Solar Sails for Spacecraft Propulsion

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We tend to think of space as being big and empty…
Can we use the environments of space to our advantage?
How does a solar sail work?

Solar sails use photon “pressure” or force on thin, lightweight reflective sheet to produce thrust.
Solar Sail Propulsion Fundamental Physics

- **Photons carry Momentum**
  - \( p = h \nu / c \)
    - \( h = \) Planck’s, \( \nu = \) frequency, \( c = \) speed of light

- **Force generated on Reflective Surface**
  - Resultant force approximately perpendicular to surface
    - The bigger the surface, the more the force
  - Can “steer” sail by changing pitch angle \( \alpha \)

- **Small, but potentially Constant Acceleration**
  - Potentially unlimited “delta V”
  - Allows some otherwise impossible orbits
Solar Sails Provide Low Thrust Propulsion

Solar Photon Pressure (R=0.9)

Pressure (N/m²)

Distance to Sun (Au)

Energy: \( W = \frac{L}{4\pi r^2} \)

Pressure: \( P = \frac{W}{c} \)

\( W_e = 1368 \text{ W/m}^2 \)

\( P_e = 9.15 \times 10^{-6} \text{ N/m}^2 \)
Net Force Drops with Increasing Pitch Angle

- For a 100 kg sailcraft, 100 m x 100 m square sail:

- Force (maximum, perp. to sun, perfect/flat reflector)
  - 0.09 N

- Acceleration (maximum)
  - $0.92 \times 10^{-3}$ m/s$^2$ (0.9 millimeters/sec$^2$)

- Force decreases with increasing pitch angle (or...)

\[
\bar{f}_{\text{tot}} = 2P_i A (\cos \theta_i)^2 \hat{n}
\]
Solar Sails Experience VERY Small Forces

- Force on a 100 m x 100 m square sail:

  ![Diagram showing force comparison between a coin and a sail](image)

  - Solar Force Equivalent at 1 AU
  - 10,000 m² (two football fields)
Solar Sail Trajectory Control

- Solar Radiation Pressure allows inward or outward Spiral
Potential Solar Sail Applications
(A Partial List!)

NEA Reconnaissance &
Small Body Science

Heliophysics & Out of the
Ecliptic Science

Earth Pole Sitting

Rapid Outer Solar System
Exploration and Escape

Toward Higher Performance Beamed
Energy Propulsion
Echo II 1964
Solar thrust effect on spacecraft orbit

- 135-foot rigidized inflatable balloon satellite
- laminated Mylar plastic and aluminum
- placed in near-polar Orbit
- passive communications experiment by NASA on January 25, 1964

When folded, satellite was packed into the 41-inch diameter canister shown in the foreground.
Znamya (Space Mirror)

- Russian experiment that flew on Progress after undocking from Mir Space Station in 1993.
- Purpose was to reflect sunlight onto the ground from space.
- 20-m diameter sail successfully deployed.
- 5-km spot illuminated Europe from France to Russia moving at 8 km/sec.
- Follow-on mission flew, but was damaged during deployment.

- 100 kg spacecraft
- 8 triangular sail blades deployed from a central hub after launch by the inflating of structural tubes.
  - Sail blades were each 15 m long
  - Total surface area of 600 m²
- Launched in 2005 from a Russian Volna Rocket from a Russian Delta III submarine in the Barents Sea:

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Rocket Failed
NASA Ground Tested Solar Sails in the Mid-2000’s
Planned to be a space flight demonstration of the solar sail developed and tested as part of the ground sail test program.
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Canceled
Mission Description:
- 10 m$^2$ sail
- Made from tested ground demonstrator hardware
NanoSail-D1 Flight (2008)

Launch:

• Falcon-1, flight 3
• Kwajalein, Missile Range
• Primary payload: Air Force PnPSat
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- Secondary P-POD payloads (2)

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NanoSail-D2 Mission Configuration (2010)

**3U CubeSat:** 10 cm X 10 cm X 34 cm
- Deployed CP-1 sail: 10 m² Sail Area (3.16 m side length)
- 2.2 m Elgiloy Trac Booms
- UHF and S-Band communications

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**NSD-001**

**NSD-002**

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**NanoSail-D**

**NanoSail-D2 Mission Configuration**

**AFRL Satellites (Trailblazer)**

**HSV-1**

**Ride Share Adapter** (Space Access Technology)

**PreSat** (ARC)

**PPOD Deployer** (Cal-Poly)

**Boom & Sail Spool** (ManTech SRS)

**Spacecraft Bus** (Ames Research Center)

**Bus interfaces Actuation Electronics** (MSFC/UAH)

**Stowed Configuration**

**NanoSail-D** (Aluminum Closeout Panels Not Shown)
Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS)
Sunjammer Solar Sail Demonstration Mission

Design Heritage:
- Cold Rigidization Boom Technology
- Distributed Load Design
- Aluminized Sun Side
- High Emissivity Eclipse Surface
- Beam Tip Vane Control
- Spreader System Design

Design Features:
- High density packagability
- Controlled linear deployment
- Structural scalability
- Propellantless operation
- Meets current needs
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Lightsail-A (The planetary society)

32 m²
No active ‘sailing’
3U cubesat
Solar Sails TODAY – Many Missions Planned

• NASA’s NEA Scout
• The Planetary Society’s LightSail-B
• The University of Surrey’s CubeSail, DeorbitSail, and InflateSail
• University of Illinois’ CubeSail
The Near Earth Asteroid Scout Will
• Image/characterize a NEA during a slow flyby
• Demonstrate a low cost asteroid reconnaissance capability

Key Spacecraft & Mission Parameters
• 6U cubesat (20 cm X 10 cm X 30 cm)
• ~86 m² solar sail propulsion system
• Manifested for launch on the Space Launch System (EM-1/2017)
• Up to 2.5 year mission duration
• 1 AU maximum distance from Earth

Solar Sail Propulsion System Characteristics
• ~ 7.3 m Trac booms
• 2.5μ aluminized CP-1 substrate
• > 90% reflectivity
Mission Concept: Characterize a Near Earth Asteroid with an optical instrument during a close, slow flyby.

Payload: Malin Space Science Systems ECAM-M50 imager

Mechanical & Structure: “6U” CubeSat form factor (~10x20x30 cm)

Propulsion: CP-1 solar sail (based on NanoSail-D2)

Avionics: Radiation tolerant LEON3-FT architecture

Electrical Power System: Simple deployable solar arrays

Telecom: JPL Iris
- 2 pairs of INSPIRE-heritage LGAs (RX/TX)
- 8x8 element microstrip array HGA (TX)

Payload Technology:
- NEA Imager (Malin)
- Star Tracker (Blue Canyon)
- RWA (Blue Canyon)
- Iris 2.0 Transponder (JPL)
- Rad Tolerant Avionics (JPL)
- LGA (JPL)
- TRAC Boom Assembly (MSFC)
- Solar Panels & HGA (MMA/AntDevCo)
- Solar Sail - Stowed (MSFC)
- Coarse Sun Sensors (SSBV)
- 18650 Lithium Batteries (SDL/Panasonic)
- RCS (VACCO)

Flight System Overview
NEA Scout Approximate Scale

Deployed Solar Sail

School Bus

Folded, spooled and packaged in here

6U Stowed Flight System
Near Earth Asteroid (NEA) Scout
• **InflateSail** is an **inflatable**, rigidizable sail for flight in Low Earth Orbit:
  • 3U CubeSat with deployed sail area of 10 m²
  • Sail supported by bistable booms
  • Inflation is driven by Cool Gas Generators (CGG): low system mass, long lifespan
Cubesail CubeSat Solar Sail Propulsion Demonstration

- The University of Illinois at Urbana-Champaign (UIUC), working with NASA MSFC, NSF, and CU Aerospace, built the flight hardware for a CubeSat-based 20 m² solar sail orbit raising demonstration mission
- Selected for flight under the NASA CubeSat Launch Initiative
Continuous Polar Observations

Sailcraft over the polar regions of the Earth
Sail tilted so the light pressure from the sunlight reflecting from it is exactly equal and opposite to the gravity pull of the Earth.
Deploy a large (>10,000 m²) solar sail near the sun to enable travel 5X faster than Voyager

Goal: Reach 250 Astronomical Units within 20 years of launch
Ground to space laser illumination of a solar sail to impart measurable $\Delta V$
My Real Motive...

INTERSTELLAR MEDIUM EXPLORATION

INTERSTELLAR PROBE 2025 - 2050

MID-TERM SAILS 2015 - 2025

NEAR-TERM SAILS 2010 - 2015

5 - 10 m DIA
- 10 g/m²

5 to 100 m DIA
- 2.5 g/m²

1-km DIA
- 0.1 g/m²

4-km DIA
- 0.1 g/m²

4.5 LY INTERSTELLAR PROBE FLYBY

1000-km DIA
- 0.1 g/m²

40 LY INTERSTELLAR PROBE RENDEZVOUS

Chemical Rocket Limit

Nuclear Rocket Limit

• INTERSTELLAR PROBE
• EUROPA LANDERS
• COMET SAMPLE RETURN

• INTERSTELLAR PROBE
• NON-KEPLERIAN EARTH ORBITS

• NEA Scout
• Solar Polar Imager
• NON-KEPLERIAN EARTH ORBITS

Solar Powered

Laser Powered

□□ = Areal Density (Sail Mass/Sail Area)
Solar Sails: A Step Toward the Stars

Honoring the late Dr. Robert Forward, the ‘father’ of laser beamed energy propulsion