Cosmic Squid: A Giant Spinning CubeSat Solar Sail

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Why Go Small?  
(i.e. CubeSat Solar Sails)

• Want to launch sooner than 2030

• Want to keep costs low

• Want more than one shot into the ISM

• Want a continuous series of probes into the ISM/to KBOs
Solar Sails

- “Traditional” architecture: four booms, four sail quadrants
- Deployed size limited by boom packaging volume, not sail packaging
- Can increase area/mass (or char. accel.) by removing booms
- Spin to deploy + preload
Cosmic Squid

- 0.1 m × 0.2 m × 0.3 m 6U CubeSat
- Ø 0.1 m × 0.3 m Stowed Sail
- 3 × 1U CubeSats

Deployed sail
Sail held in tension, deployed by spin
Sail Packaging → Sail Size

\[ V_p = \pi R_p^2 H_p = 0.00236 \text{ m}^3 \]
\[ V_s = \eta V_p \]
\[ A = \frac{V_s}{h} \]

\[ L^2 = 3r^2 \]
\[ A = \frac{\sqrt{3}}{4} L^2 = \frac{3\sqrt{3}}{4} r^2 \]

“Small”
5 um thick, 70% pack. eff. 330 m²

“Big”
2.5 um thick, 90% pack. eff. 850 m²
Size Comparison

NanoSail-D (3.5 m$^2$, 5 kg)

LightSail (5.6 m$^2$, 5 kg)

NEA Scout (9.1 m$^2$, 12 kg)

Lunar Flashlight (9.1 m$^2$, 12 kg)

IKAROS, (14.1 m$^2$, 300 kg)

Cosmic Squid 330 - 850 m$^2$, 11 - 12 kg
Performance

- Mass of each 1U CubeSat $m_u = 2 \, kg$
- Sail mass $m_s = V_s \times 1420 \, kg/m^3 = 2.4 \, - \, 3.0 \, kg$
- Total accelerated mass $m = (3m_u + m_s) \times 1.3 = 11 \, - \, 12 \, kg$
- Characteristic acceleration $a_c = (8.3 \, \mu Pa) A/m$

Char. accel. depends mainly on material thickness

"Small": 0.25 mm/s$^2$ (37 g/m$^2$)

"Big": 0.60 mm/s$^2$ (14 g/m$^2$)
Optimal Solar Sail Trajectories for Missions to the Outer Solar System

Bernd Dachwald*

German Aerospace Center (DLR), Cologne, Germany
Neptune Flyby
Non-Ideal Solar Sail with Characteristic Acceleration of 1.0 mm/s²

Limitation of Sail Temperature

$\min = 0.175 \text{ AU}$
$T_{\max} = 564 \text{ K}$

Flight Time = 1982 days

Dachwald, Optimal Solar Sail Trajectories to the Outer Solar System, 2004
Escape Velocities and Flight Times

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Spin Rate

Centripetal force on one tip CubeSat: \( m_u \omega^2 r \)
Force profile along diagonal: \( \sqrt{3} P x \)
\( P \) is the pre-load per unit length of membrane
Equating these forces at the tip:
\[
\sqrt{3} P r = m_u \omega^2 r \\
\Rightarrow \omega^2 = \frac{\sqrt{3} P}{m_u} \\
P \approx 0.05 \, Nm^{-1} \\
m_u = 2 \, kg \\
\omega = 0.2081 \, s^{-1} \approx 2 \, rpm
\]

Maximum tension: \( T_{\text{max}} = \sqrt{3} Pr \approx 4 \, N \)
Attitude Control

Vanes on each TipSat can be feathered
Provide variable SRP at each corner

Slew rate:
\[ \omega_p = \frac{\tau}{I_\omega} = \frac{A_{vane}P_{SRP}r}{I_\omega} \approx 2.46 \times 10^{-5} \text{s}^{-1} \text{ at } 0.1 \text{ AU} \]

With
\[ A_{vane} = 1 \text{ m}^2 \]
\[ r = 25 \text{ m} \]

Time for 90° slew: 18 hours
Deployment Concept

Deployment by spinning

Sail tensioned by centrifugal force, use the 3 1U CubeSats as end masses
Power

- **Option 1: PV**
  - 50 W array produces
    - 0.02 W at 50 AU
    - 0.005 W at 100 AU
  - Hibernation/Sleep/Short burst science + comm.

- **Option 2: RHU + Thermoelectrics**

- **Option 3: Betavoltaics**
Communication

• Option 1: X-Band/UHF down/uplink
• Option 2: Laser comm.
  – Synergy with imaging systems
System Architecture “Precursor”

- **Tip 1 (Communication):**
  - UHF, X-Band Radio (0.3 U)

- **Tip 2 (Command):**
  - Star Tracker (0.3 U)
  - CD&H (0.2 U)
  - Sail Monitor Camera (0.1 U)

- **Tip 3 (Science):**
  - Magnetometer / Imager (0.4 U)

- **Common for each Tip:**
  - EPS + Battery (0.2 U)
  - Deployable ACS tip vane (0.2 U)
  - Wireless comm. to other tips
System Architecture “ISM Scout”

• Tip 1 (Communication):
  - Optical Comm./Camera (0.8 U)

• Tip 2 (Command):
  - Star Tracker (0.3 U)
  - CD&H MPU (0.2 U)
  - UHF/X-Band Radio (0.3 U)

• Tip 3 (Power):
  - Nuclear Magic Power (0.8 U)

• Common for each Tip:
  - ACS tip vane (0.1 U)
  - Deployable ACS tip vane (0.2 U)
  - Wireless comm. to other Tips
Take Aways

- Can make 0.60 mm/s², 14 g/m² sails now
- 200 AU in 35 years, 7 AU/year
  - Haumea/KBO in 10 years
- Can starting building and launching precursors now
- Low cost to develop, low cost to launch
- Multiple probes to spatially and temporally sample ISM/heliopause/KBOs
Questions, Risks, and Challenges

• Lifetime
  – Other deep space CubeSat missions will address this issue
    • INSPIRE, NEA Scout, Lunar Flashlight, MarCO, Europa CubeSats?

• Survival
  – CubeSat temperature at closest solar approach

• Deployment
• Communications
• Power