Solar Sailing:
Perspective & Mission Applications

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Topics

- Solar Sailing?
- Sail Technology & the Customer
- Mission Applications
• Solar Sailing:

Photon Pressure, Solar Wind, Fields & Particles

• $F = M a$ or $M_T a_c$

$= (2 S_o A/c) \sin^2 \theta \{\text{at } 1.0 \text{ AU}}$

where $(2 S_o/c) = 9.1265 \mu N/m^2$ or $10^{-6} \text{ kg/ms}^2$
Solar Sailing History
(Ref.: C. Garner, 2000)

ⓘ 19th Century  Early Physics
(Maxwell, Arrhenius, etc.)

ⓘ 1900-1978  Early Concepts Leading to Mission/System Design
(Tsiolkovsky, Tsander, Wiley, Garwin, Cotter, Clark, Wright, etc.)

ⓘ 1980s  Studies & Hardware
(World Space Foundation,
Solar Sail Union of Japan, U3P, etc.)

ⓘ 1988-1991  US Columbus Quincentennial Jubilee
(“Solar Sail Regatta”) 

ⓘ 1990s to Present  Significant Advances in Design, Hardware, & Advocacy
(“Znamya”, NASA M&M - NASA Codes S &R,
DLR/NASA, ISP, NOAA, NMP, etc.)
**Quest 3**

**Science Objectives**
- Explore the interstellar medium and determine directly the properties of the interstellar gas, the interstellar magnetic field, low-energy cosmic rays, and interstellar dust
- Determine the structure and dynamics of the heliosphere, as an example of the interaction of a star with its environment
- Study, in situ, the structure of the solar wind termination shock, and the acceleration of pickup ions and other species
- Investigate the origin and distribution of solar-system matter beyond the orbit of Neptune

**Mission Description (Mid-Term ~ 2010)**
- Example Mission Design
  - Delta II 7425 Launch (719 kg Cap., C₃ = 0 km²/s²)
  - Flight System Launch Mass: 564 kg
  - Solar Sail Trajectory Targeted for Nose of Heliosphere
    - 0.25 AU Solar Pass, 200 AU in 15 yrs.
- Flight System Concept
  - “Flying Antenna” Design Implementation (191 kg)
  - Sized for 30 year Operations
  - Payload: Fields & Particles + Imaging

**Technology**
- Solar Sail: < 1 g/m², 200 m radius
- DSN 70m Subnet w/ Ka-band Uplink
- Next Generation ARPS
- Next Generation System On A Chip
- Ka-band S/C Components and Phased Array
- Hot-Gas Propulsion
- Micro-S/C Technology
- Low Mass/Power Instrumentation

**Measurement Strategy**
- Measure, in situ, the properties and composition of interstellar plasma and neutrals, low energy cosmic rays, and interstellar dust
- Determine the structure and dynamics of the heliosphere with in situ measurements and global imaging
- Map the infrared emission of the zodiacal dust cloud, measure in situ the distribution of interplanetary dust, and determine the radial distribution of small Kuiper Belt objects
Sail Performance Trade: $T_f$, S/C Mass, Perihelion with Sail Technology

- Circular Sail
- Sail Jettisoned at 5 AU

Sail Radius = 300 m
Perihelion = 0.20 AU
Areal Density = 0.75 g/m²

Sail Radius = 300 m
Perihelion = 0.20 AU
Areal Density = 1 g/m²

Sail Radius$^*$ = 195.5 m
Perihelion = 0.25 AU
Areal Density = 1 g/m²

$\{R_p = 0.2 \text{ AU} \\
Rs = 170 \text{ m} \\
\sigma = 1 \text{ g/m²}\}$

* Radius corresponds to required sail area (i.e., fully filled surface, no gaps)
# SEC Roadmap Missions Enabled by Solar Sail

<table>
<thead>
<tr>
<th>Time Frame</th>
<th>Mission</th>
<th>Potential Begin C/D Phase</th>
<th>Sail Radius (m)</th>
<th>Sail Areal Density (g/m²)</th>
<th>Closest Solar Approach (AU)</th>
<th>Driving Requirements For Solar Sail (Time to Target, Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mid Term</strong></td>
<td><strong>Solar Polar Imager</strong> <strong>,</strong></td>
<td>'08 - '14</td>
<td>100</td>
<td>6</td>
<td>0.5</td>
<td>High Inclination (3-5 years)</td>
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<tr>
<td></td>
<td><strong>Space Weather Sentinel</strong></td>
<td>'08 - '14</td>
<td>100</td>
<td>6</td>
<td>0.95 (Hover)</td>
<td>Hovering (&lt; 1 year)</td>
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<tr>
<td></td>
<td><strong>(SUB-L1)</strong></td>
<td></td>
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<td></td>
<td><strong>Particle Acceleration Solar Orbiter</strong></td>
<td>'08 - '14</td>
<td>87</td>
<td>9</td>
<td>0.17</td>
<td>High Inclination (3-5 years)</td>
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<tr>
<td></td>
<td><strong>Interstellar Probe</strong> *</td>
<td>'08 - '14</td>
<td>200</td>
<td>1</td>
<td>0.25</td>
<td>High Speed (200 AU in 10-15 years)</td>
</tr>
<tr>
<td><strong>Far Term</strong></td>
<td><strong>Solar Flotilla</strong> ***</td>
<td>'15 - '25</td>
<td>~500</td>
<td>1</td>
<td>0.2</td>
<td>High Inclination/?V of &gt; 50 km/s (TBD)</td>
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<tr>
<td></td>
<td><strong>Inner Heliospheric Constellation</strong> ***</td>
<td>'15 - '25</td>
<td>~500</td>
<td>1</td>
<td>0.2</td>
<td>?V OF &gt;50 km/s (TBD)</td>
</tr>
<tr>
<td></td>
<td><strong>Geospace System Response Imagers</strong> <strong>,</strong></td>
<td>'15 - '25</td>
<td>600</td>
<td>0.5</td>
<td>1</td>
<td>Hovering (~5 years On Station)</td>
</tr>
<tr>
<td></td>
<td><strong>Outer Heliospheric Radio Imager</strong> *</td>
<td>'15 - '25</td>
<td>~300</td>
<td>0.25</td>
<td>0.25</td>
<td>High Speed (2-3 years)</td>
</tr>
<tr>
<td></td>
<td><strong>Interstellar Trailblazer</strong> *</td>
<td>'15 - '25</td>
<td>1,000</td>
<td>~0.1</td>
<td>~0.1</td>
<td>Very High Speed; ?V of ~300 km/s (2,000 AU in 30 years)</td>
</tr>
</tbody>
</table>

* New SEC Roadmap Quest #3 missions enabled by sail
** Included in preliminary mission set of new “Living With A Star” (LWS) Initiative - *Sail-enabled version*
*** Potential for inclusion in LWS Initiative
Living With A Star Program

Space Weather Research Network - Element II

http://sec.gsfc.nasa.gov/lws.htm
Sail Applicability: Planetary Missions

Mid-term ESS Roadmap missions currently baseline Solar Electric Propulsion (SEP), but flight time, payload mass, and end-to-end cost substantially benefit from solar sail availability.

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<tr>
<td>Mid Term</td>
<td>CNSR</td>
<td>2008</td>
<td>160</td>
<td>5</td>
<td>~1.0</td>
<td>Flight Time &amp; Target</td>
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<tr>
<td></td>
<td>Neptune Orbiter</td>
<td>2007</td>
<td>200</td>
<td>~5</td>
<td>~1.0</td>
<td>Flight Time (&lt; 10 years)</td>
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<tr>
<td></td>
<td>Titan Explorer</td>
<td>2007</td>
<td>200</td>
<td>~5</td>
<td>~1.0</td>
<td>Flight Time (&lt; 5 years)</td>
</tr>
<tr>
<td></td>
<td>Saturn Ring Observer</td>
<td>2007</td>
<td>200</td>
<td>~5</td>
<td>~1.0</td>
<td>Flight Time (&lt; 5 years)</td>
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<tr>
<td></td>
<td>Europa Lander</td>
<td>2007</td>
<td>200</td>
<td>~5</td>
<td>~1.0</td>
<td>Flight Time (&lt; 2 years)</td>
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<tr>
<td></td>
<td>Venus Sample Return</td>
<td>2007</td>
<td>100</td>
<td>~10</td>
<td>~0.7</td>
<td>Flight Time &amp; Sample Size (&lt; 5 years)</td>
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<tr>
<td>Far Term</td>
<td>Titan Sample Return</td>
<td>2015+</td>
<td>~300</td>
<td>~2</td>
<td>~1.0</td>
<td>Flight Time &amp; Sample Size</td>
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<tr>
<td></td>
<td>Triton Sample Return</td>
<td>2015+</td>
<td>~400</td>
<td>~2</td>
<td>~0.2</td>
<td>Flight Time &amp; Sample Size</td>
</tr>
</tbody>
</table>