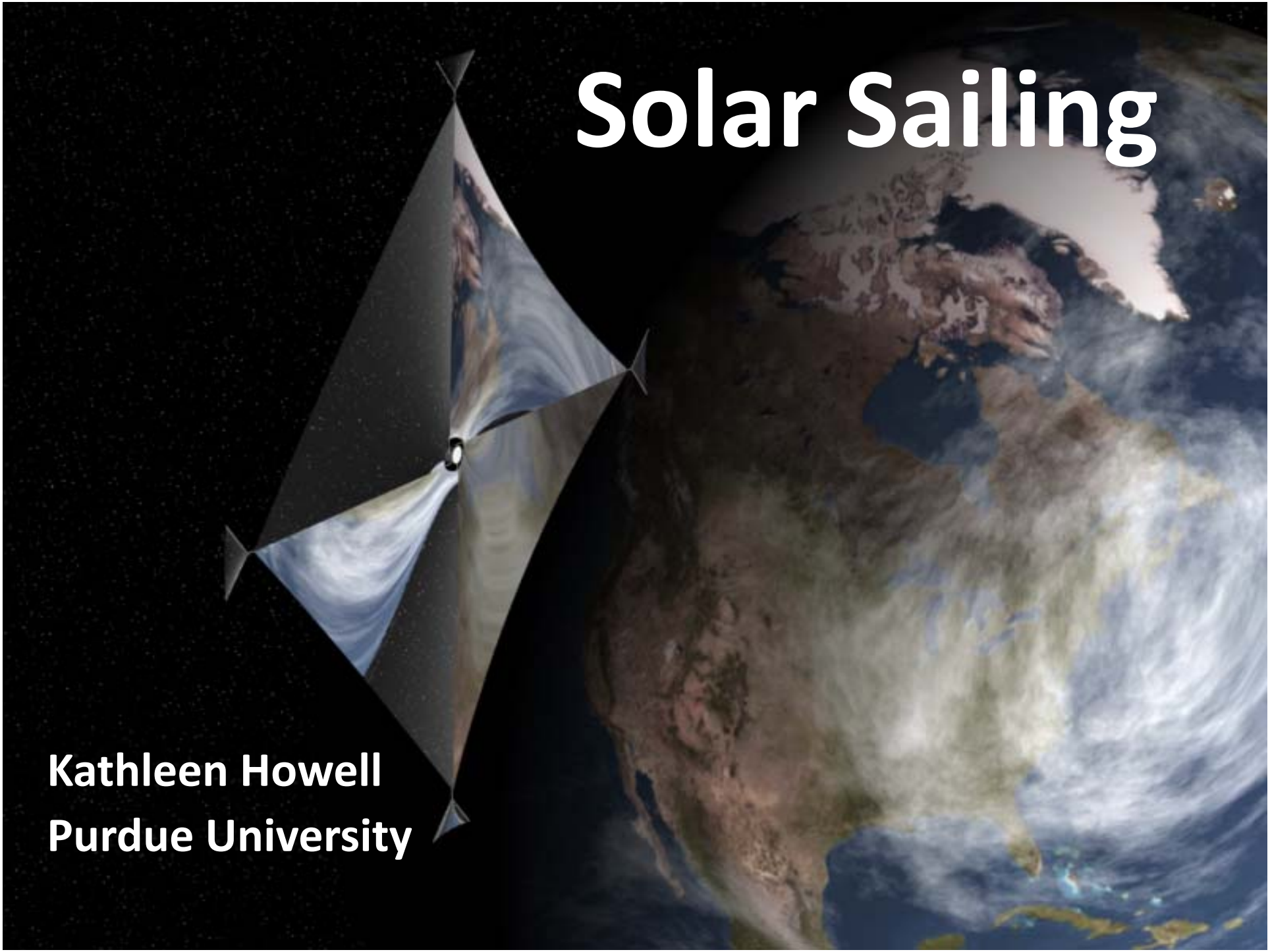
Solar Sailing

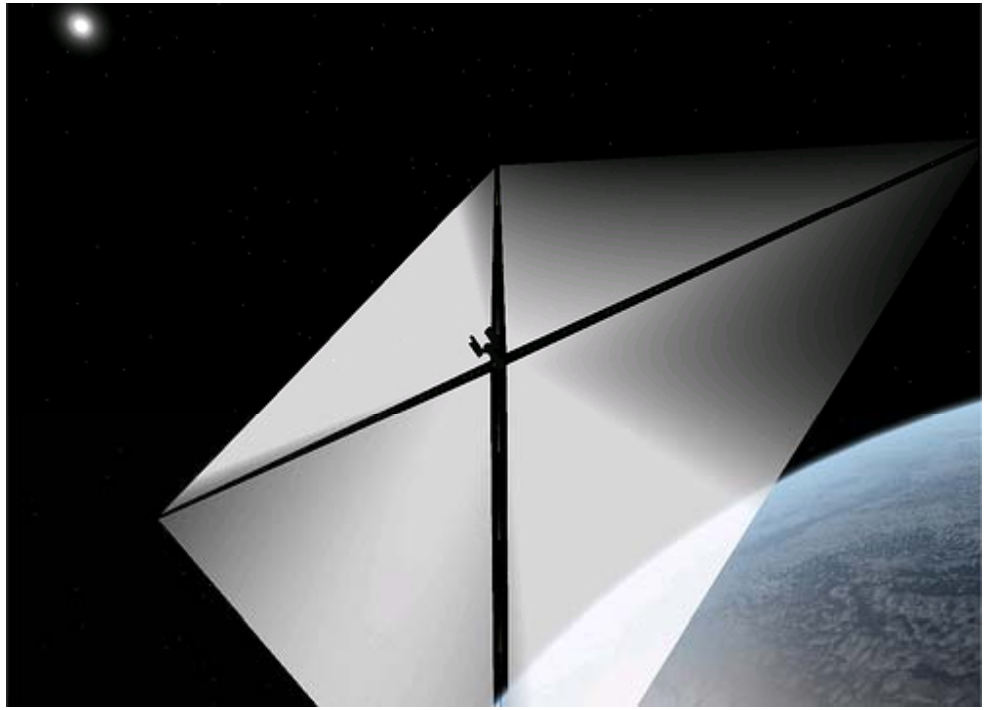


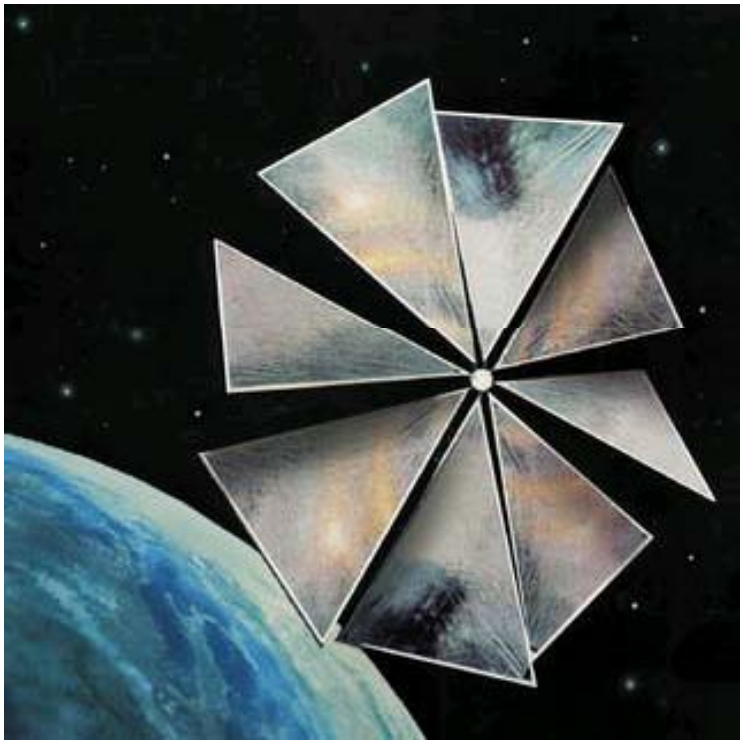
Kathleen Howell
Purdue University

What is Solar Sailing?

Sailing in space using large reflectors for propulsion

Pressure from sunlight reflecting off large, low-mass sail → force





Applications:

- Exploration of the solar system and beyond
- Delivery of science instruments/observatories
- Maintenance of special 'artificial' orbits
- Delivery of large cargos and people
- Store solar energy/reflectors for comm
- Planetary Protection

Solar Sailing is Not a New Idea

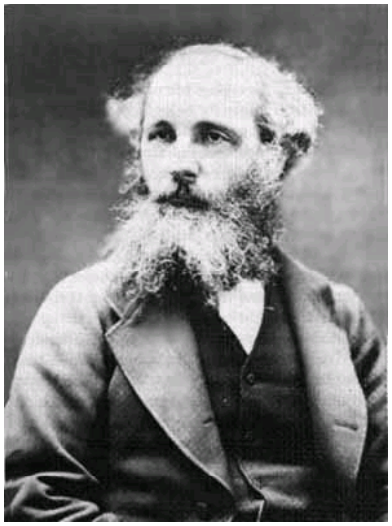
Johann Kepler → 400 years ago (1610)

Observed comet tails blown by (he thought) a solar "breeze"

Suggested to Galileo → "ships and sails proper for heavenly air should be fashioned" to glide through space

No concept of required scientific principles (winds do not exist!)

Solar Sailing is Not a New Idea



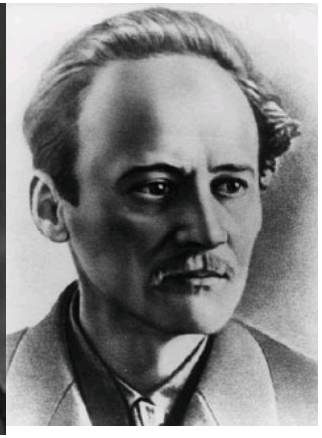
Maxwell (1831-1879)

James Clerk Maxwell

1860's modern theory of electromagnetism

1871 proved that light could exert pressure

Tsiolkovsky (1857-1935)



Tsander (1887-1933)

Konstantin Tsiolkovsky

1920's first discussed practical solar sailing

Fridrikh Tsander

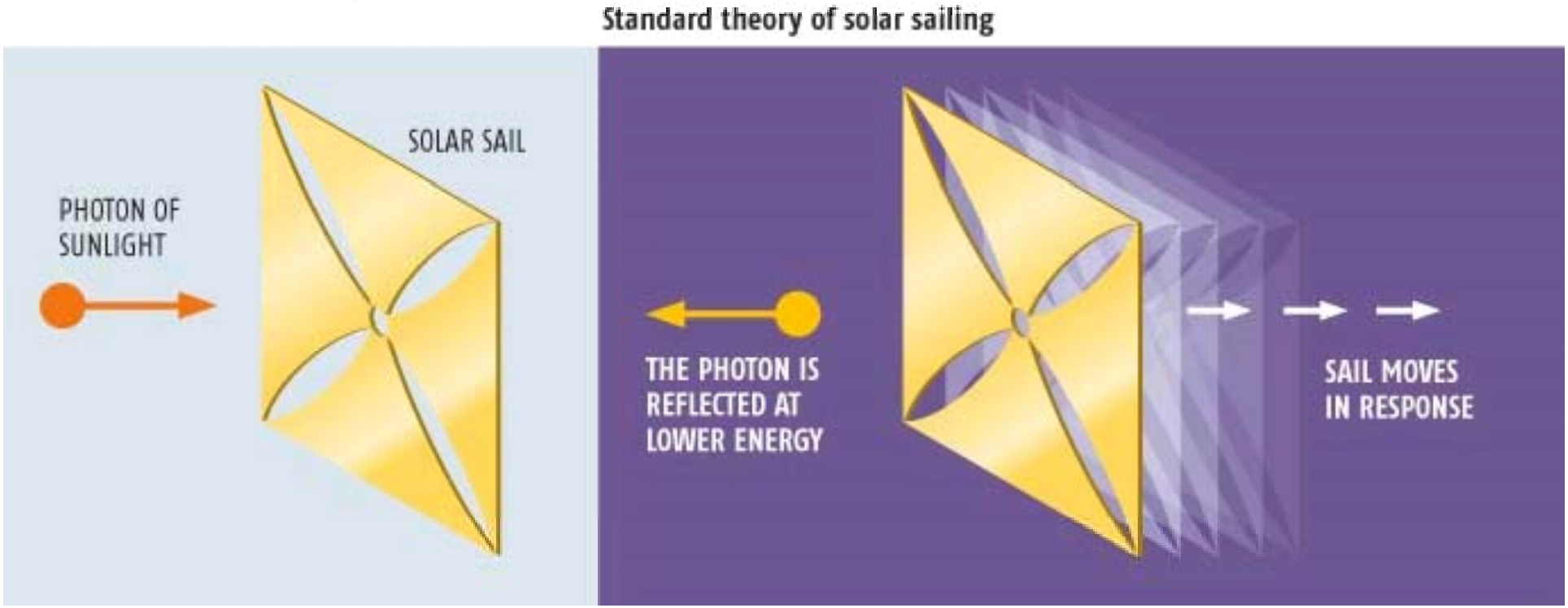
1924 → "For flight in interplanetary space I am working on the idea of flying, using tremendous mirrors of very thin sheets, capable of achieving favorable results"

Sails: Using Sunlight

Sail pointed at Sun, experiences force

⟶ Sun pushes the sail directly away

Reflected light generates reaction force
(much like reaction force of rocket)



Mylar; carbon or aluminum better; more expensive

0.0075 millimeters thick

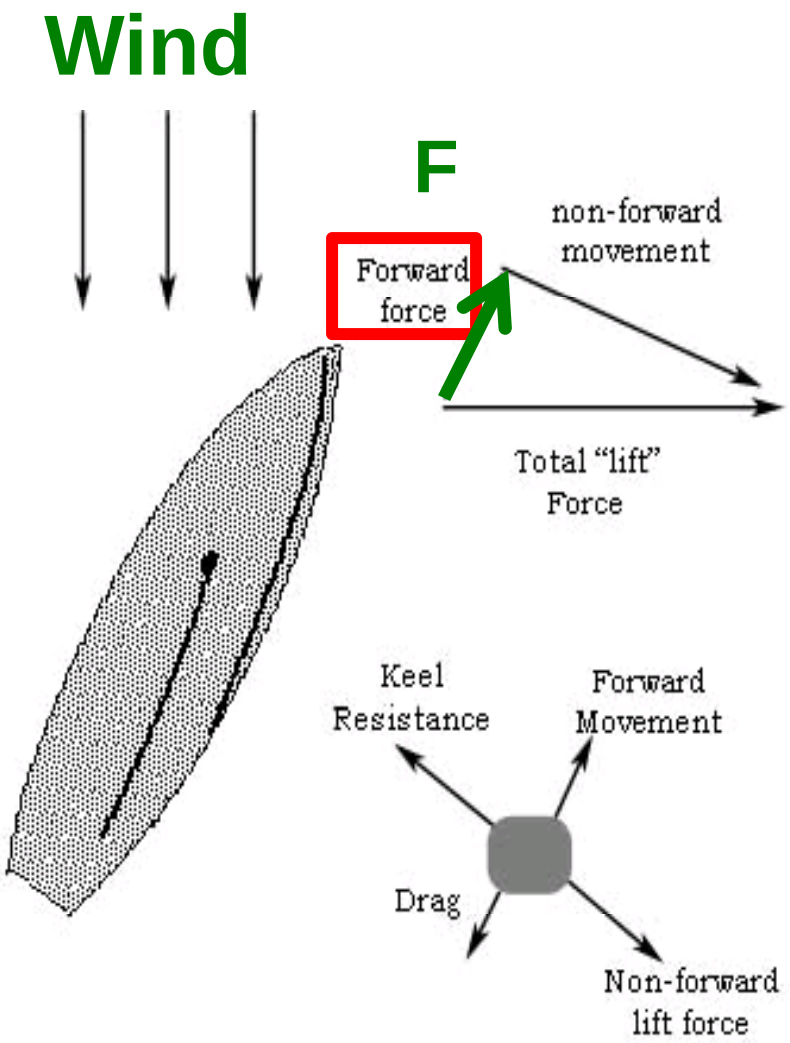
Sailboats: Using Wind

Bernoulli's Principle:

1. **Drag when wind moving over the sails (small→neglect)**

2. **Wind flows over 'airfoil' sail →receives force perpendicular to wind direction (keel resists lateral movement)**

3. **Boat moves forward**



Sails: Using Sunlight

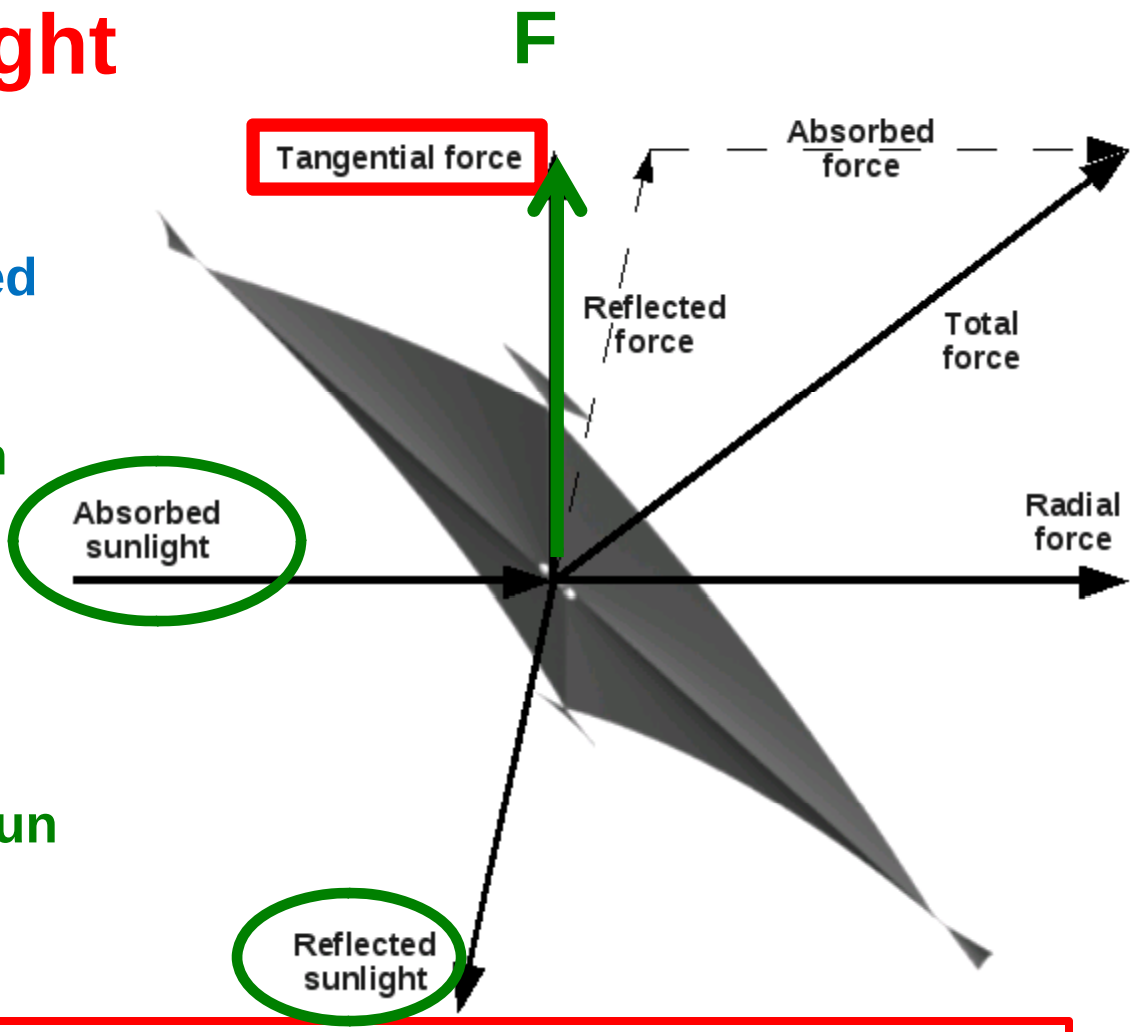
Sail tilted:

1. Less sunlight intercepted

   Forces from absorbed and reflected sunlight in different directions

2. Total force ⇩

   Zero – sail edge-on to Sun



Absorbed+part-of-reflected always radial

Sail Tilted → part-of-reflected pushes perpendicular+tangent to sunlight

Tangential force ⟹ use to maneuver in space

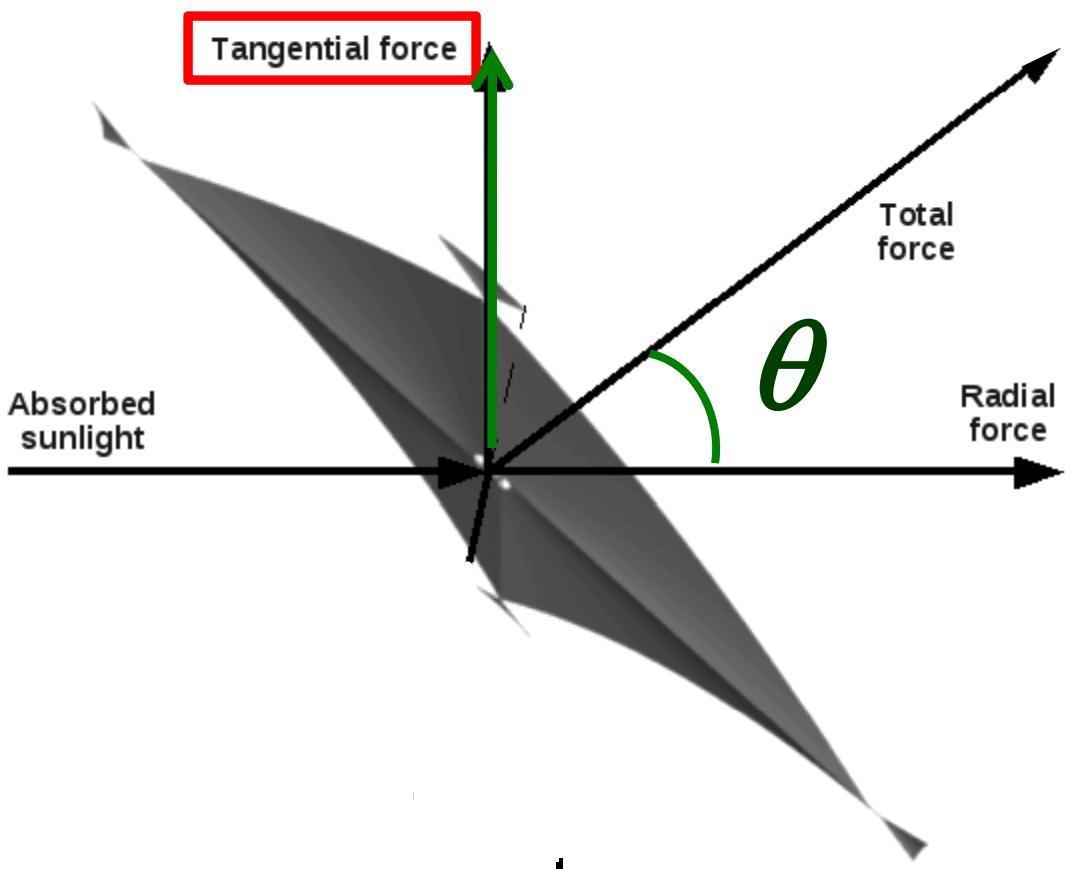
Sails: Maneuver in Space

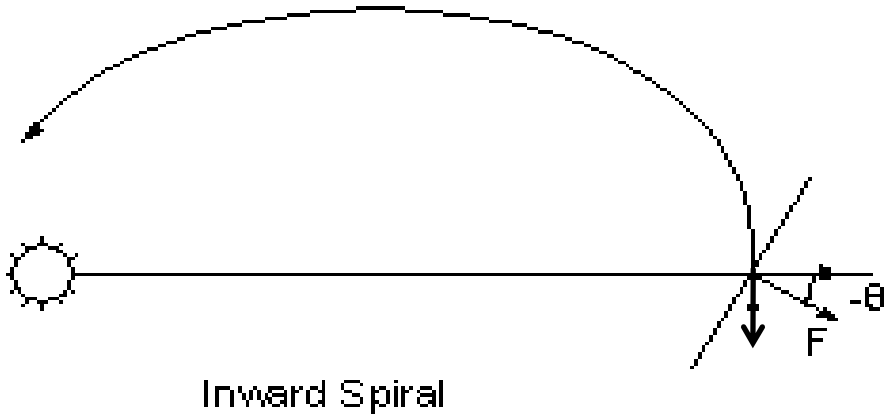
Tangential Force F

Angle

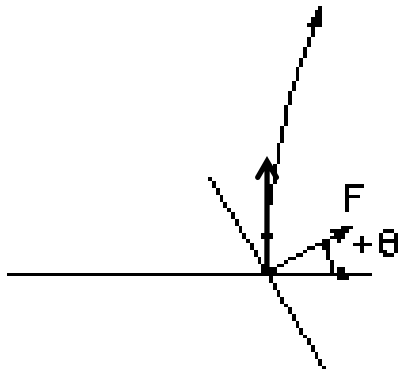
↑ gain energy – spiral out

↓ lose energy – spiral in



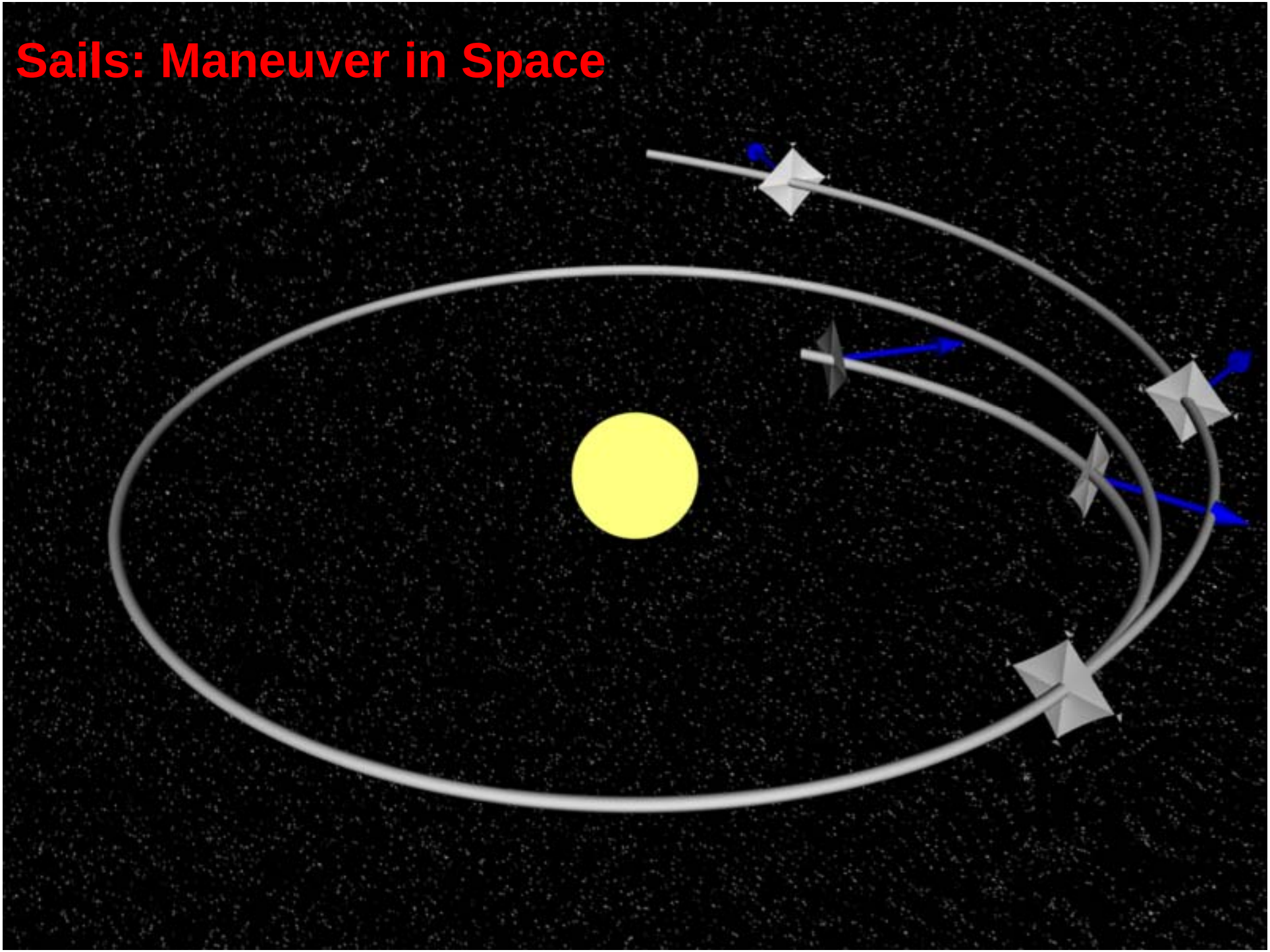


Inward Spiral



Outward Spiral

Sails: Maneuver in Space

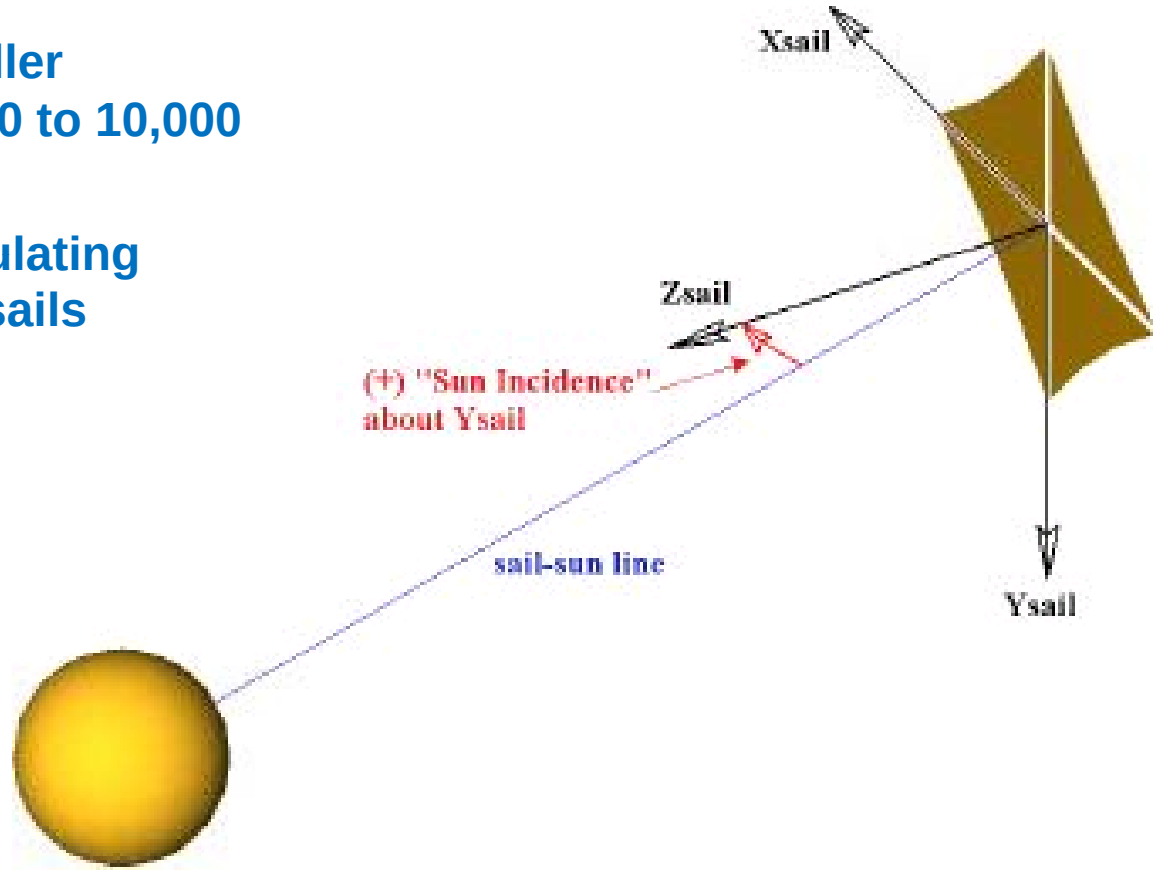


Sails: Using Sunlight ⟹ NOT Solar Wind!!!

Solar wind → charged particles streaming out from the Sun exerts force on a sail

Solar wind pressure smaller by factor of 5,000 to 10,000

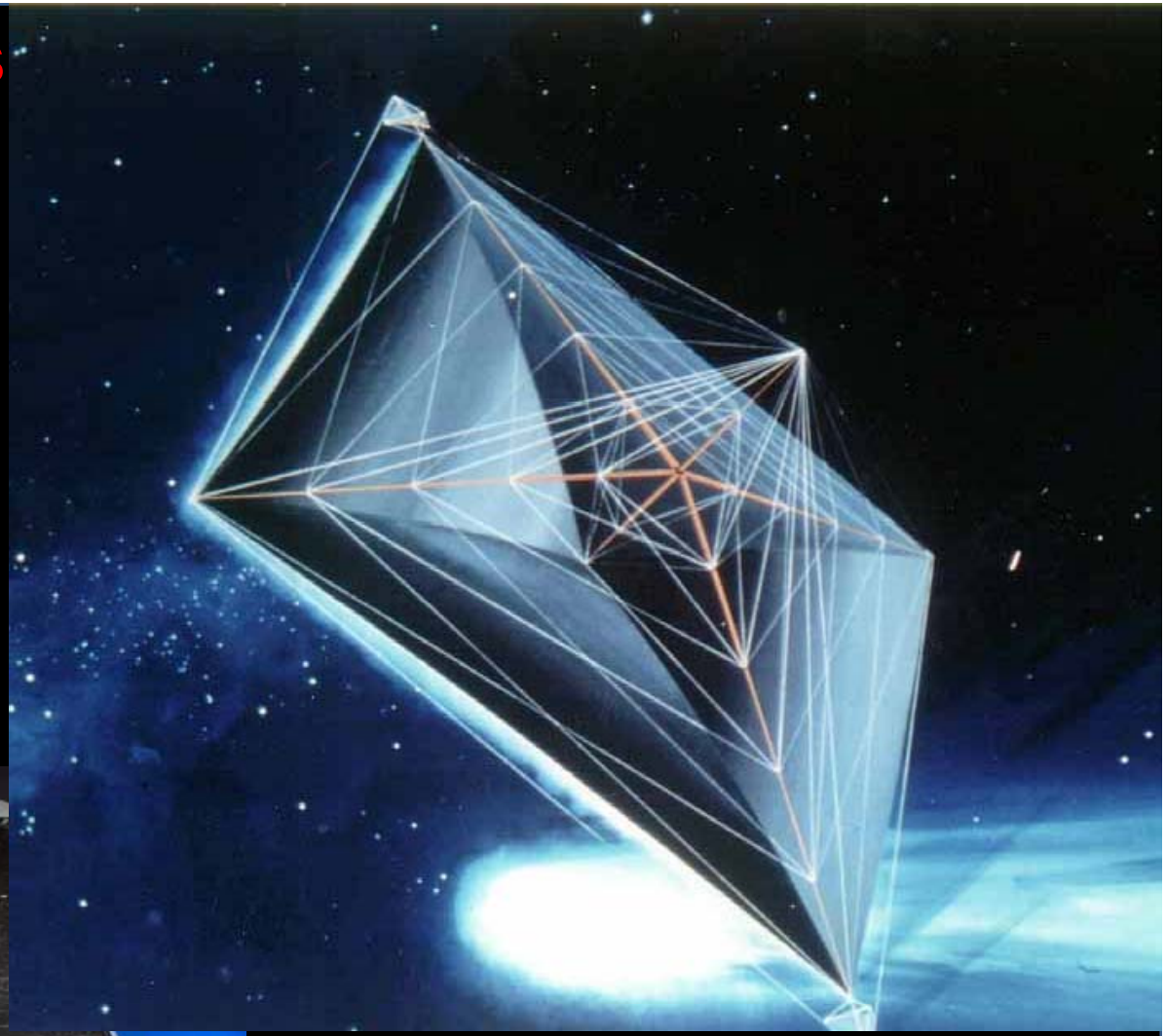
Usually ignored for calculating trajectories for sails

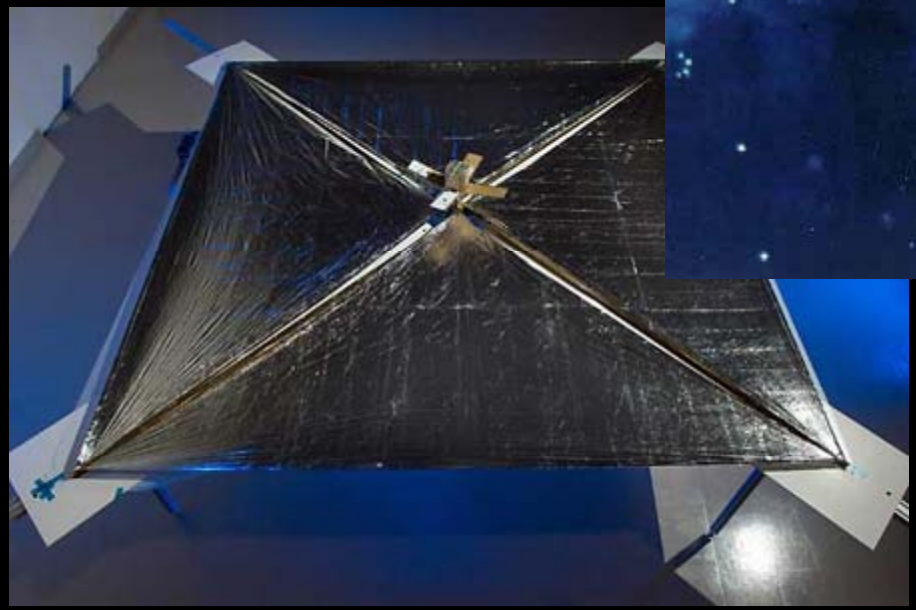


Sample Sail Types

Square Sail

- Large, flat reflective film
- 4 spars from hub
- Optimum Design
- Packing/deployment issues
- No spin to maintain tension

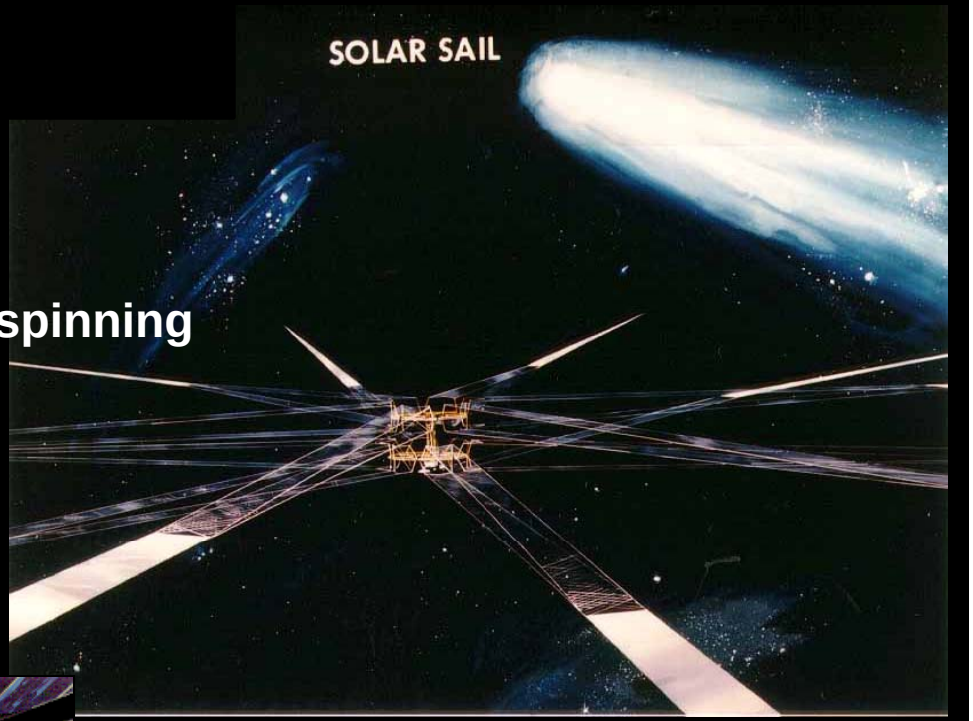


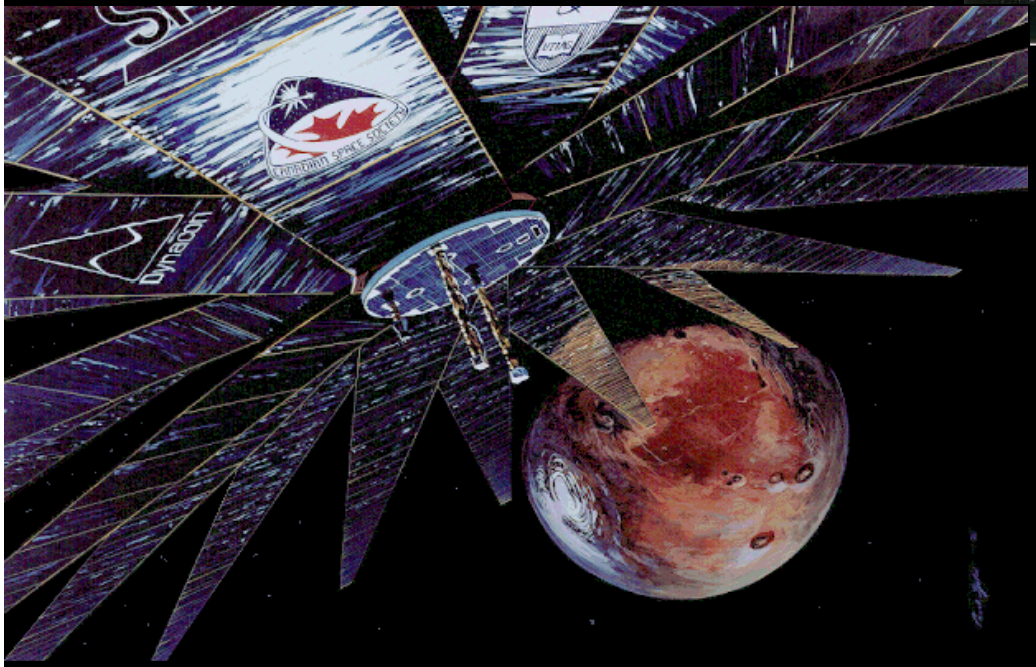


Sample Sail Types

Heliogyro Solar Sail (JPL)

- 12 vanes (7 km long)
- Extend from central hub
- Hub vanes deployed from rollers by spinning
- Vehicle continues to spin for rigidity
- Steer by tilting vanes
- Vanes require edge stiffeners



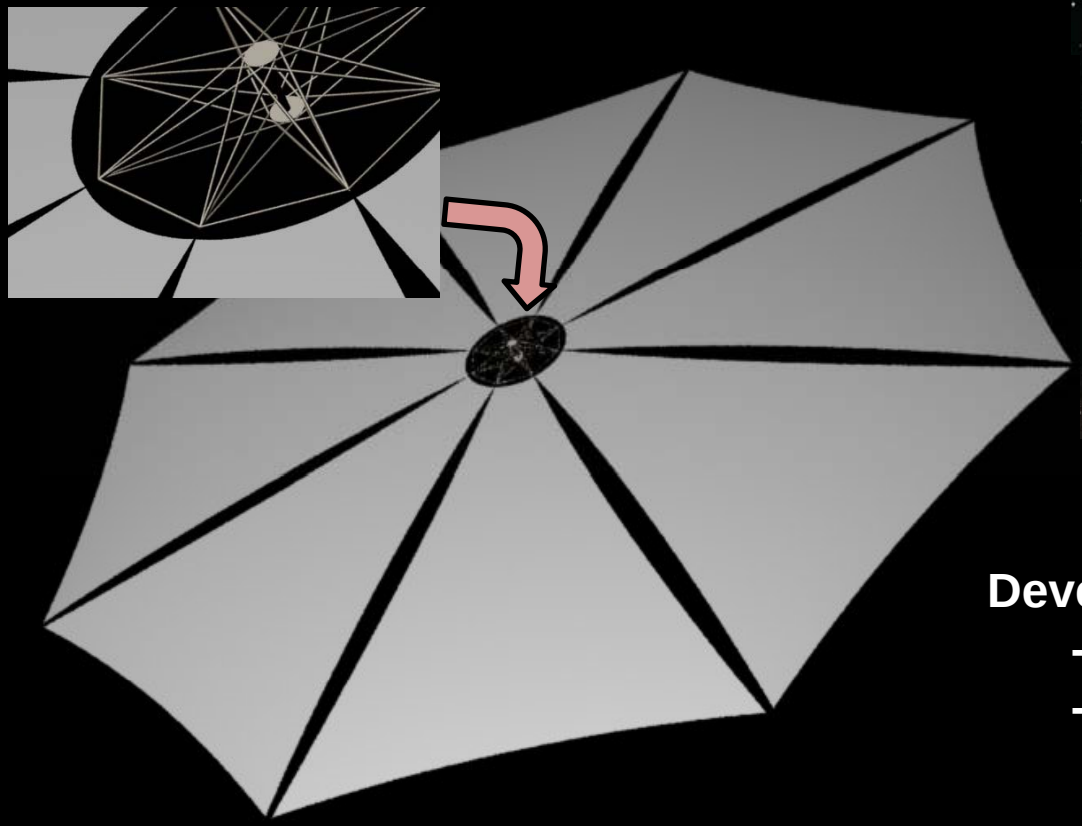


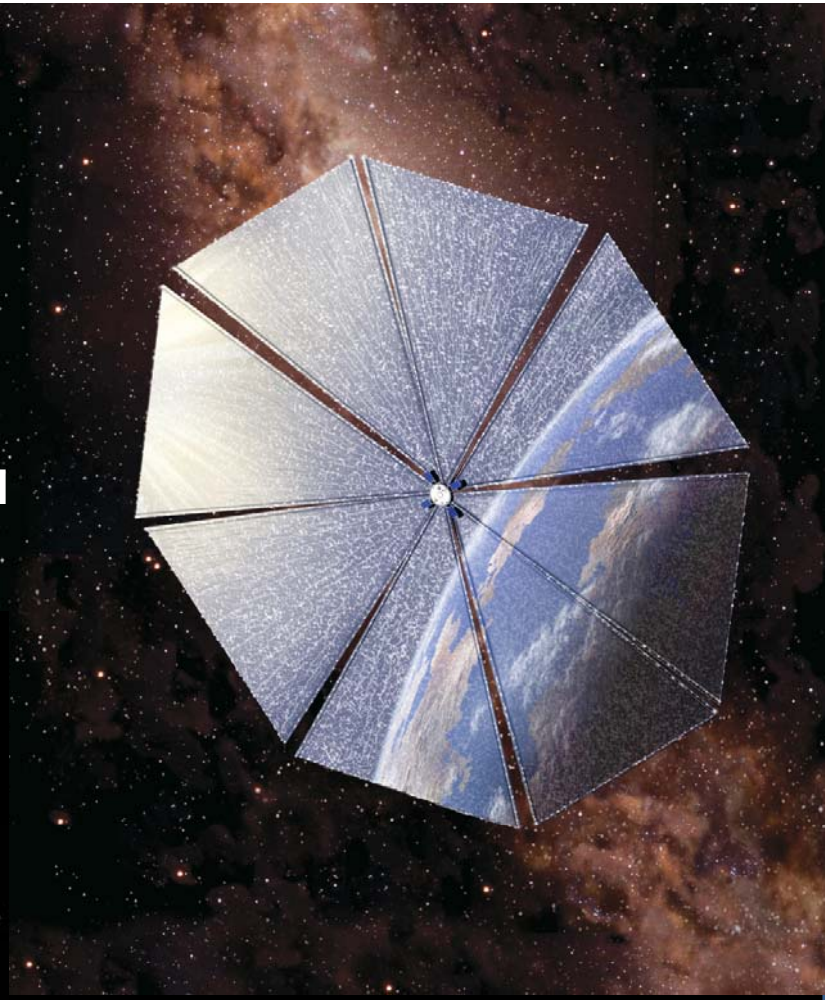
Canada Solar Sail Project
Steer by shifting ballast mass
(center mass misaligned from center of solar pressure)
create torque to turn

Sample Sail Types

Spinning Disc Sail

Circular sails → large, spinning disks
Support by lightweight tension lines carry loads except at the center → structure
to carry payload, control system, sail

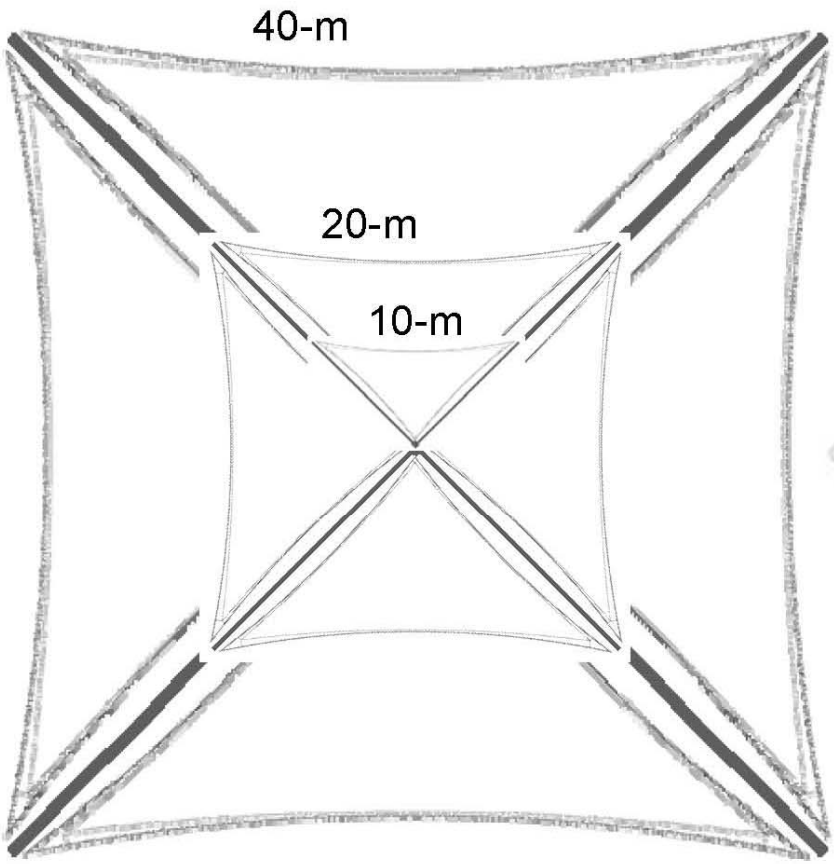




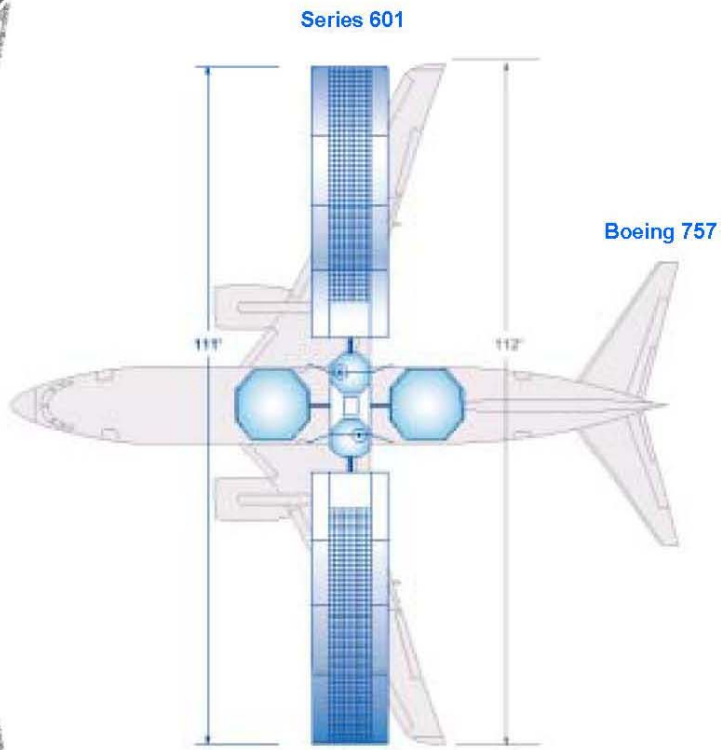
Developing spacecraft like these
--illuminate cities in Arctic circle
--future solar sails

Solar Sail Sizes

10, 20, and 40-m Solar Sail Systems



Standard spacecraft bus

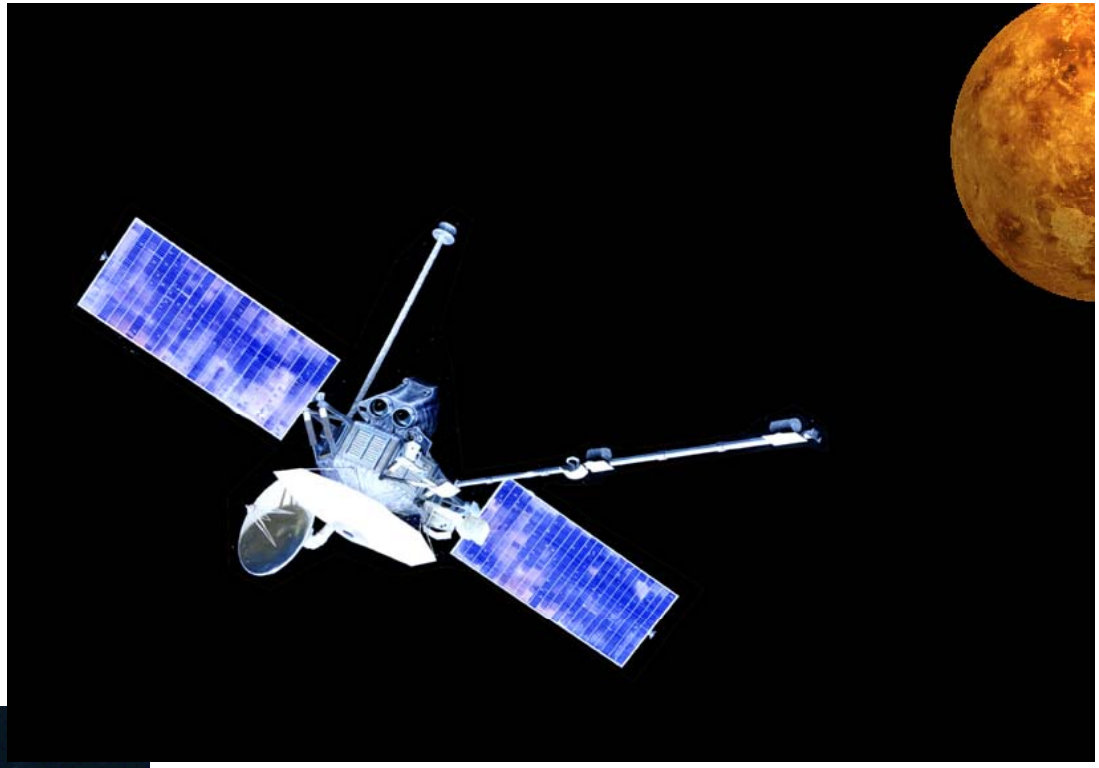


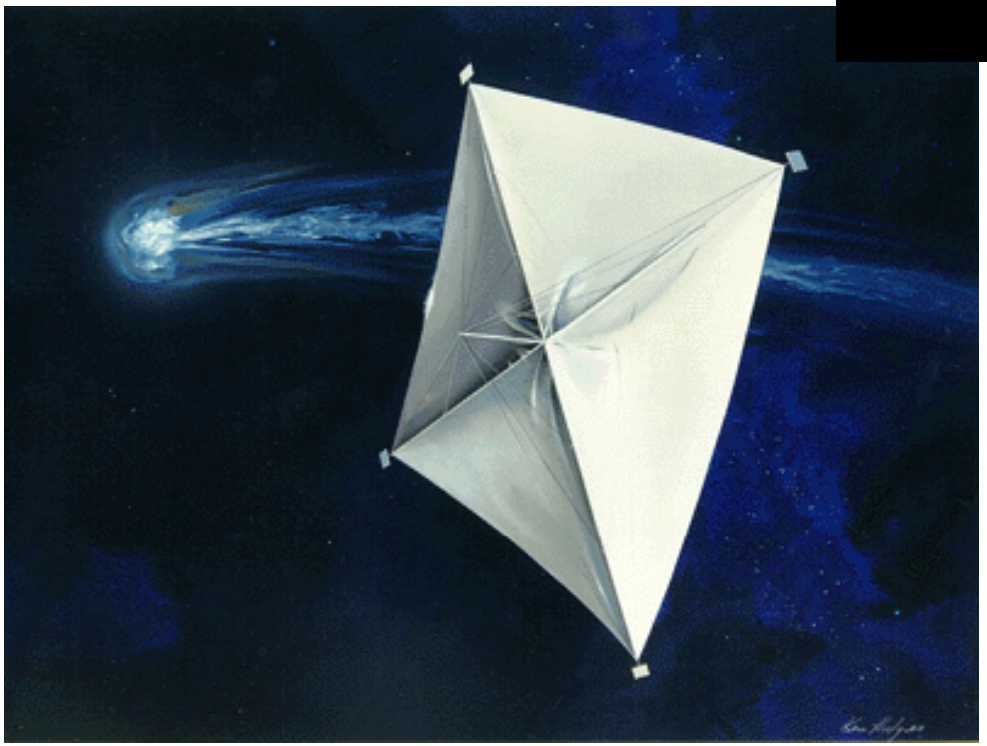
Missions

‘Solar Sailing’ for long time!

Solar Sailing initially developed at NASA/JPL to Mariner 10 mission
s/c low fuel
solar pressure for attitude control

1978 “mature technology”
ready for application to
future NASA missions!!!



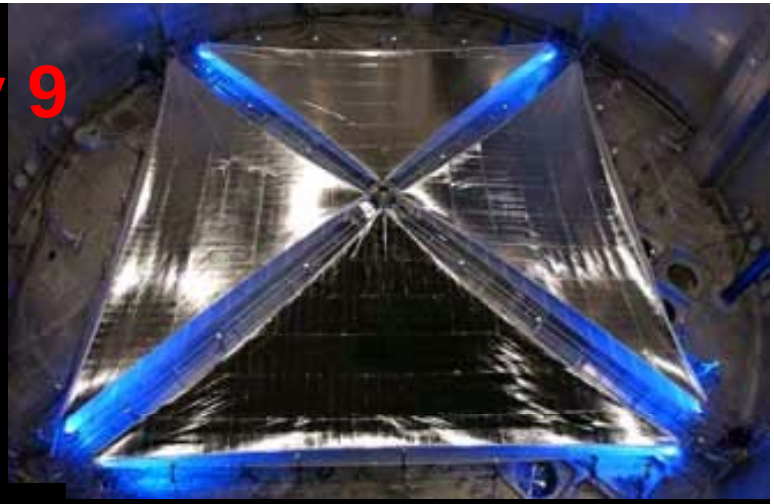


1985 Proposed
Halley’s Comet Mission

Replaced by chemical propulsion when partnership collapsed

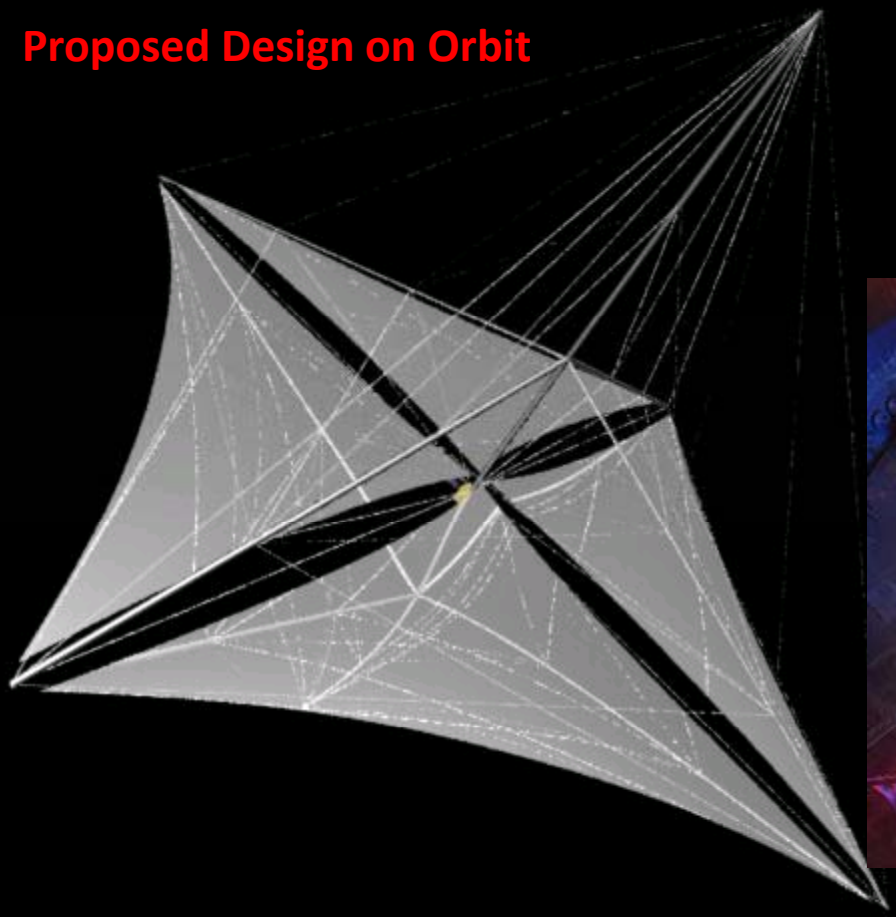
Mission: ST9 Space Technology 9

Proposed – Not selected in 2007
Tentative launch date: 2010-2011
Estimated sail size: 40x40 m



ATK's Sail 20X20 m
Successfully deployed
On ground at NASA Glenn

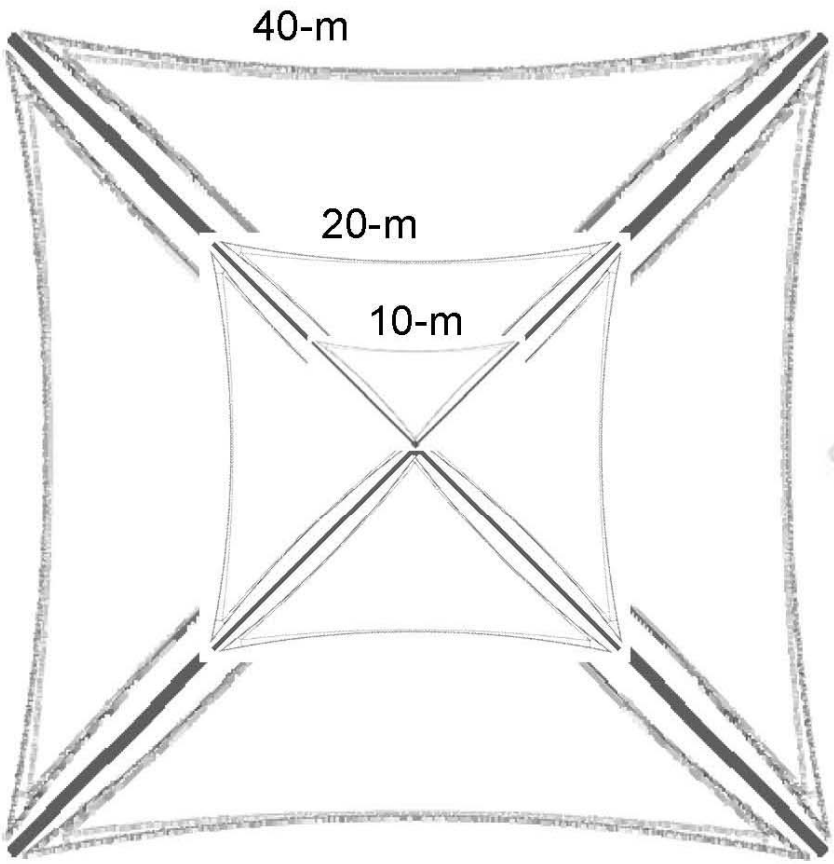
SR9 Proposed Design on Orbit



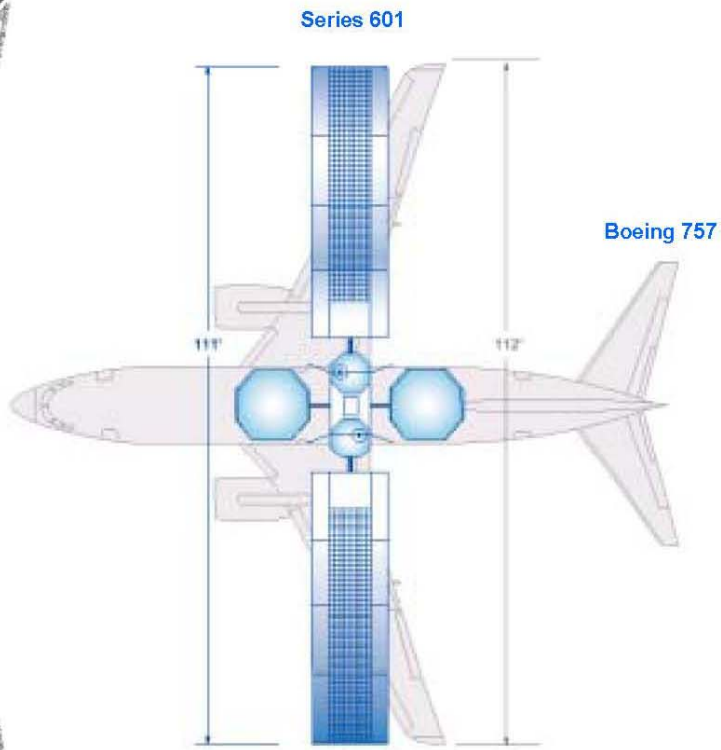
L'Garde, Inc Ground Test

Solar Sail Sizes

10, 20, and 40-m Solar Sail Systems

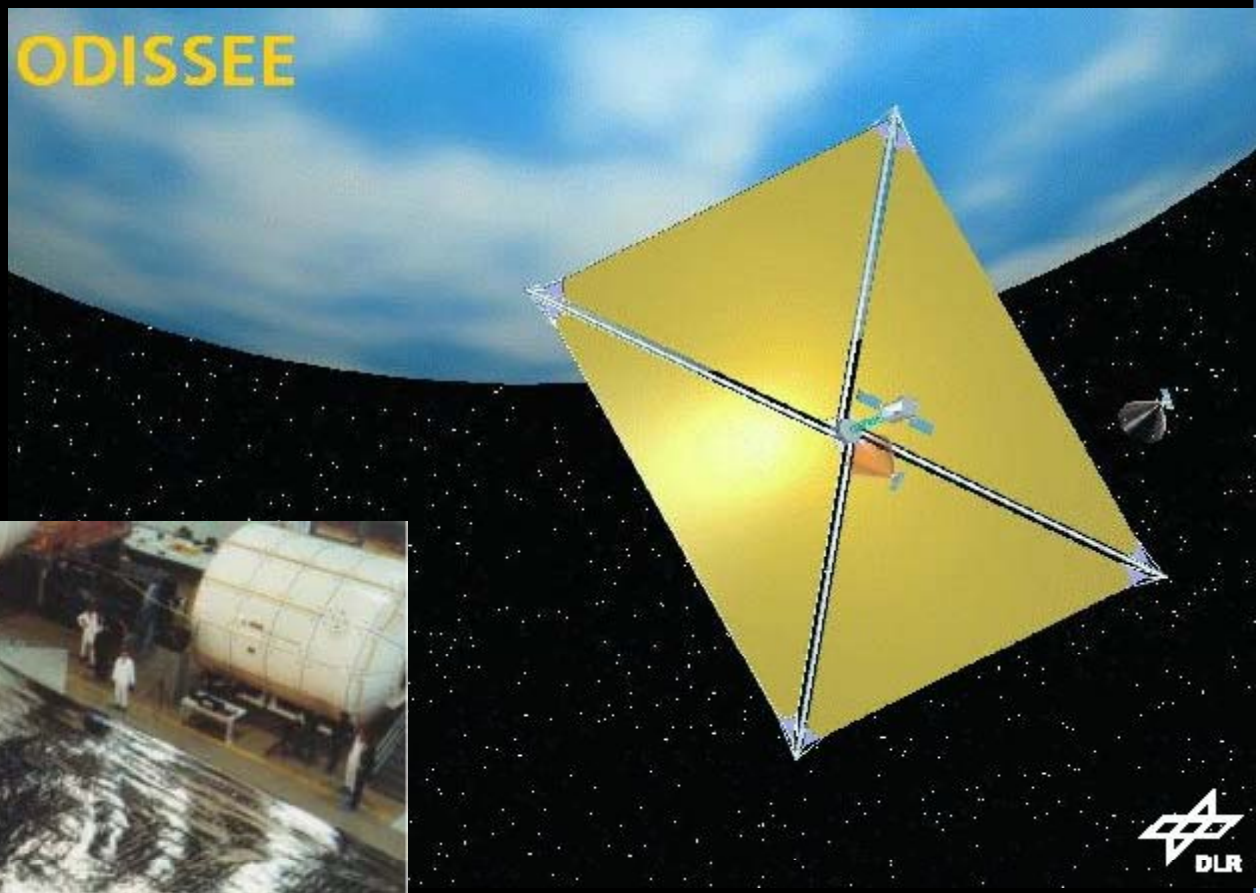


Standard spacecraft bus



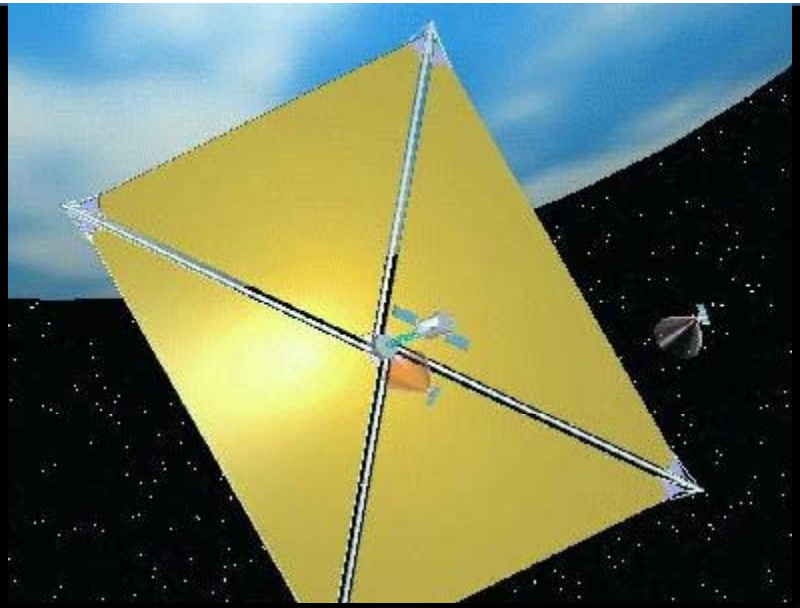
Mission: ODISSEE Orbital Demonstration of an Innovative Solar Sail driven Expandable structure experiment (DLR/JPL)

Mission Scenario--
NEA (Near-Earth Asteroid)
Sail (40x40 m)
12/99



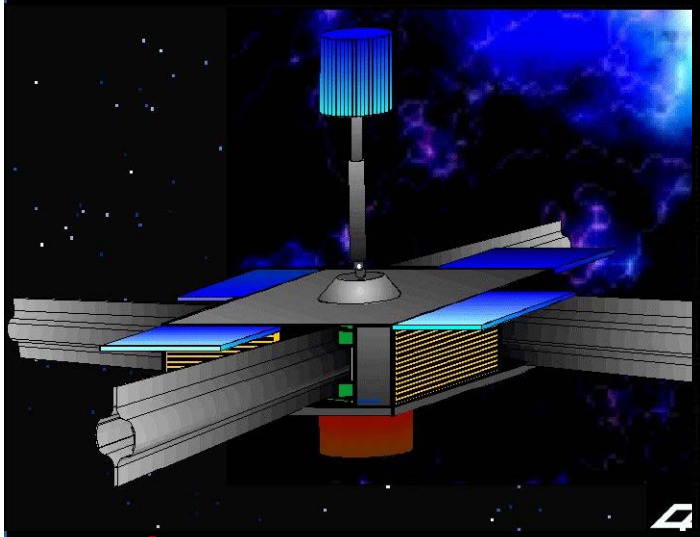
DLR successful ground deployment
20x20 m square solar sail
four triangular sail segments
valuable proof of concept

Mission: ODISSEE

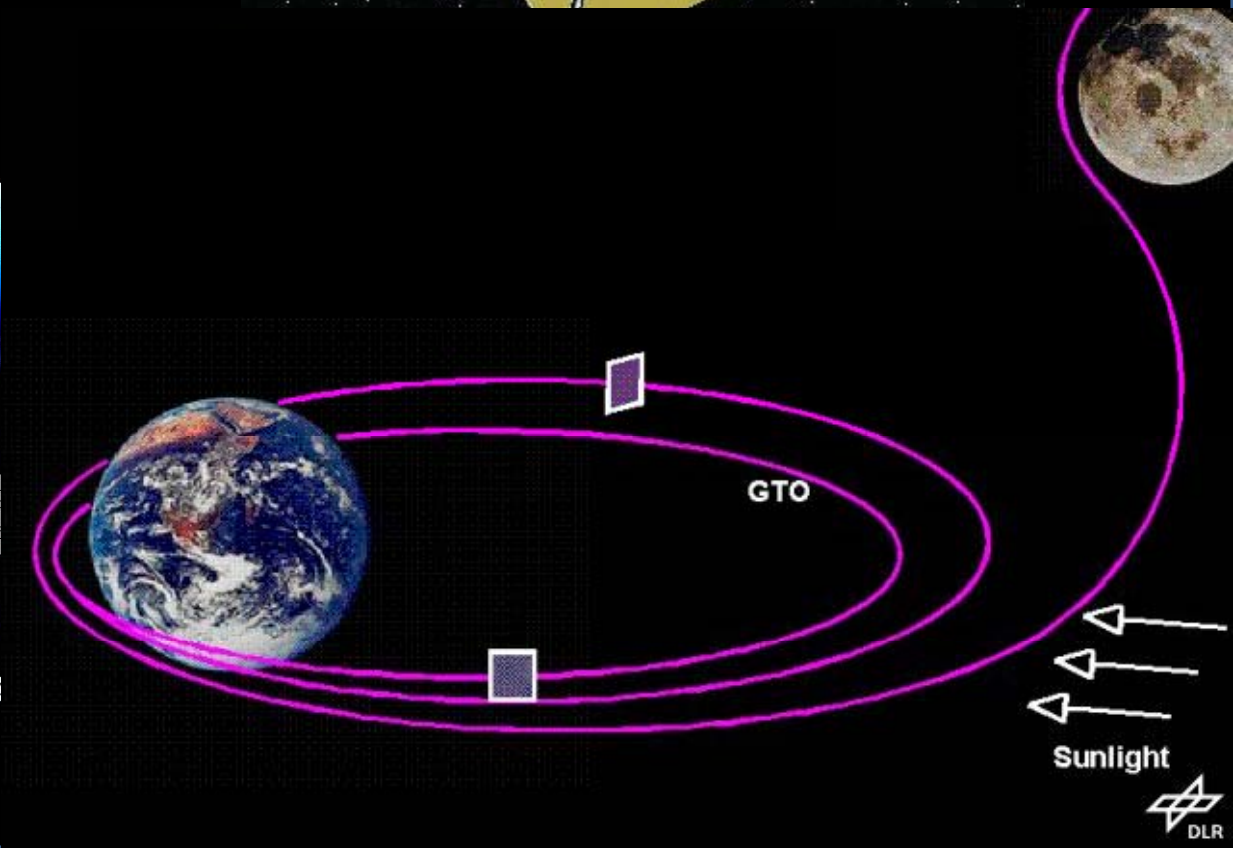


"piggyback" launch on ARIANE 5
< 100kg mass

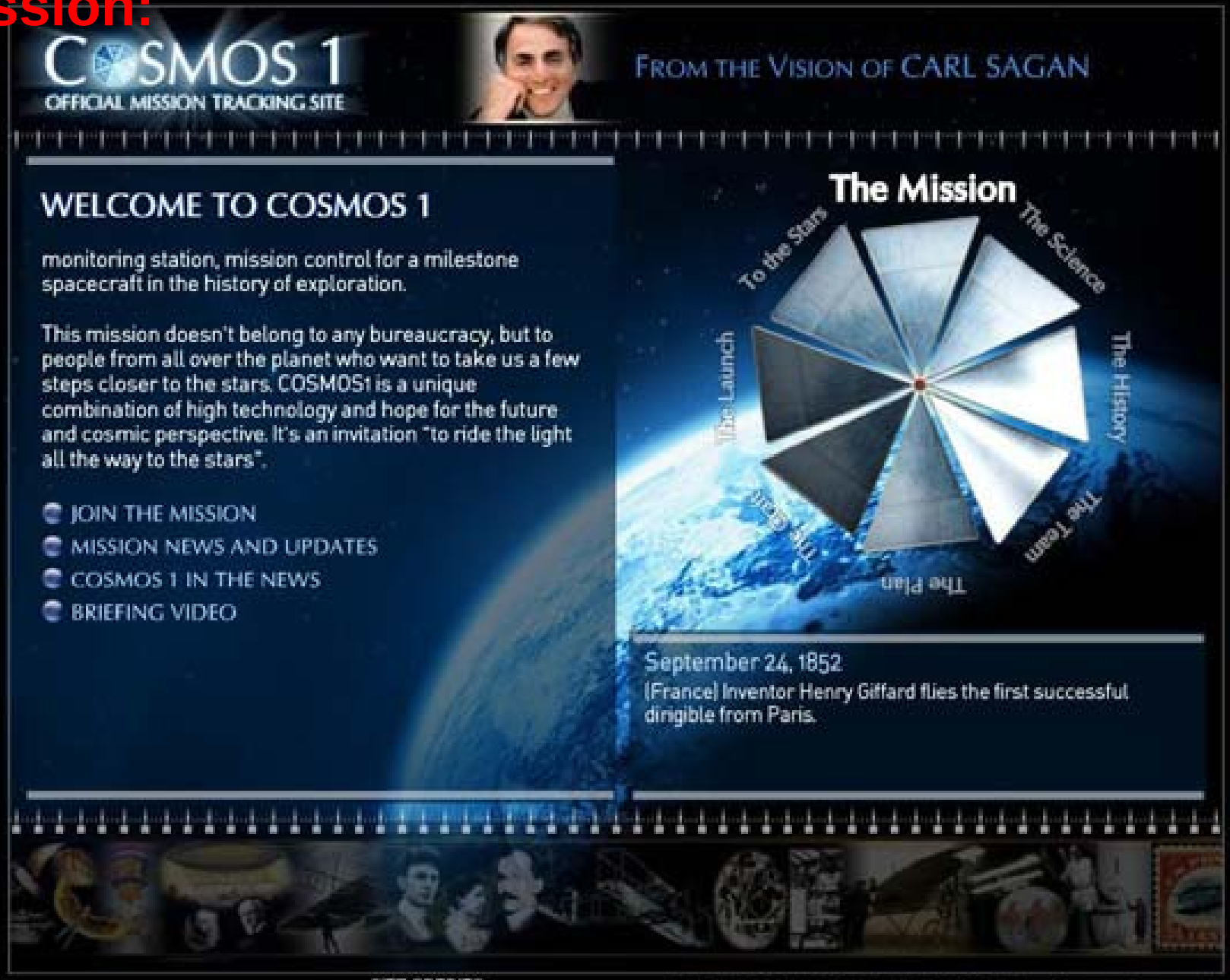
Insert geosynchronous transfer orbit
40m x 40m sail deployed
Increase orbital energy with sail
~ 500 days to achieve lunar radius
Lunar South Pole Flyby



Deploy

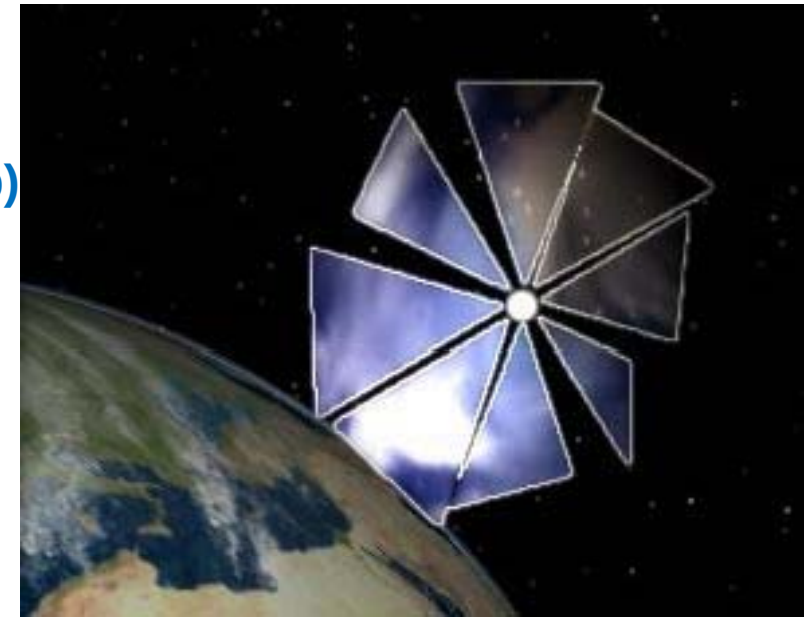


Mission:

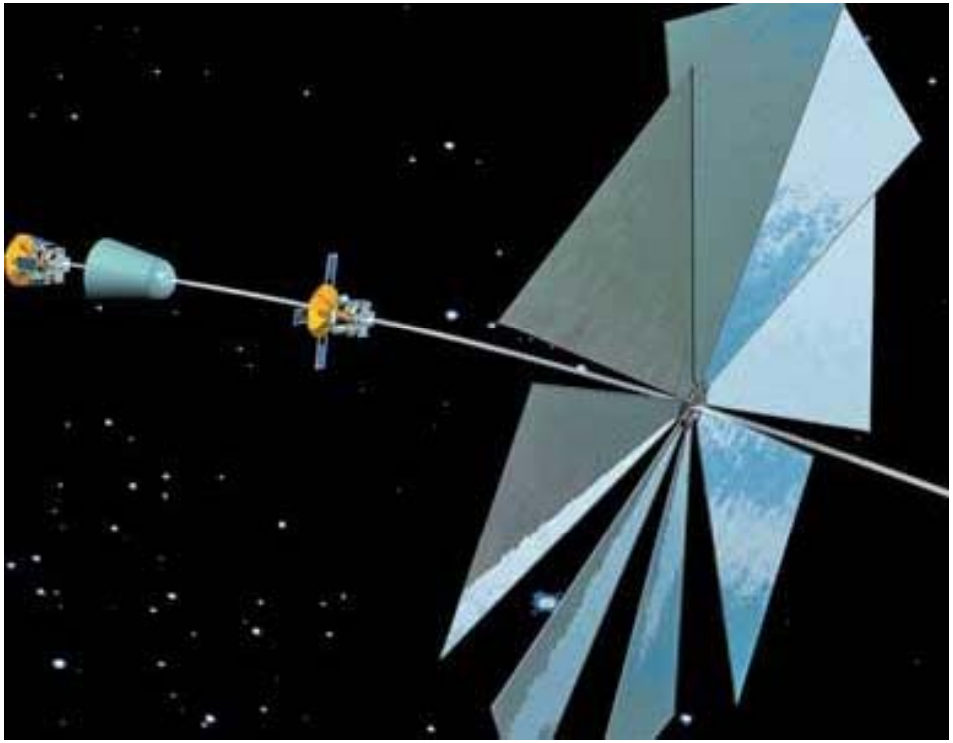

COSMOS 1
OFFICIAL MISSION TRACKING SITE
FROM THE VISION OF CARL SAGAN
WELCOME TO COSMOS 1
monitoring station, mission control for a milestone spacecraft in the history of exploration.
This mission doesn't belong to any bureaucracy, but to people from all over the planet who want to take us a few steps closer to the stars. COSMOS1 is a unique combination of high technology and hope for the future and cosmic perspective. It's an invitation "to ride the light all the way to the stars".
JOIN THE MISSION
MISSION NEWS AND UPDATES
COSMOS 1 IN THE NEWS
BRIEFING VIDEO
The Mission
To the Stars
The Science
The Launch
The History
The Team
The Plan
The Ocean
September 24, 1852
[France] Inventor Henry Giffard flies the first successful dirigible from Paris.
SITE CREDITS
LAUNCH COUNTDOWN: stay tuned

Mission: Cosmos-1

Eight triangular sails
Mylar → thin light polyester(fold-coffee cup)
30 meters wide
insert 825-kilometer near-polar orbit



Mylar suffer high temperatures + radiation
(Thin layers of carbon or aluminum mesh better; more expensive)



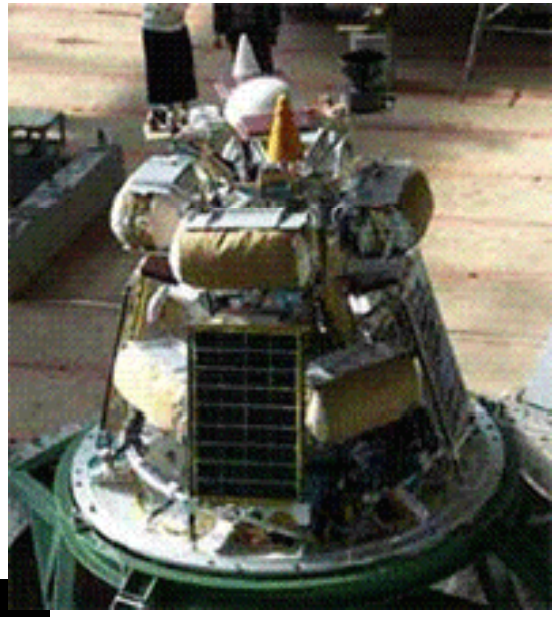
Launch 800 km altitude
Deploy triangular blades
Sunlight boosts orbital velocity

Initially light negligible
Increase acceleration over time

Mission: Cosmos-1

World's First Solar Sail
Launch planned June 21st 2005

Packed for Launch



***Cosmos 1* privately funded**
Least launch cost – Russia
Russian modified ICBM Volna
launch from a submarine in the Barents Sea
Boost to altitude of 825 km

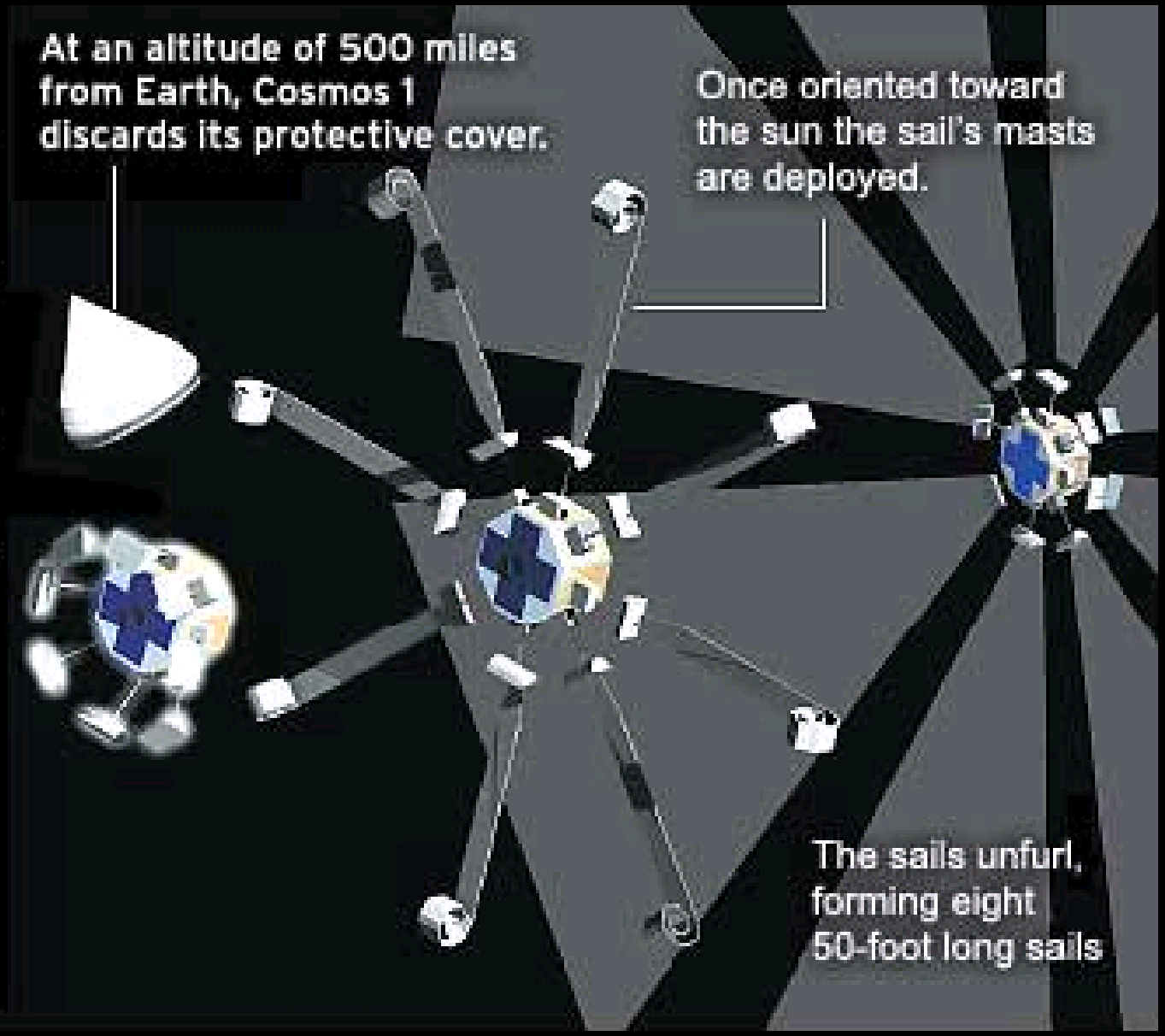
Deployment

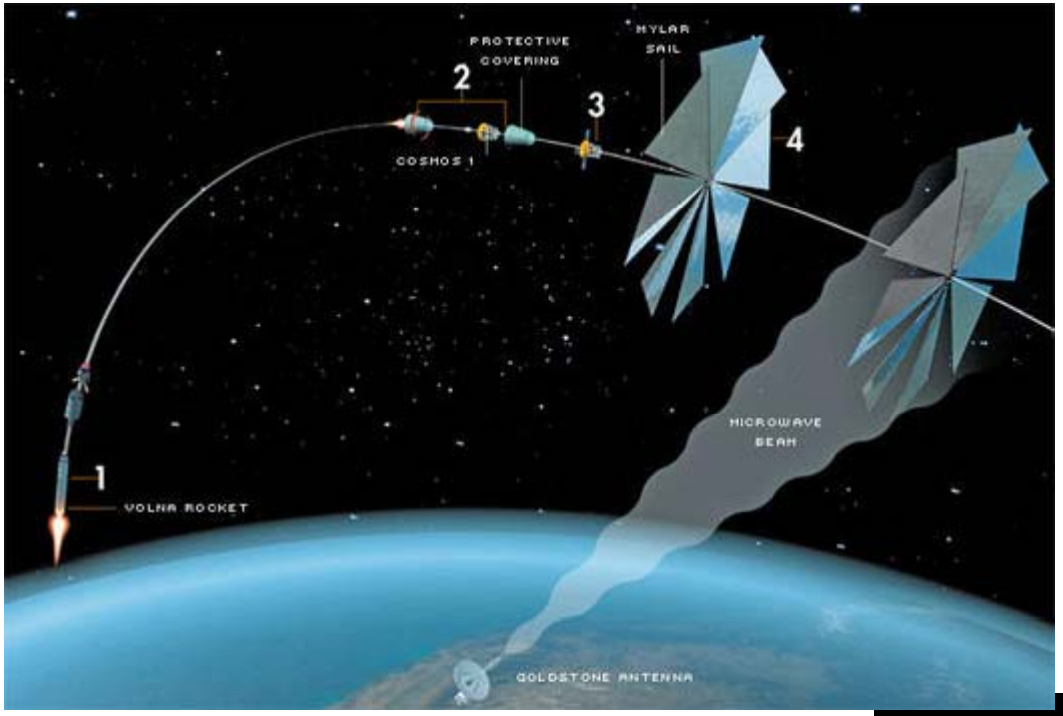
Sailing the celestial sea

The world's first solar sail-powered spacecraft, Cosmos 1, was launched Tuesday

When sunlight hits the surface of the sail, the energy of photons, or light particles, is transferred to the sail. As the light is reflected away, it gives the sail a slight push.

Gradually the craft increases speed and theoretically, it could reach a speed of 64 million miles per hour.





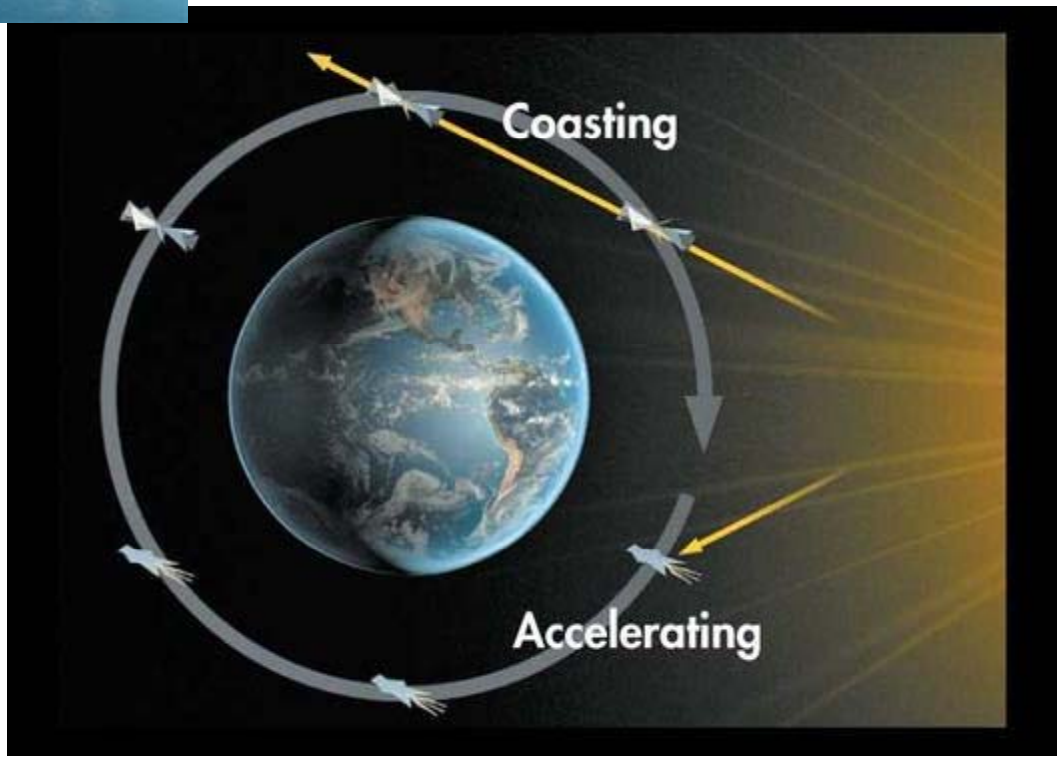
Depart Earth orbit quickly → solar sail requires more than sunlight

70-meter antenna in Goldstone, California 500-kilowatt beam of microwave energy; aim influx of high-energy photons; produce tiny change in the sail's velocity

Measure, test physics concept

***Cosmos 1* simple sail (no tilt)**

Use sunlight when head-on
Rotated blades (like Venetian blinds) turn edges to Sun for no force

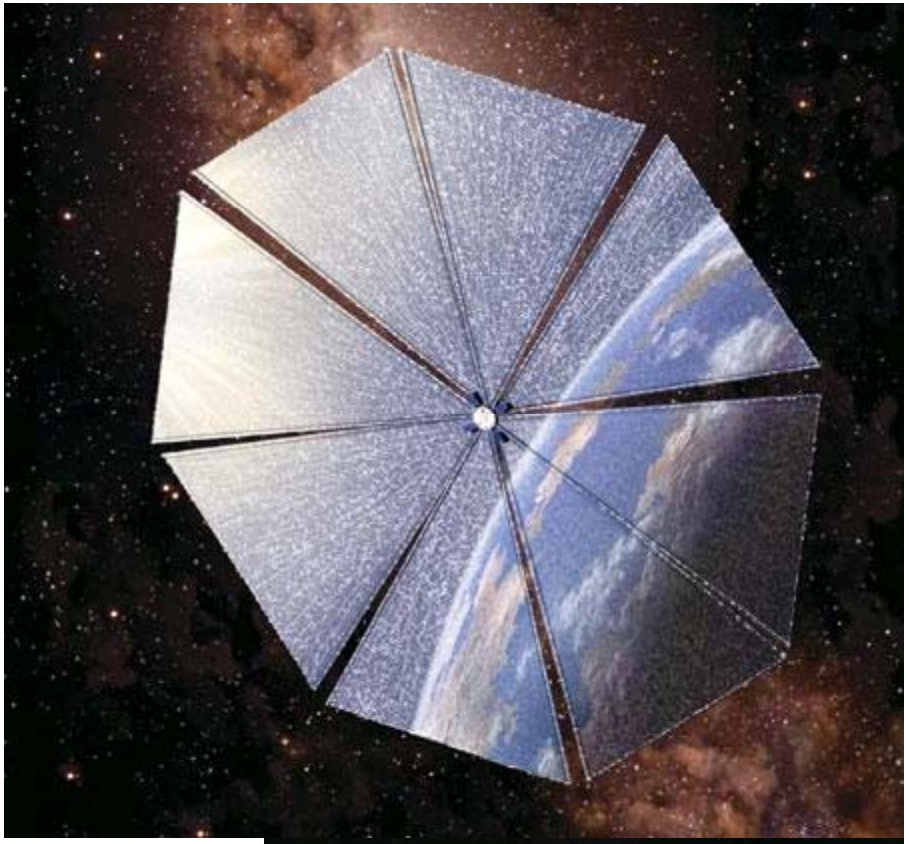


Mission: Cosmos-1

June 21, 2005

Solar-sail vehicle lost
Booster failed soon after Cosmos 1 blasted into space

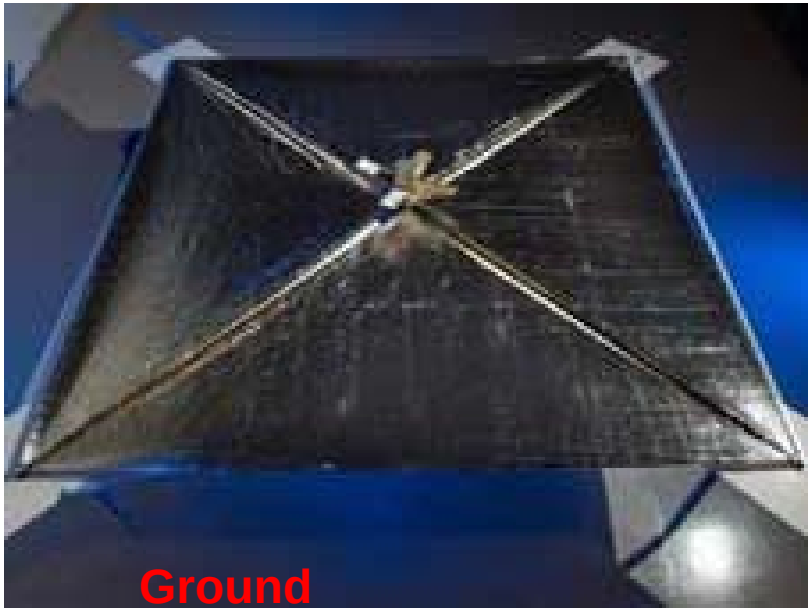
NASA and the European Space Agency have suspended research into solar sails due to budgetary constraints

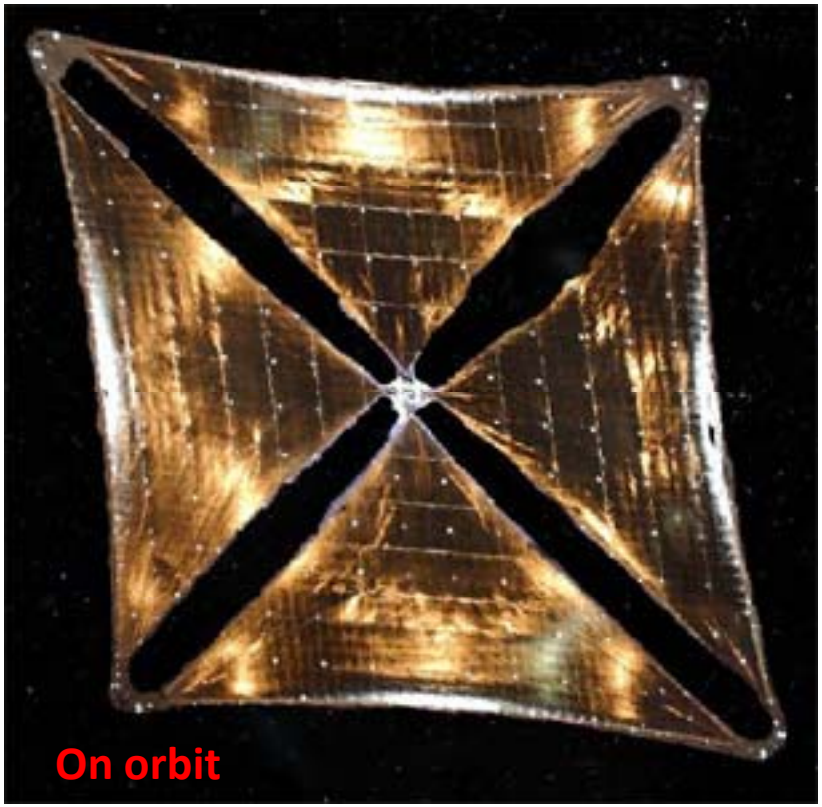



Mission: Nanosail-D
(NASA)

Mission: Nanosail-D (NASA)

Goal:
demo feasibility of deploying sails in orbit
3x3 m
plastic film coated with aluminium

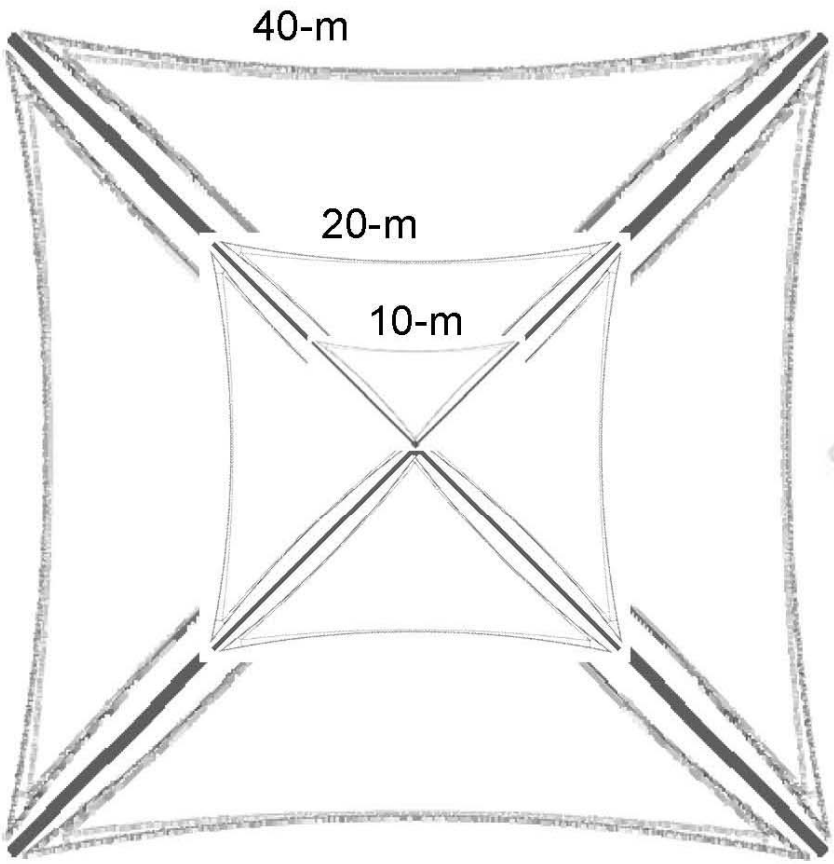




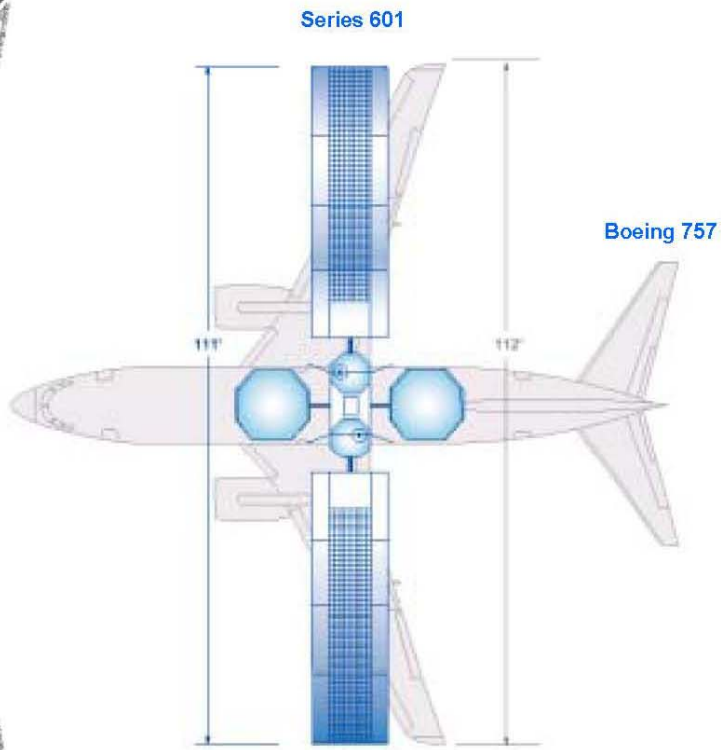
NanoSail-D ended on August 2, 2008
Two minutes after launch!
SpaceX Falcon 1 launch vehicle malfunctioned during stage separation

Solar Sail Sizes

10, 20, and 40-m Solar Sail Systems



Standard spacecraft bus



Missions: JAXA/ISAS

Japan – pursuing solar power sails

Solar Sail -- gathers sunlight as propulsion by means of a large membrane

Solar "Power" Sail -- obtains electricity from thin film solar cells on the membrane + acceleration by Sun

ion-propulsion engines accelerate ions driven by solar cells → "hybrid" engine

August 10, 2004

Deploy clover type onboard S-310 rocket
World-first successful full-fledged deployment of big films for solar sail
Lasted 230 seconds!

Missions:
IKAROS— Interplanetary Kite-Craft Accelerated by Radiation of the Sun

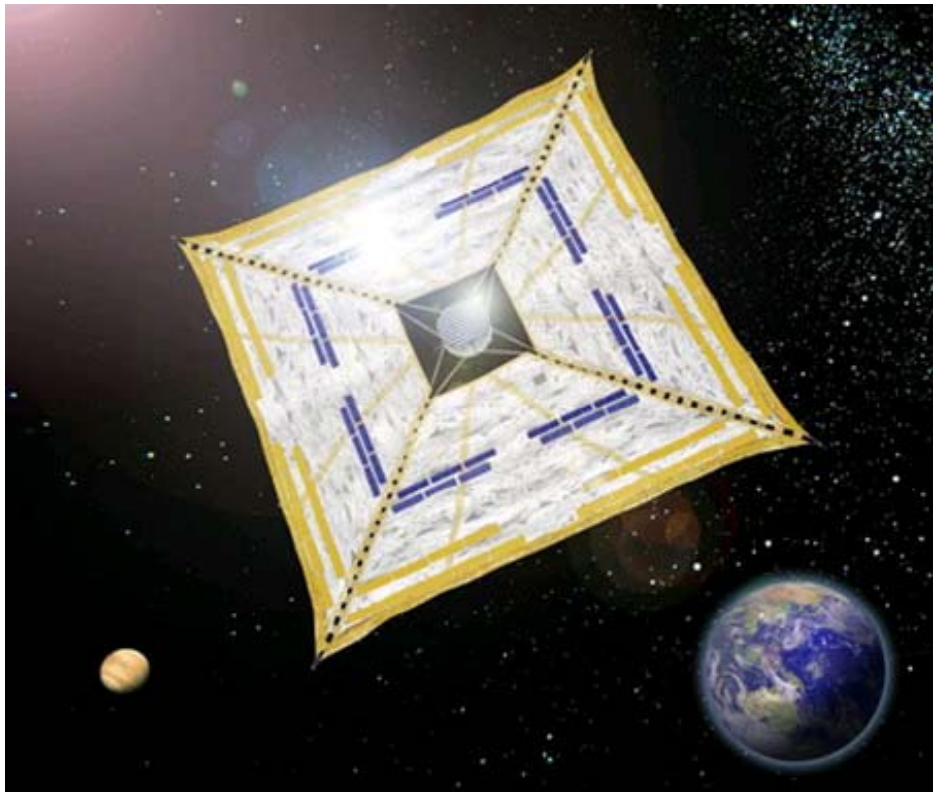
May 20, 2010 !!

hybrid solar sail—propelled partly by solar pressure, partly by traditional solar power
H-IIA rocket
'piggyback' JAXA's Akatsuki Venus Climate Orbiter

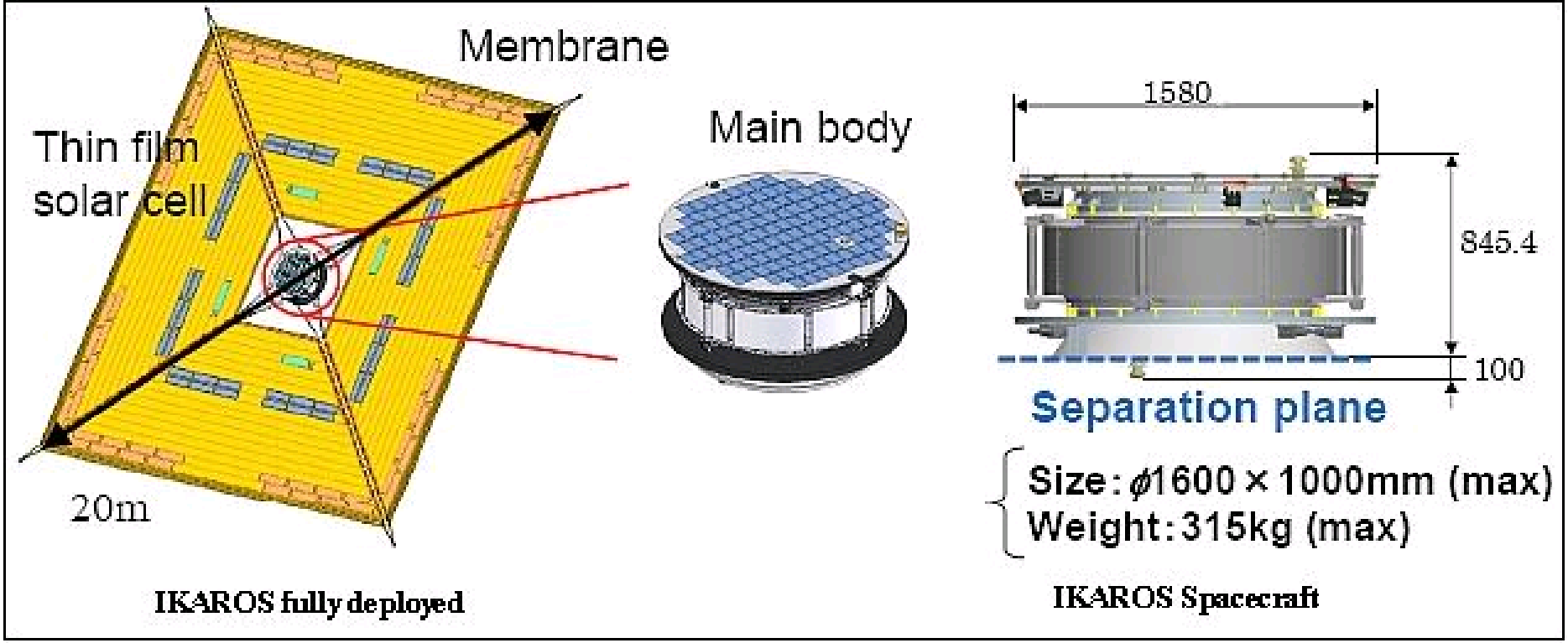
14x14 m sail -- 307-kg
separate from rocket; spin to unfurl sail
Hybrid → sail's thin-film solar cells for generate electricity - power ion engines

Six-month mission
Ikaros headed toward Venus (same traj)

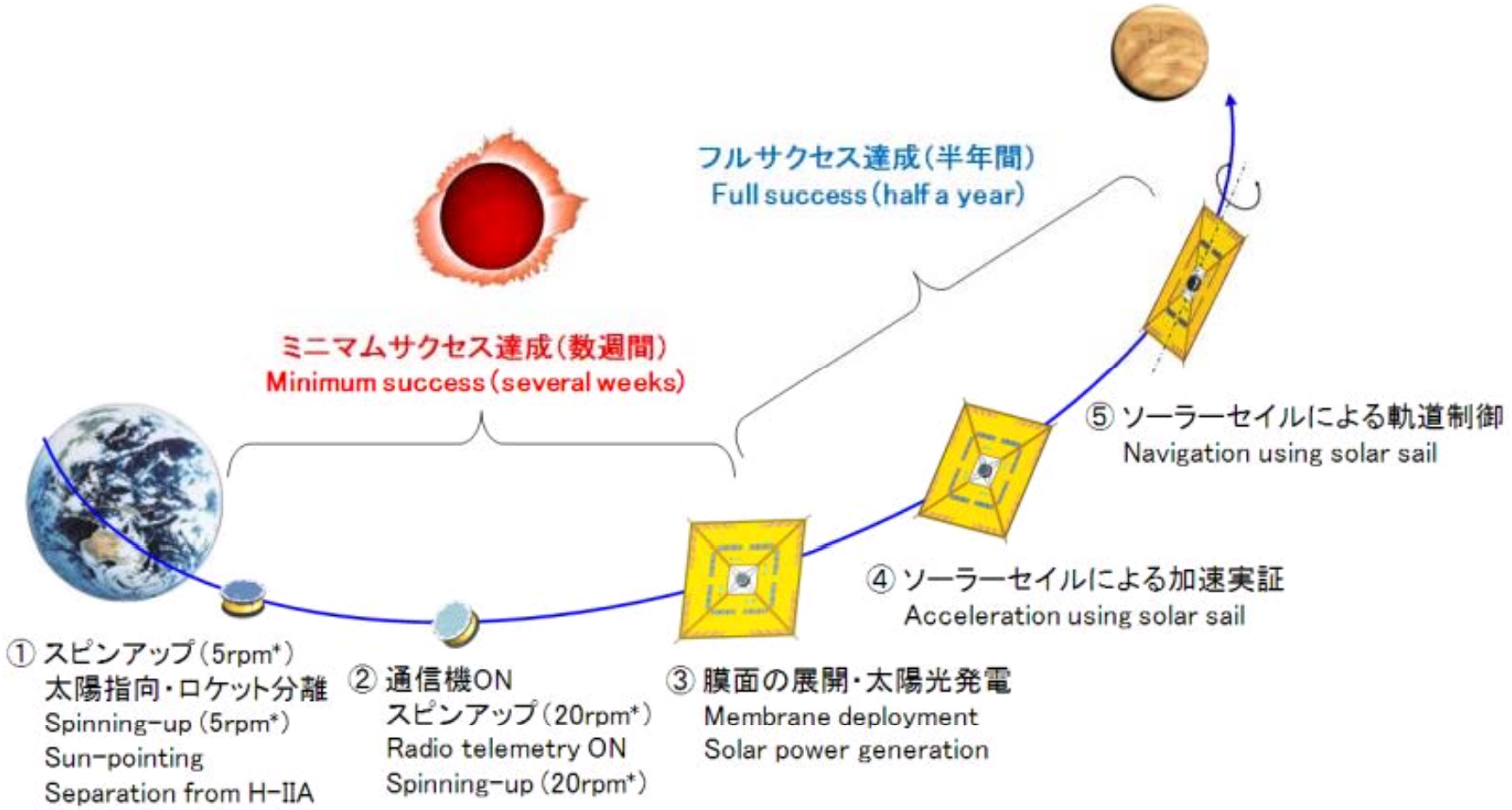
solar sail-powered craft continue even farther!



IKAROS


Membrane
Thin film
solar cell
20m
Main body
1580
845.4
100
Separation plane
Size: ϕ1600 × 1000mm (max)
Weight: 315kg (max)
IKAROS fully deployed
IKAROS Spacecraft

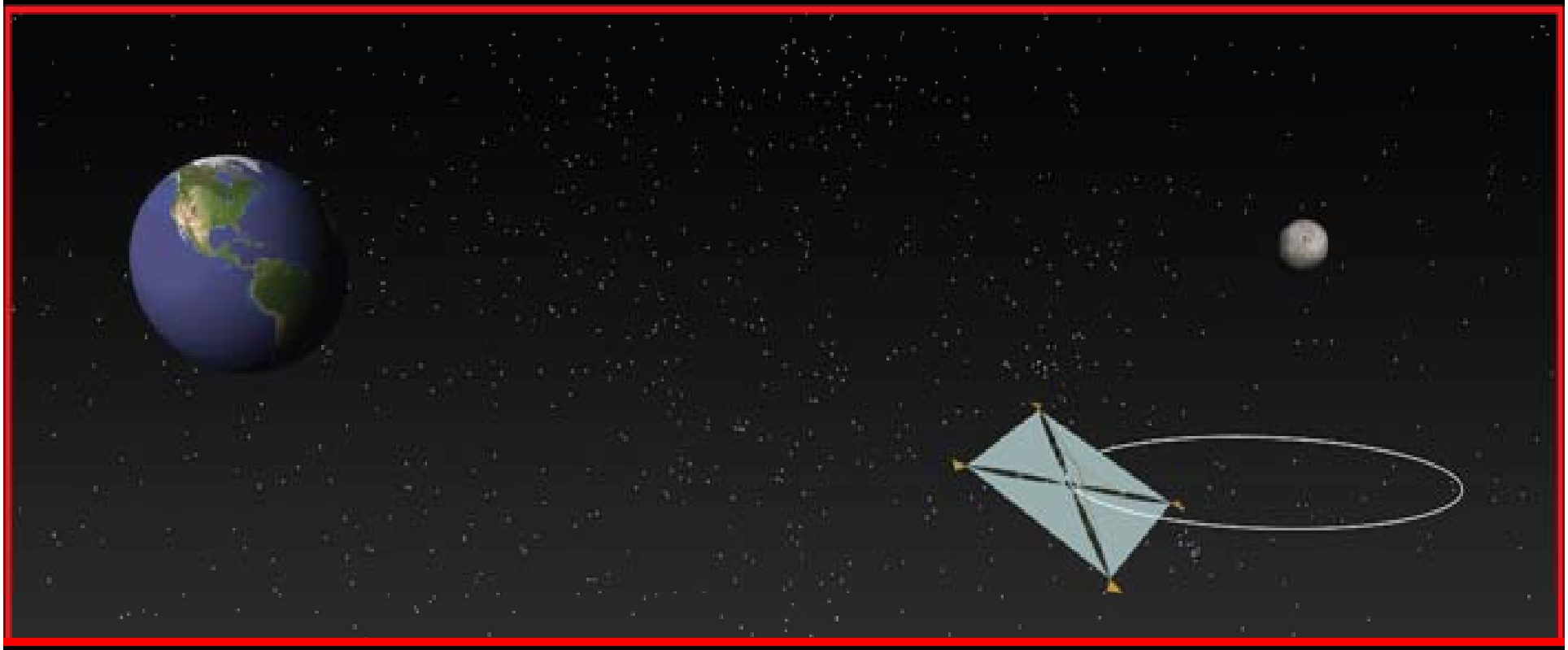
IKAROS— Interplanetary Kite-Craft Accelerated by Radiation of the Sun



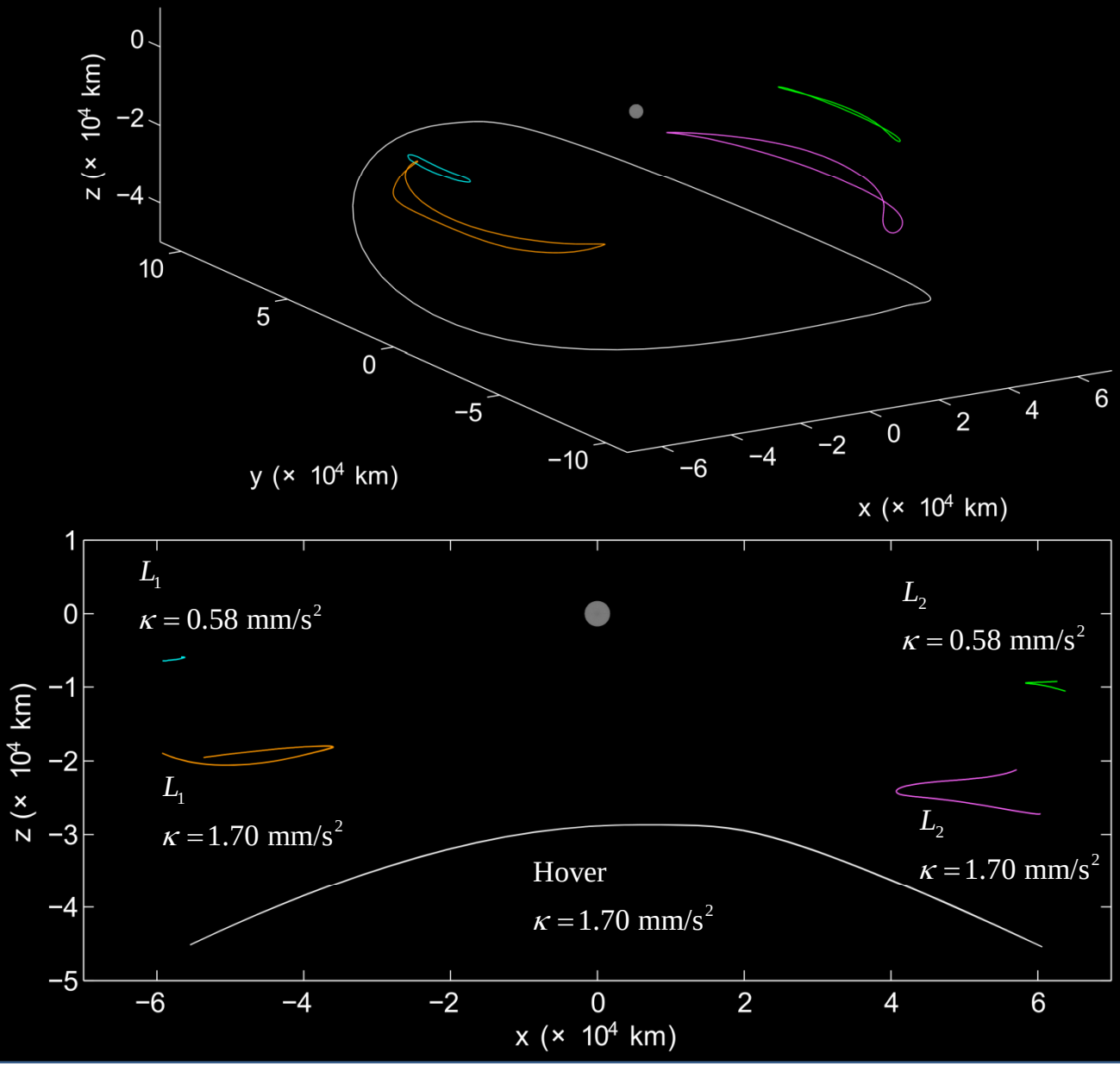
ミッションシーケンス
Mission sequence

*rpm= revolutions per minute

Manned Lunar Missions

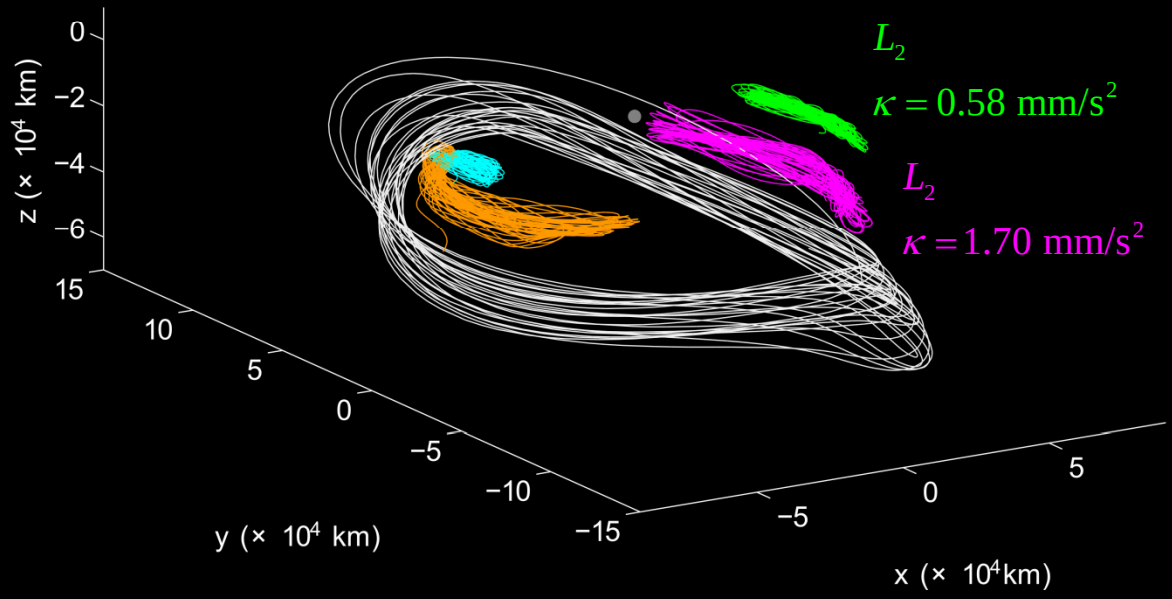


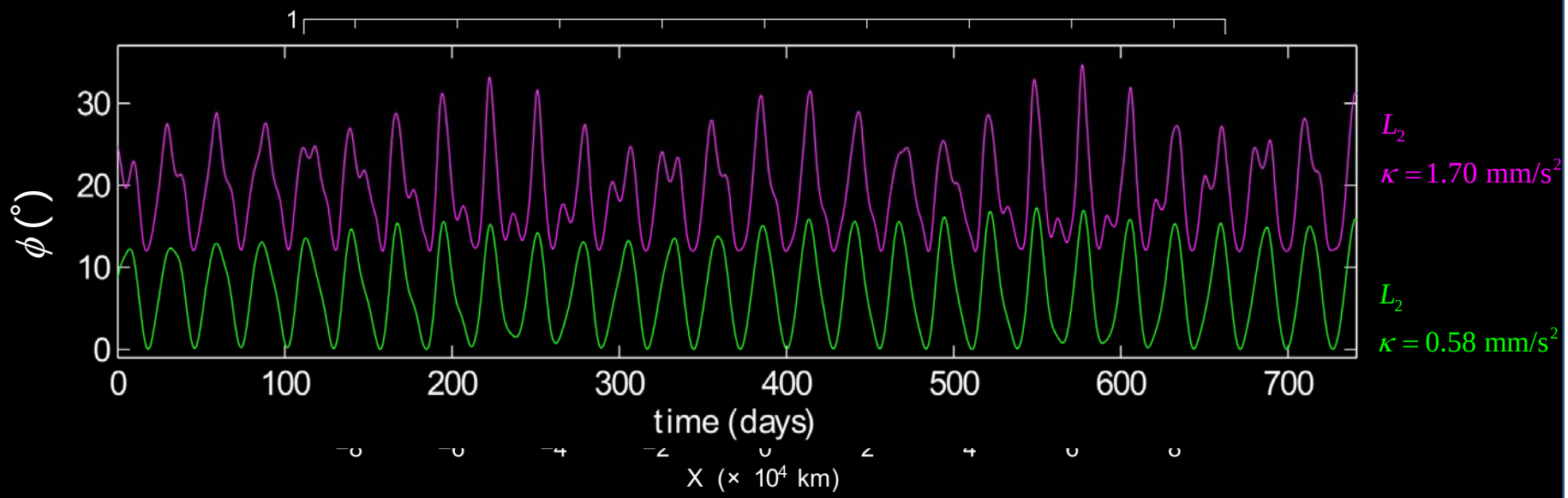
Five Near-Optimal Orbits

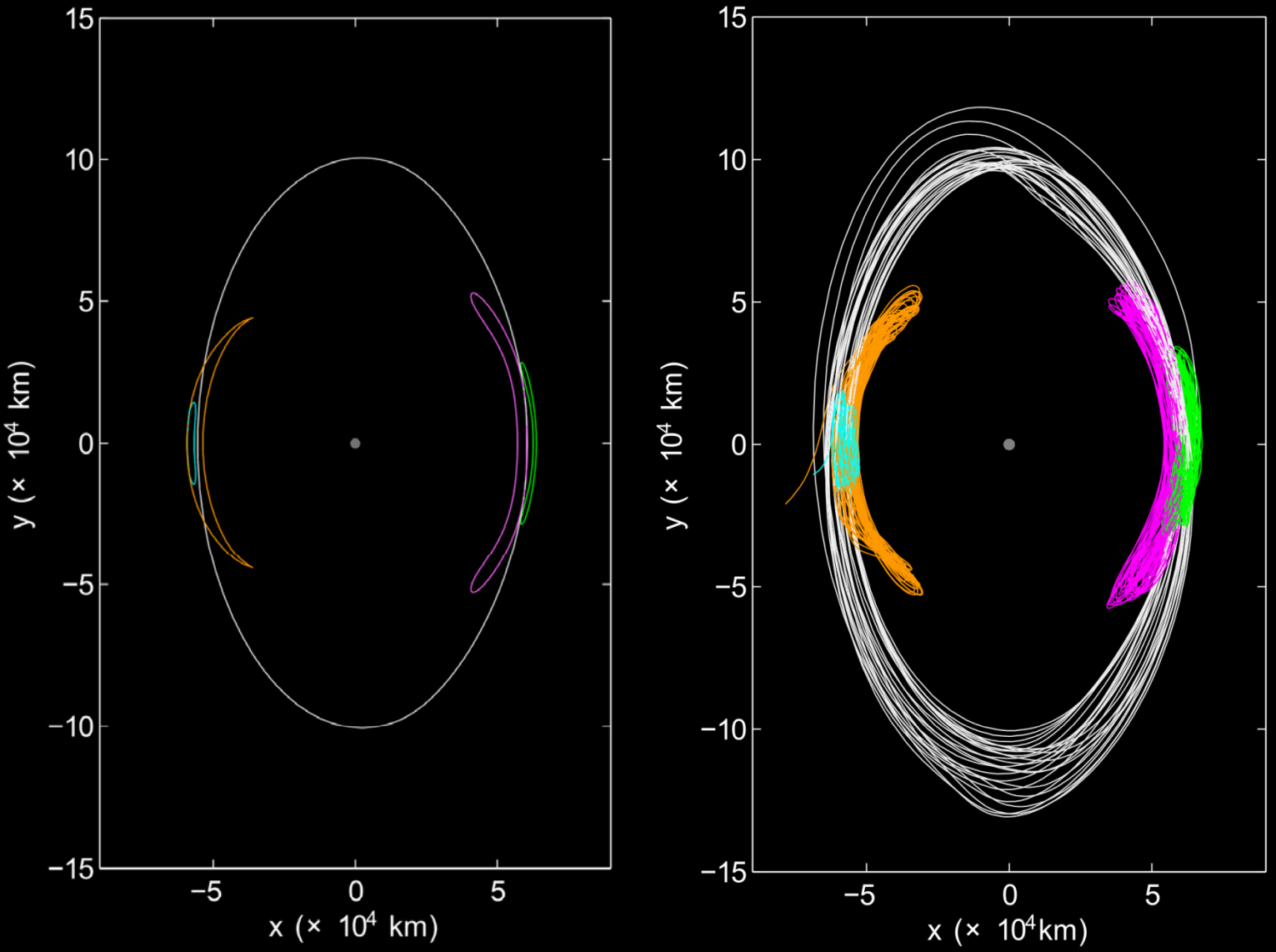


Transition to Ephemeris Model

1. Actual Sun-to-spacecraft line
2. Lunar librations



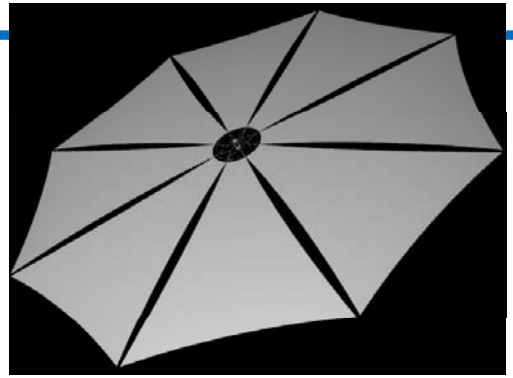



15
10
5
0
−5
−10
−15
y (× 10^4 km)
−5
0
5
x (× 10^4 km)
15
10
5
0
−5
−10
−15
y (× 10^4 km)
−5
0
5
x (× 10^4km)

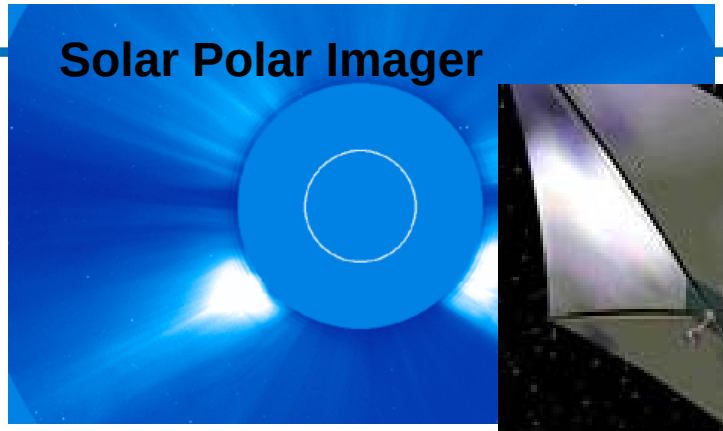
Play

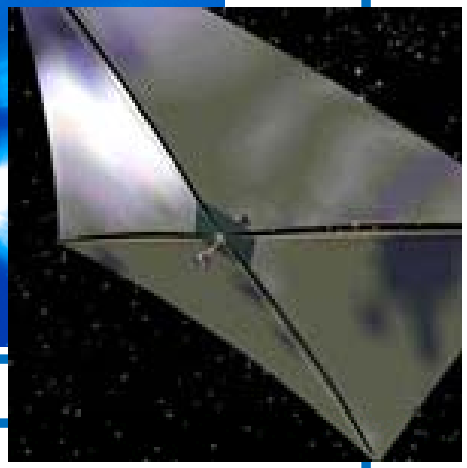
Future Solar Sailing

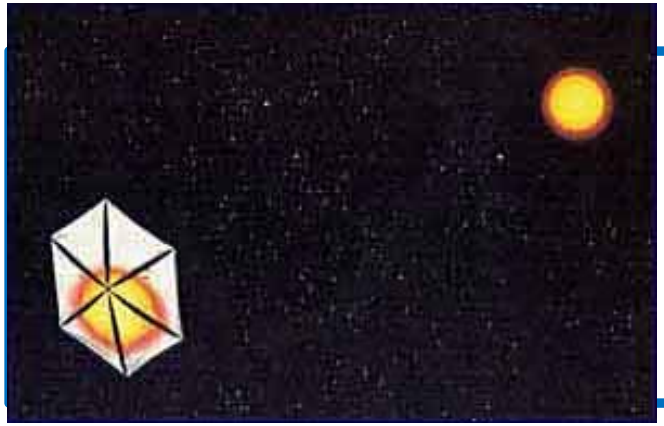
Heliostorm
2016-2020
Sail size: 150x150 m
Heliostorm -- solar storms warnings
Earth-based comm systems (Now 3 hrs)
Sail maintain closer to Sun – more warning



SPI (Solar Polar Imager)
2020-2035
sail size: 150x150 m
SPI spacecraft to orbit above Sun Pole
Maintaining position easy for a solar sail → impossible conventional







Interstellar Probe
2031
Sail Size: 250x250 m
IP Fly close to Sun then > 200AU
Solar system interacts with other solar systems?

Missions: JAXA

JAXA ‘will lead future solar system exploration using solar power sails’

Jupiter 2020 -50x50 m sail

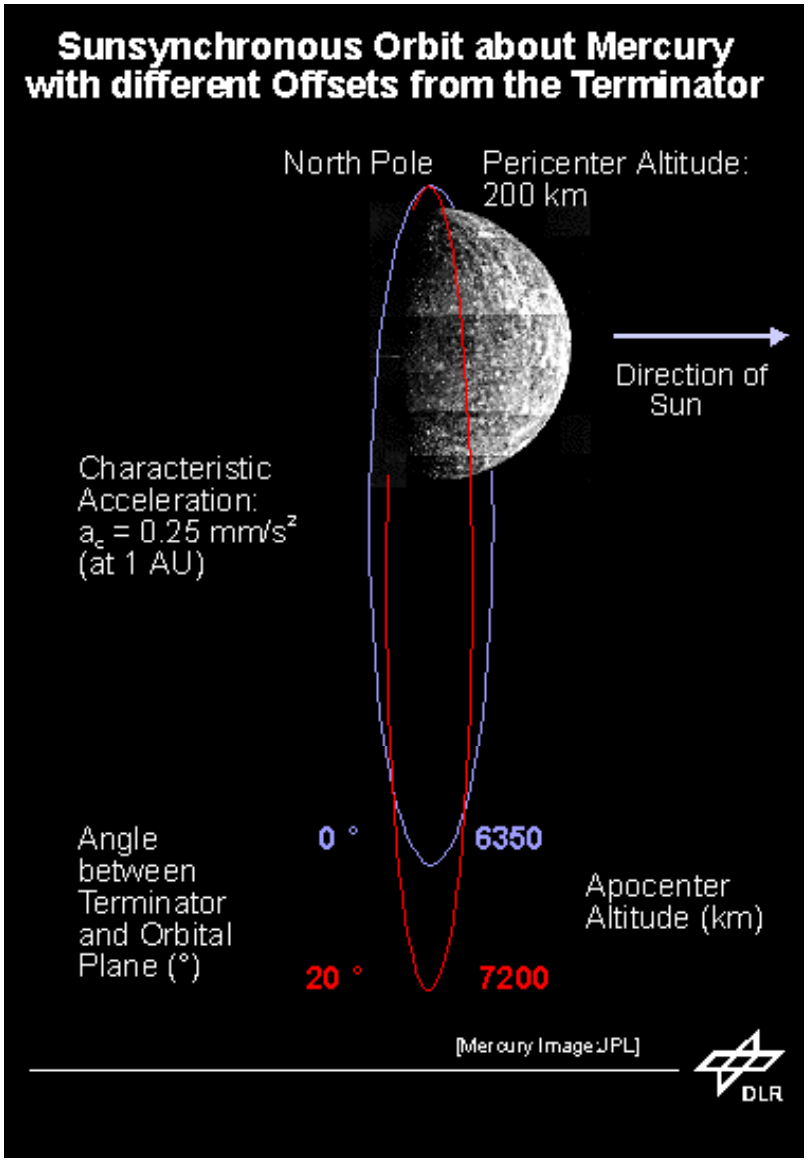
木星・トロヤ群小惑星探査計画
Jupiter and Trojan asteroids exploration mission

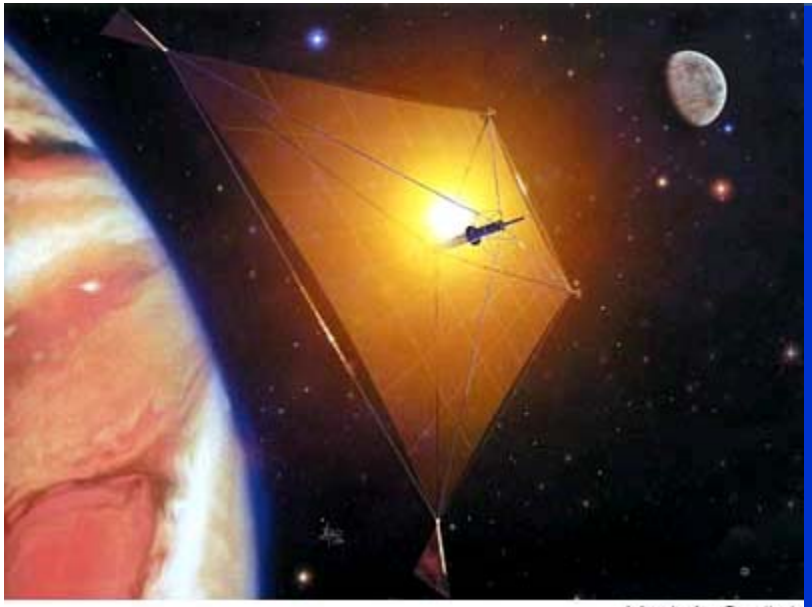
MERCURY SUN-SYNCHRONOUS POLAR ORBITS USING SOLAR SAIL PROPULSION (DLR)

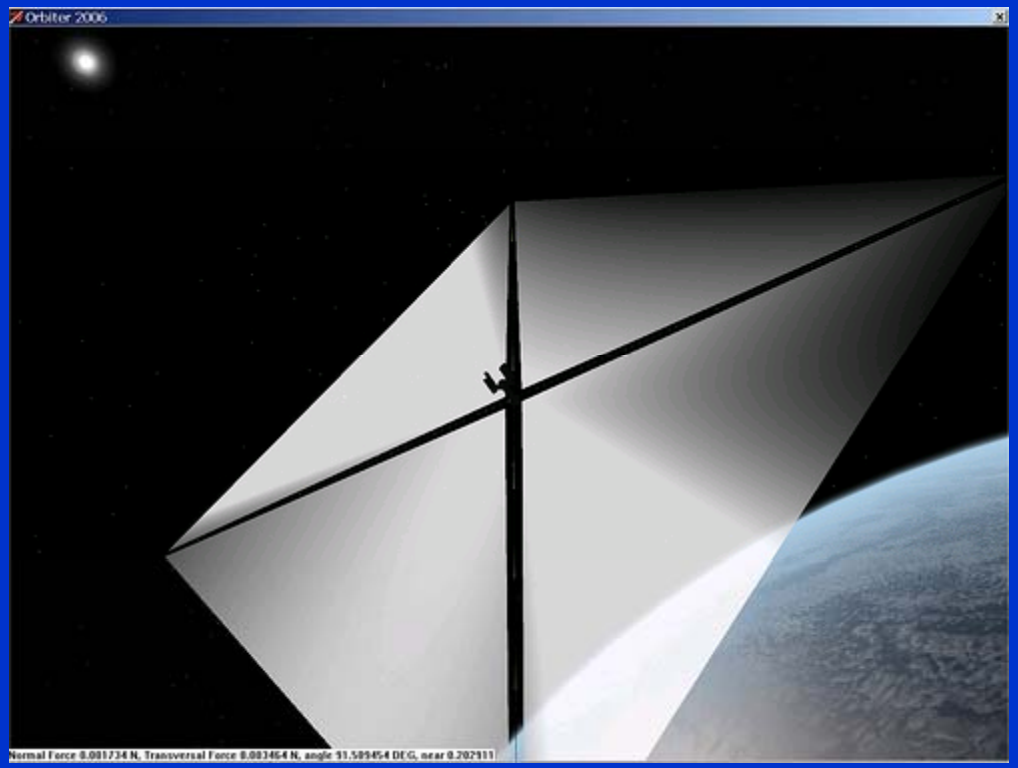
Solar sails in orbit about Mercury -- very effective
- **high solar radiation pressure**
- **weak gravitational field of the planet**

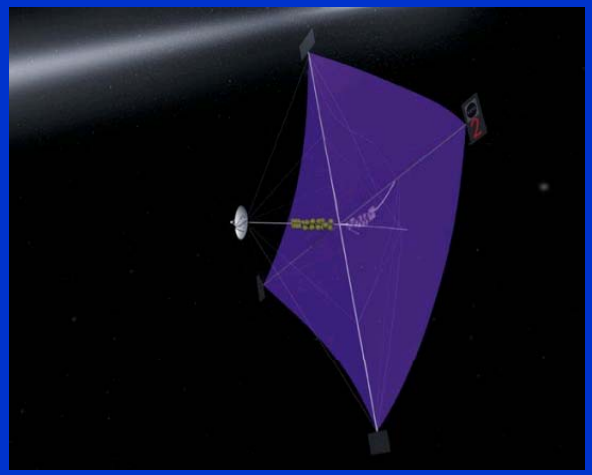
Chemical propulsion → sun-synchronous
substantial propellant
deliver to Mercury orbit
high thrust level to implement
(low s/c mass)

Extending basic concept:
Sun-synchronous solar sail orbits for other celestial bodies in inner solar system (Especially when gravitational field of target not allow sufficient orbit precession; application chemical + electric propulsion not possible due to limited mass or power supply)




Mark A. Garlick





Solar Sail technology is crucial for the next generation of space travel