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**
  - $p = hv/c$
  - $h = \text{Planck's}$, $v = \text{frequency}$, $c = \text{speed of light}$

- **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

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**Solar Photon Pressure (R=0.9)**

![Graph showing the relationship between pressure and distance to the Sun.](image)

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} \text{ m/s}^2 (0.9 \text{ millimeters/sec}^2)

- Force decreases with increasing pitch angle (or \( \theta \))

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

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

Rapid Outer Solar System Exploration and Escape

Toward Higher Performance Beamed Energy Propulsion

Heliophysics & Out of the Ecliptic Science

Earth Pole Sitting

Data Relay

Earth Observation
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
Nasa space technology Demo (2009)

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
NanoSail-D Demonstration Solar Sail

Mission Description:
- 10 m² sail
- Made from tested ground demonstrator hardware
NanoSail-D1 Flight (2008)

Launch:
- Falcon-1, flight 3
- Kwajalein, Missile Range
- Primary payload: Air Force PnPSat
NanoSail-D1 Flight (2008)

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

Rocket Failed
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

- **Adapted CP-1 sail:** 10 m² Sail Area (3.16 m side length)
- 2.2 m Elgiloy Trac Booms
- UHF and S-Band communications

**NanoSail-D2 in Orbit:** August 19, 2011 01h 19m 28s UT
Clay Center Observatory at Dexter and Southfield Schools
42.307404N, -71.172223W (WGS84)
www.claycenter.org: Focal length 12,200 mm,
Aperture = 640 mm Ritchey-Chretien
Contact: Ron Dantowitz (rondantowitz@gmail.com)

**Bus Interfacing:**
- Actuation Electronics (MSFC/UAH)
- Spacecraft Bus (Ames Research Center)
- Bus Interfaces Actuation Electronics (MSFC/UAH)
- PPOD Deployer (Cal-Poly)
- Boom & Sail Spool (ManTech SRS)
- NanoSail-D (Aluminum Closeout Panels Not Shown)

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Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS)

Liquid crystal device power was off.

Liquid crystal device power was on.
Design Features:
- High density packagability
- Controlled linear deployment
- Structural scalability
- Propellantless operation
- Meets current needs

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

83 m² ISP L’Garde Solar Sail
2004

318 m² ISP L’Garde Solar Sail
2005

1200 m² L’Garde Sunjammer Launch
2015

Sunjammer Solar Sail Demonstration Mission
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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
Near Earth Asteroid Scout

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
Flight System Overview

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

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

Telecom
JPL Iris 2.0 Transponder (JPL)
Rad Tolerant Avionics (JPL)
LGA (JPL)
Star Tracker (Blue Canyon)
NEA Imager (Malin)
Coarse Sun Sensors (SSBV)
18650 Lithium Batteries (SDL/Panasonic)
TRAC Boom Assembly (MSFC)
RCS (VACCO)
NEA Scout Approximate Scale

Deployed Solar Sail

School Bus

Folded, spooled and packaged in here

6U Stowed Flight System
Near Earth Asteroid (NEA) Scout
University of Surrey’s Inflatable Sail

- **Inflatable Sail** is an inflatable, rigidizable sail for flight in Low Earth Orbit:
  - 3U CubeSat with deployed sail area of 10 m$^2$
  - Sail supported by bistable booms
  - Inflation is driven by Cool Gas Generators (CGG): low system mass, long lifespan

![InflateSail design concept](image1)

*Fig. 1: InflateSail design concept*

![80 mg CGG](image2)

*Fig. 2: 80 mg CGG*  George C. Marshall Space Flight Center
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 m$^2$) 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 ΔV
My Real Motive…

- **Solar Powered**
- **Laser Powered**

**NEAR-TERM SAILS**
- 2010 - 2015
- 3 – 5 m DIA

**MID-TERM SAILS**
- 2015 - 2025
- 5 to 100 m DIA

**INTERSTELLAR PROBE**
- 2025 - 2050
- 500 - 800-m DIA
- 1-km DIA

**INTERSTELLAR MEDIUM EXPLORATION**
- 1.0 m DIA
- 4-km DIA

**INTERSTELLAR PROBE FLYBY**
- 4.5 LY

**INTERSTELLAR PROBE RENDEZVOUS**
- 40 LY

**TECH DEV**

- **NanoSail-D**
- **LightSail**
- **InflateSail/CubeSail**

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

**OORT CLOUD**

**INTERSTELLAR PROBE**
- 1-km DIA
- 1.0 m DIA

**EUROPA LANDERS**

**COMET SAMPLE RETURN**

**Nuclear Rocket Limit**

**Chemical Rocket Limit**

**Areal Density (Sail Mass/Sail Area)**

**4000 - 8000 m DIA**
- 1 g/m²

**1000 km DIA**
- 0.1 g/m²

**4.5 LY**

**INTERSTELLAR PROBE**

**40 LY**

**TECH DEV**
Solar Sails: A Step Toward the Stars

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