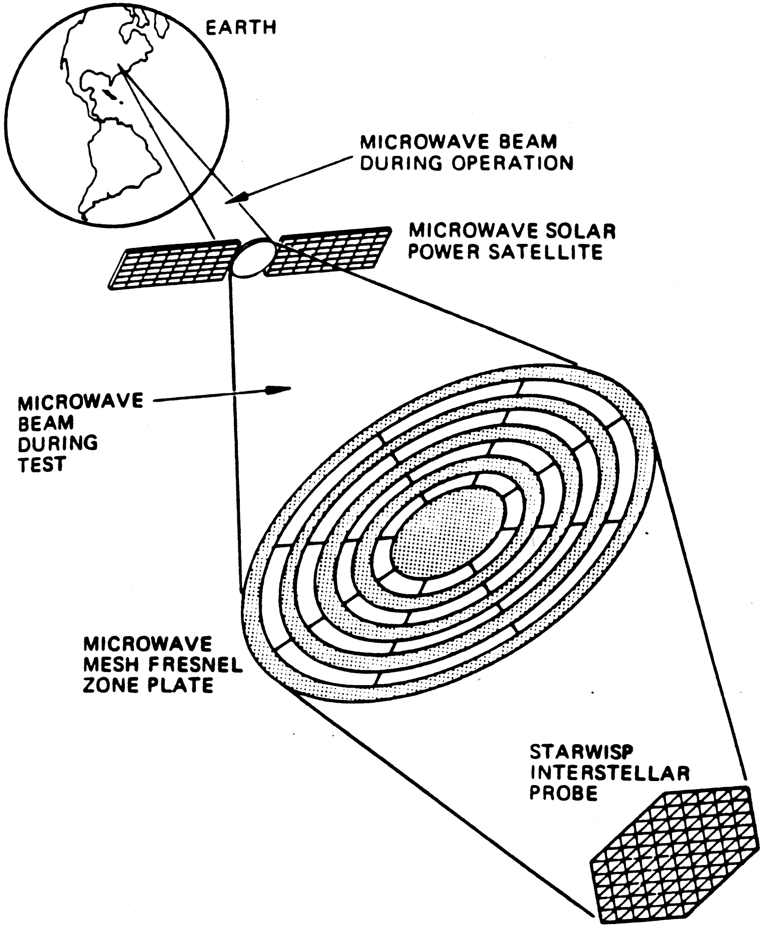


FIGURE 7.10 Operation of a Starwisp Probe. (R.L. Forward)

Mission example - interstellar fly-by

GW - Gigawatts

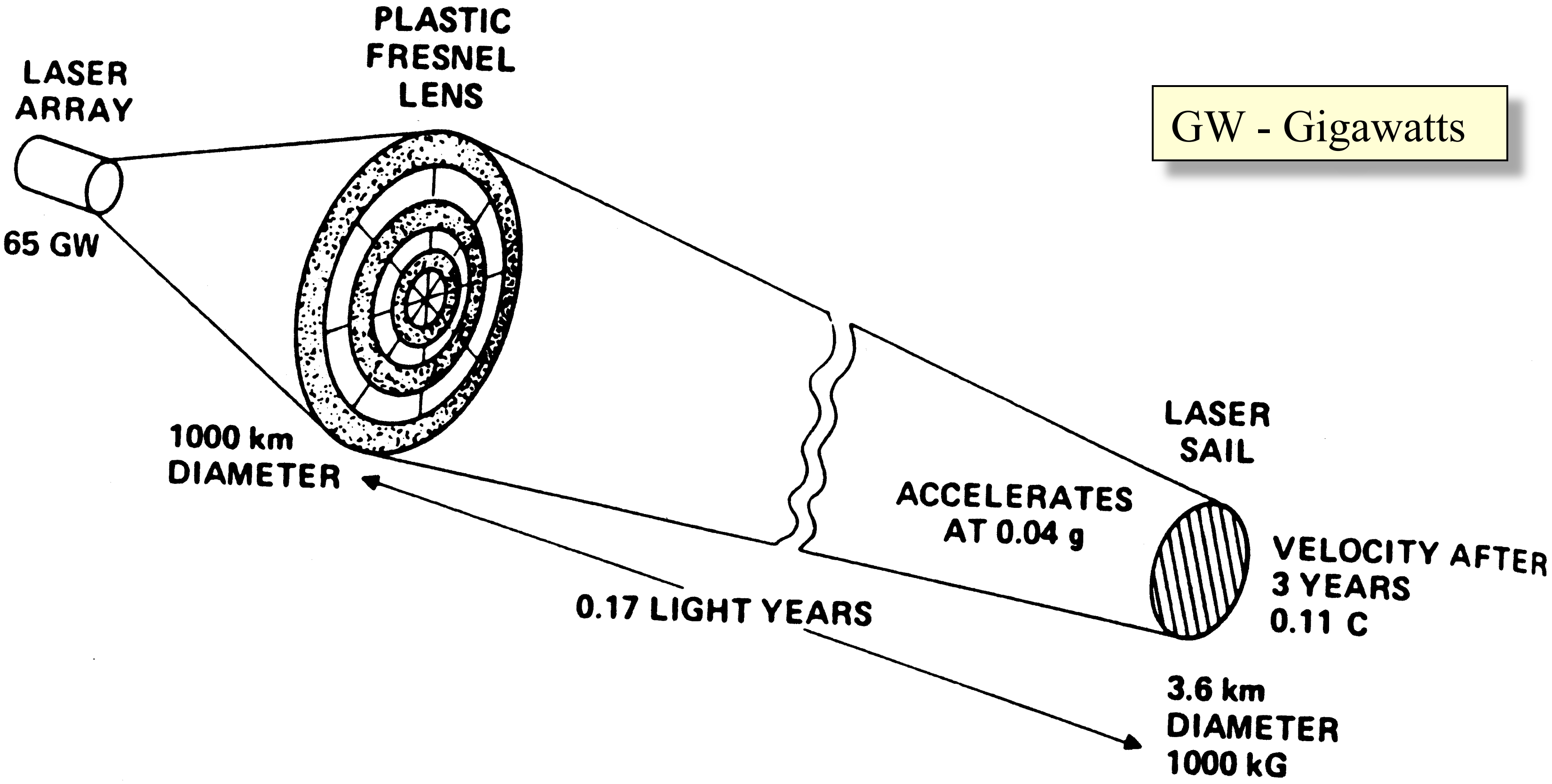


FIGURE 7.6 Profile of an Interstellar Fly-By Probe. (R.L. Forward)

Mission example - one-way interstellar flight

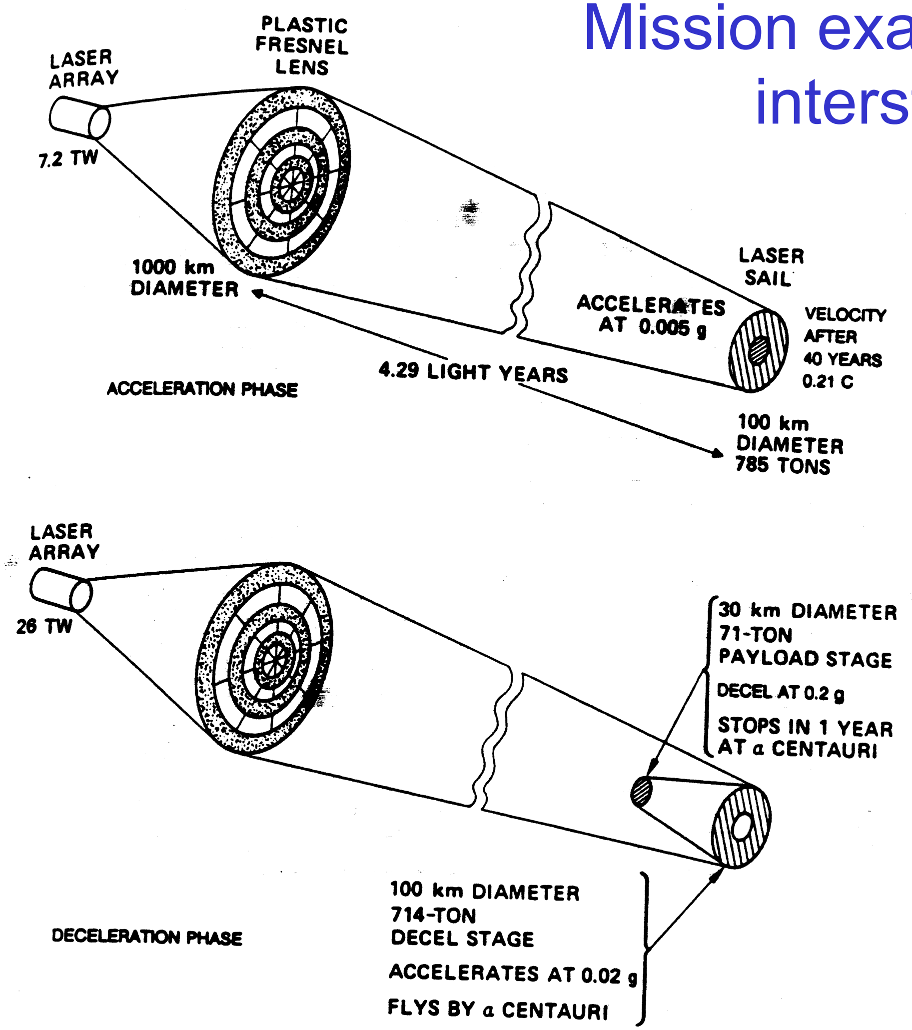


FIGURE 7.7 Profile of a Voyage to Alpha Centauri. (R.L. Forward)

TW - Terawatts

Mission example round-trip interstellar flight

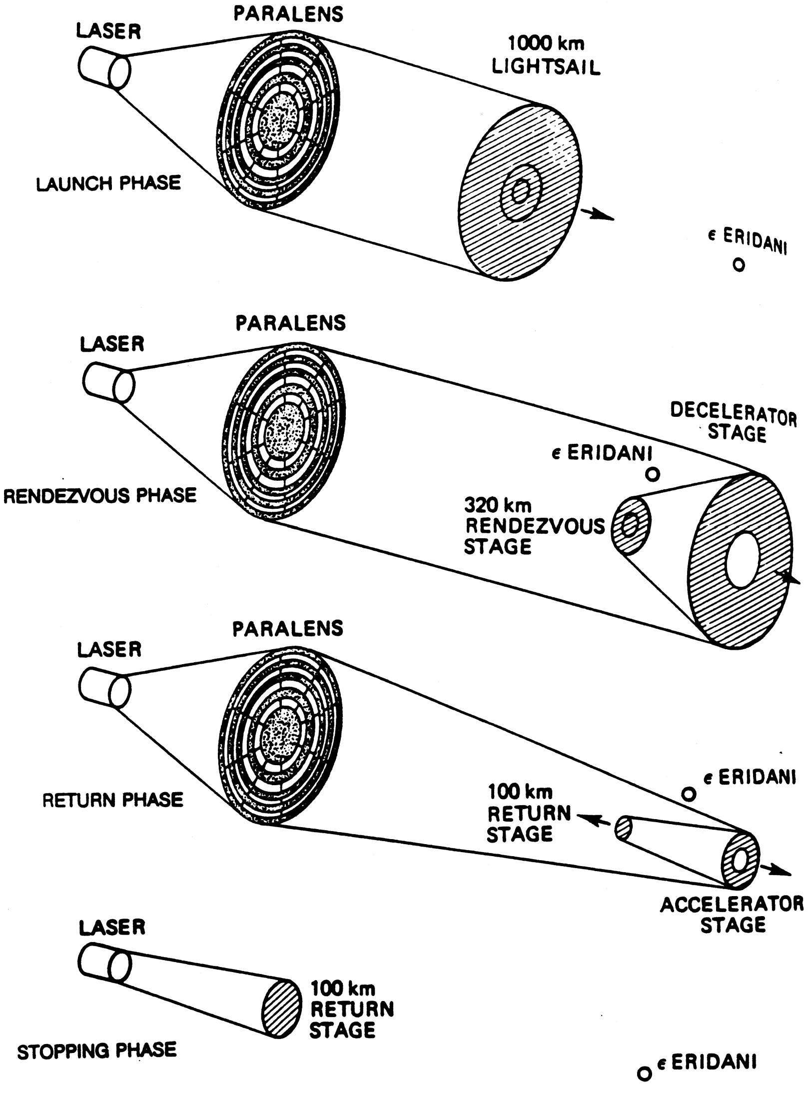
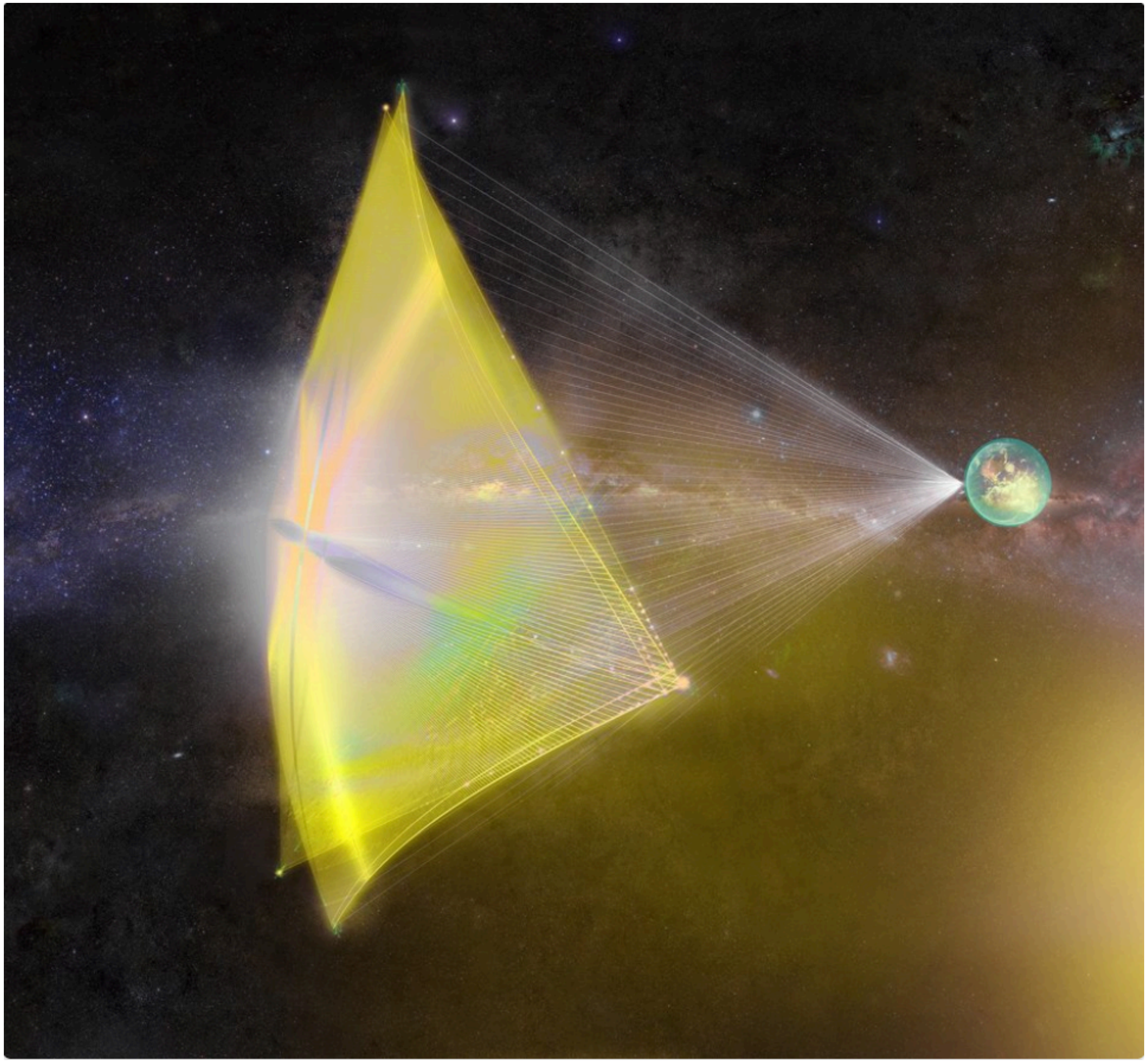


FIGURE 7.8 Profile of a Roundtrip Voyage to Epsilon Eridani. (R.L. Forward)

Breakthrough − Starshot - 2017



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

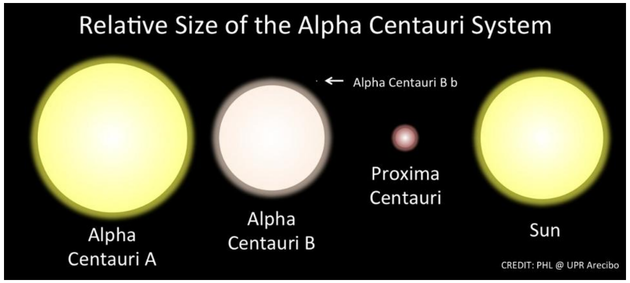
The research and engineering phase is expected to last a number of years. Following that, development of the ultimate mission to Alpha Centauri would require a budget comparable to the **largest current scientific experiments**, and would involve:

- 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 = 10^5m/sec^2

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

Sail Area = 10 m^2

Required light pressure

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

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

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

How much power does the sail have to dissipate? Assume 99.999% of the incident energy is reflected by the sail.

$$W_{dissipated} = 1.5 \times 10^4\ J/\sec$$

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/K

$$W_{dissipated} = 1.5 \times 10^4\ J/\sec = C\frac{dT}{dt}$$

$$\frac{dT}{dt} = 3.58 \times 10^3\ K/\sec$$

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

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