AA283
Aircraft and Rocket Propulsion

Space Sailing
Properties of light

- Momentum
  \[ p = \frac{h}{\lambda} \]

- Energy
  \[ E = h\nu = h\frac{c}{\lambda} = pc \]
  \[ h = 6.63 \times 10^{-34} \text{ Joule – sec} \]
  \[ c = 3.00 \times 10^8 \text{ M / sec} \]
Properties of light, cont’d

- Energy flux

\[ W = \left[ \frac{\text{Joules}}{\text{photon}} \right] \cdot \left[ \frac{\text{photons}}{\text{M}^2 \cdot \text{sec}} \right] = h\nu \cdot \left[ \frac{\text{photons}}{\text{M}^2 \cdot \text{sec}} \right] = \left[ \frac{\text{Joules}}{\text{M}^2 \cdot \text{sec}} \right] \]

At the earth's radius from the sun

\[ W_{\text{earth}} = 1368 \text{ Joules} / \text{M}^2 \cdot \text{sec} \]

\[ W_{\text{earth}} / c = 4.56 \times 10^{-6} \text{ N} / \text{M}^2 \]
Properties of light, cont’d

- Light pressure on a perfectly reflecting surface normal to the incidence direction of light
  \[ P = \frac{2W}{c} \]

  At the earth's radius
  \[ P_{\text{earth}} = 9.12 \times 10^{-6} \text{ N/M}^2 \]

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

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

\[
\frac{F_T}{\left(2\frac{W}{cA}\right)} = \frac{(1 - rs) \cos \alpha \sin \alpha}{2}
\]

where
- \( r \) = reflectivity of the front surface for the incident radiation
- \( s \) = specular reflection coefficient
- \( e_f, e_b \) = 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.

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

where \( m_{\text{total}} \) is the total mass of the ship and \( \eta \) is the sail efficiency (typically about 0.9). The key factor limiting the acceleration available is the mass loading of the sail.

\[ \sigma = \frac{m_{\text{total}}}{A} \]

The lowest available mass loading using currently available materials is about 5 gm/M²
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=pjY2V5cDpVU5cY3qPtYv3wNXstzeSAAW
NanoSail-D, Jan 2011
A Recent Private Effort – Cosmos 1
# Mass Estimates

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

<table>
<thead>
<tr>
<th>DESIGN</th>
<th>HR-820</th>
<th>Clipper</th>
<th>Ultralight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sail film</td>
<td>1821</td>
<td>824</td>
<td>162</td>
</tr>
<tr>
<td>Reflective layer</td>
<td>173</td>
<td>157</td>
<td>157</td>
</tr>
<tr>
<td>Emissive coating</td>
<td>58</td>
<td>52</td>
<td>52</td>
</tr>
<tr>
<td>Sail tendons</td>
<td>38</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Mast and booms</td>
<td>760</td>
<td>400</td>
<td>80</td>
</tr>
<tr>
<td>Boom support stays</td>
<td>130</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>Stay reels and tensioners</td>
<td>50</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Boom positioning hardware</td>
<td>80</td>
<td>70</td>
<td>50</td>
</tr>
<tr>
<td>Sail form control mechanisms</td>
<td>50</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Contingency (20%)</td>
<td>222</td>
<td>135</td>
<td>51</td>
</tr>
<tr>
<td>TOTAL MASS, kg</td>
<td>3382</td>
<td>1843</td>
<td>677</td>
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</table>

<table>
<thead>
<tr>
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<th>Clipper</th>
<th>Ultralight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of sail, m²</td>
<td>641,200</td>
<td>580,000</td>
<td>580,000</td>
</tr>
<tr>
<td>Sail loading, σ, g/m²</td>
<td>5.27</td>
<td>3.18</td>
<td>1.17</td>
</tr>
<tr>
<td>ac upper limit, m/s²</td>
<td>1.54</td>
<td>2.55</td>
<td>6.94</td>
</tr>
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</table>

*a excluded from contingency  
bexcluding operations module and payload
An Ultralight Concept

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

FIGURE 2.1 Earth Escape Times From Various Orbits.
What is L2 Libration Point?

L1  L2  L3  L4  L5

Rotating Coordinate Frame

Gravitational potential

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

CENTRIFUGAL = GRAVITATIONAL
Feasible Trajectory

Units in Earth-L2 Distance

\[ a_0 = 0.1 \text{ mm/s}^2 \]
Trajectory in the modified potential well

y (AU)

x (AU) x10-3

y

L2

To Earth

x

L2
Mission Toward the Sun
## TABLE 2.1 Inner Planets Missions Summary.

<table>
<thead>
<tr>
<th>Sail Size m</th>
<th>Mercury Rendezvous</th>
<th>Venus Rendezvous</th>
<th>Mars Rendezvous</th>
<th>Mars Aerobrake</th>
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<tr>
<td></td>
<td>days</td>
<td>tons</td>
<td>days</td>
<td>tons</td>
</tr>
<tr>
<td>800a</td>
<td>600</td>
<td>9.4</td>
<td>200</td>
<td>1.4</td>
</tr>
<tr>
<td>900</td>
<td>19</td>
<td></td>
<td>270</td>
<td>4.6</td>
</tr>
<tr>
<td>1200</td>
<td>28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000b</td>
<td>600</td>
<td>66</td>
<td>200</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>900</td>
<td>124</td>
<td>270</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>1200</td>
<td>184</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \sigma_a = 5.0 \, \text{g/m}^2 \quad \sigma_b = 3.0 \, \text{g/m}^2 \quad \text{(excluding payloads)} \]
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

FIGURE 7.6 Profile of an Interstellar Fly-By Probe. (R.L. Forward)
Mission example - one-way interstellar flight

TW - Terawatts
Mission example
round-trip
interstellar flight

FIGURE 7.8 Profile of a Roundtrip Voyage to Epsilon Eridani. (R.L. Forward)
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 = $10^5$ m/sec$^2$
- Force = $10^2$ kg-m/sec$^2$
- Sail Area = 10 m$^2$

**Required light pressure**

\[
P = \frac{2W}{c} = 10 \text{ N} / \text{m}^2
\]

\[
W = 1.5 \times 10^9 \text{ J} / \text{m}^2 - \text{sec}
\]

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.

\[
W_{\text{dissipated}} = 1.5 \times 10^4 \text{ J} / \text{sec}
\]

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

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

\[
\frac{dT}{dt} = 3.58 \times 10^3 K / \text{sec}
\]

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

\[
r = a \frac{t^2}{2} = 0.5 \times 10^5 \times 10^6 = 5 \times 10^{10} \text{ m} = 0.33 \text{AU}
\]